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Special Issue: Recent Advance on Wireless Networks

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Contents

Special Issue on Recent Advance on Wireless Networks

Guest Editorial

Wireless networks technologies had already facilitated people's daily life for more than 50 years. But, still, many new emerging applications, e.g., games, multimedia content disseminations, are motivating the further development in various areas of wireless networks. It is our great pleasure to bring you this special issue of Journal of Communications on "Recent Advance on Wireless Networks", which aims at presenting innovative and significant research on the design, implementation, usage, and evaluation of wireless networks, applications, and novel techniques.

We are deeply grateful of receiving many excellent submissions to this special issue. The reviewing and revision process for all papers was rigorous and thorough. The accepted papers fall into various areas of wireless networks design. In the following, we briefly summarize the papers included in this special issue.

The increasing number of embedded devices in the vision of the Internet of Things enables the existing Web with smart things. Conventional web services are enriched to a new way to narrow the gap between the virtual world and the physical world. In the first paper, "The Web of Things: A Survey" by Deze Zeng, Guo Song, Zixue Cheng, the architecture and a number of key enabling technologies of Web of Things are elaborated. The authors further provide illustration for a number of pioneer open platforms and prototypes, and summarize the most recent research achievements. Some systematic comparisons are also provided to highlight the insight in the evolution and future of Web of Things. A number of open challenging issues are also discussed that shall be faced and tackled by research community.

Limited energy supply in wireless sensor networks causes the biggest constraint for sensor networks applications. In the second paper, "Power Saving and Energy Optimization Techniques for Wireless Sensor Neworks" by Sandra Sendra, Jaime Lloret, Miguel García, José F. Toledo, the authors present a survey of power saving and energy consumption optimization techniques for wireless sensor networks. This survey focuses on introducing the most well known available methods to readers, and mainly analyzes these methods based on four points of view: Device hardware, transmission, MAC protocols and routing protocols.

In the third paper, "Secure Localization in Wireless Sensor Networks: A Survey" by Jinfang Jiang, Guangjie Han, Chuan Zhu, Yuhui Dong, Na Zhang, sensor nodes localization in wireless sensor networks is studied from the viewpoint of security. The paper shows how the localization process can be attacked in a number of ways, and what kinds of methods can be used to solve the security problem. The known attacks in secure localization are classified into two categories: 1) attacks on nodes and 2) attacks on information. Based on these two kinds of attacks, the secure localization schemes are discussed and reclassified into two categories: 1) secure node authentication (SNA) and secure information verification (SIV). Finally, the paper presents the open research problems of secure localization in WSNs.

The fourth paper, "A Real-time Two-way Authentication Method Based on Instantaneous Channel State Information for Wireless Communication Systems" by Xiangyu Lu, Yuyan Zhang, Yuexing Peng, Hui Zhao, Wenbo Wang, presents a simple but effective method to authenticate the legitimate transmitter in physical layer by use of channel state information (CSI). The proposed method is based on three features of the channels: 1) privacy can differentiate transmitter; 2) randomness can enhance the security by changing the authentication code on time with the change of the CSI; and 3) continuous changes on time- and frequency-domain can be used to predict the CSI reliably within channel's coherent time and bandwidth. With the widely applied pilot-aided channel estimation method and the simple channel prediction algorithm, the proposed method determines whether the current message is sent by the same transmitter by comparing the estimated CSI of the current message with the predicted CSI of the previous message, and the hypothesis testing and mutual information measure are used for authentication determination. By implementing the proposed method at both ends of the communication pair, the two-way real-time per-message authentication is achieved for wireless communication systems.

It is the truth that many regions of the world do not have access to the Internet due to lack of proper communication infrastructure, especially in the developing countries. In the fifth paper, "Delay Tolerant Network on Android Phones: Implementation Issues and Performance Measurements" by Rerngvit Yanggratoke, Abdullah Azfar, María José Peroza Marval, Sharjeel Ahmed, the authors consider the Delay Tolerant Network (DTN) as a promising solution to solve the problem of lack of connectivity for communications. The authors make the android phones to be DTN capable and carry messages with a DTN boundless. The implementation of DTN on Android phone is described in this paper, and performance measurements including DTN bandwidth and battery consumption are also given.

The study of security protocols, especially their performance, in WLAN is considered as an important research problem. The sixth paper, "A New Evaluation Model for Security Protocols" by Chao Yang, Jianfeng Ma, mainly proposes a novel security protocol simulation architecture and a simulation extending method for simulating security protocols of WLAN. The authors then set up a simulation platform for modeling security protocols based on OPNET. By having simulation on the platform, the authors demonstrate the feasibility and correctness of this new evaluation model.

The seventh paper, "On-Demand QoS Multicast Routing for Triple-Layered LEO/HEO/GEO Satellite IP Networks"

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by Zhizhong Yin, Long Zhang, Xianwei Zhou, introduces a novel triple-layered satellite network architecture including 1) the Geostationary Earth Orbit (GEO), 2) the Highly Elliptical Orbit (HEO), and 3) the Low Earth Orbit (LEO) satellite layers, which provides the near-global coverage with 24 hour uninterrupted over the areas varying from 75° S to 90° N. Based on this network architecture, the authors propose an on-demand QoS multicast routing protocol for satellite IP networks. Simulation results demonstrate the enhancement of the proposed new protocol compared with conventional non-QoS shortest path tree strategy.

We would like to express our sincere gratitude to the reviewers who provided highly constructive feedbacks. We also thank the staff at the JCM Academy Publisher for their efficient job in handling the manuscripts. Last but not the least, we would extend our sincere appreciation to the Editor-in-Chief of the Journal of Communications, Dr. Haohong Wang, for providing this opportunity and facilitating preparation of an excellent journal special issue.

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The Web of Things: A Survey
(Invited Paper)

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Abstract— **In the vision of the Internet of Things (IoT), an increasing number of embedded devices of all sorts (e.g., sensors, mobile phones, cameras, smart meters, smart cars, traffic lights, smart home appliances, etc.) are now capable of communicating and sharing data over the Internet. Although the concept of using embedded systems to control devices, tools and appliances has been proposed for almost decades now, with every new generation, the ever-increasing capabilities of computation and communication pose new opportunities, but also new challenges. As IoT becomes an active research area, different methods from various points of view have been explored to promote the development and popularity of IoT. One trend is viewing IoT as Web of Things (WoT) where the open Web standards are supported for information sharing and device interoperation. By penetrating smart things into existing Web, the conventional web services are enriched with physical world services. This WoT vision enables a new way of narrowing the barrier between virtual and physical worlds. In this paper, we elaborate the architecture and some key enabling technologies of WoT. Some pioneer open platforms and prototypes are also illustrated. The most recent research results are carefully summarized. Furthermore, many systematic comparisons are made to provide the insight in the evolution and future of WoT. Finally, we point out some open challenging issues that shall be faced and tackled by research community.**

Index Terms— **Internet of Things, Web of Things, Survey**

I. Introduction

Ubiquitous computing (a.k.a., pervasive computing), which has been extensively studied for many years, is experiencing radical changes recently as the physical world devices, e.g., home appliances and industrial machines, are becoming smart thanks to the progress in computing technology development. In parallel, the communication techniques also make much progress recently. Internet access will very likely become commonly accessible by those "smart things", motivating the concept of *Internet of Things (IoT)*.

IoT is regarded as the next big possibility and challenge to the Internet. The Internet will be no longer just a network of computers, but will potentially involve trillions of smart things with embedded systems. IoT will greatly increase the size and scope of current Internet, providing new design opportunities and challenges. Internet with smart things is generally viewed as a constrained IP network with limited packet size, high degree of packet loss, and even intermittent connectivity and characterized by severe limits on throughput, available power, and particularly the complexity that can be supported. A variety of recent research activities have been launched to address those challenging issues, from the technological to the social aspects. In particular, a central issue focuses on how to make a full interoperability of interconnected devices possible, to provide them with an always higher degree of smartness by enabling their adaptation and autonomous behavior while guaranteeing trust, privacy, and security [1].

Currently, the web has already become the major medium of communication in today's Internet. On the other hand, tiny web server technology has been researched for decades and now various embedded tiny web servers are available. More specifically, web services have been proven to be indispensable in creating interoperable applications on today's Internet. Smart things with embedded web servers can be abstracted as web services and seamlessly integrated into the existing web. It is natural to reuse existing web technologies and standards to unify the cyber-world and the physical-world. As a result, one research trend treats IoT as *Web of Things (WoT)*. As existing web technologies can be reused and adapted to build new applications and services with participation of smart things. This yields higher flexibility, customization and productivity. In brief, different from traditional view of IoT which gives everyday device an IP address and makes them interconnected on the Internet, WoT enables them to speak the same language, so as to communicate and interoperate freely on the Web.

The WoT vision depicts a view where a collection of web services that could be discovered, composed and executed. Thus enriches the scope of traditional web services by promoting the web from only cyber-world services to both cyber-world and physical-world services. Furthermore, WoT actually is an ecosystem of services not only about adding more services in but more about orchestrating various kinds of services in a graceful manner, making the services more human-centric and intelligent.

Let us use an example to illustrate the concept of WoT. After the nuclear leakage accident happened at Fukushima Dai-ichi Nuclear Power Plant on 11 March, 2011 after the devastative tsunami, people have concerned the radiation level at each places. A Japan Geigermap has then been developed by integrating Google Map web service and geiger counter readings. It provides a new web service which visualizes the crowd-sourced radiation geiger counter readings across Japan on a Google map. A snapshot is taken as shown in Fig. 1[1].

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[1] http://japan.failedrobot.com/

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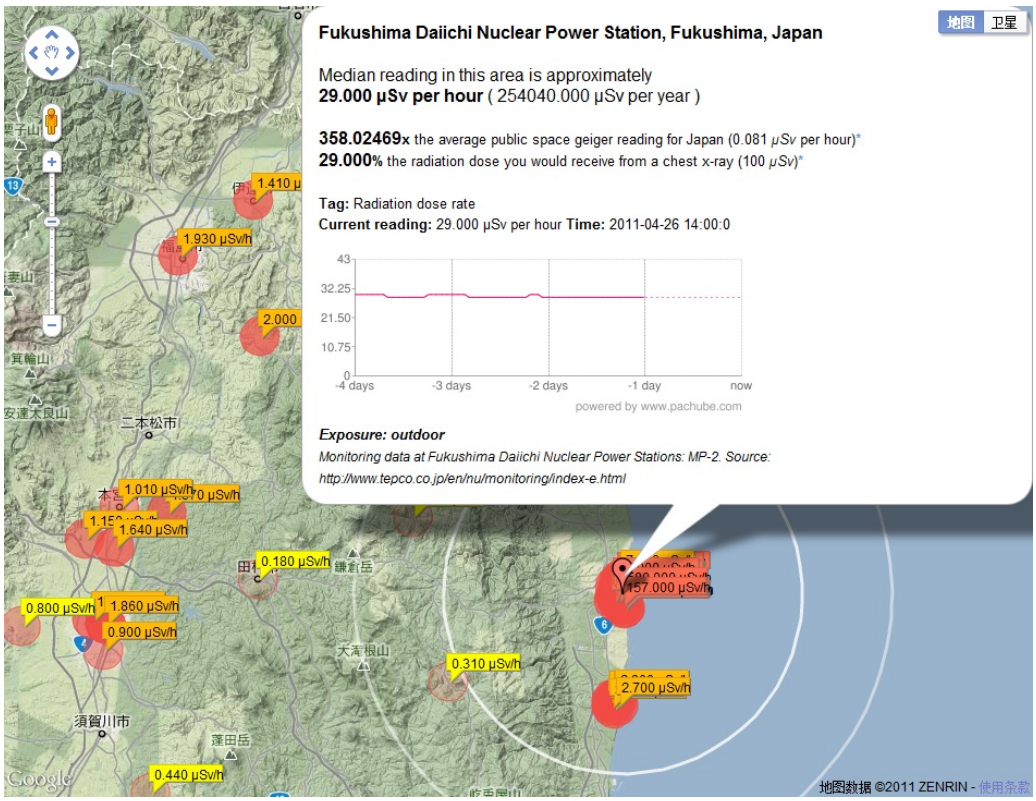

Figure 1. Snapshot of Geigermap around Fukushima Daiichi Nuclear Power Station, Fukushima, Japan

The Japan Geigermap is only a simple and straightforward example of WoT about data sharing. The power of WoT is far more beyond data sharing. The development of WoT is still at an initial stage, and there are still many issues to be tackled to fully exploit the potential of WoT. The inclusion of services from smart things makes WoT different from the traditional web. For example, the embedded tiny web servers are not as powerful as traditional ones. The service may not be always available as traction-al one due to the intermittent connectivity caused by duty cycle. Furthermore, traditional web protocols might not be suitable to provide services in the low-power and lossy networks consisting of resource constrained smart things. All these problems pose new research challenges and call for new efficient solutions. Many research activities have been actively conducted toward the solutions that fulfill such highlighted technological requirements. The main object of this survey is to give readers an overview of WoT, the state of WoT development, the potential of WoT, and the key issues that remain to be tackled. The remainder of the paper is organized as follows. In Section II, we briefly give a glance at the motivation as well as the basic concept of WoT. In Section III, we introduce the architecture about WoT including the integration methods and the web service paradigms. In Section IV, the main enabling technologies to WoT are presented. In Section V, some existing open WoT platforms and WoT application prototypes are introduced. Section VII concludes this survey work.

II. Overview of the Web of Things

The communication for smart things has been studied for decades. Several different technologies and standards have been proposed in this area. Making the smart things interconnectable such that bits can be transferred between devices is only the first step, more works are expected to make smart things interoperable such that they are understandable with each other. Interoperability is particularly essential, and a must, to build system with various devices, especially those from different manufacturers. Let us first review some of those major technologies about the interoperability issue.

Universal Plug and Play (UPnP) is a suite of networking protocols extended from the idea of the original Plug and Play to a networked system context. It was promoted by the UPnP forum[2] mainly for personal networks devices to discover each other's presence and further to establish connections on the network. UPnP is based on established protocols and standards, such as TCP/IP, UDP, HTTP, HTTPU (HTTP over UDP), SOAP, WSDL, etc. Currently, UPnP is the most popular solution for personal network implementation. However, UPnP has several drawbacks [2]:

1) There is no authentication protocol proposed for UPnP. Any devices are allowed to configure the other devices of the personal network, without any user control, resulting in a critical security issue when the smart things are available on the Internet.

[2]http://www.upnp.org

2) UPnP is not strictly standardized as some UPnP devices are based unstandardized protocols such as HTTPU, restricting its universal interconnection somehow.
3) UPnP is inapplicable to some resource-constrained devices because it normally uses a lot of heavy protocols (e.g., SOAP, WSDL, etc.) involving complex processing.

Alternatively, the JXTA technology[3] is proposed as a solution for peer-to-peer applications design, enabling interconnections of heterogeneous devices into a same network. Later on, a C language based version, JXTA-C was proposed in order to embed JXTA into resource-constrained devices [3]. Unfortunately, JXTA protocols have not been standardized and have not been widely accepted for embedded devices in industry either.

One trend is integrating the devices into the Web. It has been found that the web severs can be built in a size of only a few KBs [2], [4], [5]. It is possible to integrate the web servers into many devices directly. Those devices then proactively serve their functionality over the Web. Using the free, open, flexible, and scalable Web as the universal platform to integrate smart devices outperforms all other solutions mentioned earlier in terms of easiness, flexibility, customization and security. This idea has attracted much attention from both academia and industry, especially after the IoT concept emerges recently.

The web browsers have been available on almost any platform, from computers to PDAs, smart phones, and tablets, and become the de facto standard user interface to a variety of applications. The Web-enabled applications can be accessed from any location provided there is an Internet connection. Applied to embedded systems, web technologies can offer platform-independent interfaces such that the end-users do not need to install specific softwares and drivers for different devices. Also, developers do not have to tediously develop different softwares and drivers targeting different platforms for one thing. The Web provides a one-for-all solution. An overview of of WoT vision is shown in Fig. 2.

Furthermore, although devices become programmable, providing great opportunities to create more innovative and powerful applications, development, especially composition, of applications that run on top of those physical devices is still a cumbersome process as it requires extensive expert knowledge (e.g. specific APIs in a specific programming language) about all different physical devices. This more or less constrains development of smart things based services. Fortunately, existing web technologies (e.g. mashup), which previously targeted for cyber-world web services can be reused for application development with the participation of physical smart things provided that they can be abstracted as web services. By reusing existing web technologies, the expenses for additional infrastructure and overall implementation time can be minimized. These technologies can promote the progress of IoT significantly.

[3]http://java.sun.com/othertech/jxta/

III. Web-oriented Architecture

A general architecture of WoT is illustrated in Fig. 2. Reusing existing web architecture as the basic platform, some smart things act as web servers and directly provide web services on the web. WoT has a flat architecture, compared to the traditional server-client architecture. Two issues need consideration in such an architecture: how to integrate the physical things to the web and how to make the physical things provide composable and interoperable web services.

A. Integrating Smart Things to the Web

As shown in Fig. 2, there are two optional methods to integrate things to the Web: direct integration and indirection indirection [6]. For example, the home appliances in the figure can be viewed as directly integration while the RFIDs are indirectly integrated through a RFID reader with an embedded server. Usually a system may not solely rely on a single method, but may use both methods as a hybrid way.

1) Direct integration: To directly integrate things to the Web, it is first required that all the things must be addressable, i.e. everything must have an IP address, or must be IP-enabled when connected to the Internet. WoT also requires connectivity and interoperability at the application layer. Web server shall be embedded such that things can understand each other through the web language specified by web standards. With the development in both communication and computation technologies, it is likely that more devices will become IP-enabled and can be embedded with web server. Those devices can be directly integrated into the Web and abstracted as web services. Thus, they can directly communicate with people from any terminal with a standard web browser. Other devices can also interoperate with them through standard web operations, e.g. GET and POST.

Many pioneer solutions have been provided to directly integrate smart things to the Web. Guinard et al. [6] present a prototype directly integrating IP-enabled Sun SPOT with web server. Each device in their prototype offers its functionality through a web API. Akribopoulos et al. [7] introduce an architecture where all the small programmable objects are integrated through web services where the Sun SPOT applications and sensor data are uniformly exposed through web services. They avoid employment of additional gateways by using TCP/IP protocol in the devices directly. Also a prototype is implemented using Sun SPOT. Ostermaier et al. [8] present a prototype using programmable low-power WiFi modules for connecting things directly to the web. They leverage the ubiquity of IEEE 802.11 access points and the interoperability of the HTTP protocol. Using a loosely coupled approach, they enable seamless association of sensors, actuators, and everyday objects with each other and with the Web. All those works demonstrate convincingly that

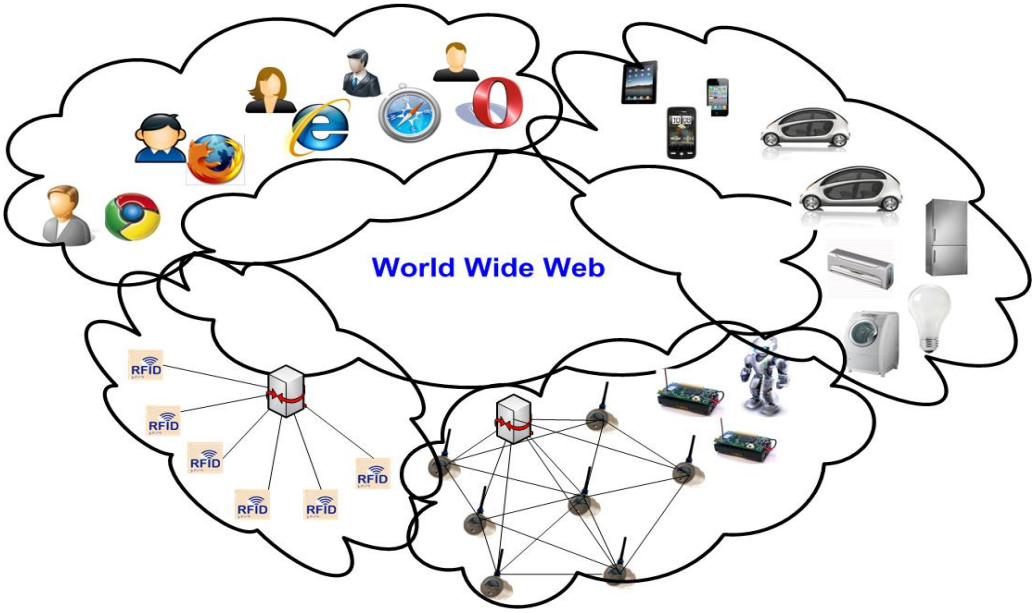

Figure 2. Overview of Web of Things

it is possible to integrate smart things directly into the Web now.

2) Indirect integration: However, not all devices can be powerful enough to be embedded with web server. Some devices are with too limited resource to allow web server embedded, such as RFID tags. On the other hand, sometimes there is no need to directly integrate all the smart things (e.g. sensor nodes in a sensor network) into the Web in the consideration of cost, energy and security. For both cases, a different pattern, indirect integration, can be adopted. In this pattern, an intermediate proxy locates between the smart things and the Web. The proxy is usually called smart gateway. To the smart things (inward), the smart gateway communicate with the smart things (e.g. reading from RFIDs) and therefore shall understand the proprietary protocols of the smart things; to the Web (outward), it abstracts the proprietary protocols or native APIs of smart things and offer uniform accessible web APIs over the Web.

Several prototypes with smart gateways to directly integrate smart things into the Web have been published in the literature. Hwang et al. [9] design a smart sensor gateway for sensing data aggregation and sensor network management. To enable using the web browser to efficiently query and manage the sensor network, the sensor gateway is embedded with a web server supporting HTTP1.1 protocol. The authors also implemented Java applet for dynamic and efficient data exchange. Trifa et al. [10] implement smart gateway for web-based interaction and management of embedded devices. The gateway enable accessing to sensor networks through a lightweight web service interface. In [11], the authors build an EPC Network prototype by using virtualization, cloud computing and web technologies. In their prototype, the RFID reader behaves like a smart gateway which locates between the cloud server and RFID tags.

B. Web service paradigms

As we are able to integrate different smart things with various capabilities intto the Web, the next logical step we shall consider is how to abstract those devices into reusable web services other than simple static or dynamic web pages. Web services are defined by the World Wide Web Consortium (W3C) as a software system designed to support interoperable machine-to-machine (M2M) communications over a network. As W3C states, there are two major paradigms of web services: REST-compliant Web services and arbitrary Web services [12]. The primary purpose of the service is to manipulate web resources using a uniform set of "stateless" operations in the former one while using an arbitrary set of operations in the latter one. Both paradigms can be adopted by smart things or smart gateways.

1) WS- Architecture:* It is usually referred as WS-* for Web Services that use Simple Object Access Protocol (SOAP) messages with an Extensible Markup Language (XML) payload and a HTTP-based transport protocol to provide remote procedure-calls (RPCs) between clients and servers. It has been popular in traditional enterprises and widely used in enterprise machine-to-machine (M2M) systems. The key technologies of WS-* are SOAP, Web Service Description Language (WSDL), Universal Description Discovery and Integration(UDDI) and Business Process Execution Language (BPEL).

SOAP [13] is an XML-based protocol to let applications exchange information over HTTP. A SOAP interface is typically designed with a single URL that implements several RPCs methods, which define a message architecture and format, hence providing a rudimentary processing protocol. The top-level XML element of SOAP message is called *envelop*, which includes two XML elements: *header* and *body*. The *header* specifies routing and Quality of Service (QoS) configuration while the *body* contains the

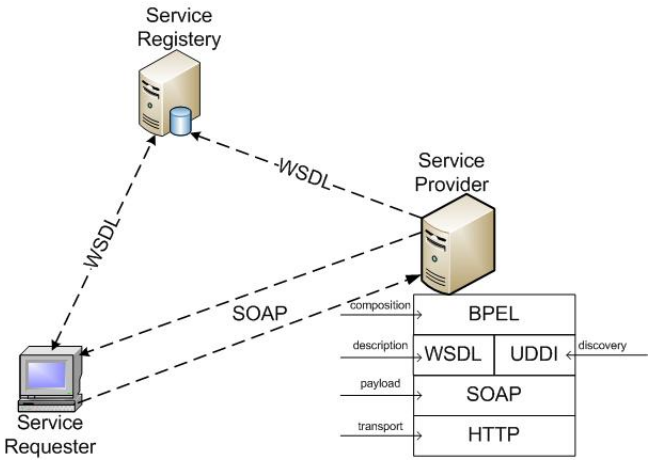

Figure 3. WS-* workflow and Protocol Stack

payload of the message indicating the interoperations.

WSDL [14] is an XML-based language describing Web services as a collection of communication end points that can exchange messages. In other words, a WSDL document describes a Web service's interface and provides users with a point of contact. The SOAP messages and sequences are abstractly described by WSDL. A WSDL *port type* contains an abstract set of operations supported by endpoints. The WSDL *binding* links the set of abstract operations with concrete protocol and data format specification for a particular port type. WSDL describes service interface, which are independent of the service implementation endpoint and how the services are implemented.

UDDI [15] is a platform-independent, XML-based registry framework for describing and discovering worldwide Web services. It can be viewed as a directory of WSDL-described web services. Web services can be registered and located in the directory. It can be requested using SOAP messages to provide access to WSDL documents, which describe the protocol bindings and message formats required to interact with the web services listed in its directory.

BPEL [16] defines a notation for specifying process behavior based on interactions of Web services. Web service interactions can be described in two ways: executable processes and abstract processes. Both can be modeled by BPEL. Executable processes model actual behavior of a participant as interactions while abstract processes describe observable behavior and/or process template. BPEL extends the WS-* interaction model to enable business transactions. BPEL defines an interoperable composition model that enable the extension of automated process integration both within and between businesses.

Fig. 3 shows the WS-* workflow as well as the protocol stack. Let us first look at the protocol stack. One may first notice that HTTP performs as transport protocol at the lowest level. Above that, SOAP handles the interaction between services. WSDL and UDDI concern the description and discovery of services at the next higher level. BPEL actually deals with the composition of services at the highest level. Now we look at how these technologies work in a WS-* workflow. Suppose all the available services have registered in the Service Registry. Service Requestor sends a service lookup request described by WSDL to Service Registry. If a suitable candidate service is found, its description is returned to the Service Requestor. Then Service Requester and Service Provider establish connectivity and communicate with each other using SOAP according to the description.

The use of WS-* for smart things dates back many years ago. A Service-Oriented Device Architecture (SODA) [17] is proposed to integrate a wide range of physical devices into distributed IT enterprise systems. In SODA, all the sensors and actuators are exposed as abstract business Web services to the programmers. A bus adapter locates in the boundary between the cyber-world and physical world realms and talks to proprietary and standard device interfaces but presents an uniform Service-Oriented Architecture (SOA) services. Pintus et al. [18], [19] also propose a SOA framework where smart things are described using WSDL standard and logical connections between smart things are modeled as web services orchestrations using the BPEL language. The SOA approach for networks with embedded systems can be also found from many other projects, such as SIRENA [20] and SOCRADES [21], [22].

2) RESTful Architecture: REpresentational State Transfer [23], [24], which was first coined by Roy Fileding in his PhD thesis [25], is considered as the "true architecture of the Web". The basic concept of REST is that everything is modeled "resource", or particularly HTTP resources, with a Universal Resource Identifier (URI). The REST architectural style is based on the following four principles [26]:

- Resource identification through URI. All the resources exposed by RESTful web services are identified by URIs. Through URI, the clients can identify their interaction targets. A global addressing space is provided for service and resource discovery.
- Uniform interface. RESTful services treat the HTTP as an application protocol instead of a transport protocol in WS-*. Therefore, the term REST is often used in conjunction with HTTP and the RESTful resources can be manipulated using HTTP verbs such as PUT, GET, POST and DELETE. PUT creates a new resource while DELETE deletes it. GET retrieves the current state of a resource in some representation while POST updates a resource with new state.
- Self-descriptive messages. Resources are decoupled from their representations such that it is free to use a variety of data formats to describe themselves provided that the appropriate representation formats are agreed and understandable by endpoints. For example, the data can be in any common-used formats such as HTML, XML, plain text, PDF, and

TABLE I.
COMPARISON BETWEEN WS*- AND REST

	WS-*	REST
HTTP	Transport protocol	Application protocol
Complexity	High	Low
Stateless	No	Yes
Mashup	No	Yes
Coupling	Tight	Loosely
Flexibility	Low	High
Security	Built-in	Self-defined

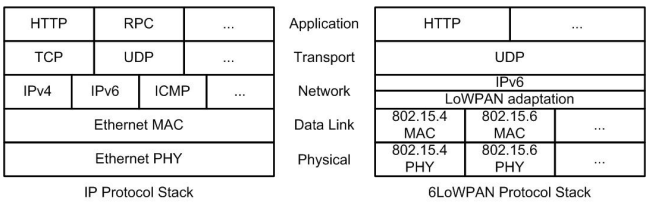

Figure 4. IP and 6LoWPAN protocol stacks

JPEG. Metadata about the resource can be used to control caching, detect transmission errors, negotiate the representation format, and perform authentication or access control between endpoints.

- Stateless operations. Every interaction with a resource itself is stateless. However, stateful interactions can be realized through hyperlinks. The state of a resource can be explicitly transferred by URI rewriting, cookies, and hidden form fields. The states can be also embedded in a response message for stateful interactions.

Notice that although REST is initially described in the context of HTTP, it is not limited to that protocol. RESTful architectures can be based on any other application layer protocols if they can provide a rich and uniform vocabulary for applications to transfer meaningful representational states. By this way, the potential of existing well-defined network protocols can be reexploited without additional efforts.

To our best knowledge, the RESTful architecture is preferred for WoT mainly for its two features. One is its low complexity and the other is its loose-coupling stateless interactions. The two features enable web servers in the RESTful architecture to be embedded into resource-constrained devices (e.g. Resource-oriented architecture [6]) and also enable easy composition (i.e. mashup) of web services. For example, according to [26], REST is the architecture of choice for tactical, ad hoc integration over the Web (i.e., mashup). The previous work on integrating sensor networks to the Internet, [27], [28], has shown that the lightweight aspect of REST makes it an ideal candidate for resource-constrained embedded devices to offer services to the world. To support this opinion, the feasibility of using RESTful web services is demonstrated in [29] with an evaluation of performance and power consumption in an IP-based multi-hop low-power sensor network. More innovative work [6], [11], [29]–[32] applies REST to smart things to abstract them into RESTful web resources mainly under the consideration of both complexity and mashability.

3) Comparison of WS- and REST:* We compare some characteristics of the two different web service paradigms as summarized in Table I.

As analyzed, REST is a more desirable web service paradigm for WoT. However, as indicated in [33], such a resource-oriented approach should not be universally considered as the miracle solution for every problem. In particular, scenarios with very specific requirements, such as high performance real-time communications, might benefit from tightly coupled systems based on different system architectures. While at the same time, for example, once interfaces are quickly created in a target programming language, they can be exposed via WSDL and are consumed just easily if the same WSDL is used by the consumer. Therefore, whether WS-* paradigm or REST paradigm shall be adopted by WoT is still a contradictory issue and we think that the two paradigms will coexist under considerations such as device capabilities and application requirements.

IV. ENABLING TECHNOLOGIES

In this section, we systematically describe and analyze the enabling technologies, including standardization activities as well as existing Web service technologies, which are directly related, or indirectly related but quite important, to WoT.

A. 6LoWPAN

To enable embedded web server on devices, the devices must be addressable, or IP-enabled at first. According to the IP for Smart Objects (IPSO) Alliance, an increasing number of embedded devices will support IP protocol. Many physical objects in the future may be directly connected to the Internet. This trend poses new opportunities for pervasive computing and the Internet. However, new challenges are also introduced. As the things are of different sorts, such as sensors, healthcare devices, RFID tags/readers, and home appliances, the protocol stack should be adaptable to devices with different and limited capabilities, i.e. low memory and low computability.

Responding to the increasing interest of connecting those resource constrained devices to the Internet, the IETF has proposed standards that enable IPv6-based networks. The IETF work group has launched a project called 6LoWPAN, which is an acronym of IPv6 over Low power Wireless Personal Area Networks. It defines encapsulation and header compression mechanisms that allow IPv6 packets to be sent to and received between resource constrained devices usually by adopting low-power radio communication protocols such as IEEE 802.15.4, 802.15.6 or power line communication.

Fig. 4 shows the IPv6 protocol stack with 6LoWPAN in comparison with a typical IP protocol stack. We notice that 6LoWPAN inserts an adaptation layer between the data link layer and the IP layer. The IP communication is

provided above the adaptation layer. The necessity of the adaptation layer is mainly because one IP packet may not fit within one layer 2 frame , e.g. 802.15.4 MAC frame.

The adaptation layer is the main component of 6LowPAN as it enable IPv6 packets to fit into IEEE 802.15.4 frame payload. It has the following functions.

- Header compression. TCP/IP headers are too large to the data link layer protocol, e.g. IEEE 802.15.4, for most devices. For example, IPv6 header has 40 bytes. Without header compression, it is impossible to transmit any payload effectively by a data link layer protocol such as IEEE 802.15.4, which has a maximum packet size of only 128 bytes. By header compression, the header overhead is much reduced. In the best case, the compressed 6LowPAN/UDP header for local unicast communication can be compressed to only 6 bytes while traditional IPv6/UPD header requires 48 bytes.
- Packet fragmentation and reassembling. The data link layer supports packets in small size. For example, IEEE 802.15.4 supports Maximum Transmission Unit (MTU) in size of only 128 bytes while IPv6 packet can be as large as 1280 bytes. This mismatch has to be handled by fragmentation and reassembling in the adaptation layer.
- Edge routing. To connect personal area networks to the Internet, edge routers, which locate on the edge between personal area networks (PANs) and the Internet, play an essential role as they route IP packets into the PAN devices from outside and vice versa. While at the same time, the edge routers also have management features such as distribution of IPv6 prefix and neighbor discovery.

Compared to traditional IP stack, the network layer is limited to IPv6 because IPv4 has reached its exhaustion recently. When a large number of, maybe in trillions, devices need IP addresses, IPv6 is able to make all devices addressable at the IP layer. Although both TCP and UDP are supported, the most common transport protocol used by 6LoWPAN is UDP. The Web can be viewed as the most popular application protocol. Web applications today mainly depend on payloads of HTML, XML, or SOAP carried over HTTP and TCP. The payload can be in size from hundreds of bytes to several KBs, which is too large for use on some 6LoWPAN nodes. Furthermore, the Web applications over 6LoWPAN shall make use of UDP for performance, efficiency and complexity reasons. Therefore, the Web applications over 6LoWPAN shall be fault tolerant due to the unreliability of UDP.

B. CoAP

In 2010, the IETF established a new working group focusing on Constrained RESTful Environment (CoRE). CoRE is characterized by its additional constraints compared to traditional IP networks. To handle those differences and tackle various challenging issues, the CoRE working group is working on a framework for applications

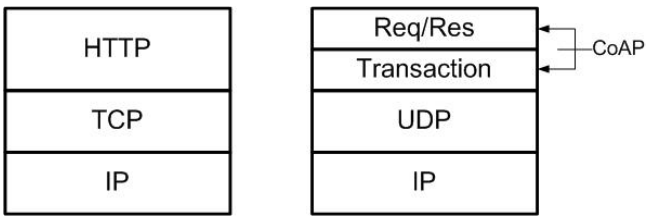

Figure 5. HTTP and CoAP protocol stacks

intended to run on the constrained networks. The framework is designed for applications such as smart energy, home appliance, industry automation, as well as other M2M applications that deal with manipulation of various resources on constrained networks, e.g. monitoring, control and management of resources. As a main part of the framework, Constrained Application Protocol(CoAP) is defined by the CoRE working group.

CoAP can be viewed as a complementary to HTTP as HTTP targets for traditional IP networks such as ethernet while CoAP targets for resource constrained networks such as wireless sensor networks. However, the CoAP protocol can also operate over traditional IP networks. CoAP could be viewed as a compression or redesign of HTTP by taking power, memory and computation constraints into account. Just like HTTP which is designed as transfer protocol for traditional web media content, CoAP is redesigned as a transfer protocol for devices to realize interoperations. The CoAP and HTTP protocol stacks are illustrated in Fig. 5.

The CoAP has the following main features:

- CoAP uses a two-layer approach[4]. Transaction layer is used to deal with UDP and the asynchronous interactions. There are four types of message defined at this layer: *Confirmable*(CON, the message requires acknowledgement), Non-Confirmable (NON, the message does not requrie acknowledgement), Acknowledgement(ACK, it is an acknowledgement to CON), and Reset(RST, the message indicates that a Confirmable message was received, but some context is missing to properly process it). The Req/Res layer is responsible for the transmission of requests and responses for the resource manipulation and interoperation. CoAP supports four request methods: GET, PUT, POST and DELETE, which are answered by a subset of HTTP compatible response codes (e.g. 200 = OK).
- CoAP is based on UDP while HTTP is based on TCP. This is because the high overhead introduced by TCP mechanism such as flow control which is not suitable to resource constrained devices and LLNs. However, CoAP also provides an optional reliable transmission even without the support of TCP. Recall that the *CON* message will be retransmitted if ACK is not received when a predetermined retransmission timer times out. The exponential back-off mechanism

[4]http://tools.ietf.org/html/draft-ietf-core-coap-03

TABLE II.
COMPARISON BETWEEN COAP AND HTTP [34]

	Bytes per-transaction	Power	Lifetime
CoAP	154	0.744 mW	151 days
HTTP	1451	1.333 mW	84 days

is used in retransmissions to avoid congestion. Furthermore, the use of UDP also introduces another benefit that enables best-effort multicast of CoAP while TCP-based HTTP does not support multicast.

- CoAP is designed to lower the header overhead and parsing complexity in order to be applied to resource constrained devices. CoAP uses a short fixed-length compact binary header of only 4 bytes followed by a compact binary option. A typical request has a total header overhead of about 10-20 bytes. A small header overhead avoids the frequent fragmentations. The authors in [34] make a comparison between CoAP and HTTP in terms of average transaction size in bytes, power consumption, and the expected battery lifetime, as shown in Table II. Obviously, traditional HTTP transaction is 10 times bigger than a CoAP transaction. The bigger transaction also results in intensive computation and communication, and consequently higher power consumption, which further shortens the battery lifetime.
- CoAP supports asynchronous transaction, which is a key requirement for M2M applications. When a request can not be responded immediately, the server first acknowledges the reception of the message and sends the response back in an off-line fashion, without risking the client to repeatedly retransmit the request.
- CoAP supports URI and built-in resource discovery. URI is an important feature of the web architecture as the resources must be identified and addressable so as to be searchable and accessible. Resource discovery is common on web. CoAP defines a built-in resource discovery format which allows both discovering and advertising the resources offered by a device.
- CoAP supports a built-in subscribe/notify push model for an end-point to notify another end-point about a resource of interest. In M2M application, it is inefficient for a client to poll whether a resource has changed or not in a pull model. Instead, CoAP provides a built-in push model where a subscription interface is provided for client to request a response whenever a resource changes. This push is accomplished by the device with the resource of interest by sending the response message with the latest change to the subscriber.

For the more detailed specification of CoAP, one may refer to [35]. Although CoAP is still working in progress, some famous embedded operating systems, Tiny OS[5] and Contiki[6], have already released their CoAP implementations. In addition, there are two open source implementations not specially designed for WSNs: one called *libcoap*[7] implemented in C language and the other called *CoAPy*[8] in Python language. A Firefox extension called *Copper*[9] that handles CoAP is also released.

C. Embedded Web Server

For the aforementioned integration of smart things into the Web, either directly or indirectly, embedded web server is indispensable. With embedded web servers, data can be transmitted between the smart things with standard web language. Traditional web servers are mainly designed for high-end computers such as workstations with plentiful CPU and memory resources. For most resource-constrained devices, the embedded web server must be small in footprint and of low complexity in processing while providing web server functionalities as many as possible, e.g. SSL. The different requirements make the traditional web servers unapplicable. Actually, pioneer work has focused on this topic for many years, even before the emergence of the IoT or WoT concept.

In [36], the authors declare that many embedded Internet devices (EID) will use HTTP instead of providing a user interface through a local front panel. They design a web server for EID which doest not require file system and doest not incur the memory and performance overhead either. Furthermore, the solution also provides interoperability between devices. Agranat in [4] shows that devices with a few KB of RAM and EEPROM are able to handle an embedded Web server because efficient TCP/IP implementation adds as little as 48K ROM and 16K RAM extra memory requirements. Can Filibeli et al. [37] design and implement an embedded web server-based home appliance network prototype system where Ethernut-based web servers are embedded into home appliances. With the help of embedded microcontrollers, the home appliances can be controlled and managed via web pages using regular web browsers. Ethernut[10] is an open source hardware and software project for building tiny embedded ethernet devices. It adopts an open source implementation of a real time operating system called Nut/OS and a TCP/IP protocol suite named Nut/Net. It has small footprint, standard C libraries and cooperative multithreading. Priyantha et. al [38] present an approach of implementing the web server on sensor nodes using only 15.8KB ROM and less than 1KB RAM . Duquennoy et al. [2], [39] propose cross-layer approaches to design efficient tiny embedded web servers and implement a prototype, named Smews, which is in size of 7KB and requires only 200 bytes volatile memory. It has been demonstrated that smart cards can be also embedded with web servers. A card with Java-based web server, called serverWebcard [40], is implemented with a TCP/IP stack

[5]http://www.tinyos.net/
[6]http://www.sics.se/contiki/
[7]http://sourceforge.net/projects/libcoap/
[8]http://coapy.sourceforge.net/
[9]https://addons.mozilla.org/en-US/firefox/addon/copper-270430/
[10]http://www.ethernut.de/

and a minimal set of HTTP1.0 functions. OMA(Open Mobile Alliance) specifies Smart Card Web Server (SCWS) standard to allow web servers to be used within smart cards such that network operators' services can be provided through web browser [41]. More importantly, SCWS is portable across any handsets with browsers.

There are much more work than those mentioned above, which implement lightweight embedded web servers with different features in different programming languages. Further efforts are on more powerful embedded web servers but with little resource requirement. It can be expected that the embedded servers will be common in future embedded devices.

D. Service Composition Development

With the emergence of IoT, huge numbers of embedded devices with various functions will be connected to the Internet. Although the connectivity allows devices to provide some specified services on the Internet, it is not the ultimate goal. To fully explore the potential of those devices, they shall be able to cooperate with each other. However, there is a tight coupling among the devices, the services provided as well as the development methods. It is not easy to integrate devices from different manufacturers. While, up to date, new applications in this field are mainly produced by designers and engineers, we claim that even users could invent new applications unforeseen by technical experts with simple and effective composition rules and easy-to-use building blocks.

Fortunately, as we have known, web servers are possible to be embedded into devices such that they can provide web services on the Internet. Even for those which can not directly provide, a smart gateway can act as a proxy to provide web service. Imagine we have several different devices such as temperature sensor, humidity sensor, GPS device as well as some healthcare devices (e.g. EKG sensor). We want to build a healthcare system which can monitor and record the health condition of patients as well as environment information (e.g. temperature, humidity, position) of the patient. Traditionally, the developer shall understand all the native APIs provided by each device and write programs to integrate information provided by those devices. This requires extensive time and technical expertise. In WoT, all the things are abstracted as web resources, which are addressable, searchable and accessible on the Web. The developer can use uniform web standard to integrate all the abstracted web resources needed as well as existing virtual web service (e.g. Google Map) together to create a mashup. Mashups are new web application/service created by composing various original web services from disparate, or even competing providers. Mashup can be viewed as a key feature of Web 2.0 or one of the main differences to Web1.0. In Web2.0, There are plentiful web service available such as Twitter, Facebook, Flickr, Linkedin, eBay, Yahoo Maps, and so on. Most provide APIs to allow developers to create more new services based on their basic services. This has become a major web application development trend. For example, a web service, called Wikipediavision[11], is created by using Google Map APIs and Wikipedia APIs to timely show the places where anonymous edits to Wikipedia are happening on Google Map. However, different from traditional Web2.0 mashup, mashups in WoT include not only virtual web services but also physical web services provided by things. Some researchers call this Web3.0 mashup and argue that we are going to enter a Web3.0 era. As more web-enabled things will be abstracted as web services and published on the Web, together with the popularity and progress of virtual world web services, more fruitful and powerful composite Web3.0 services can be envisioned in the future. We believe that Web3.0 mashup will be the main technical engine to make progress for both WoT and IoT.

In [6], Guinard et al. apply REST principles to embedded devices and present two representative Web3.0 mashup styles, physical-virtual mashups and physical-physical mashups.

1) Physical-Virtual Mashup: As indicated by its name, this mashup consists of web services from both the physical world and the virtual world. Although the embedded devices can provide some web services to answer HTTP queries from users such as checking the state of the devices or changing the state of the devices, it might not always be sufficient to satisfy the user's requirement. For example, suppose some sensor nodes are distributed over the city to monitor the temperature of different spots. It is desirable that the values can be displayed in a visual way (e.g. on a map) such that people can easily get the information about any specified spot. Under such requirement, the developer can mashup virtual map service and physical sensor web service to create a temperature monitoring web application which displays temperatures of different places on the map. Any services, either physical or virtual, are able to be mashuped if they follow the same standard (e.g. REST) and provide an uniform interface to communicate with.

Many mashup products or prototypes have been developed including both virtual and physical services. The WoT example shown in Section I can be viewed as a classical physical-virtual mashup. Guinard et al. [6] implement an application, called EnergyVisualizer, which offers a GUI on the Web to monitor the power consumption and to control different home appliances. EnergyVisualizer is built by using the self-defined RESTful Plogg API and Google Web Toolkit APIs. The mashup calls the Ploggs Smart Gateway at a constant interval by issuing a GET HTTP request to the Ploggs and feeds the response in an interoperable data in JSON format to the corresponding graphs. Furthermore, they also put switch buttons on the web page, where by clicking a button the corresponding appliance can be turn on or off. In the cloud computing industry, the providers, e.g. Amazon Web Services, Google's Google Apps, and Salesforce.com's Force.com., use web interface or API to allow users to provision and scale physical servers,

[11] http://www.lkozma.net/wpv/index.html

storage, networking, load balancing and security in real time and in multiple data centers. The systems generally use SOAP, WSDL, and other nonproprietary XML-based web service protocols.

2) Physical-Physical Mashup: As what the term indicates, the mashup consists of web services only from the physical world. In this kind of mashup, the original web services are all provided by smart things, either directly or indirectly. It enable devices with various functionalities from different manufacturers or even competitors to cooperate with each other (e.g. a humidity sensor from one vendor controlling a sprinkler system from another). The developers do not require expert knowledge about the programming methods and tools about each device as they also have been abstracted as web resources. A uniform and interposable web API can be used to communicate with all of them.

Guinard et al. [6] demonstrate how physical-world services can be combined together using mashup technologies. They implement an Ambient Meter on a Sun SPOT which polls a predetermined URL using GET method to get the energy consumption of all the devices in a room from a smart gateway. All the devices communicate with HTTP-based requests and responses. They find that it would be much time consuming if the smart gateways, the Ploggs and the Sun SPOTs only offer their native APIs. Using the same concept as [6], Kamilaris et al. [42] develop an energy-aware/cost-aware smart home platform. Besides integrating the services to provide the energy consumption about the home appliances, they further integrate the smart grid web services to provide the real-time tariff. The composite service allows residents to save energy as well as money by defining rules through the Web.

V. Open Platforms and Prototypes

In this section, we list some open platforms and ptotypes that have been implemented and presented in the literatures. Most of those platforms have been available on the Internet and accessible by web browsers. Web service APIs are also provided such that users can use them to create more innovative applications or services.

SenseWeb [43], [44] is developed at Microsoft Research. It offers a platform mainly targeting for particpatory sensing. A sensor gateway is used by sensors as a uniform interface to share sensory data. SOAP-based APIs are used to allow developing sensing applications with shared sensing resources. For example, SensorMap [45] is one such application. It mashes up sensor data from SenseWeb on a geographical map interface. In particular, it enable selective sensor queries and data visualization. Also the access and management of sensors are conducted in an authentical way. Nath et al. [45] point out that to realize the full potential of a portal like SensorMap, it should be easily extensible and mashed up with other applications and services. They are currently working on a set of modulars and composable APIs to facilitate mashing up SensorMap with other services.

SensorBase[12] [46] implemented in the Center for Embedded Networked Sensing (CENS) at UCLA uses a relational database table as its data abstraction and SQL-centric APIs. It is a web application that not only provides the user with the functionality of a traditional database management system, but also runs under the notion of a Web 2.0 data experience with a responsive user interface design and RSS data feed techniques.

Sensorpedia[13] [47] is a web-based application developed at Oak Ridge National Laboratory, enabling people to share, find, and use sensor data online. It provides users a Google Maps interface where users can search and explore published sensor data. Sensorpedia applies several design principles common to many popular Web2.0 sites. The Sensorpedia APIs allow accepting and publishing data by established standards such as the Atom Syndication Format. The APIs also support rapid development of customized third-party applications to meet specific user requirements.

Sensor.Network [48], [49] implemented by Gupta et al. in Sun Microsystems is a Web-based infrastructure for storing, sharing, searching, visualizing and analyzing data from heterogeneous devices. Interactions amongst devices or with end users are through an open REST-base API. They also propose a category-based search mechanism and security mechanisms for authentication, authorization and confidentiality.

Pachube [14] is a venture capital funded data brokerage platform for IoT, managing millions of data points per day from thousands of individuals, organizations and companies around the world. Pachube provides APIs entirely based on HTTP requests, and conforms to the design principles of REST. The "physical-to-virtual" APIs provided by Pachube enable quick and easy development of applications that add value to networked objects and environments. The WoT example, Japan Geigermap, shown in Section I is built by Pachube service and Google Maps service.

Vazquez et al. [50] propose Flexco, which is a flexible architecture for implementing monitoring applications based on wireless sensor networks. They propose a three-layer architecture (i.e. Sensors and Actuators Layer, Coordination Layer and Supervision Layers), which enables intelligence distribution and decision at different levels. On its top Supervision layer, a web interface is proposed for end users to access and manage the sensor data.

TinyREST architecture is proposed in [27], where the authors implement a prototype using MICAz motes. Especially, they introduce a new HTTP method, SUBSCRIBE, which enables clients to register their interests to specific sensors/actuators services with various personalized parameters depending on each client's needs. Also, a multithreaded light-weight HTTP-2-TinyREST gateway is provided between clients and sensors/actuators.

The pico-REST (pREST) [30] is an access protocol

[12] http://sensorbase.org/
[13] http://www.sensorpedia.com/
[14] http://www.pachube.com/

proposed by Drytkiewicz et al. with the goal of bringing the Web simplicity and a holistic view on data and services to pervasive systems. In a REST style, pREST emphasizes abstraction of data and services as resources. A particular concern is to provide the functionality in the absence of proxy nodes or infrastructure services like directory servers.

The EnergieVisible [6], [51] software can be used to easily monitor the power consumption of devices connected to Bluetooth-enabled smart plugs (Ploggs). The software retrieves all Ploggs in the environment through a smart gateway using REST APIs and exposes their functionalities (i.e. power consumption data and an on/off switch) via a visualized web page.

Table III summarizes and compares some work mentioned above from different aspects. The work whose features are unknown is not listed in the table.

VI. Open issues

To fully explore the potential of WoT, many challenging issues still need to be tackled. In this section, we review some open issues.

A. Heterogeneity and Scalability

Although WoT is a good approach to handle the heterogeneity problem, some minor heterogeneity problems of devices and requirements still exist.

The popularity of WoT requires a tremendously huge number of devices to be integrated to the existing Web. These devices are diverse in terms of data communication methods and capabilities (e.g., protocol stack, data-rate, reliability, etc.), computational and storage power, energy availability, adaptability, mobility, etc. The heterogeneity at the device level seriously challenges to the popularity of WoT. WoT is the concept of standardizing communication channel at the application layer. Without the interoperation support from lower layers, WoT is just a castle in the air. This issue is still under investigation, but it is hard to find a one-fit-all solution as new devices may appear in the future.

On the other hand, consumers of data are heterogeneous: someone might ask for realtime information while some others might need archived data streams from the past. Their needs vary in terms of data quality, spatial resolution, and sampling rates. Further, different applications might implement disparate data processing or filtering. WoT shall be open to support these various applications whose characteristics and requirements may be extremely diverse, in terms of bandwidth, latency, reliability, etc. These heterogeneity traits of the overall system make the design of a unifying framework and the communication protocols a very challenging task, especially with devices with vastly different levels of capabilities.

In addition, management of WoT becomes very difficult in a large distributed environment, and solutions to dominate the complexity need to be found. Without a careful management mechanism design, it might result in an inevitable performance degradation. The power of WoT comes from the growth of participant number of devices. A management mechanism shall be able to distinguish both the functionalities and the capabilities of devices. Otherwise, it can not specify or allocate appropriate devices and services for user application requirements. It is nontrivial to manage growing number of devices in a graceful manner, especially when the devices are heterogeneous in functionalities and capabilities. On the other hand, the resource-constrained devices, although are able to be embedded with web servers, are still limited to handle large number of requests. Unlike a stand-alone system, one device is shared by a small number of applications. In WoT, it is hard to say how many application requests need to be handled by a device, especially when it provides public services. To keep the resource usage scalable and to avoid unnecessary denied accesses to some applications, it is essential to design mechanisms that can coordinate the smart things under the consideration of both their capabilities and user application requirements. Also, it is possible to improve the scalability by more advanced embedded web server techniques.

B. Security and Privacy

Openness and sharing are always contradictory to security and privacy. One practical consideration in enabling widespread adoption of WoT arises in ensuring security of shared resources against misuse, protecting the privacy of users who share parts of their data, and providing estimates of reliability or verifiability of web service against malicious intervention or inadvertent errors. Although the security and privacy have been extensively studied for decades and some techniques have become mature, not all existing technologies can be directly applied to smart things in WoT. The problem is exacerbated by introducing large-scale, distributed, heterogeneous and low-capability smart things.

For security, the CoRE working group has been exploring approaches to security bootstrapping that are realistic under the given constraints and requirements of the network. To ensure that any two nodes can join together, all nodes must implement at least one universal bootstrapping method. Security can be achieved using either session security or object security. Cipher suite will also be redesigned so as to be implemented with a minimal requirement. In [52], the author presents an analysis of security threats to the 6LoWPAN adaptation layer from the point of view of IP packet fragmentation attacks and proposes a protection mechanism against such attacks using time stamp and nonce options that are added to the fragmentation packets at the 6LoWPAN adaptation layer.

Allowing the information available on the Web poses a perceived privacy threat. The approach to use existing authentication service from third parties has been advocated. For example, Sensorpedia [46] relies on open data portability standards such as OData[15], oEmbed[16],

[15]http://www.odata.org/

[16]http://www.oembed.com/

TABLE III.
A BRIEF COMPARISON OF EXISTING OPEN PLATFORMS AND PROTOTYPES (PART OF THE TABLE REFERS TO [49])

	Sensor.Network	SensorBase	Pachube	SenseWeb	TinyREST	pREST	EnergieVisible
Integration	Hybrid	Hybrid	Hybrid	Hybrid	Indirect	Direct	Indirect
Web service paradigms	RESTful	WS-*	RESTful	WS-*	REST	REST	REST
Data formats	XML, JSON	XML, JSON	JSON	Text	Unknown	XML	JSON
Architecture	Centralized	Centralized	Centralized	Centralized	Distributed	Distributed	Distributed
Interoperability	No	No	No	No	Yes	Yes	Yes

OpenID[17], and OAuth[18] to ensure current and future interoperability with other web-based software applications. Some web service might be shared within restricted groups only. For example, home appliance web service shall be only accessible to family members. Following the idea of leveraging existing social structure on online social networks (OSNs, e.g. Twitter, Faceook, Linkedin, etc.) and their APIs to define the access privilege of smart things, Guinard et al. implement a prototype, called Social Access Controller(SAC), which is an authentication proxy between users and smart things. OSN-based methods can handle the access control between people and things but are unable to deal with the access control between things. Universal but distributed access control mechanism is expected to enable interoperation between things while preserving the privacy of the owners.

C. Search and Discovery

Both people and things may need to discover the existence, functionality and information of their desired web services. For example, things require identities of smart things and web services within their environment in order to negotiate about shared goals to create a new mashup according to some requirement. Search engine is essential to WoT. Generally, as indicated in [53], there are two fundamental approaches to construct a search engine for WoT. In the push approach, sensor outputs are proactively pushed to a search engine, which uses the data to resolve queries reactively. However, this method lacks of scalability in the smart things-based crowd-sourcing environment. It can be only applied to a system with limited number of devices. Alternatively, in the pull approach, only upon receiving a user query, the search engine forwards it to the sensors to pull the relevant data. This method is scalable but challenged by the accuracy and timeliness. Here, we focus on the latter one.

The increasing penetration of Web with smart things leads to more crowd-sourcing than ever before. A large amount of information and physical world web services of various sorts become available on the Web. Although more services may be beneficial and convenient to people, it becomes a nightmare to the search engine of WoT. The search engine is already not an easy issue in Web2.0 crowd-sourcing with a mass of web contents created everyday, not to mention Web3.0 crowd-sourcing introduced by trillion of smart things.

Furthermore, a key service for WoT will be the search engine that allows to search a physical-world service with certain properties. The traditional Web is dominated by static or slowly changing contents that are manually typed in by humans. The contents in WoT are rapidly changing because they are automatically produced by smart things. Thus, a search engine for WoT shall support searching rapidly changing content. This is a key challenge because existing search engines are based on the assumption that most web contents change slowly such that it is sufficient for the search engine to update an index at a low frequency. This is clearly impossible for the WoT where the states of many physical world devices changes are at frequency of minutes or even seconds. On the other hand, some Web content or service is significant only during a specified duration. In addition, future mashup shall be created dynamically on-demand according to the context. The source web services may need to be searched and obtained dynamically and in realtime. This issue becomes more challenging due to the dynamics of WoT, introduced by its features such as mobility and intermittent connectivity of smart things. The search engine for WoT shall support real-time search of information and real-time discovery of web services.

There has been some pioneer work on this issue. Ostermaier et al. [53] show how the existing web infrastructure can be leveraged to support publishing of sensor and entity data. They implement a prototype of real-time search engine, called Dyser, which enables finding the real-world devices that exhibit a certain state at the time of the query. In [54], the authors survey and clarify relevant existing approaches (e.g. Snoogle [55], Microsearch [56], MAX [57], etc.) according to query type, language, scope, accuracy and so on. Mayer et al. [58] present DiscoWoT, a semantic discovery service for Web-enabled smart things. DiscoWoT is based on the application with multiple discovery strategies to a representation of web resource, where arbitrary users can create and update the strategies at runtime using DiscoWoT's RESTful interface.

D. Ambient Intelligence

The ultimate goal of IoT or WoT is to build an ecosystem that can provide user-oriented and environment-aware services. In other words, the web services shall be sensitive and responsive to the presence of people and the condition of environment. Ambient Intelligence(AmI) has been much addressed on stand-alone systems, such as wireless sensor and actuator networks. The sensor capable of recognizing simple emergency situation may fire an

[17] http://openid.net/
[18] http://www.oauth.net/

alarm and the actuator can take an action accordingly. When it comes to AmI in WoT, new opportunities and challenges are exposed. The community effect of the web services available on a larger-scale Web shall be further addressed. One may easily find different public services on the Web and build private web services using standard web-enabled devices in personal area network. The challenges first come from the heterogeneity and availability of smart things that provide web services. Unlike standalone systems where the devices are predetermined and configured according to the application requirement, some AmI applications in WoT may need to discover the required web services first. The QoS, even the existence, of the web service is unknown. Furthermore, this situation is exacerbated by the unexpected user requirements and environment (e.g. time, location, etc.).

Recall that mashup technology is a key enabling technology of WoT. It can be expected that the mashups will be dominant in WoT. Another challenge of AmI in WoT is that the mashup shall intelligently adapt to user requirements and runtime environment. In other words, it shall be context-aware. In such a condition, dynamic mashup could be a good option. Other than developing static mashup by integrating existing web services together, rules about how to mashup services should be defined such that the basic web services are dynamically added or deleted on-demand. The whole mashup processes are transparent to the users and without human intervention. For example, to build a healthcare system for the elderly requires some private services to monitor and record their health conditions and some public services to know the environment information (e.g. temperature, humidity, light, traffic, etc.) about the places where they locate. The public services to be integrated shall be dynamically chosen according to their positions. In an emergency condition, some services shall be automatically activated and integrated, e.g., the control service for automatic syringe might be activated and responded accurately according to the health condition and the environment parameters known from the other services.

AmI of WoT is far more powerful and sophisticated than those examples. To fully explore the potential of smart things, more innovative solutions are expected to be proposed. Those solutions shall be able to orchestrate all available web services in a graceful manner and enable more intelligent user-oriented services. Some existing artificial intelligent concepts and technologies, such as Collective intelligence [59] and Semantic web services [60], may deserve revisiting in the hope of finding new efficient solutions feasible to smart things on the Web.

VII. Conclusion

IoT is the next big possibility and challenge of the Internet. It does not merely concern the connectivity of smart things, but more about the interaction or interoperation between things and between things and people. This requires that all the smart things can speak the same language to communicate freely with each other. It has been considered as a good solution to extend existing web architecture to this new domain by incorporating smar things into the Web. The extended Web is called as WoT in the literature and it has become a major trend to promote the development of IoT.

In this paper, we first give an overview of WoT, including the history and motivation, and the comparison with previous technologies (e.g., UPnP, JXTA, etc.). It shows many advantages of WoT over previous technologies. The key concept of WoT is abstracting everything into web service. The first issue to consider is to integrate smart things to the Web by either direct integration or indirect integration, depending on their capabilities. The next issue is how to abstract the integrated smart thing to web services. We introduce and compare two major web service architectures: WS-* architecture and RESTful architecture. Some key enabling standards and technologies (e.g. 6LoWPAN, CoAP, mashup, etc.) related to WoT are also discussed and examined. As examples for case study, we compare some pioneer implementation of open platforms and prototypes for WoT which provide web service APIs for sensory data sharing and device interoperabilities. Since we are still at the preliminary stage of WoT, many open challenging issues are also briefly analyzed. We believe that WoT will be indispensable in people's future lives and more efforts to tackle those challenging issues shall be made from both industry and academia to promote the progress of WoT.

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Power saving and energy optimization techniques for Wireless Sensor Networks

(Invited Paper)

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Abstract— **Wireless sensor networks have become increasingly popular due to their wide range of applications. Energy consumption is one of the biggest constraints of the wireless sensor node and this limitation combined with a typical deployment of large number of nodes have added many challenges to the design and management of wireless sensor networks. They are typically used for remote environment monitoring in areas where providing electrical power is difficult. Therefore, the devices need to be powered by batteries and alternative energy sources. Because battery energy is limited, the use of different techniques for energy saving is one of the hottest topics in WSNs. In this work, we present a survey of power saving and energy optimization techniques for wireless sensor networks, which enhances the ones in existence and introduces the reader to the most well known available methods that can be used to save energy. They are analyzed from several points of view: Device hardware, transmission, MAC and routing protocols.**

Index Terms— Power-saving strategies, energy consumption, energy management, network communication protocols, wireless sensor networks.

I. INTRODUCTION

A Wireless Sensor Network (WSN) can be defined as a network of small embedded devices, called sensors, which communicate wirelessly following an ad hoc configuration. They are located strategically inside a physical medium and are able to interact with it in order to measure physical parameters from the environment and provide the sensed information [1]. The nodes mainly use a broadcast communication and the network topology can change constantly due, for example, to the fact that nodes are prone to fail. Because of this, we should keep in mind that nodes should be autonomous and, frequently, they will be disregarded. This kind of device has limited power, low computational capabilities and limited memory. One of the main issues that should be studied in WSNs is their scalability feature [2], their connection strategy for communication [3] and the limited energy to supply the device.

The desire to advance in research and development of WSN was initially motivated by military applications such as surveillance of threats on the battlefield, mainly because WSN can replace single high-cost sensor assets with large arrays of distributed sensors. There are other interesting fields like home control, building automation and medical applications. A number of hospitals and medical centers are exploring the use of WSN technology in a wide range of applications, including pre-hospital and in-hospital patient monitoring and rehabilitation and disaster response. WSNs can also be found in environmental monitoring applications such as marine fish farms [4] and fire detection in forest and rural areas [5].

As we already mentioned, sensor nodes in WSNs are usually battery powered but nodes are typically unattended because of their deployment in hazardous, hostile or remote environments. A number of power-saving techniques must be used both in the design of electronic transceiver circuits and in network protocols. The first step towards reduced power consumption is a sound electronic design [6], selecting the right components and applying appropriate design techniques to each case.

One of the major causes of energy loss in the WSN node is the idle mode consumption, when the node is not transmitting/receiving any information but listening and waiting for information from other nodes. There is also an energy loss due to packet collision, as all packets involved in the collision are discarded and must be retransmitted. A third cause of energy loss is the reception of packets not addressed to the node. The fourth major source of wasted energy is the transmission –and possible retransmission- of control packets, as these can be seen as protocol overhead.

There are several studies that present different aspects related to power saving techniques, but all of them are focused in a single way to improve the energy consumption and save power in WSNs. The main objective of this paper is to present a survey of the different power saving and energy optimization techniques for WSNs and ad-hoc connections, so we will tackle this issue from several perspectives in order to provide a whole view in this matter.

The paper is organized as follows. Section 2 shows some previously published surveys related to power saving techniques in WSN. The description of the typical hardware architecture that can be seen in any sensor node and the considerations that should be taken in into account for energy-aware sensor deployment are show in section 3. Section 4 describes the main energy parameters that should be considered in the transmission system.

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Some important energy-aware MAC protocols are explained in Section 5. In Section 6, we discuss different routing protocols that are focused on saving energy methods. Finally, the conclusion is drawn in Section 7.

II. EXISTING SURVEYS

The power management schemes of wireless sensor networks have attracted high attention in recent years. Much published research has addressed all kinds of issues related to them.

We can find several works related to energy conservation techniques. They tend to focus on comparative routing protocols or MAC-protocols. Some of them show techniques related to the operation mode of the nodes and its radio system. In this section we will see some of these works, and we will provide some of the key conclusions presented in these papers.

In [7], G.P. Halkes et al. compared S-MAC and T-MAC, which try to save energy by introducing a duty-cycle to mitigate idle listening time, with CSMA/CA. This choice was taken because it is the most important cause of energy consumption in typical sensor network scenarios where the communications between nodes is not continuous. They show the effects of low-power listening, a physical layer optimization, in combination with these MAC protocols. The results show that using a low-power listening is very effective at mitigating idle listening. The absolute lowest energy consumption is reached in combination with T-MAC, while the results about S-MAC show that this protocol suffers from over-provisioning. Since its duty cycle is fixed for all nodes, often a rather large value must be selected to avoid dropping messages under peak loads, which causes S-MAC's idle-listening to deteriorate for increasing traffic loads. Although S-MAC achieves acceptable results, they are not as good as those of T-MAC with low-power listening. T-MAC presents an aggressive time-out policy that allows it to adapt seamlessly to variations in traffic induced by typical sensor network applications at the expense of a reduction in peak throughput. T-MAC performs slightly better for variations over time (events) than for variations in location.

V. Raghunathan et al. [8] review several techniques to address the energy consumption challenge. This work also describes recent advances in energy-aware platforms for information processing and communication protocols for sensor collaboration. The article looks at emerging and hitherto largely unexplored techniques such as the use of environmental energy harvesting and the optimization of the energy consumed during sensing. The paper presents some promising research directions for alleviating the energy problem in WSNs, including hierarchical architectures, ultra-low-power MAC protocols, environmental energy harvesting, and energy aware sensing. The authors explain and present an architecture of sensor node in order to be considered energy efficient. At the same time, they present a wireless sensor module, a heliomote, which is used in different tests in order to show that it is possible to provide energy to the nodes from alternative sources instead of from a battery, which has a limited life time. They also compare three MAC protocols. These are B-MAC, STEM-T, and WiseMAC, which are characterized by low power consumption in the media access process.

Another significant work is presented by N. A. Pantazis et al. in [9]. The authors focus their explanations on the fundamental concepts of energy management, including the need of power management in the wireless sensor network, and discuss the side effects of power management in terms of cost. They say that the cost of power management must always be borne in mind when speaking about a power control system. The cost of power management is important for evaluating the performance of a power control system, no matter what the specific objectives may be. Throughout the document, they describe different types of power management systems and different approaches and goals they may have. The authors divide the power conservation mechanisms into two main categories based on their primary objectives. On the one hand, Passive PCMs are divided into three sub-categories: Physical Layer, Fine-Grain, and Coarse-Grain PCMs. In the implementation of the Coarse-Grain PCMs, two basic approaches were distinguished: Distributed and Backbone-based. On the other hand, the classification of the Active PCMs is based on the layer (MAC, Network, and Transport). Various algorithms were studied for each classification. Each power management scheme is discussed in terms of objective, mechanism, performance, and application scenario. The similarities and differences between schemes of the same clustering category are also presented. The authors conclude the paper by stating that although the performance of the presented power management schemes is promising, further research would be necessary to address other issues, such as quality of service (QoS). Energy-aware QoS in wireless sensor networks will certainly ensure guaranteed bandwidth, or delay, through the duration of a connection as well as provide the most energy-efficient path.

S. Saxena et al. review the main approaches for energy conservation in wireless sensor networks in [10]. They presented a systematic and comprehensive classification of the solutions related to save energy. This involves characterizing the interactions between different protocols and exploiting cross-layer interactions. They also made a protocol classification and explain each part. The authors comment that most of the solutions presented by other authors are based on the assumption that the radio energy consumption is much higher than data sampling or processing consumption, while many real applications have greater power consumption in data sampling/processing than in radio transmission. Furthermore, they observed that the data acquisition research field of has not been fully explored in terms of energy conservation. Finally, the authors come to the conclusion that there is an increasing interest towards MAC protocols used for time synchronization and energy conservation in the recent years. They also made a reference to the node's mobility, which is yet another challenging task in energy optimization.

Another survey related to protocols and energy-saving techniques is [11]. It was presented by K. Akkaya et al. This paper surveys several routing protocols for sensor networks and presents a classification of various pursued approaches. The classification is focused on three main categories: data-centric, hierarchical and location-based. This work analyzes several protocols that use contemporary methodologies such as network flow and quality of service modeling. From this work, several conclusions can be extracted. On the one hand, many protocols base their functions in some attributes such as data and query in order to avoid overhead-forming clusters, the use of specialized nodes, etc. However, in some cases, where queries can be more complex schemes, such attribute-value pairs may not be enough. On the other hand, routing protocols based on cluster are carried out by group sensor nodes to efficiently relay the sensed data to the sink. The cluster heads are specialized nodes that are sometimes chosen in function of their available energy. A cluster-head performs the data aggregation and sends it to the sink. The authors show a table which summarizes the classification of the protocols covered in this survey. They also included in the table whether the protocol is utilizing data aggregation or not, since it is an important consideration for routing protocols in terms of energy saving and traffic optimization. In their future works they will study the factors that affect cluster formation, cluster-head communication and how to form clusters in order to improve energy consumption and contemporary communication metrics, such as latency.

Finally, C. E. Jones et al. present in [12] a study on power saving techniques in WSN. This paper addresses the incorporation of energy conservation considerations on all layers of the wireless network protocol stack for mobile devices. Therefore, throughout the document, the authors cover the protocol stack and gradually introduce various energy saving modes (starting from low-power design within the physical layer). They show different sources of power consumption within mobile terminals and general guidelines for reducing the power consumed. They also show energy efficient protocols within the wireless networks' MAC layer, power saving protocols within the LLC layer and power aware protocols within the network layer. Finally, they provide some battery power considerations that should be taken into account.

As far as we know, there is not any survey such as the one presented in this paper. We will tackle power saving techniques and energy saving issues in WSNs from all perspectives, starting from the hardware side until arriving at the routing protocol side.

III. Energy Issues in Hardware

This section describes the main functional blocks of a sensor node. Each of these blocks has intrinsic energy losses, mainly due to its function. The main considerations to be taken into account in a sensor node for deploying a WSN are presented. Finally, some of the main sources of energy loss in the WSN are discussed.

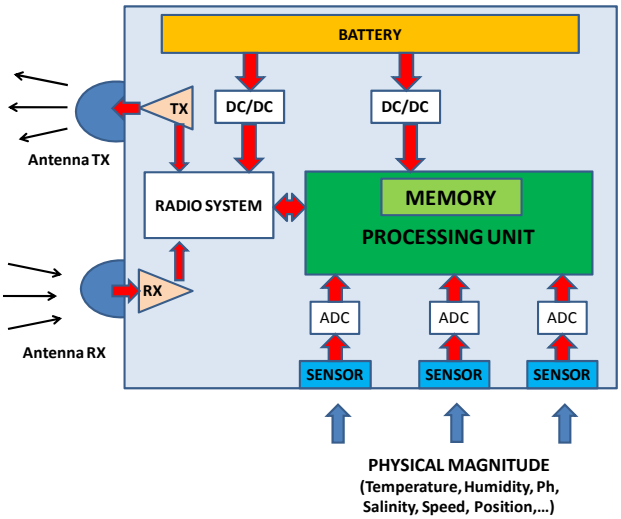

Figure 1. Block diagram of a typical wireless sensor node.

A. *Wireless senor node hardware structure*

A sensor node is an electronic device that is used as an interface between the physical magnitudes that can be sensed from the medium and a data wireless network [13, 14].

A node is made up of four main parts: (1) a power unit, consisting of a battery and a number of DC/DC converters, (2) a processing unit -which usually consists of a small processor and memory, (3) the physical sensors and (4) the transceiver circuit (radio system that should be formed by a transmitter and a receiver). Figure 1 shows the block diagram of a typical wireless sensor node.

- The Processing Unit (PU) is responsible for reading out the physical sensors, extracting relevant information from the digitized data and implementing the network protocols. The PU of a wireless sensor node determines both the energy and the computing capabilities of a sensor node.
- The radio system allows wireless communication between the nodes in the network and to the outside world. Factors such as modulation scheme, data throughput in the network, transmission power and duty cycle can directly affect the energy consumption characteristics of the global system. In general, a node can work basically in three different operating modes: active (either transmit or receive), idle and sleep. Some studies on WSN and routing protocols show that contrary to popular belief, power consumption in idle mode is considerably high, comparable to the energy consumed in active mode [15]. For this reason, it is recommended to completely shut down the radio transceiver when it is not going to be used. Moreover, some important issues must be considered, e.g., a change in the system state and the related transient effects in the transceiver generate a significant increase in the amount of energy dissipated.

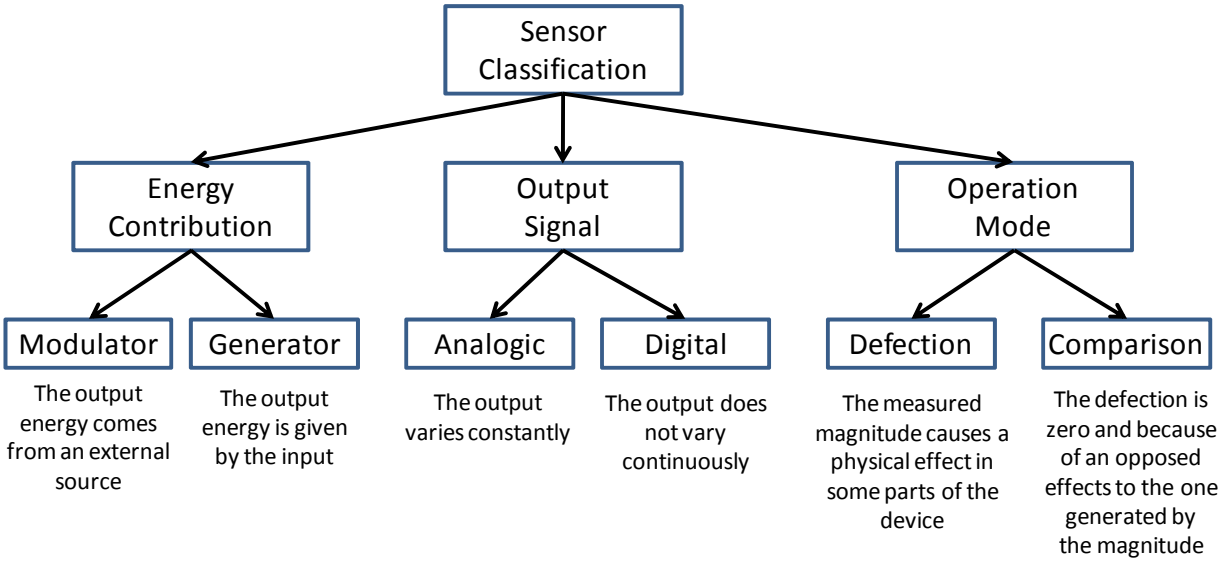

Figure 2. Sensor classification.

- Sensors transform a physical or chemical magnitude (instrumentation variable) into a useful electrical signal. Several examples of instrumentation variables are temperature, distance, acceleration, inclination, displacement, pressure, humidity and pH. The electrical signal can be derived from a change (like resistance or capacity) in the sensor. All sensors can be classified and included within one of the groups shown in figure 2 [16].
- Batteries are complex elements whose operation depends on many factors including the size of the battery, the electrode material and the rate of diffusion of the active materials in the electrolyte. There are many types of rechargeable and non-rechargeable batteries that can be used in WSN applications. According to their electrochemical composition, which determines the energy efficiency, we can distinguish between Ni-Cd, Ni-Zn, Ag-Zn, Ni-MH and lithium ion batteries, among others. There are some important effects to consider, like the relaxation effect and the rated capacity effect [13], which largely determine the battery life.
- DC/DC converters (also called voltage regulators) are responsible for providing appropriate voltages to the different circuits in the sensor node. Linear regulators have larger energy losses (approximately the output current multiplied by the voltage drop across the device) than switched regulators (typical energy loss in the range 5-15%). Thus, the design of the voltage regulator section has a large impact on the node power consumption.

It is possible to recharge the sensor node battery with energy extracted from the environment, like light, wind, vibration [17] and electromagnetic fields.

B. Characteristics and requirements of a wireless sensor node.

When a WSN is being implemented, particular sensor nodes features must be taken into account. In this sub-section we discuss some of the characteristics and requirements that are sought in the design and development of a wireless sensor node [13, 14]. These are the following:

- High energy efficiency, in order to increase the node autonomy.
- Low cost, as a network that covers a large area can consist of hundreds or thousands of nodes. An estimation of the number of the nodes that are required to cover a given area is presented in [18].
- Distributed Sensing, in order to cover a large area despite the obstacles in the environment.
- Wireless communication, as it is the only choice for nodes deployed in remote areas or where no cabling infrastructure is available.
- Multi-hop networking. Depending on the radio parameters [19], it can be more efficient to reach a distant node or a base station using two or more wireless hops than a single large distance hop.
- Local data processing in the node, like zero suppression, data compression and parameter extraction can reduce the transmitted payload, and, thus, the power consumption.

C. Factors to be considered in the network and in its protocol design.

Despite the limited bandwidth of the wireless links, limited processing power and limited energy supply in the wireless nodes, many network designs are focused on taking advantage of the network in order to mitigate these limitations. One of the main pursued objectives of the WSN design is to prolong the network lifetime and prevent information degradation and loss.

In order to provide the right communication between the wireless sensor nodes some design factors and considerations that depend on the type of required application should be taken into account [20, 21, 22]. Table 1 shows some of the major considered items and their descriptions.

TABLE I.

Item	Description
Connectivity	The connectivity in a WSN depends on the random distribution of nodes, mainly due to node failures that may cause the network topology and network size to change. However, the complete interconnection of nodes is desired.
Coverage	Radio coverage is an important design parameter in WSNs. A sensor can only monitor a limited area, but it should be connected with other nodes in order to transmit the sensed information. The limit is set by the wireless technology, the accuracy of the transmission and the data rate (lower data rate in larger distances).
Data aggregation	Data aggregation is the combination of data from different sources according to a specific aggregation function, e.g., duplicate suppression, minimum, maximum and average. In a network, nodes may generate duplicate packets. Therefore, it is important to reduce the number of duplicate packets in the network in order to reduce the energy consumption and latency in communications.
QoS	The latency in a circuit sets the delivery time data from the transmitter to the receiver. However, sometimes power consumption is more important than complete data accuracy. Therefore, routing protocols should be aware of the quality of service and adapt to each situation.
Node deployment	The node Implementation in the WSN depends on the type of application and directly affects the performance of the routing protocol. On the one hand, it can be a deterministic distribution, where sensors are placed manually and the data is routed through default routes. On the other hand, it can be a random distribution, where the resulting distribution of the nodes is not uniform. It always has to find the optimal clustering that allows the best connectivity. Sometimes it has to assume that the network has an energy-efficient behavior. Because the communication between nodes is usually limited in bandwidth and the packet's delivery time, the most probable routes can be formed by multi-hop wireless paths.
Energy consumption	Sensor nodes often use limited energy sources such as batteries. Therefore, the implementation of energy saving techniques is needed.
Fault tolerance	Some sensor nodes may fail and stop the data transmission due to power shortage, physical damage or environmental interference. Node failures should not interfere with the purpose of the network. Therefore, MAC layer protocols and routing protocols must adapt to the formation of new links and routes. The network should remain functional and should continue data transmission. Sometimes, if there are many node failures to implement redundancy techniques at various levels may be necessary to ensure a good level of fault tolerance
Network Dynamics	Many network architectures have stationary sensor nodes. However, the mobility of the nodes is necessary in many applications. The routing of messages between mobile devices is more difficult as the path stability, the bandwidth, energy, etc, becomes a more important consideration. Moreover, the position of sensor can be detected by the network either dynamically or statically using a periodic monitoring.
Transmission Media	In a multi-hop sensor network, the nodes involved in the communication process are connected by a wireless medium. The traditional problems associated with a wireless channel (for example, the losses by vegetation or rain attenuation, the error in height, etc. [5]) may also affect the operation of the sensor network. Good Medium Access Control (MAC) should be used in order to save energy.
Scalability	The number of sensor nodes that can form a network could be of the order of hundreds, thousands or more. Therefore, the network and routing systems must be able to handle large number of sensor nodes. Moreover, the administrator should assume that the network could grow.
Data sensing and reporting model	Data sensing and reporting as well as the data speed in wireless sensor networks depends on the type of application. Data reporting can be categorized as either time-driven (continuous), event-driven, query-driven, and hybrid [23]. The use of a reporting model depends on the type of required monitoring in the system. However, it is possible to use mixed models, which bring together the advantages of various types of reporting models. The routing protocol, also plays an important role in this item, because its performance is greatly influenced by the model of data presentation, and this fact is related to energy consumption and reliability of the chosen route.

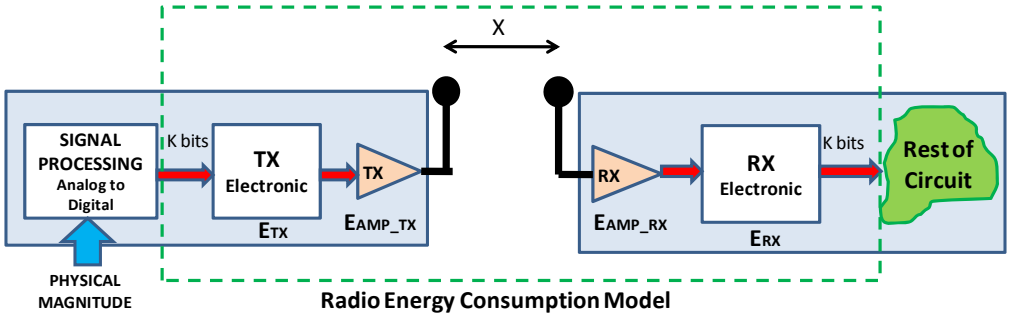

Figure 3. Radio energy consumption model.

$$E_{bit} = \frac{\left((P_{tx\_e}+P_{tx\_out})\cdot\left(\frac{header+payload+trailer}{Rate}\right)+P_{tx\_ini}\cdot T_{tx\_ini}\right)}{payload} + \frac{\left(P_{rx\_e}\cdot\left(\frac{header+payload+trailer}{Rate}\right)+P_{rx\_ini}\cdot T_{rx\_ini}\right)}{payload} + \frac{E_{decoding}}{payload} \quad (1)$$

Where each parameter represents:

E_{bit} : energy consumed per bit
P_{tx_e}: Power consumption in electronic transmission.
P_{tx_out}: Output transmit power.
P_{rx_e}: Power consumption in electronic reception
P_{tx_ini}: Start-up power consumed in Transmission.
T_{tx_ini}: Transmitter start-up time.
P_{rx_ini}: Start-up power consumed in reception.
T_{rx_ini}: Receiver start-up time.
Header: Length of packet header
Payload: Length of packet payload
Trailer: Length of packet trailer
$E_{decoding}$: Decoding energy per packet.

IV. Energy Consumption in Transmission

The sensor output is usually an analog signal. After signal conditioning (amplification, filtering) and digitization, data are processed locally in the node. As a result, a packet is eventually sent to the network using a transmitter circuit. The signal level needs to be amplified before reaching the antenna and propagated through a dispersive medium, such as water [23] or air (which does not generate as many losses as water) [5]. This guarantees an acceptable signal level at the receiver input. In addition, adequate modulation techniques should be implemented in order to minimize the loss of information.

The inverse system is implemented at the receiver node. The first stage is an amplifier or attenuator that sets the input level at the receiver circuit. The receiver applies the appropriate demodulation to obtain the original bit sequences, which are interpreted by the node.

Each of these stages involves electronic circuits that generate a considerable level of energy consumption. The distance between transmitter and receiver must also be taken into account in order to calculate the overall power dissipation [24]. Figure 3 shows the described block diagram. Equation 1 can be used to estimate the energy consumed per bit in the transmitter-receiver model depicted in figure 3 [25]. Several energy saving methods are discussed in [26].

A first, obvious measure consists of adjusting the transmission power to the characteristics of the propagation path, like attenuation and range. Other more sophisticated techniques can be used, like preventing the duplication of packets in the network by using specialized routing protocols.

A frequently used approach is to control the node activity, switching the operation mode between active, idle and sleep modes. The processor consumes the most amount of energy in the active mode. In this mode the device can receive and send data and control packets and can perform data processing. Equation 1 represents this energy value as Ptx_e and Prx_e. In sleep mode, a device consumes the least amount of energy as the transmitter is turned off, the frequency of the main processor may be reduced and it is not possible to realize any processing operation. A considerable amount of time is required to enter and exit this mode. An intermediate state for a node, between active and sleep, is the idle state. In this mode, a device consumes less energy than in the active mode, as no data processing can take place. The device can quickly enter and exit this mode.

A scheme for dynamic power management in WSNs is described in [27]. This work proposes five different operation modes and the rules to switch between them.

A technique called Sparse Topology and Energy Management (STEM) is described in [28]. It reduces the energy consumption in the monitoring state to a bare minimum while ensuring satisfactory latency for transitioning to the transfer state by efficiently waking up nodes from a deep sleep state. The designers have full flexibility in trading latency, density, and energy versus each other.

The work presented in [29] describes several techniques to reduce dynamic power consumption in mobile battery-powered 802.11 WLAN systems. The authors propose to reduce the device energy consumption from its initial design, bearing in mind that, usually, small devices consume less power. But, the price of the final product is considerably increased when reduced manufacturing technology is used.

V. MAC Protocols

The MAC (acronym for medium access control) sub-layer is responsible for regulating the access to a physical

medium shared by several devices. MAC protocols must avoid collisions due to simultaneous transmissions and must perform other important functions like addressing, error checking and delivery notification. An efficient MAC protocol should possess many characteristics. The most important are:

- Predictability of delay
- Adaptability
- Energy efficiency
- Reliability
- Scalability

In this section, a number of works that propose MAC protocols concerned with energy efficiency are briefly described.

A. Energy and Rate based MAC Protocol - ER-MAC

The first work that can be cited is the one presented by R. Kannan et al. [30]. This work presents the Energy and Rate based MAC Protocol (ER-MAC). It is based on TDMA and aims at avoiding energy waste. Packet loss due to collisions is absent because two nodes do not transmit in the same time slot. Although packet loss may occur due to other reasons like interference and loss of signal strength, there is no need to use a contention mechanism because the slots are pre-assigned to each node. ER-MAC uses the concept of periodic listen and sleep. Each node is assigned two TDMA slots for transmission and nodes know the transmission slots of its neighbors. Nodes periodically share information about their power levels and determine whether to use one or two slots for transmission. The proposed protocol is simulated in a scenario of 100 nodes. The results show that ER-MAC achieves a significant increase in energy savings compared to other existing MAC layer protocols.

B. Dominating-awake-interval protocol, Periodically-fully-awake-interval protocol and Quorum-based protocol.

In [31], the authors propose three asynchronous protocols that are directly applicable to MANET technology based on IEEE 802.11. These protocols are named as dominating-awake-interval protocol, periodically-fully-awake-interval protocol and quorum-based protocol. The authors state that devices really send more beacon packets than original IEEE 802.11 standard and they study the best manners to wake-up the devices. Designed protocols use the following rules: (1) send the highest number of beacons in order to prevent the problem of false neighbors and (2) mobile hosts in power saving mode must put more emphasis on sending beacons. Their protocol does not use a clock synchronization system. Moreover, the patterns to wake-up two devices overlap as a function of the difference of time between them. Finally, in order to predict the exact timing to wake-up, when a host hears a beacon from another host, it must wake-up based on another time pattern. The simulations of their protocol show that it is efficient, saves energy and establishes the most likely route.

C. Distributed Wireless Ordering Protocol - DWOP

V. Kanodia et al. present the design and the analysis of the Distributed Wireless Ordering Protocol (DWOP) [32]. It is a distributed scheduling algorithm and media access protocol for wireless ad-hoc networks. It exploits overheard information from other nodes to estimate channel contention. The design of DWOP is based on a graph-theoretic problem formulation. It allows well-characterized deviations from the reference order in more complex topologies and achieves the exact reference ordering in fully connected graphs. DWOP enables QoS differentiation as well as fairness when combined with TCP. A theoretical model indicates that the scheme provides rapid convergence for newly arriving nodes, and extensive simulations indicate that nearly exact reference ordering can be achieved, even in complex asymmetric and perceived-collision topologies. The authors use the piggybacking head-of-line packet priorities in IEEE 802.11 control messages. This allows the nodes to assess the relative priority of their own queued packets. Moreover, the authors propose a distributed stale entry detection method that enables a quick recovery to the steady state.

D. Battery Aware Medium Access Control - BAMAC

Usually, MAC protocols for ad-hoc wireless networks are designed without taking into account the state of the node battery. In [33], S. Jayashree presents a MAC protocol in which each node contains a table that contains information about the battery charge level for each of its neighbors (close nodes that can be accessed). RTS, CTS, Data and ACK packets carry information regarding the battery level of the node that originated the packet. Any listening node fills its table with the information of the load levels of each neighboring nodes. This protocol uses a back-off mechanism, in order to determine which node should receive the packet. The goal of the back-off mechanism is to provide a near round-robin scheduling of the nodes which is based on some temporal parameters like the longest possible time required to transmit a packet successfully, including the RTS-CTS-Data-ACK handshake and the Short and DCF inter-frame spacing durations used in IEEE 802.11. Factors such as the minimum size of the contention window and rank are also considered. The nodes are scheduled based on their remaining battery capacities, that is, the higher the remaining battery capacity, the lower the back-off period. The algorithm allows a node to send the packet to a neighboring node with a higher level of battery. In this way, a uniform rate of battery discharge is guaranteed across all the nodes and consequently, the network lifetime will be longer, because the fall of nodes will be later. The proposed protocol is implemented using GloMoSim simulator and it is compared with the DWOP protocol. The simulations show that the battery life lasts around 70% and reduces battery consumption to nominal packet transmission by 21% compared with IEEE 802.11 and MAC DWOP protocol.

E. Wireless Indoor Flexible High Bit rate Modem Architecture - WIND-FLEX

G. Razzano [34] describes a control architecture that is widely used in local area networks on the structure of WIND-FLEX (Wireless Indoor Flexible High Bit rate Modem Architecture). The author studies the energy consumption in a wireless modem and presents a control method based on fuzzy logic, which has already been applied for determining the transmission power in CDMA (Code-Division Multiple-Access). Power consumption depends on the data rate and thus a reduction in the energy consumption is possible selecting the bit data rate as a function of the traffic situation.

F. Distributed Coordination Function - DCF

In [35], E.-S. Jung and N. H. Vaidya present a mechanism for optimizing the energy saving mechanism in the Distributed Coordination Function (DCF) of IEEE 802.11 networks. In DCF, the time is divided into beacon intervals. At the beginning of each beacon interval, each node in power saving mode periodically wakes up in a period of time called ATIM window. During this period, nodes exchange packets to determine whether the node needs to stay in active mode during the remaining time of the beacon. The energy saving and performance achieved by the nodes is directly proportional to the size of the ATIM window. The authors propose a dynamic adaptation mechanism where a suitable size of ATIM window can be chosen according to network conditions. The protocol has been called Dynamic Power Saving Mechanism (DPSM). A node is able to turn off the wireless network interface every time it finishes the packet transmission process. Initially, each node starts with a minimum ATIM window size, which is increased if they meet some rules. The authors show that the proposed system improves energy consumption without degrading the network performance.

G. Multiple Access with Collision Avoidance

Multiple Access Collision Avoidance MACA [36] protocol makes use of RTS, CTS, DATA and ACK sequences to operate. MACA proceeds as follows:

1) Before sending a message, the transmitter sends a RTS control message ("ready to send"), containing the length of the upcoming data message. The time taken to transmit a control message (~30 bytes) is called a slot.

2) If the receiver hears the RTS and is not currently "deferring," it replies with a CTS control message ("clear to send"), which includes a copy of the length field from the RTS.

3) Any station that hears a CTS defers any transmissions for long enough to allow someone to send a data message of the specified length. This avoids colliding with the CTS sender (the receiver of the upcoming data message).

4) Any station that hears an RTS defers any transmissions for a single slot (long enough for the reply CTS to be received, but not long enough for the actual data message to be sent, because contention is receiver-local).

5) Backoff: if no CTS response is received for an RTS, the sender must retransmit the RTS. It waits for an integer number of slots before retransmitting. The integer is chosen randomly between 1 and BO (backoff counter). BO is doubled for every retransmit, and reduced to 1 for every successful RTS-CTS pair.

H. Multiple Access with Collision Avoidance for Wireless - MACAW

MACAW (MACA for Wireless) [37] presents a series of improvements to the basic MACA algorithm. First, the authors suggest a less aggressive backoff algorithm because the exponential increase/reset to 1 policy of MACA leads to large oscillations in the retransmission interval. They propose to increase the backoff by 1.5 after a timeout, and decrease it by 1 after a successful RTS-CTS pair. Moreover, they arrange values for the backoff counter between clients in order to let the clients with lower backoff counter access the media. They also changed the backoff counter to be per-destination, rather than a single counter. The second proposal is that receivers should send an ACK to the sender after successfully receiving a data message. This is suggested because the minimum TCP retransmission timeout is relatively long (0.5 seconds), so it takes a long time to recover from lost or corrupted messages. A link layer timeout can be more aggressive, because it can take advantage of the knowledge of the individual link latency (rather than the end-to-end timeout in TCP). Thirdly, they propose two related techniques for allowing transmitters to more effectively avoid contention:

- A DS (Data Sending) packet should be sent after a successful RTS-CTS exchange, just before the data message itself. The idea here is to explicitly announce that the RTS-CTS succeeded, so that if a pad can hear an RTS but not the CTS response, it does not attempt to transmit a message during the subsequent data transfer period. The reasoning here is subtle: as noted before, contention is only at the receiver, so one wouldn't think that a node that can hear the RTS but not the CTS should avoid transmitting. However, sending a message requires that the sender hear the CTS response (as well as the eventual ACK); therefore, if another node within range is sending, it would be pointless to also try to transmit.
- Suppose that two devices, A and B, in different cells/cluster are competing for the channel, if one of them "wins", it will effectively monopolize the channel. The authors propose to fix it by the following manner: when a receiver hears an RTS while it is deferring a transmission, at the end of the deferral period it replies with an RRTS ("ready for RTS") packet, prompting the sender to resend the RTS.

Note that the best-case performance of MACAW is actually lower than that of MACA, because the additional ACK and DS messages sent by MACAW incur overhead. However, MACAW is much more resistant to interference, and ensures much fairer allocation of the medium among different transmitters.

I. *Power Aware Multi-Access protocol with Signalling-PAMAS*

In [38], the authors develop a multi-access protocol for ad hoc radio networks. The protocol is based on the original MACA protocol [36], with the addition of a separate signaling channel. The protocol conserves the battery power of the nodes by intelligently powering off the nodes that are not actively transmitting or receiving packets. This protocol uses 6 operational modes for the node. It is based on RTS-CTS Schemes and achieves these power savings without affecting the delay or throughput behavior of the basic protocol. The RTS-CTS message exchange takes place over a signaling channel that is separate from the channel used for packet transmissions. This separate signaling channel enables the nodes to determine when and how long they can be powered off. In order to characterize the energy conserving behavior of PAMAS protocol, the authors provide several simulations where they compared the energy used by PAMAS without power conservation and PAMAS with power conservation. The results show that this improvement over the MACA protocol, produce energy savings of approximately 10%.

J. *Sensor MAC – S-MAC*

S-MAC [39] is an improvement of PAMAS. It reduces further wastage from idle listening by making idle nodes shut off their radios. S-MAC reduces the waste of energy and self-configures. It adopts a contention-based scheme in order to have collision avoidance and good scalability. Overhearing makes contention-based protocols less efficient, so each node chooses a schedule, stores the schedule table, and exchanges it with its neighbors before starting its periodic listen and sleep modes. Their schedules are broadcasted to all their immediate neighbors, thus the time interval for listening and sleeping can be selected according to different application scenarios. In order to demonstrate the effectiveness and measure the performance of S-MAC, the authors implemented it on a wireless sensor network test bed. Motes were developed by some researchers of the University of California, Berkeley. These devices were based on an 8-bit Atmel AT90LS8535 microcontroller running at 4 MHz. However, S-MAC does not avoid collisions between two RTS or CTS messages (like PAMAS), which is a significant wastage of energy. Moreover, the sleep time interval is the same for each node, which is unfair for the nodes with less energy. To make weaker nodes sleep more can increase efficiency. Furthermore, S-MAC assigns sleep schedules without taking into account the criticality of a node.

K. *Floor Acquisition Multiple Access - FAMA*

FAMA is another MACA-based scheme that requires every transmitting station to acquire the control of the floor (i.e., the wireless channel) before it actually sends any data packet [40]. Unlike MACA or MACAW, FAMA requires that collision avoidance should be performed both at the transmitter as well as at the receiver.

In order to "acquire the floor", the transmitter node sends a RTS using either non-persistent packet sensing (NPS) or non-persistent carrier sensing (NCS), and the receiver replies with a CTS packet, which contains the address of the source node. Any station that hears the CTS packet will know which station has acquired the floor. CTS packets are repeated long enough for the benefit of any hidden sender. Authors recommend NCS variant for ad hoc networks since it addresses the hidden terminal problem effectively.

L. *Interleaved Carrier Sense Multiple Access - ICSMA*

The presence of exposed terminals is a significant problem in ad hoc wireless networks. S. Jagadeesan et al. propose a new MAC protocol called Interleaved Carrier Sense Multiple Access (ICSMA) Protocol for Ad hoc wireless networks to solve this problem in [41]. ICSMA reduces the number of exposed terminals and tries to maximize the number of simultaneous sessions in ad hoc networks. ICSMA access mechanism is based on the RTS-CTS-DATA-ACK access mechanism of the IEEE 802.11 DCF. It bases its operation in the use of two identical channels, where its handshaking process is interleaved between them. A node can originate the transmission in either channel 1 or channel 2 depending on the channel availability. In the ICSMA access mechanism, node A sends a RTS packet over channel 1 to Node B after waiting for a time period of DCF Inter Frame Spacing (IFS). Node B verifies the E-NAV in order to find out the availability of free time slots. If there are free available slots, then it responds a CTS packet over the channel 2 within Short Inter Frame Space (SIFS) time. If the CTS packet is not received by Node A successfully, it assumes a collision of the RTS packet or unavailability of Node B and it tries to send the RTS again after a back-off time (it uses a back-off mechanism similar to that used in IEEE 802.11 DCF). When Node A receives the CTS packet over channel 2, it transmits a DATA packet over channel 1, within SIFS time and expects the ACK through channel 2. If the ACK does not arrive within SIFS time, then Node A assumes a collision and attempts a re-transmission after back-off time. The simulations show that this protocol performed better than IEEE 802.11 when they are compared in terms of throughput, channel access delay, throughput fairness, and delay fairness.

M. *Multiple Access with Collision Avoidance by Invitation - MACA-BI*

Another MAC protocol based on MACA is MACA-BI. It was presented by F. Talucci et al. in [42]. MACA-BI eliminates the need of RTS packets, thus reducing the overhead given by each packet transmission and simplifying the implementation, while preserving the data collision free property of MACA. MACA-BI is less vulnerable to control packet corruption than MACA. In addition, the "receiver driven" mechanism of MACA-BI automatically provides traffic regulation, flow control and congestion control. This protocol is more robust to failures such as hidden terminal collision, direct collision or noise corruption and it also is less sensitive to the TX-

RX turn-around time. In order to test the performance of this protocol the authors developed an analytical model in a single-hop configuration and a simulation model to evaluate it in multihop environments (all of them operating at 1 Mbps). The results show the efficiency of MACA-BI in wireless networks where improving the steady (predictable) traffic at higher channel speeds plays a key role. Collisions between control packets, and between control and data packets, may exist because of carrier sense failure due to non-zero propagation delays or due to the hidden terminal transmission. The authors conclude by letting us know that the probability of collisions among data packets is not possible in MACA-BI. The best manner to recover from this kind of data loss is only by using explicit ACKs.

N. Multiple Access with Reduced Handshake - MARCH

Multiple Access with Reduced Handshake (MARCH) protocol, presented by C.-K.Toh et al. in [43], improves communication throughput in wireless multihop ad hoc networks by reducing the amount of control overhead. It combines the advantages of both sender and receiver-initiated protocols. Unlike other receiver-initiated protocols, MARCH operates without resorting to any traffic prediction. This protocol reduces the number of handshakes required to transmit a data packet, so it outperforms other sender-initiated protocols. The novelty of this approach is that a mobile host (MH) has knowledge of the data packet arrival of its neighboring MH from the overheard CTS packets. The simulation results show that MARCH outperforms MACA in several issues. MARCH protocol has a lower probability of control packet collision. Therefore its control overhead is much lower than MACA at all traffic loads. Furthermore, because it exploits the fact that control messages are overheard by the neighbors, this protocol is more deterministic and does not resort to network prediction, unlike most receiver-initiated protocols.

O. Hop-Reservation Multiple Access - HRMA

In [44], Z. Yang et al. describe a multichannel MAC protocol for ad-hoc networks operating with simple FHSS radios on ISM bands. HRMA is based on a common hopping sequence for the entire network and requires half-duplex slow frequency-hopping radios with no carrier sensing to operate. In HRMA the time is slotted. The protocol can be viewed as a time-slot reservation protocol in which a time slot is also assigned a separate frequency channel. Each slot consists of one synchronizing period, one HR period, one RTS period and one CTS period, each of which is used to exclusively send or receive the synchronizing packet, the HR packet, the RTS packet, and the CTS packet, respectively. For synchronization purposes, a special slot, called synchronizing slot, is defined. It has the same size as the regular slot. Each slot is assigned to a frequency hop. All the nodes that are not transmitting or receiving data packets are called idle nodes. They must hop to the synchronizing frequency and exchange synchronizing messages during the synchronizing period of each slot. During the HR, RTS and CTS periods of each slot, all idle nodes must dwell on the common frequency hop assigned to each slot. HRMA dynamically allocates frequency bands to nodes using a common frequency-hopping pattern. In this way, the data and acknowledgements are transmitted without hidden-terminal interference, which allows merging systems and permits nodes to join existing systems. The simulation results show that HRMA's throughput performance is significantly better than the slotted ALOHA. HRMA can achieve a maximum throughput that is comparable to the theoretical maximum value, especially when data packets are large compared to the slot size used for frequency hopping. This high throughput is obtained through a very simple reservation mechanism without the need of complex code assignment.

P. Receiver-Based AutoRate (RBAR) protocol - RBAR

Receiver-Based AutoRate (RBAR) protocol is a rate adaptive MAC protocol [45]. G. Holland et al. base their design on different assumptions. The first one is that the rate selection can be improved by providing timelier and more complete channel quality information. The second one is that the channel quality information is best acquired at the receiver and, finally, the third one is that the transmitting channel quality information to the sender can be costly, both in terms of the resources consumed in transmitting the quantity of information needed as well as the potential loss in timeliness of the information due to transmission delays. The novelty of RBAR is that it allows the channel quality estimation mechanism to directly access all of the information made available to it by the receiving hardware, for more accurate rate selection. The rate selection is performed on a per-packet basis during the RTS/CTS exchange, just prior to data packet transmission. Simulations show that this protocol results in a more efficient channel quality estimation which is then respected in a higher overall throughput. RBAR can be implemented inside IEEE 802.11 without significant changes.

There are some other works proposing other MAC protocols. Some of them are new proposals and others are schemes based on existing protocols. However, we have presented in this paper the most important ones. Table 2 shows the classification of the explained protocols. It summarizes the main characteristics of each one. A dash (-) means that the information is not provided by the authors or it cannot be correctly ascertained from their paper.

VI. ROUTING PROTOCOLS

Routing protocols provide different mechanisms to develop and maintain the routing tables of the nodes of the network and find a path between all nodes of the network. Routing protocols must be adaptable to any type of topology to allow reaching any remote host in any network. Initially, a metric used for measurement must be defined in the routing protocol in order to find the best route. A routing protocol must be designed looking for very specific main objectives. Among the functions that it should have, here we highlight the following:

TABLE II.

Classification			MAC Protocol	Collision Avoidance	Reliability	The Energy is taken into account	Adaptability	Delay Predictability
Contention-Based Protocols	Sender-initiated Protocols	Single-Channel Protocols	MACAW	Yes	Reliability in the channel which is shared between participating nodes.	More efficient than MACA	-	-
			FAMA	Yes	-	-	-	-
			MACA	Yes	When the delivery is unidirectional	Few efficient	-	-
		Multi-Channel Protocols	S-MAC	No	-	Yes	Yes	-
			ICSMA	Yes	-	-	-	-
			PAMAS	-	-	Yes	-	-
	Receiver-initiated Protocols		MACA-BI	Yes	-	-	-	Yes
			MARCH	Yes	-	-	-	No
Protocols with Reservations mechanisms	Synchronous Protocols		DPSM	-	-	Yes	-	-
			HRMA	Yes	-	-	-	-
			DCF	-	-	Yes	-	-
	Asynchronous Protocols		Periodically-Fully-Awake	Yes	-	Yes	-	-
			Quorum-Based	Yes	-	Yes	-	-
			Dominated-Awake	Yes	-	Yes	-	-
Protocols with scheduling mechanisms			DWOP	-	-	Yes	-	-
			ER-MAC	-	-	Yes	-	-
Other MAC protocols			BAMAC	-	-	Yes	-	-
			RBAR	No	-	-	Yes	-

- Maintain a reasonably small routing table.
- Choose the best route to a given destination. This would imply be the fastest, most reliable, highest capacity or the least cost route.
- Maintain a regular basis to update the routing table when nodes change their position appear in the network.
- Have a small number of messages in order to waste low bandwidth and save energy.
- Require little time to converge in order to provide the most updated network.

In this section, we will review the most well known routing protocols for WSNs that are related to energy saving techniques.

A. Energy Aware Routing protocol - EAR

Energy aware routing protocol [46] is a reactive protocol that aims to increase the lifetime of the network. This protocol seeks to maintain a set of paths instead of maintaining or enforcing one optimal path at higher rates, although the behavior of this protocol is similar to directed diffusion protocols. These routes are selected and maintained by a probability factor. The value of this probability depends on the lowest level of energy achieved in each path. Because the system has several ways to establish a route, the energy of a path cannot be determined easily. Network survivability is the main metric of this protocol. The protocol assumes that each node is addressable through a class-based addressing scheme which includes the location and the type of nodes. When the protocol starts, there is a process of flooding, which is used to discover all the routes between various source/destination pairs and their costs. This will allow creating routing tables, where high-cost paths are discarded. By using these tables, data is sent to its destination with a probability that is inversely proportional to the cost of the node. The destination node performs a localized flooding in order to maintain the paths that are still operative. Compared to other protocols, the energy aware routing protocol provides an overall improvement of 21.5% in energy savings and increases the network life by about 44%. However, having to collect location information, and the establishment of the steering mechanism for nodes, complicates the path settings.

B. Low Energy Adaptive Clustering Hierarchy - LEACH

Heinzelman et al. presented in [47] a hierarchical clustering algorithm for sensor networks called Low Energy Adaptive Clustering Hierarchy (LEACH). It is a clustering based protocol that includes the formation of distributed groups. It randomly selects a few nodes as cluster heads (CHs) and rotates this role to evenly

distribute the energy load among the nodes of the network. In LEACH, CH nodes compress the data arriving from the nodes in their respective groups, and send summary packets to the base station. This reduces the amount of information transmitted to the base station. Data collection is centralized and is carried out periodically. Therefore, this protocol is appropriate when constant monitoring of the WSN is needed. The operation of LEACH is separated into two phases, the setup phase and the steady-state phase. In the setup phase the groups are organized and certain fraction of nodes are elected as CHs. In the steady-state phase, data transfer to the base station occurs. All elected CHs announce to the other nodes of the network, through a broadcast message, that they are the new CHs. All non-CH nodes, after receiving this notice, choose the group they want to belong to. This decision is based on the intensity of the warning signal. Non-CH nodes inform the appropriate CHs that it is a member of their group. After receiving all messages from the nodes that wish to be included in the cluster, the CH node creates a TDMA program and assigns to each node a time slot to transmit data. This program is broadcasted to all nodes in the cluster. During the steady state, the sensor nodes can sense and transmit data to the CHs. The CH node, after receiving all data, adds its information and sends it to the base station. After some time, which is determined a priori, the network returns to the setup phase again and starts another round of new CHs election. Each group communicates using different CDMA codes in order to reduce interference with nodes that belong to other groups. Although LEACH is able to increase the network lifetime, there are still a number of questions about the assumptions used in this protocol. LEACH assumes that all nodes have enough transmission power to reach the base station and each node has the computational power to support different MAC protocols. Therefore, it is not applicable to networks deployed in large regions. It also assumes that nodes always have data to send, and nodes that are located close to each other have correlated data. It is unclear how the CHs are uniformly distributed over the network. Therefore, it may happen that the elected CHs are concentrated in one part of the network, so some nodes may not have a CH in their surroundings. Moreover, the idea of dynamic clustering can result in an extra overhead that can increase the energy consumption. Finally, the protocol assumes that all nodes start with the same amount of energy in each round of election, and assumes that a CH consumes approximately the same amount of energy.

C. Hybrid Energy-Efficient Distributed clustering-HEED

The paper in [48] proposes a method of saving energy for clusters of nodes in WSNs. HEED (*Hybrid Energy-Efficient Distributed clustering)* periodically selects the main nodes in the cluster according to a set of parameters such as residual energy and a secondary endpoint. It also seeks to extend the network lifetime by distributing energy consumption. It also tries to reduce high control on the network. The authors explain the grouping process and the determination of the responsible node. The system does not take care of the type of technology used. This work compares HEED protocol with others. HEED optimizes the use of resources according to the network density and the application requirements.

D. Hierarchical Power-Aware Routing (HPAR)

Another example of hierarchical protocol is presented by Q. Li et al. in [49]. The Hierarchical Power-Aware Routing (HPAR) protocol bases its operation on the division of the network into groups of sensors. Each group is formed by geographically close sensors covering a zone. Each zone is treated as an entity. In order to perform the routing between nodes, each zone is allowed to decide how a message is routed through the other areas, so maximizing the battery life of the nodes. Messages are routed along the path that has the maximum value on all the remaining minimum power values. This route is called max-min path. In order to send a message through an area, the route through the area and the sensors involved in estimating the power level of the area should be found. Each message is routed through the areas with the information about the estimation. The role of area management for message routing is assigned to a node. This protocol is based on the idea that the use of high residual energy nodes can be more expensive than the path with minimum energy consumption. The protocol seeks a balance between minimizing the total power consumption (using Dijkstra algorithm to find the path with least power consumption) and maximizing the minimal residual power of the network.

E. Power-Efficient Gathering in Sensor Information Systems - PEGASIS

In [50], an enhancement over LEACH protocol was proposed. The protocol, called Power-Efficient Gathering in Sensor Information Systems (PEGASIS), is a near optimal chain-based protocol. The basic foundation of this protocol is that nodes need only to communicate with their nearest neighbors, taking turns to communicate with the base station. When all nodes have established a connection with the base station, a new round will start and so on. This type of communication between nodes reduces the power required to transmit data through a path and ensures power distribution in all nodes. Therefore, PEGASIS has two main objectives. On the one hand, PEGASIS increases the lifetime of each node using collaboration techniques and, as a result, the network lifetime is extended. Moreover, the protocol allows only local coordination among close nodes, so the bandwidth consumed in communication is reduced. In addition, PEGASIS assumes that all nodes maintain a comprehensive database of the location of other nodes. To set the distance that each node has to its neighbor, the protocol uses the received signal strength to subsequently adjust the intensity of the signal in order to hear just one node. By contrast, PEGASIS requires adjustments to dynamic topologies in order to know where to find the destination node and in order to know where to route their data. Simulation results show that PEGASIS is able to double the network lifetime in comparison to using LEACH protocol.

F. Hierarchical-PEGASIS

An extension and improvement of PEGASIS (called hierarchical-PEGASIS) was introduced in [51]. Its aim is to reduce the delay of the packets transmitted to the base station. This protocol bases its operation in the assumption that only those spatially separated nodes may transmit simultaneously. It is a chain-based protocol with CDMA capable nodes, which constructs a chain of nodes forming a hierarchical structure and each selected node in a particular level transmits data to the node in the upper level of the hierarchy. In the performance test, the authors simulate simultaneous data transmissions to show how it avoids collisions through approaches that incorporate signal coding and spatial transmissions. The simulation shows that the new method ensures data transmitting in parallel and reduces the delay significantly. It has also shown that the proposal improves the previous version (PEGASIS) by a factor of about 60.

G. Minimum Energy Communication Network - MECN

In [52], the authors propose a protocol, called Minimum Energy Communication Network (MECN), which calculates the energy efficiency of the subnets. It uses low-power GPS system. MECN identifies a region for every node. The region consists of nodes in a surrounding area where the transmission through those nodes is more energy efficient than direct transmission. The enclosure of a node is created by joining all regions that the region of the node can achieve. The main idea of MECN is to find a subnet that has fewer nodes and requires less transmission power between two particular nodes. In this way, global minimum power paths are not taken into account for all the network nodes. This is done using a localized search for each node considering its region. MECN is self-reconfigurable and thus can dynamically adapt to node failures or to the deployment of new sensors.

H. Small Minimum Energy Communication Network - SMECN

Small Minimum Energy Communication Network (SMECN) [53] is an improvement of MECN. In their algorithm, the authors considered for MECN the possible obstacles between any pair of nodes. Simulations show that SMECN is more energy-efficient than MECN and the links cost maintenance is lower. In addition, the number of hops for transmissions is decreased. On the other hand, finding a sub-network with a smaller number of edges introduces more overhead in the algorithm.

I. Threshold sensitive Energy Efficient sensor Network - TEEN

Threshold sensitive Energy Efficient sensor Network protocol (TEEN) [54] was developed for reactive networks. Sensor nodes continuously detect the environment but data transmission is only carried out when a parameter reaches a threshold value. The sensed value is stored in an internal variable in the node, called the sensed value (SV). There are two thresholds, hard threshold and soft threshold. When a parameter reaches its hard threshold value, the node switches on its transmitter and sends the sensed data to the cluster head. The soft threshold is a small change in the value of the attribute that causes the node to change to transmit mode and to start the transmission process. It gives a more accurate picture of the network, even if it means higher energy consumption. Thus, the user can decide on the tradeoff between energy efficiency and data accuracy. When CHs are changed, the new values of the above parameters are broadcasted. The main drawback of this system is that if the thresholds are not received, the sensed reported is not transmitted, and the user does not get any data from the network. In the TEEN protocol, the process of data detection consumes less power than the transmission of messages, so that energy consumption in this system is less than proactive networks. In addition, if necessary, the user can modify the soft threshold and broadcast the new parameters to the other sensors.

J. Adaptive Threshold sensitive Energy Efficient sensor Network - APTEEN

On the other hand, Adaptive Threshold sensitive Energy Efficient sensor Network protocol (APTEEN) [55] is a hybrid protocol that changes the frequency and threshold values used in the TEEN protocol according to the user needs and the type of application. The main feature of the APTEEN scheme is that it includes a combination of proactive and reactive policies. It has the possibility of adjusting the interval timer and the threshold values so as to redress power consumption according to the type of implemented application. In APTEEN, the node continuously monitors the environment, and only the nodes that detect an attribute value above the hard threshold will transmit data. The nodes will also transmit when the attribute value changes are equal to or greater than the soft threshold. If a node does not send data over a period of time equal to the timer, it will have to retransmit lost data. APTEEN uses a modified TDMA scheme to implement the hybrid network. The operation is based on the performance of TDMA, where a transmission time slot is assigned to each node in the cluster. The biggest weakness is the additional complexity to implement the features of the threshold and timer. APTEEN performance is between LEACH and TEEN in terms of energy dissipation and lifetime of the network. TEEN offers better performance by decreasing the number of transmissions.

K. ACtive QUery forwarding In sensoR nEtworks-ACQUIRE

In [56], Sadagopan et al. proposed a technique for querying sensor networks, which was called ACtive QUery forwarding In sensoR nEtworks (ACQUIRE).This protocol is a novel mechanism for data extraction in energy-constrained sensor networks. The key features of ACQUIRE are the injection of active queries into the network with triggered local updates. ACQUIRE performs its function in an energy efficient manner compared to other approaches. The network is a distributed database where complex queries can be further divided into several sub queries. The sink node sends a query, which is then forwarded by each node.

Nodes with relevant data will respond. It is not a continuously persistent query, so the flooding does not dominate the costs associated with querying. Moreover, when data aggregation is employed, duplicate responses can generate in suboptimal data collection in terms of energy costs, so, once the query is being resolved completely, it is sent back through either the reverse or shortest-path to the base station. Moreover, ACQUIRE can provide efficient query by adjusting the value of the look-ahead number of hops. When the number of hops is equal to the network diameter, ACQUIRE mechanism behaves similar to flooding mechanism. ACQUIRE protocol shows good results with optimal parameter settings that outperform all the other schemes on complex, one-shot, non-aggregate queries for replicated data. It can reduce the energy consumption of other approached by more than 60% in some cases.

L. Information-Driven Sensor Querying and Constrained Anisotropic Diffusion Routing – IDSQ and CADR

Two routing techniques called information-driven sensor querying (IDSQ) and constrained anisotropic diffusion routing (CADR) are presented by M. Chu et al. in [57]. The main idea of both protocols is to maximize the information gain, by choosing the best query sensors and route data, while latency and bandwidth are minimized. This is achieved by activating only the sensors that are close to a particular event, thus data routes are dynamically adjusted. There are some differences between these protocols. While CADR aims to be a general form of directed diffusion, IDSQ is based on a protocol in which the querying node could determine which node can provide the most useful information while balancing the energy cost. Moreover, in CADR, the local information/cost gradient and end-user requirements are used in order specify an information/cost objective, and routes data, for each node. In addition, CADR can diffuse its queries only to the sensor nodes that can get the data (by only activating the right ones). IDSQ can be seen as a complementary optimization procedure because it does not specifically define how the query and the information are routed between sensors and the base station. However, simulation results shows that directed diffusion techniques, where queries are diffused in an isotropic fashion and reaching nearest neighbors first, are less energy-efficient than these approaches. A disadvantage of both protocols is that both need too much processing in their nodes.

M. COUGAR

Another data-centric protocol, presented by Y. Yao et al., is COUGAR [24]. This protocol views the network as a huge distributed database system. The main idea is to use declarative queries to summarize query processing such as the election of relevant sensors, etc. COUGAR utilizes in-network data aggregation to obtain more energy savings. In order to reduce resource usage and thus extend the lifetime of a sensor network, COUGAR uses a user query technique, where a query optimizer generates an efficient query plan for in-network query processing. Through an additional query layer that lies between the network and application layers, this protocol supports the summary. COUGAR adds an architecture for the sensor database system, where sensor nodes elect a leader node in order to perform data aggregation and transmit the data to the sink. This fact provides in-network computation ability that can provide energy efficiency in situations where the number of sensors generating and sending data to the leader is very large. In contrast, COUGAR has some drawbacks. On the one hand, the addition of a query layer on each sensor node may add an extra overhead in terms of energy consumption and memory storage. On the other hand, in order to obtain successful in-network data computation, synchronization among nodes is required before sending the data to the leader node. Finally, the leader nodes should be dynamically maintained to prevent them from being hot-spots.

N. Geographic Adaptive Fidelity - GAF

Geographic Adaptive Fidelity (GAF) was presented by Y. Xu et al. in [15]. It is an energy-aware location-based routing algorithm designed primarily for mobile ad hoc networks, although it may also be applicable to sensor networks. This protocol divides the network area into fixed zones where nodes collaborate with each other to play different roles and form a virtual grid. The main goal of GAF is the energy conservation by turning off unnecessary nodes in the network without affecting the level of routing fidelity. There is a virtual grid formed to cover an area. Each node uses a GPS-indicated location to associate itself with a point in the virtual grid. Inside these virtual grids, the nodes associated with the same point on the grid, receive the same value in terms of the cost of packet routing. GAF defines three states. These states are: discovery, for determining the neighbors in the grid, active reflecting participation in routing, and sleep, when the radio is turned off. GAF can increase the network lifetime even increasing the number of nodes, because, some nodes located in a particular grid area can remain in sleep mode in order to reduce the global energy consumption of the network. When a node is in sleep mode, it can change its state from sleep mode to active mode in order to balance the network load. Furthermore, the parameters related to the time for the sleep mode are specified during the routing process. In addition, to handle mobility, each node in the grid estimates its transmission time in the grid and sends its data to its neighbors. The sleeping neighbors adjust their sleeping time accordingly in order to keep the routing fidelity. Simulation results show that GAF performs as well as a regular ad hoc routing protocol in terms of latency and packet loss and increases the lifetime of the network by saving energy. However, GAF can be considered as a hierarchical protocol without aggregation, and consequently it can have the same weaknesses as a hierarchical protocol.

O. Geographic and Energy Aware Routing - GEAR

Geographic and Energy Aware Routing (GEAR) is a location based routing protocol too. It was presented by

Y. Yu et al. in [58]. The main idea of this protocol is to restrict the number of queries in directed diffusion considering a certain region rather than sending the queries to the whole network. In GEAR, each node keeps an estimated cost and a learning cost to reach the destination through its neighbors. In order to estimate the cost as a combination of the residual energy and the distance to a destination, it uses energy aware and geographically-informed neighbor selection heuristics to route a packet towards the destination region. The learned cost is obtained as a refinement of the estimated routing cost around the holes of the network. A hole is generated when a node does not have any closer neighbor to the target region than itself. If there are no holes, the estimated cost is equal to the learned cost and it is spread one hop back every time a packet reaches the destination. We can distinguish two phases in the algorithm flow. In the first one, when a node receives a packet, it checks its neighbors to see if there is a neighbor closer to the target region. The nearest neighbor node is selected as the next hop. When the network registers a hole, one of the neighbors is picked to forward the packet based on the learning cost function. In the second phase, when a packet has reached the region, it can be diffused in that region by either recursive geographic forwarding or by restricted flooding. Restricted flooding is usually used when the sensors are not densely deployed while recursive geographic flooding is more energy efficient in high-density networks. GEAR reduces energy consumption in the route setup and it performs better than GPSR in terms of packet delivery. The simulations show that for an uneven traffic distribution, this protocol delivers from 70% to 80% more packets than GPSR. For uniform traffic pairs GEAR, it delivers from 25% to 35% more packets than GPSR.

P. Sequential Assignment Routing - SAR

Sequential assignment routing (SAR) [59] was the first protocol for sensor networks that includes the notion of QoS in its routing decisions. The SAR algorithm generates multiple trees where the root of each tree is a one hop neighbor from the sink. Each tree grows outward from the sink by taking into consideration the QoS metric, the energy of each path and the priority level of each packet. This algorithm selects the path based on them. When the sensor node has exclusive use of a path, the energy resources are estimated by the number of packets. As a result, each sensor node selects its path to route the data back to the sink. Simulation results show that it offers less power consumption than other network algorithms, which only focus the energy consumption of each packet without considering its priority. In contrast, SAR maintains multiple paths from nodes to the sink which generates an overhead because of the tables and states maintenance of each sensor node, especially when the number of nodes is too big.

Q. SPEED

A real-time communication protocol for sensor networks, called SPEED, is proposed by T. Hea et al. in [60]. SPEED is specifically tailored to be a stateless-localized algorithm with minimal control overhead. This protocol provides three types of real-time communication services, called, real-time unicast, real-time area-multicast and real-time area-anycast, for ad hoc sensor networks. SPEED is an efficient and scalable protocol for sensor networks where the resources of each node are scarce. It can also provide congestion avoidance when the network is congested. In this protocol, each node maintains information about its neighbors and uses geographic forwarding to find the paths. Furthermore, SPEED tries to ensure a certain speed for each packet so each application can estimate the end-to-end delay for the packets by dividing the distance to the sink by the speed of the packet before making the admission decision. The beacon exchange mechanism collects information about the nodes and their location. Then, the delay estimation at each node is calculated by the elapsed time when an ACK is received from a neighbor as a response to a transmitted data packet. After that, the node, which meets the speed requirement, is selected. If it is not possible, the relay ratio of the node will be checked. The Neighborhood Feedback Loop module calculates the relay ratio by looking at the packet failure ratios of the neighbors of a node. The algorithm eliminates congestion by sending messages back to the source nodes, thus they will pursue new routes. SPEED maintains a desired delivery speed across the network through a novel combination of feedback control and non-deterministic QoS-aware geographic forwarding. The design takes into account that the end-to-end delay depends on not only single hop delay, but also on the distance a packet travels. SPEED algorithm tries to support a real-time communication service with a desired delivery speed across the wireless sensor network, so the end-to-end delay is proportional to the distance between the source and the destination. Delivery speed is always smaller than the actual speed of the packet in the network, unless the packet is routed exactly along a straight line.

R. Directed Diffusion

Directed diffusion is data-centric protocol where all nodes in the directed diffusion-based network are application aware. This protocol was presented by C. Intanagonwiwat et al. in [61]. Directed diffusion protocol is suitable for query applications, which does not need global network topology maintenance. In addition, it enables diffusion to achieve energy savings by selecting good paths empirically and by caching and processing the data. This protocol has several features that can be highlighted. On the one hand, directed diffusion has the potential for significant energy efficiency. It outperforms an idealized traditional data dissemination scheme like omniscient multicast, even with an un-optimized path selection. On the other hand, diffusion mechanisms are stable under certain ranges of network dynamics. By contrast, this protocol is not the most suitable for continuous monitoring of a medium, because the computational requirements needed are high, which will imply more energy consumption.

S. Rumor Routing

Rumor Routing [62], presented by D. Braginsky et al. is a variation of the Directed Diffusion protocol. It represents a compromise between flooding queries and flooding event notifications. This protocol was designed for contexts in which geographic routing criteria are not applicable because a coordinate system is not available or the phenomenon of interest is not geographically correlated. The protocol is based on the following assumption: when the number of events is low, compared to the number of queries, event flooding can be efficient. Rumor routing algorithm uses long-lived packets called agents, to flood events through the network. When a node detects an event, it adds such event to its local table and generates an agent. Agents travel through the network in order to propagate information about local events to distant nodes. When a node generates a query for an event, the nodes that know the route, can respond to the query by referring its event table, thus the cost of flooding the whole network is avoided. Simulations show that Rumor Routing algorithm is a good method for delivering queries to events in large networks under a wide range of conditions, while maintaining energy requirements lower than other alternatives. Its design is able to be adjusted to different application requirements, to support different queries to event ratios, successful delivery rates, and route repair. In addition, it is capable to handling node failures and degrade its delivery rate linearly with the number of failed nodes.

T. Self Organizing Protocol - SOP

In [63], Subramanian et al. proposed a genetic architecture and a self-organizing protocol that allows large number of sensors to coordinate among themselves. The main goals of the algorithm are to minimize power utilization, localize operations and tolerate node and link failures. This routing protocol is based on a hierarchical architecture where groups of nodes are formed and merge when needed. It uses the Local Markov Loops algorithm in order to support fault tolerance. SOP can consider mobile or stationary sensors. Collected data are forwarded through the nodes to the most powerful base station.

U. Two-Phase geographic Greedy Forwarding - TPGF

We can also find papers which present protocols for very specific applications. In [64], presented by L. Shu et al., authors propose an efficient Two-Phase geographic Greedy Forwarding (TPGF) routing algorithm for Wireless multimedia Sensor Networks (WMSNs). TPGF is different from other geographic routing algorithms, because TPGF is a pure geographic routing algorithm that does not include the face routing concept and also does not require the computation and preservation of the planar graph in WSNs. This fact allows more links to be available for TPGF to explore more node disjoint routing paths. However, TPGF does not have the well-known Local Minimum Problem. The operation of this algorithm is divided mainly in two phases. In the first of them, the algorithm should explore the possible routing path, guarantying the correct delivery through routing path while bypassing holes in WMSNs. The second phase is responsible for optimizing the found routing path with the least number of hops. TPGF can be considered an iterative algorithm due to it can be executed repeatedly to find multiple node-disjoint routing paths. The algorithm structure contemplates as inputs, the location of the current forwarding node, the location of the base station and the locations of 1-hop neighbor nodes; meanwhile, its outputs are the location of the next-hop node or successful acknowledgement or unsuccessful acknowledgement. The goals of the simulation try to demonstrate that TPGF can find more routing paths and prove that it can have shorter average path length than other algorithms like GPSR. To evaluate the TPGF routing algorithm, the authors use a sensor network simulator NetTopo. The network size in simulation is fixed as 600 × 400. For each fixed number of sensor nodes and transmission radius, the average number of paths and the average path length are computed from 100 simulation results using 100 random seeds for network deployment. The simulations results show that, on the one hand, TPGF can find much more number of paths than that of GPSR on both GG and RNG planar graphs. In addition, the after optimization the average path length of TPGF is much shorter than GPSR and finally, it is proved that TPGF can have shorter average path length than that of GPSR.

V. Energy Consumed uniformly-Connected K-Neighborhood - EC-CKN

Related with Network lifetime, Z. Yuan et al. present a paper [65] where propose a new sleep scheduling algorithm, named EC-CKN (Energy Consumed uniformly-Connected K-Neighborhood) algorithm, to prolong the network lifetime. In this work, the authors propose a new sleep scheduling algorithm, named EC-CKN, which is proposed to balance the energy consumption and prolongs the network lifetime. This algorithm takes the nodes' residual energy information as the parameter to decide whether a node to be active or sleep and not only can achieve the k_connected neighborhoods problem, it also can assure the k awake neighbor nodes have more residual energy than other neighbor nodes at the current epoch. To do the simulations, the authors suppose a model of transmitter and receiver, considering the power consumption of each part of the circuit, depending on the number of bits transmitted. To these nodes, the sleep scheduling algorithm is applied. The algorithm takes an input parameter K, the required minimum number of awake neighbors per node. In EC-CKN, a node broadcasts its current residual energy information and computes a subset of neighbors. Before the node can go to sleep it makes sure that all nodes in subset are connected by nodes with major amount of energy and each of its neighbors has at least k neighbors from subset. With this process, the system guarantees, that if a node has less than k neighbors, none of its neighbors goes to sleep and if it has more than k neighbors, at least k neighbors of them decide to remain awake.

TABLE III.

	Network Structure				Main Functions						Energy
Routing Protocol	**Flat**	**Hierarchical**	**Location Based**	**QoS based**	**Scalability**	**Data Aggregation**	**Mobility**	**Query Based**	**Multipath**	**Negotiation Based**	**Power Consumption**
ACQUIRE	Yes	-	-	-	Limited	Yes	Limited	Yes	No	No	-
APTEEN	-	Yes	-	-	Good	Yes	Fixed BS	No	No	No	Maximum
CADR	Yes	-	-	-	Limited	Yes	No	No	No	No	-
COUGAR	Yes	-	-	-	Limited	Yes	No	Yes	No	No	Limited
Directed Diffusion	Yes	-	-	-	Limited	Yes	Limited	Yes	Yes	Yes	Limited
EC-CKN	-	-	-	YES	Good	No	No	Yes	-	-	-
Energy Aware Routing	Yes	-	-	-	Limited	No	Limited	Yes	No	No	-
GAF	-	-	Yes	-	Good	No	Limited	No	No	No	Limited
GEAR	-	-	Yes	-	Limited	No	Limited	No	No	No	Limited
HEED	-	Yes	-	-	Good	Yes	Yes	No	No	No	-
Hierarchical-PEGASIS	-	Yes	-	-	Low	No	Fixed BS	No	No	No	Maximum
HPAR	-	Yes	-	-	Good	No	No	No	No	No	-
IDSQ	Yes	-	-	-	Limited	Yes	No	No	No	No	-
LEACH	-	Yes	-	-	Good	Yes	Fixed BS	No	No	No	Maximum
MECN	-	Yes	-	-	Low	No	No	No	No	No	Maximum
PEGASIS	-	Yes	-	-	Low	No	Fixed BS	No	No	No	Maximum
Rumor Routing	Yes	-	-	-	Good	Yes	Limited	Yes	No	No	-
SAR	-	-	-	Yes	Limited	Yes	No	Yes	No	Yes	-
SMECN	-	Yes	-	-	Low	No	No	No	No	No	Maximum
SOP	-	Yes	-	-	Low	No	No	No	No	No	-
SPEED	-	-	-	Yes	Limited	No	No	Yes	No	No	-
TEEN	-	Yes	-	-	Good	Yes	Fixed BS	No	No	No	Maximum
TPGF	-	-	Yes	-	Good	Yes	No	No	-	-	-

The information needed to maintain this situation is extracted by computing locally with 2-hop neighborhood information and from the information about the residual energy exchanged. To prove its energy consumption, authors show a comparison between the energy consumption and network lifetime comparison among CKN and EC-CKN algorithm. Finally they conclude that the energy consumption in EC-CKN based WSN is well balanced.

There are more works published proposing other routing protocols for WSNs. Some of them are new, while others are based on existing protocols. Table 3 classifies the energy-aware routing protocols described in this section. It shows their main characteristics. A dash (-) means that the information is not provided by the authors or it cannot be correctly ascertained from their paper. Fixed BS means fixed base station.

VII. CONCLUSION

In this paper, we have presented the main causes of energy loss in wireless sensor nodes.

The main characteristics required to make a wireless sensor node and the factors to be considered when implementing a WSN or ad-hoc network have been discussed.

We discussed the energy wastage given by the electronic circuit. Therefore, counting on a sound electronic design that includes the right components for the sensor device is absolutely essential.

Finally, we show and compare several MAC and routing protocols that have been designed to optimize the power consumption without compromising the data delivery in WSNs.

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Secure Localization in Wireless Sensor Networks: A Survey

(Invited Paper)

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***Abstract*— Secure localization of unknown nodes in a Wireless Sensor Network (WSN) is an important research subject. When WSNs are deployed in hostile environments, many attacks happen, e.g., wormhole, sinkhole and sybil attacks. Two issues about unknown nodes' secure localization need to be considered. First, the attackers may disguise as or attack the unknown and anchor nodes to interfere with localization process. Second, the attackers may forge, modify or replay localization information to make the estimated positions incorrect. Currently, researchers have proposed many techniques, e.g., SeRLoc, HiRLoc and ROPE, to solve the two issues. In this paper we describe the common attacks against localization, and survey research state of secure localization.**

***Index Terms*— wireless sensor network, security, localization**

I. Introduction

Localization is one of the most important topics in Wireless Sensor Networks (WSNs) since many fundamental techniques in WSNs, e.g., geographical routing [1], geographic key distribution [2], and location-based authentication [3] require the positions of unknown nodes. Also, the positions of unknown nodes play a critical role in many WSNs applications, such as monitoring applications include environmental monitoring, health monitoring, and tracking applications include tracking objects, animals, humans, and vehicles [4].

When a WSN is deployed in hostile environments, it is vulnerable to threats and risks. Many attacks exist, e.g., wormhole, sinkhole and sybil attacks, to make the estimated positions incorrect. Specifically for some applications, e.g., military applications like battlefield surveillance or environmental applications like forest fire detection [5], incorrect positions may lead to severe consequences, e.g., wrong military decisions on the battlefield and false alarms to people [6]. Hence, the issues of secure localization must be addressed in WSNs.

Secure localization can be considered from two aspects. First, we discuss the attacks on nodes, since an attacker can compromise or pretend to be an unknown or an anchor node to interfere with localization process. Therefore, we need secure node authentication (SNA). Second, we discuss the attacks on information, since an attacker can forge, modify or replay localization information to make the estimated positions incorrect. Thus we need to detect the correctness of localization information, which we call secure information verification (SIV) in the paper.

The remainder of paper is organized as follows: Section II states problem statement. Section III describes attack model. Section IV and V present the schemes of SNA and SIV. Section VI gives the conclusions and open research problems.

II. Problem Statement

Before discussing secure localization problems, it is essential to take a look at some general concepts used in the localization process. Basically, there are two categories of sensor nodes: unknown and anchor nodes. Unknown nodes in the network have no knowledge of their positions and no special hardware to acquire the positions. Anchor nodes, also called beacon nodes, in fact, their positions are obtained by manual placement or additional equipments such as GPS (Global Positioning System). Therefore, unknown nodes can use localization information of anchor nodes to localize themselves. Usually, the localization process can be divided into two steps: 1) information acquisition and 2) position determination.

A. Information acquisition

Roughly speaking, existing localization schemes of WSNs are classified into two categories: range-based schemes [7], [8] and range-free schemes [9], [10]. For range-based localization schemes, the distance or angle information is measured by RSSI (Received Signal Strength Indicator) [11], TOA (Time of Arrival) [12], Time Difference on Arrival (TDOA) [13] and AOA (Angle of Arrival) [14]. For range-free localization schemes, the localization is realized based on network connectivity or other information, which can be obtained by DV-Hop [15], Convex Optimization [16] and MDS-MAP [17].

B. Position determination

Location determination schemes have two categories: 1) terminal-based schemes and 2) infrastructure-based schemes [18]. In terminal-based schemes, the unknown node localizes itself. After connecting available information about distances/angles and positions of anchor nodes,

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the position of an unknown node can simply be computed by trilateration [15], multilateration [19], and triangulation [14]. In infrastructure-based schemes, reference nodes including trusted neighbor nodes, mainly anchor nodes to localize the unknown node.

Adversaries can attack localization in both two steps. The goal of the adversary is to make the unknown nodes obtain false positions, by compromising normal nodes to send false localization information, or pretend to be a legitimate node to forge, modify or replay signals. Thus, security measures are needed to make the estimated positions still correct under attacks.

III. Attack Model

Localization process can be attacked in a number of different ways. Researchers have addressed a set of known attacks [18]. The known attacks can be divided into two categories: external and internal attacks. The adversary is external if it is outside the WSN and implements malicious behaviors without right cryptographic key. Otherwise, the adversary is internal, in which case the adversary controls one or more fraudulent nodes. In this paper, the attacks are classified into two categories: 1) attacks on nodes and 2) attacks on information.

A. Attacks on Nodes

In this paper, malicious nodes contain attackers and compromised nodes. An attacker is an external node which intrudes into the WSN. A compromised node is an normal node (an unknown or an anchor node) in the WSN compromised by the attacker. Attacks on nodes are listed as follows:

Compromise: Node compromise is the most fundamental attack in WSN that leads to other kinds of attacks. It occurs when an attacker gains control of a node in the WSN. Normally, compromised nodes can be obtained by the following methods: 1) attackers capture normal nodes and reprogram them; 2) attackers deploy nodes with larger computing resources such as laptops to attack normal nodes [20]. With compromised node, an attacker can alter the node to listen information in the WSN, revoke legitimate nodes, input malicious data, and cause internal attacks, e.g., DoS attack.

Replication: If an adversary manages to capture a node and extract the authentication/encryption keys, it can produce a large number of replicas having the same identity (ID) from the captured node and integrate them into the WSN at chosen locations, which is called the node replication attack. Since the credentials of replicas are all the clones from the captured nodes, the replicas can be considered as legitimate members of the network [21]. It is always assumed that the adversary cannot create new IDs for replicated nodes, since otherwise the attackers will have to create the corresponding security information (keys, codes, etc.), which is very difficult and even infeasible in most cases [22]. Once the adversary replicates one or more sensor nodes, it can execute the malicious operations. For instance, the replicas may inject false localization information into the WSN.

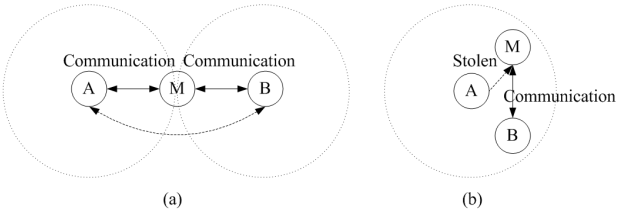

Figure 1. Node impersonation attack: (a) the Invisible Node attack. The malicious node M simply stands between two nodes A and B that are not in direct range. The invisible node M silently repeats the communication between nodes A and B, which misleadingly assume that nodes A and B communicate directly. In this way, the malicious node succeeds in impersonating node A to node B and vice versa. (b) the Stolen Identity attack. The malicious node M succeeds in stealing all the authentication credentials from a legitimate node A, such as the certified signature keys. If the malicious node outraces the legitimate node in updating the stolen credentials, then the credentials of the legitimate node will not be valid anymore. Thus, only the malicious node will be able to communicate with node B. This kind of attack is not just a matter of stealing a nodes identity, but also a matter of abusing the trust relationships that other parties may have had established with the legitimate node.

Impersonation: One form of node impersonation attack is the Invisible Node attack, and the other one is the Stolen Identity attack [23], as shown in Figure 1.

Sybil attack: Sybil attack is launched by a malicious node which has virtually multiple identities (IDs). We refer to a malicious node's additional identities as Sybil nodes. A Sybil node can get an identity in one of two ways. It can fabricate a new identity, or steal an identity from a legitimate node [24]. A sybil node can send messages with different IDs. For example, in localization process, one malicious node may masquerade as several anchor nodes to send false information at the same time.

Wormhole attack: In a wormhole attack, an attacker records a packet or individual bits of a packet at one location in the network. Then, it tunnels the packet (possibly selectively) to another location and replays it. The tunnel can be established in many different ways, for example, through an out-of-band channel, packet encapsulation, high-powered transmission, packet relay and protocol deviations [25]. In localization process, the attack may tunnel totally different and erroneous localization information.

B. Attacks on Information

In the localization systems, unknown nodes always use the localization information of anchor nodes to localize themselves. The target of malicious nodes is usually to make localization information incorrect. Attacks on information are listed as follows:

Forgery: Forgery attack is the malicious node sends misleading information in the localization systems. For example, in the active system [26], the malicious node pretends to be an anchor node to voluntarily send localization information. In the passive system [26], the malicious node pretends to be an unknown node to be localized.

Alteration: Alteration attack is the most direct attack. This attack targets the information exchanged between an unknown and an anchor node. Adversaries may directly alter the coordinates, time or the number of hops and increase the localization error of unknown nodes. For example, in Collaborative Collusion [27], all malicious node can collaborate with each other to alter the information they receives or replays.

Interference: Interference attack is the malicious node interferes with the signal measurements. For example, in range-based localization systems, malicious nodes may place obstacles between signal sender and receiver to prolong transmission time, change angle of arrival or weaken received signal strength [28].

Replay: Replay attack is the most common or simple attack, especially when the capability and resources of the adversary are limited. In this attack, the malicious node congests the information transmission between sender and receiver, then replays the outdated information. Using the outdated information, the unknown nodes calculate inaccurate positions. Unlike other attacks, replay attack can destroy the whole network with one node.

Flooding: Similar to data flooding attack on routing protocol [29], flooding attack on localization is the malicious node broadcasts large quantities of useless data packets to all nodes in its communication range. The common characteristic of flooding attack is to exhaust the available network communication bandwidth so that the other nodes can not communicate with each other. Moreover, the sender and receiver are busy to send or receive the excessive packets from the attacker and consume a lot of network resources.

Selective forwarding: In selective forwarding attack [30], the malicious node behaves like black hole and refuses to forward sensitive messages and simply drops them, ensuring that they are not propagated any further. The selective forwarding attack is difficult to detect. First, to avoid raising suspicions, an adversary selectively drops packets instead of dropping every packet. In addition, there are many reasons result in packet dropout, e.g., unreliable wireless communications. And in some cases, sensor nodes go into sleep state to save power. They cannot send and receive data in this period. Therefore, it is essential to identify the packet dropout is caused by selective forwarding or any other reasons.

IV. Secure Node Authentication

Many secure localization schemes have been proposed [27]. They can be classified into two categories: SNA and SIV. For SNA, in most cases, unknown nodes are localized based on the reference nodes, e.g., trusted anchor nodes. A number of schemes have been proposed to secure the positions of unknown nodes, which are called secure localization for unknown nodes [31], [32]. However, none of these schemes can work properly when the anchor nodes are compromised. Thus, secure localization for anchor nodes is needed.

A. Secure Localization for Unknown Nodes

In general, the main localization algorithms are classified into two categories: range-based and range-free. In this paper, we also classify secure localization for unknown nodes into this two categories.

1) Range-based Secure Localization: Based on the distance-bounding protocols [33], Capkun et al. propose the verifiable multilateration (VM) technique [31], [34]. With a central authority and several anchor nodes which are also named verifiers, VM enables a secure computation and verification of the unknown nodes' positions in the presence of attackers. In VM, verifiers $(v_1, ..., v_n)$ which are in the communication range of the unknown node u perform distance bounding to the node u and obtain distance bounds $db_1, ..., db_n$. These distance bounds, as well as the positions of the verifiers are then reported to the central authority. The authority computes an estimate position $(\hat{x}_u, \hat{y}_u)$ of the unknown node using distance bounds. Then, the authority runs two tests: 1) σ- test: for all v_i, does the distance between $(\hat{x}_u, \hat{y}_u)$ and v_i differ from the measured distance bound db_i by less than the expected distance measurement error σ? 2) point in the triangle test: does $(\hat{x}_u, \hat{y}_u)$ fall within at least one physical triangle formed by a triplet of verifiers? If both the σ and the point in the triangle tests are positive, the authority accepts $(\hat{x}_u, \hat{y}_u)$ as correct; else, the position is rejected.

Based on VM, the authors propose a secure cooperative positioning mechanism called SPINE [31], [34]. SPINE is executed in three phases: 1) the unknown nodes measure distance bounds to their neighbors; 2) the distance bounds are verified through VM; and 3) the positions of the unknown nodes are computed by a distributed algorithm, or by the central authority using a centralized positioning algorithm. Therefore, nodes in SPINE cannot produce erroneous distance measurements. However, SPINE has some drawbacks, e.g., in order to perform verifiable multilateration, a high number of verifiers are required.

Capkun et al. use the Covert Base Station (CBS) and Mobile Base Station (MBS) to verify the positions of unknown nodes [32], [35]. In the CBS case, for infrastructure-centric localization, the public base station (PBS) sends a nonce firstly. When a node replies to the nonce, all the CBSs compute its position together based on TDOA and check if this position is consistent with the time differences. If not, an attack is detected and the estimated position is rejected. For node-centric localization, the unknown node broadcasts a radio signal and an ultrasound signal at the same time, then each CBS obtains the estimated distance based on the arrival time differences of two signals. Also, the CBS obtains calculated distance using nodes reported location and CBS' location. Finally, the CBS compares estimated and calculated distances and rejects inconsistent ones. In the MBS case, it first requires unknown nodes to broadcast a radio signal. After a given period of time, it moves to a different location to broadcast a ultrasound signal. Then the MBS implements the same operations as a CBS does.

In [36], Anjum et al. present a secure localization algo-

rithm called SLA. It is considered that each anchor node has a capability to vary power level. Each power level is assumed to correspond to a different communication range. When an unknown node is localized, the sink node requests anchor nodes to send localization nonce to the node at different power levels. As a result, each unknown node receives a set of unique nonce and retransmits them back to the sink. The sink then determines the position of the unknown node. Compared with VM, SLA do not need fine-grained time synchronization. But the model of power level and transmission range is just suitable for out-door environment not in-door ones [37]. In addition, SLA has a few drawbacks: 1) anchor and sink nodes are all assumed to be trusted; 2) only considering a single sensor node being compromised and ruling out collaborative attacks between sensor nodes; 3) SLA is a centralized approach which creates bottle-neck at the base station.

Zhang et al. [38] propose SLS for ultra-wideband (UWB) sensor networks. To localize a node, anchor nodes first measure their respective distance to the node with a modified two-way ToA approach, called K-distance. The anchor leader then collects all the distance estimates whereby to derive a MMSE location estimate. Subsequently, SLS employs a location validity test by checking whether the location is inside the polygon formed by all the anchor nodes to detect possible attacks. Compared with VM, SLS is more robust and gernal, e.g., using mobile anchor nodes to replace static ones and making each anchor node take turns to act as the leader to balance their resource usage. However, the process of SLS is more complex than that of VM and consumes higher energy.

In [39], based on an attack-driven model specified with the Petri net, an enhanced secure localization scheme (ESLS) is proposed, which extends the idea in [38] and defends against not only distance reduction attacks but also distance enlargement attacks. The major contribution is the first time to use the Petri net to validate a security scheme for WSNs.

In [40], Arisar et al. present a two-way "Greet, Meet and Locate" (GML) mechanism for secure location estimation based on geographical sectorization. GML comprises of three phases: Greet, Meet and Locate. 1) Greet: a light-weight authentication scheme, the HB^+ Protocol, is used to perform two-way authentication, individually by unknown and anchor nodes. 2) Meet: the Diffie Hellman key exchange algorithm is used that allows exchange of secret shared keys between two users in an adversarial environment over an insecure communication medium. 3) Locate: the location is estimated via ToA based technique. Moreover, a double-averaging mechanism is also presented to minimize the localization error.

In [41], Alfaro et al. provide three algorithms that enable the unknown nodes to determine their positions in presence of neighbor sensors that may lie about their locations. The first algorithm is called the Majority-Three Neighbor Signals. When an unknown node is localized, all the neighbor anchor nodes send their locations to it. For every three anchor nodes, the unknown node uses trilateration to calculate a position. Then, a majority decision rule is used to correct the final position of the unknown node. The second algorithm is the Majority-Two Neighbor Signals. The unknown node uses only two neighbor anchor nodes, therefore the correct location is one of the two points of intersection of the two circles centered at two neighbors. The third algorithm is called the Tabulated-Two Neighbor Signals. It is assumed the unknown node may trust one of the neighbor anchor nodes. Then, the unknown node implements the second algorithm for every neighbor anchor nodes except the trusted one. Finally, the unknown node calculates the occurrence frequency of each position and accepts the most frequently occurring one as the correct position. The three algorithms have been extended to localize unknown nodes in [42].

Comparison of the above mentioned schemes is shown in table I.

TABLE I.
COMPARISON OF RANGE-BASED SECURE LOCALIZATION

Algorithm	Technique	Observation
VM	Distance-bounding	Nanosecond clock
SPINE	Distance-bounding	Nanosecond clock High number of anchor nodes
Capkun et al. [32], [35]	CBS and MBS	Centralized approach Rely on locations of CBS
SLA	Distance-bounding Vary power level	Centralized approach Resist only one compromised sensor node
SLS	K-distance approach, MMSE, validity test	Complex Higher energy consumption
ESLS	Petri net	Higher energy consumption
GML	HB^+ Protocol Diffie Hellman ToA	Complex
Alfaro et al. [41]	Trilateration Majority decision	Dense network

2) Range-free Secure Localization: In [43], the authors propose a distributed range-free localization algorithm called SeRLoc, which does not require any communication among unknown nodes. The SeRLoc uses trusted locators equipped with a set of higher-power sectored antennas to replace anchor nodes. The locators have longer transmission range than unknown nodes. They send anchor beacons to unknown nodes, in which contains their positions and the sectors of the antenna. When a node hears multiple locators, it computes the center of gravity of the sectors corresponding to locators as its position. The SeRLoc is robust against severe WSN attacks, such as the wormhole attack, the sybil attack and compromised sensor nodes. However, SeRLoc is based on the assumption that no jamming of the wireless medium is feasible. And it does not protect against attacks on locator's information, which are avoided by checking network properties such as sector uniqueness and communication range. Moreover, in order to minimize the region of sector intersection to improve localization, we need to increase the number of locators and sectored antennas.

In order to reduce the influence on localization ac-

curacy in the SeRLoc caused by different attacks, e.g., misleading anchor beacons. Later, a robust positioning system (ROPE) is proposed [44]. Combining the techniques in SeRLoc and VM [31], ROPE provides both the location determination and location verification function. In location determination, each unknown node obtains its exact location by VM when it is inside at least one triangle formed by locators, and still estimates its location by center of gravity when it is not inside any triangle. The location verification mechanism verifies the location claims of the unknown nodes. Since every unknown node can communicate with at least one locator, when an unknown node reports data to a locator, the locator can verify the unknown node's position by the execution of the distance bounding protocol. Compared with SeRLoc, ROPE is resistant to jamming of the communication medium, limits the maximum spoofing impact and prevents location spoofing due to the Sybil attack, with relatively low density deployment of locators. However, ROPE has higher hardware requirements, e.g., nanosecond time synchronization and instantaneous processing capacity, which is not suitable for low cost WSN.

Based on SeRLoc, in order to minimize the region of sector intersection without increasing the number of locators and sectored antennas, the same authors propose an improved method called high-resolution range-independent localization (HiRLoc) [45], which achieves greater localization accuracy through rotatable antennas and variable transmission power, while increases computational and communication complexity.

In [46], Zeng et al. present a Secure HOp-Count based LOCalization scheme (SHOLOC), which is resistant to different attacks, e.g., hop-count reduction attack and forging packets. In SHOLOC, a protocol combining modified TESLA [47] and hash mechanisms is proposed to authenticate anchor nodes' location information and protect hop-count information. In order to detect wormhole attacks, anchor nodes are responsible to check the distance-impossibility between nodes. Finally, the least median squares (LMS) [48] is used to deal with bad location references.

In [49], [50], Probabilistic Location Verification (PLV) algorithm is proposed. The main idea is to leverage the statistical relationships between the number of hops in a sensor network and the Euclidean distance that is covered. First, an unknown node broadcasts message in the network using flooding, which contains its location as well as the hop count. Each verifier receiving the message can compute the relative distance between it and the unknown node. Then, each verifier computes its probability slack and maximum probability values. Finally, a central node collects the two probability values from all verifiers and a common plausibility for the location advertisement is computed. The central node uses the plausibility to accept or reject the location.

Based on the basic DV-Hop localization process, Wu et al. propose a label-based secure localization scheme to defend against the wormhole attack by removing the packets delivered through the wormhole link [51]. Firstly, the anchor nodes are differentiated and labeled according to their geographic relationship. Then, unknown nodes are further differentiated and labeled by using the labeling results of neighbor anchor nodes. After eliminating the abnormal connections among the labeled neighbor nodes which are contaminated by the wormhole attack, the DV-Hop localization procedure can be conducted. The Label-Based DV-Hop Localization scheme is capable of detecting the wormhole attack and resisting its adverse impacts with a high probability.

In [52], Labraoui et al. similarly propose a Wormhole-free DV-hop Localization scheme (WFDV), to thwart wormhole attacks in DV-Hop algorithm. The main idea of WFDV is to plug-in proactive countermeasure named infection prevention to the basic DV-Hop scheme. Infection prevention consists of two phases: Neighbor List Construction (NLC) and Neighbor List Repair (NLR). NLC applies RSSI and RTT (round trip delay of a link), and utilizes local information to construct neighbor lists. NLR is applied only when a wormhole attack is suspected to remove the packets delivery through the wormhole link. In this phase, frequency hopping and RTS/CTS mechanism are used to confirm the existence of a wormhole and repair the neighbor lists. After eliminating the illegal connections, the DV-Hop localization procedure can be successfully conducted.

Comparison of the above mentioned schemes is shown in table II.

TABLE II.
COMPARISON OF RANGE-FREE SECURE LOCALIZATION

Algorithm	Technique	Observation
SeRLoc	Encryption Sectored antennas	Extra hardware Totally trusted beacons
ROPE	Encryption Sectored antennas	Extra hardware
HiRLoc	Encryption Sectored antennas	Extra hardware Complex
SHOLOC	TESLA Hash mechanisms	Resist simple attacks
PLV	Plausibility Test	Centralized approach
Wu et al. [51]	Label-Based Scheme	Resist only wormhole attack
WFDV	NLC, NLR	Resist only wormhole attack

B. Secure Localization for Anchor Nodes

1) Secure Localization schemes: Du et al. [53] propose LAD (Localization Anomaly Detection) to detect abnormal anchor nodes in the localization process. When sensor nodes are deployed in groups, each node follows two-dimensional Gaussian distribution, which is centered at the deployment point of the node's group. It is assumed that the localization phase has already been ended, and each unknown node has already obtained a position. LAD uses the known deployment information and the group relationship between neighbor sensor nodes to check whether the computed positions of the unknown nodes are consistent with the known deployment knowledge, according to three metrics: the Difference metric, Add-All

metric and Probability metric. LAD has a high detection rate and low false alarm rate, but does not deal with abnormal anchor nodes after detecting them.

Liu et al. [54] introduce a suite of techniques to detect and remove compromised anchor nodes. The anchor node performing the detection is called the detecting node and the anchor node being detected is called the target node. First, the detecting node using a different node ID, called detecting ID, pretends to be an common node and sends request message to each other. Once the target node receives the message, it sends back a beacon signal that includes its own location. Since the detecting node knows its own location, it can calculate the distance between them based on its own location and the target node's location. If the difference between them is larger than the maximum distance error, the detecting node can infer that the received beacon signal is malicious. Then, the wormhole detector and RTT (round trip time) are used to filter replayed beacon signals from Wormholes and locally replayed beacon signals respectively. Finally, the base station checks if the alert counter of the target node exceeds the fixed threshold. If yes, the target node is considered as a malicious one and revoked from the network.

In DRBTS [55], [56], Srinivasan et al. propose a novel reputation based scheme called Distributed Reputation-based Beacon Trust System (DRBTS) for excluding malicious anchor nodes. DRBTS is a distributed security protocol as an extension of the scheme in [54]. In DRBTS, every anchor node monitors its 1-hop neighborhood for misbehaving nodes and accordingly updates the reputation of its neighbor anchor node in the Neighbor-Reputation-Table (NRT). So that unknown nodes can choose some trusted anchor nodes, based on a quorum voting approach. The unknown nodes will only use the anchor node trusted by its neighbor anchor nodes to compute its position.

Since most of secure localization techniques cannot survive malicious attacks in hostile environments where a majority of anchor nodes launch colluding attacks, Wang et al. [57] propose a novel localization algorithm called TMCA. The TMCA is a distributed algorithm based on the cooperation of non-beacon neighbor nodes. It is robust against some known attacks such as the wormhole attack, sybil attack and replay attack. Even when there are more colluding malicious anchor nodes than benign anchor nodes in WSN, TMCA can still work well to generate precise localization results.

Comparison of the above mentioned schemes is shown in table III.

TABLE III.
COMPARISON OF SECURE LOCALIZATION FOR ANCHOR NODES

Algorithm	Technique	Observation
LAD	Three metrics	Requires deployment knowledge No action dealing with anomaly
Liu et al. [54]	RSSI,RTT Wormhole detector	High number of anchor nodes
DRBTS	Encryption	Dense network
TMCA	MMSE	More time consumed

V. SECURE INFORMATION VERIFICATION

SIV schemes can be divided into two categories: filtering and verifying location information.

A. Filtering location information

Many works have been done for filtering the impact of erroneous location information of anchor nodes. In [58] Li et al. introduce the idea of being tolerant to attacks rather than eliminating them. Two classes of localization: triangulation and RF-based fingerprinting, are examined. For the triangulation-based localization, LMS [48] is used to filter the bad localization information. Different from traditional methods that minimize the mean square error, LMS method minimizes the median of square errors. For the fingerprinting-based method, the traditional Euclidean distance metric is not secure enough. Hence, they propose a median-based nearest neighbor scheme.

Liu et al. [59], [60] propose two range-based robust methods to tolerate malicious attacks. The first method is a attack-resistant location estimation called ARMMSE. First, ARMMSE uses MMSE-based methods to estimate unknown nodes' position. Then ARMMSE assesses if the estimated position can be derived from a set of consistent location information of anchor nodes. If yes, the estimation position is accepted; otherwise, the inconsistent location information will be identified and removed. This process may continue until a set of consistent location information is found or it is not possible to find such a set.

The second method is the voting-based location estimation. The ARMMSE obtains a set of location information, which satisfies that the mean square error of the location computed by the subset is below a threshold. In the voting-based algorithm, the deployment field is quantized into a grid of cells. Each anchor node votes to the divided cells, and the centroid of the cells with the highest vote is the estimated position of the unknown node.

In [61], Zhong et al. prove that there are algorithms providing a guaranteed degree of localization accuracy, if the number of malicious anchor nodes k is less than or equal to $\frac{n-3}{2}$ ($k_{\max} = \frac{n-3}{2}$), where n is the number of anchor nodes. Also, two algorithms are proposed to localize the unknown node based on finding a region inside $k_{\max} + 3$ rings. However, such result is obtained under the condition that the measurement error ε is ideally small. In Pollution Attack [62], the adversary can still seriously distort the estimated position when $k_{\max} = \frac{n-3}{2}$ holds.

In [63], Misra et al. propose a critical threshold B for the number of malicious anchor nodes that can be tolerated in the localization process without undermining accuracy. If there are n anchor nodes in the communication range of an malicious node, the maximum number of malicious anchor nodes that can be tolerated is $\lfloor \frac{n}{2} \rfloor - 2$. Then, an enhanced mutually authenticated distance bounding technique (E-MAD) is presented to filter compromised anchor nodes The E-MAD protocol prevents distance reduction attacks. Therefore, the malicious anchor nodes

collude to confuse the localization process by causing an enlargement of the estimated distance.

Comparison of the above mentioned schemes is shown in table IV.

TABLE IV.
COMPARISON OF FILTERING METHODS

Algorithm	Technique	Observation
Li et al. [58]	Triangulation RF-based fingerprinting	High number of anchor nodes
Liu et al. [54]	Pairwise keys Voting scheme	High number of anchor nodes
Zhong et al. [61]	-	Require small measurement error
Misra et al. [63]	E-MAD	Resist only distance reducing attack

B. Verifying location information

Several Verification schemes are proposed based on the distance bounding protocol [33]. Brands and Chaum propose distance bounding protocol to make the prover (P, the claimant waiting to be verified as normal or not) unable to reduce its distance to the verifier (V). The bounding process is: V sends bit α_i to P, and P sends bit $\beta_i = \alpha_i \oplus m_i$ to V immediately after P receives α_i from V. Then, V computes an upper-bound on its distance to P based on the maximum of time delay between sending out α_i and receiving β_i back. Such schemes rely on fine-grained time synchronization, because V needs to measure RF (radio frequency) signal and the transmit time of the signal with nanosecond precision.

In order to reduce the requirement for precise nanosecond clock and sophisticate hardware, Sastry et al. [3] propose the Echo protocol to check whether a prover P is really inside the particular region. In Echo, the verifier V sends a nonce to P using RF and starts the timer, then the prover P immediately echoes the nonce back using ultrasound. V can use the elapsed time to compute the distance between them. Since the ultrasound signal transmits slower than RF, compared with distance bounding protocol, Echo does not require absolutely precise clock and immediately process capability. However, without any kind of authentication, it is possible for an attacker to usurp an honest prover's response and attach its own identity.

In [64] Meadows et al. present a new protocol for distance bounding that requires less message and cryptographic overhead than similar protocol in [33]. First, a full-scale formal analysis of a distance bounding protocol is given to reduce message and cryptographic complexity without reducing security. Then, the collusion attack is addressed. It is showed that the conventional distance bounding protocols are inadequate to collusion attacks.

In [65], Vora et al. propose a new location information verification protocol based on the broadcast nature of radio communication. There are two kinds of verifiers: an acceptor and a rejector. According to the verifier's ability to locate the prover, the network is divided into three zones: the acceptance zone, the ambiguity zone and the rejection zone. A particular protection zone is secure if every point outside the protection zone is also in the rejection zone. The acceptors and rejectors are deployed inside and at the boundary of protected region respectively. The verification process is the prover step by step increases its signal strength and broadcasts a signal, until a verifier hears the signal and responds. The verifiers accept the prover if none of the rejectors hears the prover during the process.

In [66], Hwang et al. propose an algorithm to detect the phantom nodes, by getting each node's largest consistent subset which contains all the normal nodes. The algorithm is divided into two main phases: distance measurement phase and filtering phase. In the first phase, each node measures the distances to its neighbors. In the second phase, each node first randomly picks up two neighbors to create a local map. Then in each such map, we try to find the largest consistent subset by checking each node that whether its measured ranges are consistent with its ranges in the map. The above processes are repeated for given times and the largest subset in all the runs is selected, which contains all the normal nodes. In this method, all nodes play the role of verifier. Even the number of phantom nodes is greater than that of honest nodes, we can still filter out most phantom nodes.

In [67], Wei et al. propose two lightweight location verification algorithms, namely, Greedy Filtering by Matrix (GFM) and Trustability Indicator (TI). In GFM algorithm, the Verification Center(VC) calculates several matrices, e.g., Observation Matrix, Difference Matrix and Weight Matrix, based on unknown nodes' estimated positions and their neighborhood observations. These matrixes are used to identify and revoke inconsistent location information. In TI algorithm, VC calculates trustability indicators for each unknown node and accepts those whose final indicators are greater than a threshold.

In [68], Delaet et al. propose the first deterministic distributed protocol, FindMap, for accurate identification of faking sensor nodes based on a distance ranging technique. It is showed that when RSSI is used, FindMap handles at most $\lfloor \frac{n}{2} \rfloor - 2$ faking sensor nodes. When the time of flight (ToF) technique is used, FindMap manages at most $\lfloor \frac{n}{2} \rfloor - 3$ misbehaving sensor nodes. However, it is proved that no deterministic protocol can identify faking sensors if their number is $\lfloor \frac{n}{2} \rfloor - 1$.

In [69], Li et al. focus on an in-region verification problem and propose a secure location verification (SVLE) algorithm. A client (any node needs to be verified) first broadcasts a random challenge nonce. The anchor nodes receiving the nonce calculate the signal strength based on the signal attenuation model. Then, the signal strength, the ID of the client and anchor nodes' location information are sent to base station. Finally, the base station continues to execute the algorithm called VerSec to verify the validity of the signal strength. A node will be considered as an adversary if its signal strength is incompatible with that of other nodes in region.

Comparison of the above mentioned schemes is shown in table V.

TABLE V.
COMPARISON OF VERIFYING METHODS

Algorithm	Technique	Observation
Distance bounding	-	Trusted verifiers
	-	Nanosecond clock
Echo	-	Trusted verifiers
Meadows et al. [64]	-	Just giving analysis
Vora et al. [65]	RSSI	Trusted verifiers
Hwang et al. [66]	-	More time consumed
Wei et al. [67]	GFM, TI	Centralized approach
FindMap	RSSI,ToF	Rely on distance bounding
SVLE	VerSec	Centralized approach

VI. CONCLUSION

In order to address security problem in WSN, a number of methods have been proposed, e.g., secure routing [70], [71], key management [72] and sensor selection scheme [73]. This paper focuses on the secure localization survey. We reclassify the known attacks on localization systems and the proposed secure localization schemes.

The future research directions of secure localization algorithms possibly are: 1) Build up more realistic and destructive attack models against secure localization. 2) Improve security schemes to enhance detection rate for anomaly without nanosecond clocks, additional hardware and any deployment information. 3) Research new localization determination or verification proposals to reduce the localization time and energy consumption. 4) Evaluate the performance of secure localization algorithms with a series of standards. 5) Use other research domains' technology, e.g., the Petri net [39]. 6) Extend to new challenges in special WSNs, e.g., Mobile Multimedia Sensor Networks (MMSNs) [74].

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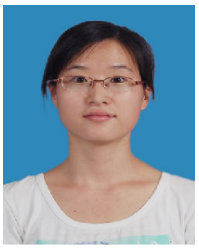

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A Real-time Two-way Authentication Method Based on Instantaneous Channel State Information for Wireless Communication Systems

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***Abstract*—Traditional solutions handle security at the application layer, which causes huge signaling overhead and long delay if authentication is implemented for every signal to enhance the security of wireless communication systems. In this paper, a real-time and two-way authentication method is proposed, which is based on the characteristics of radio channel including randomness and privacy. For the proposed method, the unique instant channel state information (CSI) can be used to authenticate the transmitter. In frequency- and time-selective fading channels, the current estimated CSI is compared with the predicted CSI, which is implemented at the previous frame, in order to authenticate the validation of the received signal. Both the hypothesis testing and mutual information measure methods are used for authentication determination, and the Mont Carlo simulation results verify the efficiency of the proposed method.**

***Index Terms*—Physical-layer security; authentication; channel state information (CSI); channel estimation; channel prediction; hypothesis testing; mutual information measure.**

I. INTRODUCTION

Authentication is the process where claims of identity are verified. Most mechanisms of authentication of mainstream wireless communication systems, such as cellular mobile communication systems [1], wireless broadband access systems [2] and wireless sensor networks (WSN) [3][4], are based on traditional cryptography encryption and functioned at high layer. The authentication is set up by invoking the higher layer protocol stack at call establishing, location updating, and other value-added service.

In wireless communication system, especially the acentric networks like WSN and wireless ad hoc networks, the broadcast nature of the channels makes it easy for wiretapping and other attacks via air interface, and the existing security mechanism for wireless communication does not contain the appropriate design of real-time identity authentication [5][6]. Moreover, two-way authentication, which means the communication pair should authenticate each other, is required to avoid fake user (source) attacks and fake base station (sink) attacks [7][8]. Under this circumstance, a reliable two-way real-time authentication mechanism is urgently needed. However, if every message is authenticated in order to strengthen the real-time security, the current authentication process will call the upper layer authentication protocol, which will bring about huge signaling overhead and result in very long delay. Obviously the wireless communication system cannot endure such huge signaling overhead, and the authentication caused protocol processing delay makes the quality of service (QoS) unacceptable. Therefor more effective and real-time two-way authentication mechanism is urgently needed.

Recently channel-like fingerprint has been used to enhance the security in physical layer (PHY) [9]-[15]. Besides the broadcast feature, the radio channels feature randomness and privacy as well due to the multipath propagation effect of radio waveform [16]. That is to say, (1) randomness means the channel state information (CSI) varies rapidly and randomly. With the characteristics of randomness, the authentication is more reliable because the random and variable CSI makes the authentication code (namely, the CSI) change fast. (2) privacy means the CSI of the link between communication pair is unique due to the CSI decorrelates rapidly in space and time if the paths are separated by the order of an RF wavelength or more in scatter rich environments. Based on the randomness and privacy features of channel, Faria et.al firstly proposed a scheme in [9] to detect identity-based attacks by using the signal strength information, namely, the instantaneous signal-to-noise ratio (SNR). Xiao et al. proposed the authentication methods using the CSI information in [10]-[12], and then extended the PHY authentication methods to multiple-input multiple-output (MIMO) systems [13][14] and orthogonal frequency-division multiplexing (OFDM) systems [15].

In this paper, we propose a real-time two-way authentication method in physical layer based on instantaneous CSI. Our method differs with the existed methods on that we estimate and predict the CSI, and then compares the predicted CSI with the newly estimated CSI. When the predicted CSI and the estimated CSI is highly correlated, the identity of the authenticated user is said to be verified. Our method can be reliably used as PHY authentication is due to the observation that the CSI changes continuously in time- and frequency-domain, and results in the predicted CSI will be highly correlated with the previous estimated CSI of the same channel. Since the pilot-aided channel estimation and simple prediction methods are widely applied to obtain the CSI in all kinds

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of wireless communication systems including single carrier (SC)/multiple carrier (MC) systems and single-input single-output (SISO)/MIMO systems in all sorts of selective fading channels, the proposed method needs no complicated channel modeling and parameters identification as done in [12], and can be easily applied without introduction of extra complexity, which is of importance for energy-constraint networks like WSN. Since the simplicity of our method, real-time per-message authentication is easily realized. Moreover, CSI is usually estimated at both sides of the communication pair, and then two-way authentication is achieved by implementing the proposed method at both ends.

The main contributions of the proposed authentication method are listed below.

1) CSI estimation and prediction based real-time authentication method is developed in PHY. This method facilitates application in wireless communication systems due to the widely used pilot-aided CSI estimation and simple CSI prediction method without induction of extra complexity or any changes to the exist systems.

2) Two-way authentication is achieved when the proposed method is implemented at both sides of the communication pair, and also no extra complexity is introduced due to the CSI estimation is widely applied to obtain CSI in current wireless communication networks.

3) Mutual information (MI) measure as well hypothesis testing is employed for the authentication determination.

The rest of the paper is organized as followed. System model is introduced in Section II, and the proposed method is presented in detail in Section III. In Section IV, numerical simulation is implemented to verify the performance of the proposed method, and we conclude the paper in Section V.

II. SYSTEM MODEL

A. Network topology

As shown in Figure 1, we use the same system model as that in [10]-[12], which we borrow from the conventional terminology of the security communication by setting three different parties: Alice, Bob and Eve. Alice broadcasts signals, and both Bob and Eve can receive the signals transmitted through wireless environment. However Bob is only would-be receiver while Eve is the eavesdropper.

Authentication is set up when call establishing, location updating, by invoking the higher layer protocol stack. However during the authentication process, if the active Eve cracks the random number which is used to compute security key, he can get the security key via A8 algorithm [1]. Then Eve can impersonate as Alice to communicate with Bob and intercept and capture what he wants. Since the authentication does not implement for each signal, Eve can act as Alice during the session.

In order to avoid the fake identity of Eve as Alice, we propose an active two-way authentication method which provides real-time and efficient authentication in PHY per message between Alice and Bob, in spite of the presence of Eve. Since Eve is within range of Alice and Bob, and capable of impersonating Alice to send her malicious signals to Bob, Bob must have the ability to differentiate between legitimate signals from Alice and illegitimate signals from active Eve.

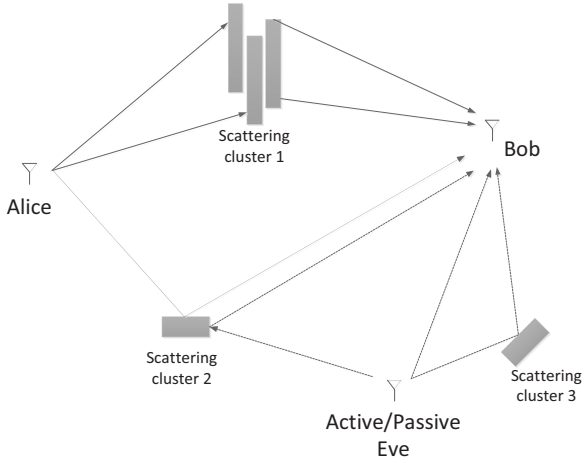


Fig. 1: The system model, where Alice sends messages to Bob over multipath channel with the eavesdropper Eve.

Consider a simple transmission in which Bob seeks to verify that Alice is the transmitter of the present message. Suppose that Alice transmits probes into the channel at a rate sufficient to assure temporal coherence between channel estimates and that, prior to Eve's arrival, Bob has estimated and saved the Alice-Bob channel. After a while, Eve wishes to convince Bob that he is Alice, Bob must verify that if the signals is still send by Alice at this time. The CSI of linked between Alice and Bob is a result of the multipath environment, as time goes on it has changed [16]; Bob may use the saved CSI of Alice-Bob link to predict present CSI [10]-[15]. Bob may also use the received signal to estimate the CSI and compare it with the predicted one for the Alice-Bob link. If these two CSI are highly correlated, then Bob will conclude that the source of the message is the same as the source of the previously sent message. If the channel estimates are not similar, then Bob should verdict that the transmitter is likely not Alice.

In the following sections, the notations we will use are listed as followed, where bold italic stands for vector.

$\boldsymbol{\hbar_{AB}}$,$\boldsymbol{\hbar_{BA}}$:CSI vectors from A to B and from B to A;

$\tilde{\boldsymbol{\hbar}}_{\boldsymbol{AB}}$,$\tilde{\boldsymbol{\hbar}}_{\boldsymbol{BA}}$,:Noisy CSI vectors from A to B and from B to A;

$\mathscr{H}_0$,$\mathscr{H}_1$:The null hypothesis and the alternative hypothesis;

α,β:Type I and Type II error;

χ^2:Chi-square distribution;

F_{χ^2}:Distribution function of chi-square distribution;

T_C,B_C:The channel's coherent time and bandwidth;

f_m:The Doppler shift;

$J_0(\bullet)$:The first kind zero-order modified Bessel function.

B. Channel Model

In wireless communication environment, rich scattering and the movement of the terminals cause multipath and dispersion in the time, frequency and angle domains. Without loss of generality, only the SISO channels are considered in this paper, and it is quite straight to extend to MIMO channels. In the case of SISO channel, parameters in time- and frequency-domain,

the multipath delay and the channel fading, can characterize the features of the channel.

Firstly the time/frequency coherence model of the channel is introduced by computing the coherence of signal's envelope [16]. Suppose the two envelopes are $r_1(t)$and $r_2(t)$, their frequency deviation is$\Delta f = |f_1 - f_2|$, and the correlation coefficient is

$$\begin{aligned}\rho_r(\Delta f,\tau) &= \frac{R_r(\Delta f,\tau)-\langle r_1\rangle\langle r_2\rangle}{\sqrt{[\langle r_1^2\rangle-\langle r_1\rangle^2][\langle r_2^2\rangle-\langle r_2\rangle^2]}} \\ &= \frac{\int_0^\infty r_1 r_2 p(r_1,r_2)dr_1dr_2-\langle r_1\rangle\langle r_2\rangle}{\sqrt{[\langle r_1^2\rangle-\langle r_1\rangle^2][\langle r_2^2\rangle-\langle r_2\rangle^2]}}\end{aligned} \quad (1)$$

where $p(\tau) = \frac{1}{T}e^{-\tau/T}$ is the power delay profile. The signal fading is assumed to obey the Rayleigh distribution, and we can get the approximate expression of the correlation coefficient

$$\rho_r(\Delta f,\tau) \approx \frac{J_0^2(2\pi f_m\tau)}{1+(2\pi\Delta f)^2\sigma_\tau^2} \quad (2)$$

where $J_0(\bullet)$ is the first kind zero-order modified Bessel function,f_m is the maximum Doppler shift.

The correlation coefficient is $\rho_r(\Delta f) \approx \frac{1}{1+(2\pi\Delta f)^2\sigma_\tau^2}$ when τi s zero, and the correlation coefficient is $\rho_r(0,T_C) \approx J_0^2(2\pi f_m T_C)$ when Δf is zero. When the coherence bandwidth is defined with the limitation of $\rho_r(\Delta f) = 0.5$, the coherence bandwidth is $B_C = \frac{1}{2\pi\sigma_\tau}$, and the coherence time is $T_C \approx \frac{9}{16\pi f_m}$ which is inversely proportional to the maximum Doppler shift. It is well known that the CSI remains invariant within the coherence time, otherwise the CSI varies independently.

As a result, we can predict the CSI accurately based on the previously estimated CSI when the time interval and frequency gap are within the channel's coherent time and coherent bandwidth. In this paper, we always assume that the message interval is within the channel's coherent time, and the frequency band used by the same user keeps the same within the same frame duration.

III. CSI PREDICTION-BASED AUTHENTICATION METHOD

A. Method Description

Three-step authentication method is proposed for Bob to identify Alice from Eve. Before the PHY authentication, it is assumed the traditional high layer authentication has successfully authenticated Alice, and Bob has gotten and saved the initial CSI estimate $\boldsymbol{\hbar_{AB}(t)}$ between Alice and Bob at the time t via channel probe method, such as pilot-aided channel estimation. Illegal Eve can make use of the vulnerabilities of existing authentication schemes to pretend to be Alice. At the time $t+\tau$, Bob receives another message, and Bob implements the proposed three-step PHY authentication to identify whether the sender is still Alice.

Step 1: Bob estimates the present CSI $\boldsymbol{\hbar(t+\tau)}$ without knowing the identity of the sender.

Step 2: Bob predicts the present legal channel response $\boldsymbol{\hbar_{AB}(t+\tau)}$ using the saved $\boldsymbol{\hbar_{AB}(t)}$ via prediction method [20][21].

Step 3: Bob decides that the sender is still Alice if $\boldsymbol{\hbar(t+\tau)}$ and $\boldsymbol{\hbar_{AB}(t+\tau)}$ are highly correlated, otherwise Bob declares an intrusion. If the sender is still Alice, Bob saves $\boldsymbol{\hbar(t+\tau)}$ for the following PHY layer authentication.

Implementing this three-step authentication at both Alice and Bob, two-way real-time authentication is achieved.

B. Authentication Determination

Bob can use a hypothesis testing to determine whether current and prior communication attempts are made by the same user via the CSI [17][10]. Due to the noise, estimation error and prediction error exist, and Bob stores a noisy version of vectors $\boldsymbol{\hbar(t+\tau)}$ and $\boldsymbol{\hbar_{AB}(t+\tau)}$,

$$\widetilde{\boldsymbol{\hbar}}\boldsymbol{(t+\tau)} = \boldsymbol{\hbar(t+\tau)} + \boldsymbol{N_1} \quad (3)$$

$$\widetilde{\boldsymbol{\hbar}}_{\boldsymbol{AB}}\boldsymbol{(t+\tau)} = \boldsymbol{\hbar_{AB}(t+\tau)} + \boldsymbol{N_2} \quad (4)$$

where $\boldsymbol{N_1}$ and $\boldsymbol{N_2}$ are independent and identically distributed(i.i.d) complex white Gaussian noise with the same covariance $N(0,\delta^2)$.

We set the null hypothesis

$$\mathscr{H}_0 : \widetilde{\boldsymbol{\hbar}}\boldsymbol{(t+\tau)} = \widetilde{\boldsymbol{\hbar}}_{\boldsymbol{AB}}\boldsymbol{(t+\tau)} \quad (5)$$

$$\mathscr{H}_1 : \widetilde{\boldsymbol{\hbar}}\boldsymbol{(t+\tau)} \neq \widetilde{\boldsymbol{\hbar}}_{\boldsymbol{AB}}\boldsymbol{(t+\tau)} \quad (6)$$

and test statistic

$$L = \frac{1}{\delta^2}\left\|\widetilde{\boldsymbol{\hbar}}\boldsymbol{(t+\tau)} - \widetilde{\boldsymbol{\hbar}}_{\boldsymbol{AB}}\boldsymbol{(t+\tau)}\right\|_2 \quad (7)$$

If the claimant is Alice, $L \sim \chi^2_{2N,0}$, otherwise , $L \sim \chi^2_{2N,delat}$,and $delta = \frac{1}{\delta^2}\left\|\boldsymbol{h_{EB}(t+\tau) - h_{AB}(t+\tau)}\right\|_2$. We define k is the threshold and the rejection region for $\hbar_0$ as $L > k$. Thus, the Type I error is

$$\alpha = P_r\{L > k \mid \mathscr{H}_0\} = 1 - F_{\chi^2_{2N,0}}(k) \quad (8)$$

and the Type II error is

$$\beta = P_r\{L < k \mid \mathscr{H}_1\} = F_{\chi^2_{2N,\mu_L}}(k) \quad (9)$$

therefore the detection rate is $1-\beta$. Where $P_r\{\bullet\}$ is the probability density function.

Next, the mutual information (MI) of the predicted CSI and the estimated CSI can also be used as the measure parameter. MI, from another aspect, is a quantity that measures the mutual dependence of the two variables. So we can use MI to weigh the dependence between the estimated and predicted channel response.

The MI is defined as [17]

$$I(\widetilde{\boldsymbol{\hbar}}, \widetilde{\boldsymbol{\hbar}}_{\boldsymbol{AB}}) = H(\widetilde{\boldsymbol{\hbar}}) + H(\widetilde{\boldsymbol{\hbar}}_{\boldsymbol{AB}}) - H(\widetilde{\boldsymbol{\hbar}}, \widetilde{\boldsymbol{\hbar}}_{\boldsymbol{AB}}) \quad (10)$$

And we set normalization MI η as

$$\eta = \frac{I(\widetilde{\boldsymbol{\hbar}}, \widetilde{\boldsymbol{\hbar}}_{\boldsymbol{AB}})}{H(\widetilde{\boldsymbol{\hbar}}_{\boldsymbol{AB}})} \quad (11)$$

If the sender is still Alice and in ideal conditions, we can get $\widetilde{\boldsymbol{\hbar}} = \widetilde{\boldsymbol{\hbar}}_{\boldsymbol{AB}}$, and $\eta = 1$. In practical conditions duo to the presence of noise, η is near to 1. Otherwise will be close to zero.

TABLE I: Parameters for the simulated OFDM system

Item	value	Item	value
Bandwidth: BW	10MHz	OFDM symbol: Ts	100 us
Carrier freq.: f_c	2GHz	Modulation	QPSK
Sampling freq.: f_s	10MHz	Vehicle speed	3, 60, 120 km/h
FFT size: N	1024	Doppler freq.: f_d	17, 333, 666 Hz
No. Tx antenna:	1	No. Rx antenna:	1
Channel estimation:	Least Square (LS)	Channel prediction:	Winner Filter [21]
Channel model:3GPP Veh. A [22]	Relative delay (ns): 0, 310, 710, 1090, 1730, 2510		
	Average power (dB): 0, -1, -9, -10, -15, -20		

IV. Numerical Simulations

A. Simulation system

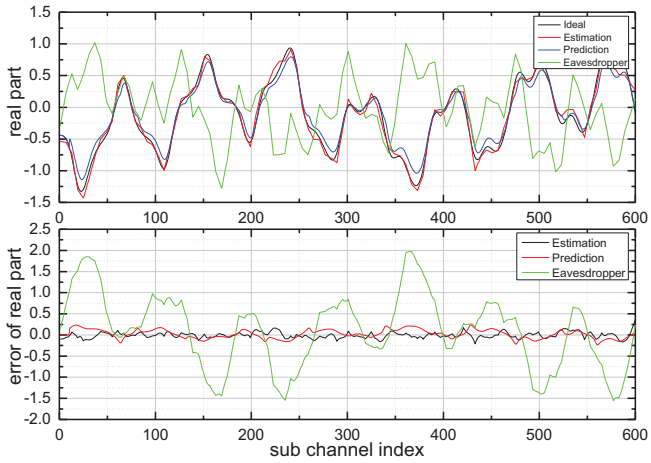
We use MATLAB to implement simulations. The topological structure of the simulated system is shown in Figure 1, and the simulated OFDM system is the third generation long term evolution (3G-LTE) system [18] whose main parameters are listed in Table 1. Vehicular Channel A model from ITU-R M.1225 [22] is adopted, and three types of moving speed are considered to simulate the terminal with low, medium, and high moving speed. Pilot-aided Least Square (LS) algorithm is used to estimate the CSI, and Winner Filter algorithm [21] is adopted to predict the CSI.

B. Simulation results

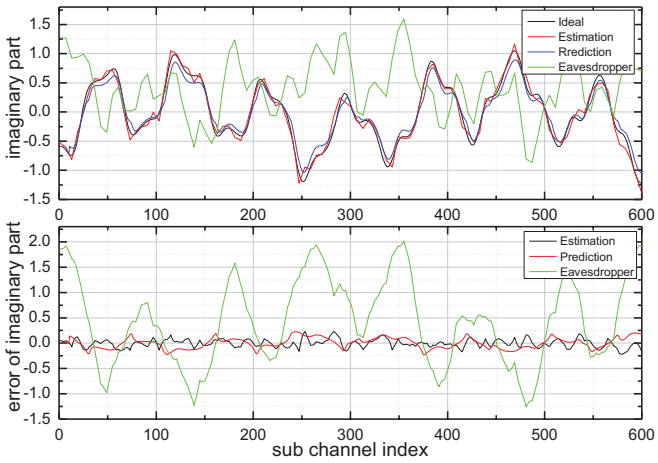
Firstly we testify the correlation of the CSI between the legitimate user and the eavesdropper. The simulation results are presented in Figure 2 and Figure 3. The signal-to-noise ratio (SRN) is 15dB, and the CSIs are compared in Figure 2. It is clear that the estimated and the predicted CSI of the legitimate user are highly correlated with the ideal CSI of the legitimate user, while the CSI of the eavesdropper is much different to the legitimate user's ideal CSI. In Figure 3, we present the correlation of different CSI with the legitimate user's ideal CSI, and we can see that the predicted CSI and estimated CSI of the legitimate user are highly correlated with the ideal CSI, while the eavesdropper's CSI is lowly correlated with the legitimate user's CSI. All these simulate results confirm the CSI can be used to authenticate the access user.

Next we testify the MI of different CSI, and the simulation results are shown in Figure 4. From the figures we can see that both the MI between the estimated CSI and the ideal CSI of the legitimate user and the MI between the predicted CSI and the estimated CSI of legitimate user are much larger than the MI between the predicted CSI and the estimated CSI of the eavesdropper. This observation verifies that the MI can be used to recognize the transmitter.

Last we evaluate the proposed method and compare it with the method proposed in [10][11]. In Figure 5 the detection rate performance is shown when hypothesis testing method is employed to identify the transmitter. From the simulation results it is clear that the proposed method outperforms the reference method in all kinds of scenarios. We also observe that the detection rate of both methods decreases with the increase of vehicle speed due to the channel estimation and prediction are more unreliable when Doppler spread becomes larger and larger, and the reference method degrades more than the proposed method due to the proposed method can track the CSI change and then decreases the error of authentication determination. The detection rate performances are presented in Figure 6 and Figure 7 when MI measure is employed to identify the transmitter in several scenarios. When the MI threshold is set 0.65, the changes of the detection rate performance of the authentication methods at different vehicle



(a) The real part of the channel response.



(b) The imaginary part of the channel response.

Fig. 2: The CSI comparison at SNR=15 dB.

speed are presented in Figure 6. The curves in Figure 6 show the same trend as that in Figure 5, that is the proposed method outperforms the reference method, and as the mobile speed increases the performance gap between the two simulated method becomes larger. In figure 7, we present the detection rate of two authentication methods at mobile speed of 60 km/h while the MI threshold varies from 0.6 to 0.7, and the simulation results show that at the low SNR the proposed method outperforms the reference better.

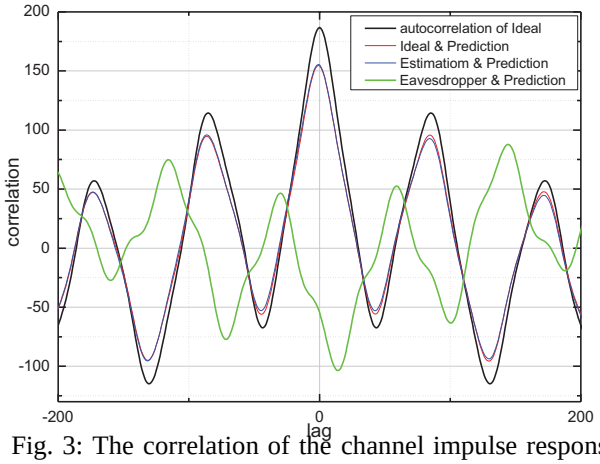


Fig. 3: The correlation of the channel impulse response at SNR=15dB.

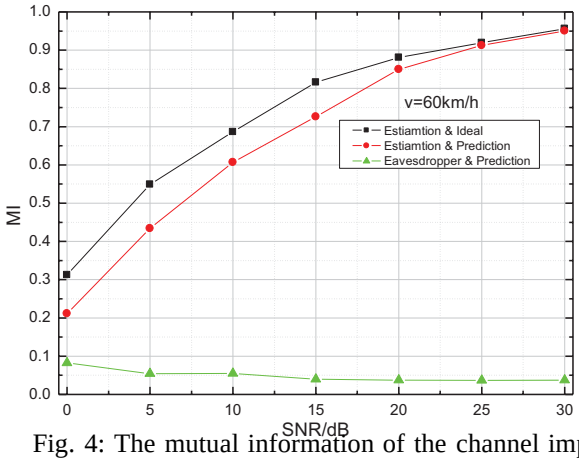


Fig. 4: The mutual information of the channel impulse response.

V. Conclusion

The random channel fading, which causes a big problem for reliable communication, is used to the physical layer security due to its features of randomness and privacy. In this paper, a CSI-based real-time two-way authentication method is proposed in the physical layer to enhance the security. Since the CSI varies continuously, the CSI is reliably predicted from the previous estimated CSI and then compared with the estimated CSI at the next frame after received the frame from the transmitter. By use of hypothesis testing and mutual information method, the reliable discrimination is achieved between a legitimate sender and an intruder or attacker.

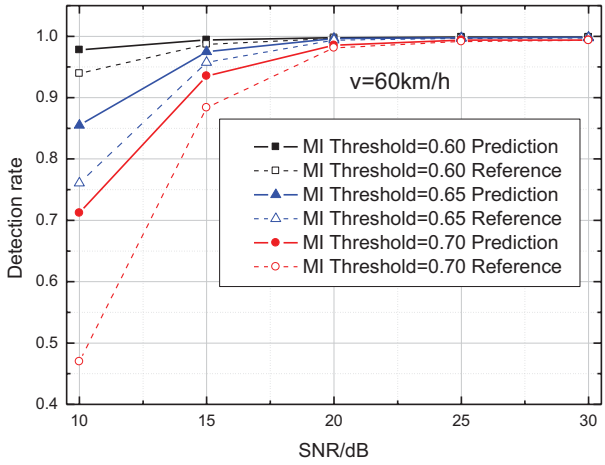


Fig. 5: The detection rate versus signal-to-noise ratio with different thresholds at vehicle speed of 60 km/h when MI measure is employed to authenticate transmitter.

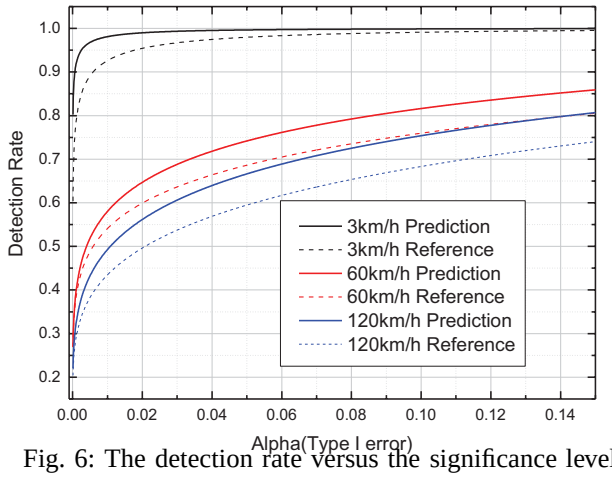


Fig. 6: The detection rate versus the significance level α when hypothesis testing method is employed to authenticate transmitter.

Acknowledgment

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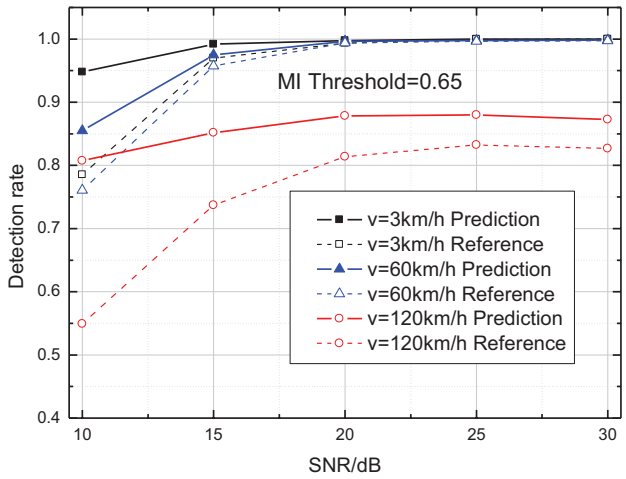

Fig. 7: The detection rate versus signal-to-noise ratio for MI threshold is 0.65 at different vehicle speed when MI measure is employed to authenticate transmitter.

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Delay Tolerant Network on Android Phones: Implementation Issues and Performance Measurements

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***Abstract*— Many regions of the world do not have access to the Internet due to lack of proper communication infrastructure. Delay Tolerant Network (DTN) provides communication in a challenging network condition such as high communication delay and intermittent connectivity. DTN is a promising solution to solve lack of connectivity problems in developing regions such as rural areas. DTN works in a store-and-forward approach, where the data is stored in a server and forwarded to a suitable carrier. The android phones can be made DTN capable to become a carrier for DTN bundles. Android phone is one of the front runners as the DTN carrier because of its portability and increasing popularity. In this paper, we have described the implementation of DTN on Android phone and the performance measurements including DTN bandwidth and battery consumption.**

***Index Terms*— Delay Tolerant Network (DTN), Wi-Fi, Android phone, Bundle, Access Point, Server.**

I. Introduction

The advancement in development of technologies has made it possible to carry powerful mobile devices. These devices are capable of Bluetooth and Wi-Fi connectivity and storing large amount of data. These devices can be used to store even gigabits of data because of the improved capacity of portable storage such as SD Card. As a result, in some conditions, physically carrying the network data in the devices can be cheaper than setting up a network infrastructure [1]. For example, it might be more cost effective to make a person carry gigabits of data everyday in his/her smart phone across twenty villages while travelling by his car or bike, rather than building an infrastructure in the village. This can be accomplished by the implementation of Delay Tolerant Networking (DTN) in the mobile devices.

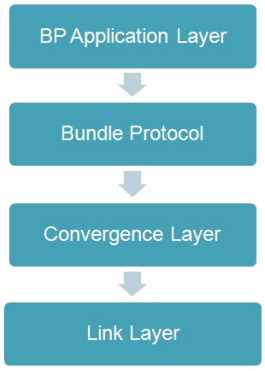

Figure 1. DTN layer architecture

DTN provides communication in highly stressed environments such as variable delays, discontinuous connectivity and high bit error rate. The current DTN implementation is based on Bundle Protocol (BP) [2]. The BP relies on the services of a convergence layer. The convergence layer converts BP messages to link layer and vice versa in order to practically make the network communication. The link layer can be any link layer protocol. For our implementation we used TCP/IP as link layer protocol. This architecture is shown in Fig. 1.

The protocol data units (PDU) of DTN are known as "bundles". The bundles may be split up into fragments and the source and the destination of the bundles are identified by the end point identifiers [3]. When the bundles are created, they are specified with the bundle expiration time. Bundles may move from one DTN node to another in a broken path [4]. Bundles may arrive to a node and find the link between the current node and the next node broken. The bundles reside in the node until the expiration time is over.

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Android is an operating system designed for mobile devices [5]. The Android Software Development Kit (SDK) provides all the tools and APIs for developing. The application development is made with a new Java library named Java Android library [6]. Our target mobile device platform is Android because of its openness and profound industry support. The source code for the platform is publicly available and currently 50 leading telecom, hardware, software companies are registered as its members [7]. Thus, our challenge is to implement the protocol on the platform for facilitating the exchange of data between the mobile device and the network.

Our primary contributions are as follows. Firstly, we have developed an Open source DTN implementation on Android platform that is fully compatible with RFC 5050 [2]. Secondly, we are the first to report power consumption on DTN implementation. Thirdly, we have found that the power consumption for upload is lower than download DTN data. This insight supports people deploying DTN in practice. In particular, the deployment should favor upload over download in order to minimize power consumption.

The rest of the paper is organized as follows: related works are discussed in section 2. The implementation issues of DTN on Android phones are discussed in section 3. The performance measurements of DTN on android phone are discussed in section 4. A general discussion is presented in section 5. Finally, some conclusions are drawn in section 6.

II. Related Works

Our aim is to develop an Open source DTN implementation on Android platform that is compatible with RFC 5050 [2]. We target for Opensource software for others to be benefited from it and further improvement by the DTN community. And, it must be compatible with the standard for interoperability with other existing implementations. There are several DTN implementations available including DTN2 [8], IBR-DTN [9], Spindle [10], and Java BP-RI [11]. Nonetheless, none of them is compatible with the Android platform, Open source license, and the standard. As a result, our solution is unique.

DTN2 is an Open source implementation developed by the DTN research group. It is mainly implemented as a testing of basic DTN functionalities and it is not very efficient [9]. It follows the standard and aims to "embody the components of the DTN architecture, while also providing a robust and flexible software framework for experimentation, extension, and real-world deployment" [8]. It heavily relies on standard C++ library and Oasys system library. But neither of them is available on the Android platform.

IBR-DTN is another Open source implementation specially designed for embedded system such as Wi-Fi router [9], to allow access points (APs) to be used as a compact "plug-and-play" DTN-Modules for vehicular or stationary applications. Even though it is a great idea and it has been tested to work efficiently - consumes less main memory and has more throughput than DTN2 and our implementation – our solution is more portable, less expensive and the infrastructure involved is less complex since it is based on mobile devices. The IBR-DTN platform is written in C++ but the development language for Android platform is Java. As a result, this implementation is also not compatible with our solution.

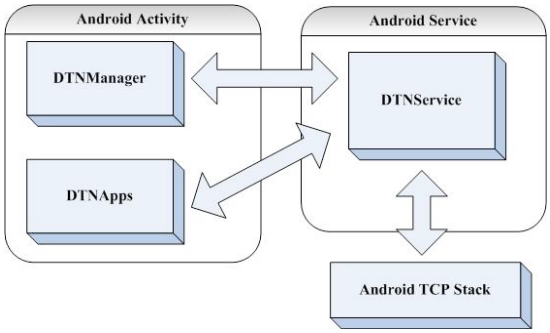

Figure 2. Major software components

Spindle is a DTN implementation built on top of DTN2 for using in the military context [10]. It follows the standard and, unlike our work, has advanced features such as efficient routing algorithm, complex name management, and knowledge-based DTN. The source code is not publicly available. Furthermore, similar to DTN2 and IBR-DTN, it is developed in C++ and as a result incompatible with our platform.

Java BP-RI is a DTN implementation written in Java. It does not comply with the standard because it follows the draft version 4 of the Bundle Protocol. Even though it is written in the same language for Android platform, it uses the Java-RMI feature, which is not available on the platform [11][12].

III. Implementation Issues

Three implementation issues on Android platform are discussed in this section. Section 3.A elaborates on technical challenges. Section 3.B explains overview of the implemented software components. Section 3.C shows the internal design of DTNService, which is the main component responsible for DTN logic.

A. Technical Challenges

During the beginning of our work, we identified three viable alternatives to implement DTN on Android. The alternatives are porting from DTN2 [8], porting from Java BP-RI [11], and implementing from scratch in Android. We finally decided to take the first option, porting from DTN2, because it is the best option in term of flexibility to adapt to Android platform, software license, efforts required for existing DTN developers to understand and use the result. The details of the analysis are discussed in [13].

While porting DTN implementations from DTN2, we face three major technical challenges including size of the software, differences between programming languages, and missing of system programming library.

The size of DTN2 software is very large. It composes of approximately 4MB of source code and 394 source files. Porting huge software to another platform is not trivial. In particular, if we made even a small design

mistake, it will cost us a lot of time to correct. As a result, one has to be very careful in designing and implementing software as this size.

While DTN2 is implemented in C++ [8], the major language for Android is Java. As a result, we have to find workarounds when there are some features available in C++ but not in Java. For example, in C++, one can inherit multiple classes but this is not possible in Java. We redesign and implement new programming classes in order to support this.

DTN2 relies heavily on OASYS, system-programming library written in C++. For example, many main data structures in DTN2 are inherited from classes in OASYS. However, the aforementioned library is not available in Android SDK. Thus, porting DTN2 to Android is not straightforward. We have to cope with this either by finding equivalent classes in the SDK or implementing from scratch if they are not available.

B. Software Components Overview

There are three software components in the implementation. They are: DTNService, DTNManager, and DTNApps. These components interact with each other and with the Android TCP/IP stack. The interactions are illustrated in Fig. 2.

DTNService is a backend application serving DTN communication. As a result, even though the user is using other applications such as making a phone call or reading text messages, he/she is still able to send/receive DTN transmission. To be able to run in backend in the Android platform, this component is implemented as Android Service [14]. And, this component uses TCP/IP stack of the Android platform to achieve network communication.

Because DTNService is running in backend, there is a need for a user interface for interacting with the service. This is where DTNManager shows up. It is a frontend application for the user to configure, monitor, and manage the DTNService. This frontend application is designed as Android Activity [15]. The user interface for DTN manager is shown in Fig. 3. The DTNManager supports several management actions including starting, stopping, restarting, configuring, and monitoring status of DTNService.

DTNApps are the applications running on top of the DTNService. As a result, they are in BP application layer as shown in Fig. 1. Two sample DTN applications developed are DTNSend and DTNReceive. DTNSend is a DTN application allowing users to send text messages over DTN. On the other hand, DTNReceive is a DTN application allowing users to receive text messages over DTN. Because both of them are frontend applications similar to DTNManager, they are mapped to Android Activity [15].

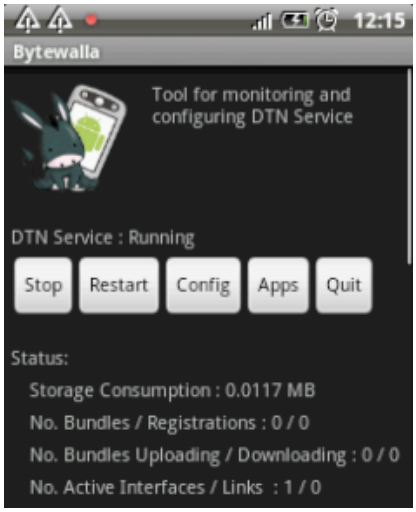

Figure 3. DTN Manager, GUI for managing DTN service

C. DTNService Internal Design Summary

The design of DTNService follows very closely the design of DTN2, the DTN reference implementation written in C++ by the DTNRG [8]. Hence, the design has similar characteristics of the reference implementation by which it is a modular design. In other words, the system composes of several plug-in components working together. When there is a new function to be added to a particular component, other parts need not to be changed. This makes the system very easy to extend. For example, if anyone would like to add new routing algorithm to the DTNService, he/she can simply extend the BundleRouter class without making any modification to the other parts.

The DTNService composes of nine running modules including Bundle Daemon, Contact Manager, TCP Convergence Layer, Discovery, Persistent Storage, Registration, Bundle Router, Fragmentation manager and APILib.

DTNService is an event driven system. There are several types of events, for example, bundle receiving event, bundle transmitted event, or contact initiation event. The system works according to the event handling functions defined in event handling components including Bundle Daemon, Bundle Router, and Contact Manager.

The communication among the running modules with each other in order to respond to an event is illustrated in Fig. 4. The arrow represents the communication between each module. The brief summaries of all modules are discussed below.

Bundle daemon is the main event handler of the system. It is the central processing unit and responsible for communicating with other module for processing the bundle event. Every bundle event will be checked first by the daemon. If the Bundle daemon determines that other two event processing components including Bundle Router and Contact Manager should process the event as

well, it will forward event to the components. Otherwise, it will just remove the event.

Contact Manager is the service in charge of detecting new opportunities of connections. Each opportunity of connection ("opportunistic link") with a neighbor ("contact") is under the control of Contact Manager which also does the scheduling of the links.

TCP Convergence Layer is the transport mechanism over TCP that the DTN application uses for transmitting bundles to a next hop.

Discovery is the method by which other nodes can be aware of the "existence, availability, and addresses of other DTN participants" [16]. Discovery is based on IP protocol where each node sends and listens to IP UDP announcements to discover remote neighbors.

Persistent storage is the storage mechanism that stores data objects permanently on the disk. Persistent storage is a generic implementation. It can store any kind of objects on the disk. It also stores unique identifier of every available object in the database to identify the object.

Registration is defined as "A registration is the state machine characterizing a given node's membership in a given endpoint" [2]. This module handles the specified registration created from the Bundle Daemon. Every bundle received by the daemon will be checked with this module and if it is matched, it will be delivered to the registration for further processing.

Bundle router is the main decision maker regarding forwarding the bundles. Depending on the implementation, it may contain the routing table as a database for making the routing decision. The router implemented here is the static Bundle Router which mainly relies on the routing table database configured before the system starts. The router is used by the Bundle Daemon for checking and finding an appropriate next hop to send the DTN bundle. Then, if it finds the next hop, it will forward the DTN bundle to the Contact Manager for initiating a communication with the hop.

Fragment manager makes fragments of the large bundles. It also keeps the state of all the fragmentary bundles and partially received bundles. Finally it reconstructs the whole bundle from the received fragments.

APILIb provides Application Programming Interface (API) for making a DTN application on Android platform. The API will communicate with Bundle Daemon to achieve the API calls. As a result, this is the channel for other components such as DTNApps to programmatically use DTNService. This component is implemented by Android Binder [17]. A DTN application developer can bind with this Binder. Then, the developer can call an API from the Binder interface. For example, if the developer would like to write an application for sending a DTN bundle, he/she can call "dtnsend" Binder interface provided in this component.

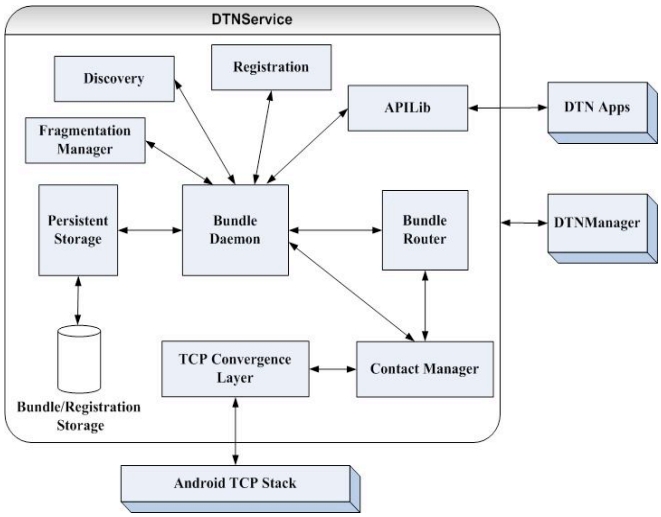

Figure 4. DTNService internal design

IV. Performance Measurements

Our test environment consists of two servers running DTN2 and an Android phone as shown in Fig. 5. The specification of the servers and android phone are shown in table 1 and 2.

We made two custom codes in order to make the tests. The first code is a script to generate DTN bundles with different sizes. The script inputs parameters including the number of DTN bundles, initial bundle size, the incremental value, number of repetition of bundles with the same size, source Endpoint ID, and destination Endpoint ID of the DTN bundles.

The second script is for recording the performance of the Android phone. This script was added to the Android DTN system. For getting DTN Bandwidth, the recording code supports recording of the upload/download time of each individual DTN bundle. For getting the battery consumption, the code hooks on the battery status change API of the Android phone. Every time the battery level is changed, the upload/download size is recorded.

In order to evaluate the performance, 105 DTN bundles are generated to be routed from one server to the other. The parameter for bundle repetition was set to 3. As a result bundles with 35 different sizes with each size having 3 instances were generated. This was done to get the average bandwidth value for bundle of each size. The initial bundle size was 100KB. Each of the remaining bundle size was incremented by 100KB. So the size of the last 3 bundles was 3.5MB.

TABLE I.
SPECIFICATION OF THE DTN2 SERVERS

CPU	Intel Celeron 1.8 GHz
System Memory	512 MB ECC DDR
Total Hard Disk Size	40 GB
Operating System	Linux Ubuntu 8.04
DTN Software	DTN2 version 2.6

TABLE II.
SPECIFICATION OF THE ANDROID PHONE

Model	HTC Tattoo
Processor	Qualcomm® MSM7225™, 528 MHz
Operating System	Android™ 1.6
DTN Software	Android DTN
Phone Memory	256 MB
Network Interface	Wi-Fi®: IEEE 802.11 b/g
Battery	Rechargeable Lithium-ion battery Capacity: 1100 mAh

A. Bandwidth Analysis

The time for downloading the 105 bundles is shown in Fig. 6. There was 189013.1 KB of data in total. In this case the bundles were downloaded from the server to the Android phone. The graph shows a linear increase in download time with the increase of bundle size. This follows a linear equation of the general form y=mx+b. This is expected because while downloading the bundles, there were no other download activities running which can consume the bandwidth.

The average download bandwidth is calculated below:

Average Download Bandwidth
= Total Bundle Size / Total Download Time
= 189013.1 KB / 3680.36 s
= 51.36 KB/s

The bandwidth analysis for upload time is shown in Fig. 7. The bundles were sent from the Android phone to the other server. As expected, the upload time increased linearly with the increase of bundle size. An average value for the upload bandwidth is as follows:

Average Upload Bandwidth
= Total Bundle Size / Total Upload Time
= 189013.1 KB / 3134.999 s
= 60.29 KB/ s

A comparative study between the download and upload bandwidth is shown in Fig. 8. For small bundles of size 100 KB, the download and upload times are identical. Up to the bundle size of 1.5MB, there is a very small difference in upload and download time. After that, the difference increases as the download time increases. A significant observation made from this figure is that the download time is always higher than the upload time.

B. Battery Consumption Analysis

The battery consumption was recorded with a fully charged battery of HTC tattoo phone. The 105 bundles had a total of 189013.1 KB = 184.68 MB of data.

Fig. 9 shows the cumulative battery consumption for downloading the bundles. No other applications were run in the phone during the period the data were recorded. This ensured the battery power was consumed only by the DTN software. The battery consumption rate was high for first 22 MB of data. But after that there was a drop in battery consumption till 75 MB of data. Then it went high a bit and continued in a linear way. At the end 44% of the total battery charge was consumed for downloading 184.68 MB of data. The average battery consumption rate is calculated as follows:

The HTC Tattoo phone has 1100 mAh for 100% battery power. This means 1 % battery power= 110 mAh. As a result, the Average DTN download battery consumption rate

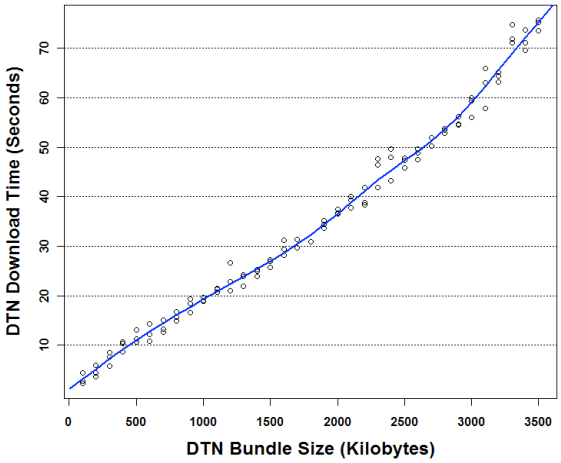

Figure 6. Download bandwidth

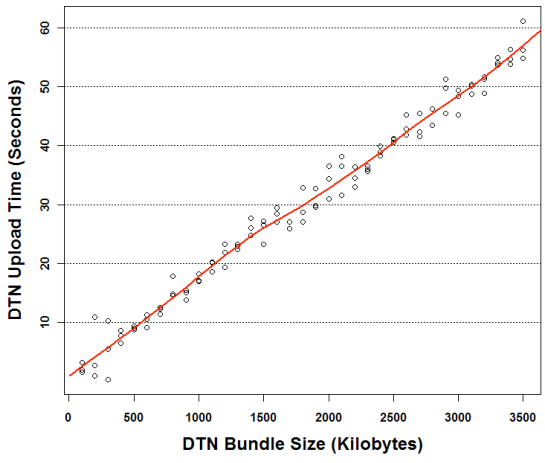

Figure 7. Upload bandwidth

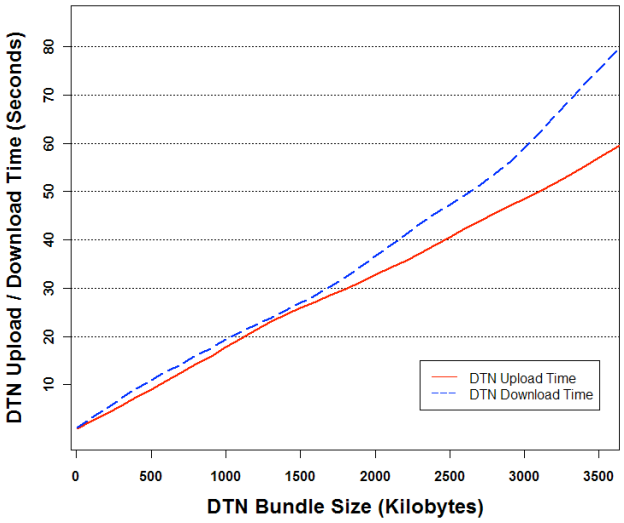

Figure 8. Comparisons between download and upload bandwidth

= 44*110 mAH / 184.68 MB
= 26.20 mAH/MB

Fig. 10 shows the cumulative battery consumption for uploading bundles. Unlike download battery consumption, the upload battery consumption maintains a very linear increase. 36% of the total battery power was consumed for uploading 184.68 MB of data. The average battery consumption rate is calculated as follows:

Average DTN upload battery consumption rate
= 36*110 mAH / 184.68 MB
= 21.44 mAH/MB

A comparative study is shown between the cumulative download and upload battery consumption in Fig. 11. The battery consumption for uploading data is always lower than the battery consumption for downloading data.

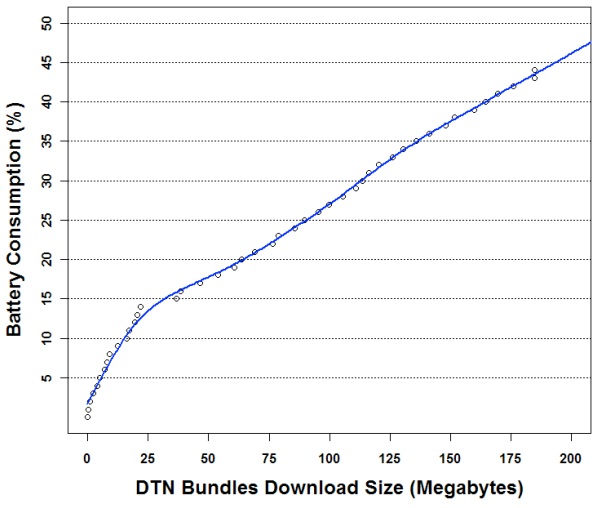

Figure 9. Cumulative battery consumption for download

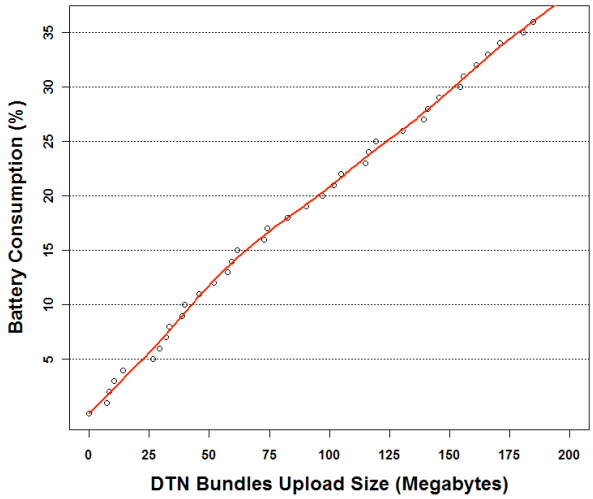

Figure 10. Cumulative battery consumption for upload

V. Discussion

Our implementation has some limitations. The routing algorithm is based mainly on the routing entries in the routing table. The entries are specified in the configuration file before the DTNService is started. As a result, all the DTN routes have to be known before the system begins operation. This is suitable for a simple network topology, for example, when there are few DTN nodes in the system such as servers in the villages, city, and the data carrier. In real world situation where there are possibly much more DTN nodes and complex network configurations, this routing table will be very difficult to manage and may make the whole network inefficient.

If a disruption in the connection happens, the bundle is discarded and must be transmitted again once the connection is back. This approach is not suitable in environments with often disruptions in connectivity. The

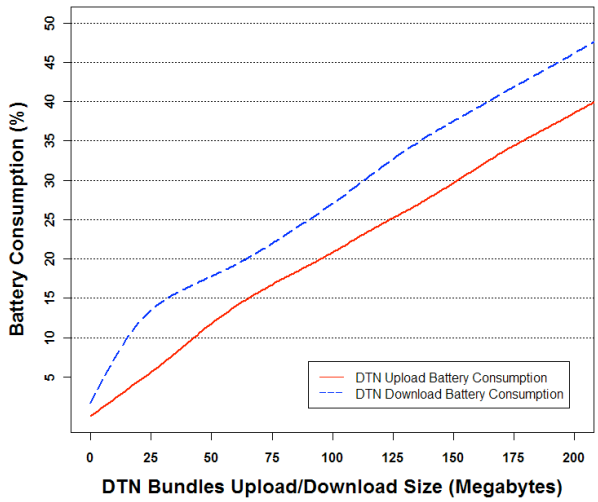

Figure 11. Comparison between battery consumption for download and upload

sender node might have to send the same bundle several times, and might not be able to transmit it completely before the bundle expires.

The DTNAPI implemented here is a shared process application programming interface (API). As a result, all the DTN applications implemented in this project runs in the same process as DTNService. This is fine if there are no DTN applications consuming too many resources running simultaneously with the DTNService. But this is not the best practice for making an API for interacting with a backend service on Android platform. This is because an Android application running in the same process shares the Dalvik Java Virtual machine (Dalvik Java VM) [5]. And, a Dalvik Java VM will be shutdown if it consumes too many resources. As a result, if there is one DTN application exhausts system resources such as main memory, the DTNService and other DTN applications will be affected as well.

Considering the performance issues, this is the first time where the power consumption on DTN implementation has been measured. From our measurements we can say that download time is always higher than the upload time. On the other hand, battery consumption for uploading data is always lower than the battery consumption for downloading data. So, upload data consumes less power than download data. Moreover, upload power consumption linearly increases with bundle size but download power consumption does not show this property. In particular, downloading consumes high power for first 0 - 40 MB and consumes less power and increases linearly for 40 - 200 MB.

VI. Conclusions

Implementation of DTN on Android platform is a relatively new concept. The goal of this paper was to develop DTN software for Android platform. The software supports static routing and shared process application programming interface environment. A lot of work can be done based on this. Effective routing algorithms / protocols are required for real world deployment. Both Delay Tolerant Routing for Developing Regions [18] and Probabilistic Routing Protocol (PRoPHET) [19] are the promising routing algorithm / protocols to be implemented. Reactive fragmentation can be implemented for supporting environments with disruptions in connectivity. The sender node can start transmitting an entire bundle, and in case of a failure in the connection, both the remaining and the received portion of the bundles can be converted into valid fragments of DTN bundles. An API can be created, which will be called from different processes other than the DTNService to solve the problem of resource exhaustion. This can be accomplished by a technique called Inter-process communication (IPC). IPC on Anroid platform is done by using a combination of AIDL [20] and Parcelable [21]. The security concerns were not taken into account in this implementation. The main focus was to make the network working. Security mechanisms can be developed by implementing the Bundle Security Protocol [21] on the Android phone.

Acknowledgment

This work was a part of a Communication Systems Design (CSD) project in the Royal Institute of Technology (KTH), Sweden. We would like to thank Professor Björn Pehrson, Marco Zennaro, Avri Doria, Elwyn Davies and Hervé Ntareme for their continuous support throughout the project.

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A New Evaluation Model for Security Protocols

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***Abstract*-Till today, the study of performance of security protocols of WLAN has been one of research focuses. Whereas, owing to enormous complexity and low efficiency of modeling security protocols, there has been by now no uniform method or technology that can be used generally to simulate and evaluate security protocols, and no simulation system available that can well support research on performance of security protocols. So in view of the status quo, we, in this paper, mainly propose a novel security protocol simulation architecture and a simulation extending method for simulating security protocols of WLAN, and then set up a simulation platform for modeling such protocols based on OPNET, a famous simulation software. Finally, with an instance of extending and simulating a security protocol of WLAN, the validity and the universality of the simulation architecture and the extending method as well as the feasibility and correctness of the simulation platform are demonstrated.**

I. INTRODUCTION

Security in wireless network, such as WLAN[1] ,is a critical concern[2]. More and more scholars focus on the study of WLAN security protocols[3]. However, how to evaluate security protocols in terms of security and performance is an important and tough task[4]. There are three common approaches which can be exploited to carry on evaluation of security protocols—testing, mathematical analysis and simulation[5]. Due to lower costs and maneuverability, the simulation approach has been widely used.

However, the simulation approach has some disadvantages in terms of efficiency and extensibility. To the best of our knowledge, there exists no unified simulation approach on how to evaluate WLAN security protocols, because of the complexity and inefficiency of security protocols modeling. Moreover, popular simulation tools, such as OPNET[6] and NS2[7] , do not have built-in security protocol models or universal interfaces to support the evaluation of WLAN security protocols, which leads to lots of repetitive works and low comparability of different performance researches[8].

To address the problem mentioned above, we propose, in this paper, a universal and extensible security protocol simulation platform for WLAN. First of all, the architecture design of the platform is presented. One of the key features of it is the ability to provide a universal interface to incorporate various security protocols into the simulation platform conveniently and exactly. Furthermore, a general method for security protocols extension is demonstrated. It specifies how to modify the protocol module and embed it into the simulation platform, which standardize the extension process. Finally, according to the proposed architecture and method, we implement the simulation platform in OPNET and validate its feasibility, correctness and universality through extending and simulating WEP[15] and EAP-TLS[16] security protocols. The results show that our simulation platform has characteristics of universality and extensibility.

The rest of this paper is organized as follows. Section II discuses the related work of security protocol simulation. Section III designs the architecture of the simulation platform for WLAN security protocols. Section IV provides a detailed description of the simulation interface and the core components of the architecture. Section V describes the method for security protocols extension. In section VI, we present a simulation experiment for the validation of the proposed platform. Finally, Section VII concludes this paper.

II. RELATED WORK

There are two lines of researches focusing on security protocol simulation in the research community.

The first one focus on how to utilize various kinds of methods and tools to simulate and evaluate WLAN security protocols, and improve them through the analysis of the simulation results. This kind of research is extremely popular, such as [9] [10] [11] and so on.

The second one concentrates on how to develop a simulation platform or framework to standardize the simulation and evaluation of security protocols, which is very useful in improving the efficiency and extensibility of security protocol simulation. However, only a few research works, described below, have been reported on this topic.

Zhao et al. established a simulation framework to model BGP security protocols and PKI system[12]. With this framework, they evaluated certification path building

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algorithms and improved the performance of the algorithms. However, the main consideration of this paper focuses on how to use the framework to evaluate the performance of security protocols, which is similar to that of the first kind of research focus. In fact, the proposed framework cannot serve as a universal simulation platform for certain sort of security protocols.

Yang et al. proposed a model to simulate authentication protocols at application layer of mobile ad hoc network based on OPNET simulation environment[13]. The main idea of their work is seemingly the same as ours. However, this paper does not present a universal and extensible security protocol simulation platform but a concrete process model in OPNET. The feasibility and correctness of the process model is also not validated. Furthermore, the simulation model proposed in their paper is built on the application layer, which not only falls short of reality, but also fails to provide an extensible and unified security protocol simulation interface.

Yang et al. constructs a node model to implement IEEE802.1x authentication function in OPNET[14]. However, their paper focuses on designing a special simulation model to simulate a concrete protocol, rather than designing a universal simulation platform. Because of its special interface to the simulation tools, the model proposed in their paper lacks universality and reusability. Furthermore, due to its non-standard design method, the results conducted by this model have low comparability.

III. THE ARCHITECTURE

This section presents the architecture of the simulation platform. The designing ideas of the architecture are as follows. Although all kinds of WLAN security protocols are distinctly different in terms of data field, exchange process, encryption algorithm and so on, they perform main functions, such as authenticating, port controlling and framing, all on the data link layer of the OSI architecture. To satisfy the needs of incorporating various security protocols into the simulation platform conveniently and exactly, an extensible and standard security protocol simulation interface is designed between data link layer and network layer, and divided into several function modules to manage data stream, identify and schedule protocols. It makes the simulation architecture a universal, highly configurable and practical solution to simulate WLAN security protocols.

As illustrated in Figure 1, the architecture has the following functional components.

Security Protocol Modeling

This component is responsible for modeling the simulated protocols. Due to the complexity of security protocols, we need to simplify them and abstract their exchange processes in order to incorporate them into the simulation platform. Furthermore, correlative parameters of security protocols should also be represented in appropriate forms so that they can be correctly coded. The exact parameters and abstract process of protocols are necessary in simulation. Finally, basic algorithms of security protocols, such as encryption algorithm, should also be implemented in this component.

Protocol Simulation

This component is the core of the simulation architecture.

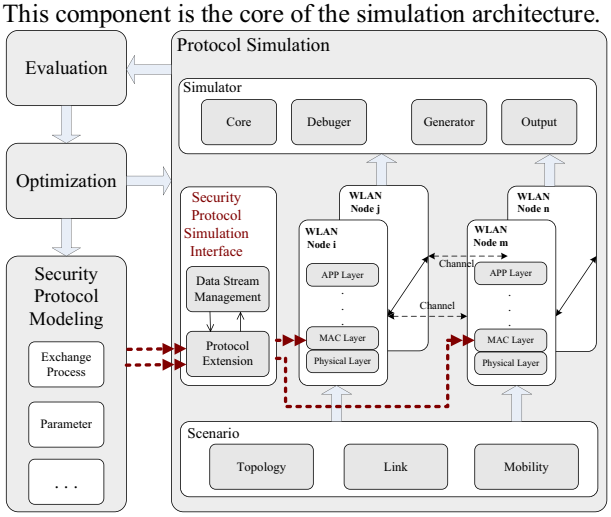

Figure 1 Architecture of Security Protocol Simulation Platform.

In this component, an extensible and standard security protocol simulation interface is proposed and integrated into the data link layer of WLAN nodes. The interface consists of several sub-components, including Data Stream Management Module (DSMM), Multi-Protocol Extension Slot (MPES) and so on. As one of the most important components, the interface can be used to distinguish between normal data stream and authentication stream, guide them into right modules, load and initialize new security protocol modules, and encapsulate security protocol packets, which plays a key role in extending various security protocols. The detail of simulation interface will be described in section IV.

Simulation is based on the specific scenario with different network topologies, link characteristics and node mobility models. Based on the scenario settings, WLAN nodes, mainly supported by physical layer and data link layer, communicate with each other by the wireless channel. All nodes are independently managed and controlled by a core module. The generator module generates a set of traffic packets; the debugger module is used to test and debug the simulation program; the output module exports and displays the simulation information at any moment. All the behaviors of nodes make up of an integrated simulation environment as well as the actual WLAN.

Evaluation and Optimization

The evaluation component is responsible for evaluating security protocol performance according to the simulation results. The appropriate performance metrics, such as

complexity of encryption algorithms, packet loss rate, communication overhead, throughput, handover delay and so on, should be determined initially. After the evaluation is completed, it is required to determine which component should be modified so as to obtain optimal performance. This is the main purpose of the optimization module.

IV. Simulation Interface

As the key component of the architecture, the security protocol simulation interface can be exploited to embed various security protocols into the simulation platform conveniently and exactly. Based on the layered OSI architecture, the simulation interface is implemented between data link layer and network layer and divided into three function modules: Data Stream Management Module (DSMM), Security Protocol Identifying and Scheduling Module (SPISM), and Multi-Protocol Extension Slot (MPES). These modules are responsible for managing data stream, identifying and scheduling protocol, and extending various security protocols, respectively. The function modules and their relationship are illustrated in Figure 2, in which the solid line with arrowhead and the dashed line with arrowhead denote the direction of authentication and normal data stream respectively.

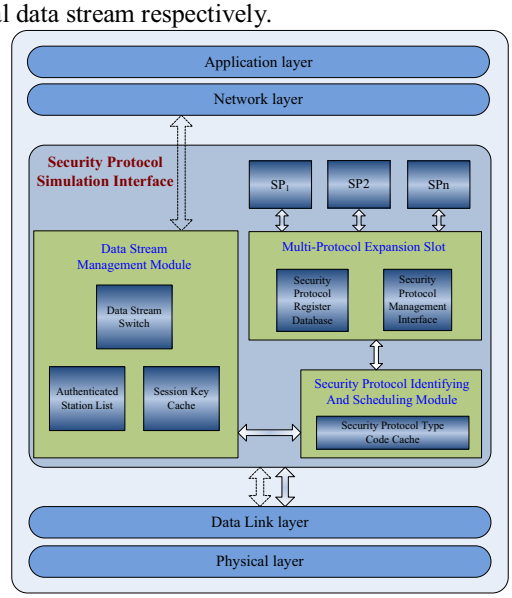

Figure 2 Security Protocol Simulation Interface.

A. Data Stream Management Module(DSMM)

The DSMM is mainly responsible for identifying, managing, encrypting and decrypting data stream. After entering the simulation interface, data streams is intercepted by the DSMM. Then, according to the interface control information, data streams will be divided into two classes—authentication data stream and normal data stream, and be guided into right modules. Furthermore, a Session Key Cache providing keys used to encrypt data stream, and an Authenticated Station List storing the authenticated station information are built in the DSMM.

The control flow chart of the DSMM is depicted in Figure 3. The solid line with arrowhead and dashed line with arrowhead denote the authentication data stream and normal data stream respectively.

B. Security Protocol Identifying and Scheduling Module (SPISM)

The SPISM is mainly responsible for identifying the type of authentication protocols and scheduling the corresponding security protocol module. When a node joins a new network, the SPISM will identify the type of the authentication protocol in the current network and select the scheduling algorithm to wake up the corresponding authentication protocol module, which will in turn establish a security association between the node and the authentication server. To realize the function above, the SPISM has a sub-module, Security Protocol Type Code Cache, in which the type of security protocols is registered during the initialization phase.

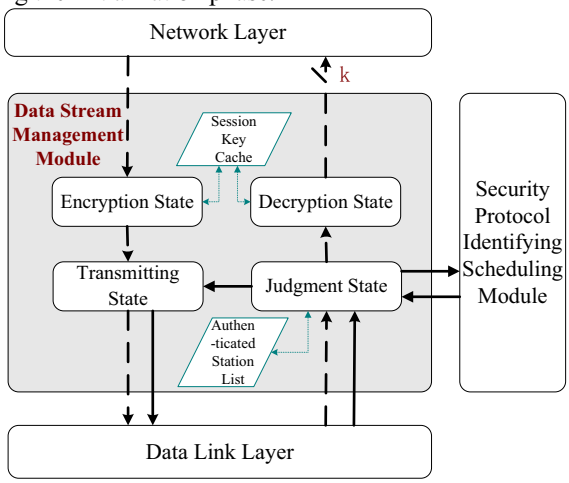

Figure 3 DSMM Control Flow Chart.

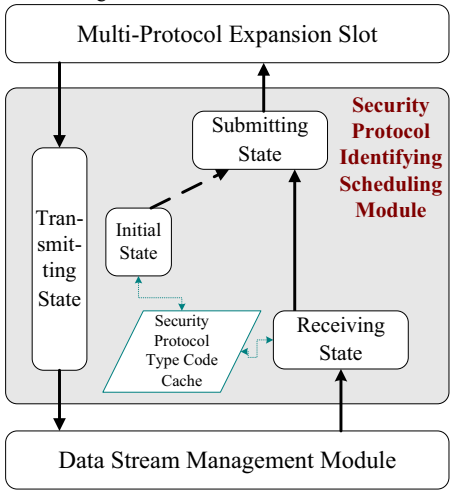

Figure 4 SPISM Control Flow Chart.

The control flow chart of the SPISM is depicted in Figure 4. The solid line with arrowhead and dashed line

with arrowhead denote the authentication data streams and initial data streams respectively.

C. *Multi-Protocol Expansion Slot (MPES)*

The MPES is mainly responsible for adding, registering, managing and deleting various security protocols through a built-in Security Protocol Management Interface sub-module. It also has a sub-module of Security Protocol Register Data Base to store correlative information of all kinds of security protocols and the mapping relationship between these security protocols and their type codes. Furthermore, the "plug and play" function of security protocol modules is realized with the help of the sub-modules.

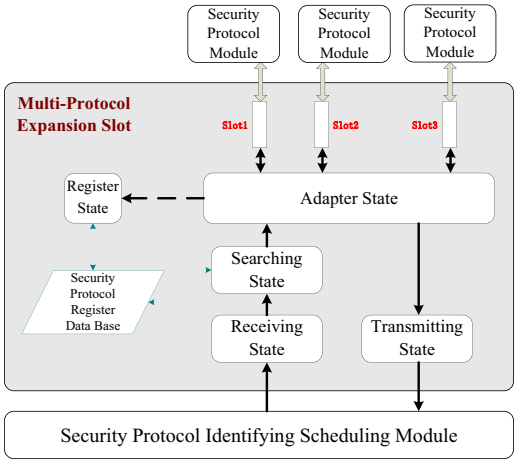

Figure 5 MPES Control Flow Chart.

The control flow chart of the MPES is depicted in Figure 5. The solid line with arrowhead and dashed line with arrowhead denote the authentication data stream and register data stream respectively.

V. Extension Method of Security Protocol

This section proposes a general method of how to embed various security protocols into the simulation platform, which standardize the extension process. The main designing idea is that based on the functions provided by the simulation interface, the extension method modifies the security protocol module in terms of frame format, management interface and protocol address, and must be simple and universal enough to embed new protocols into the simulation platform. In detail, the extension method includes three manipulations:

Designing Unified Frame Format (UFF): A unified frame format to encapsulate all sorts of security protocols is defined. Through the standard frame format, the simulation platform could support different types of security protocols without amending the way function modules deal with different security protocol frames.

Designing Interface Control Unit (ICU): A standard ICU between the security protocol modules and other modules is definitely defined. It provides a unified interface for function modules to exchange management information such as loading, deleting and configuration information.

Designing Service Access Point (SAP): Security protocol modules are marked with protocol address called SAP and registered in a database, which provides a convenient method for other modules to search for and communicate with them.

The extended security protocol modules are shown in Figure 6.

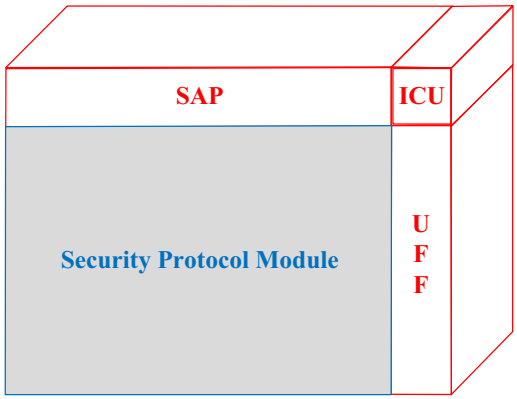

Figure 6 Extended Security Protocol Modules.

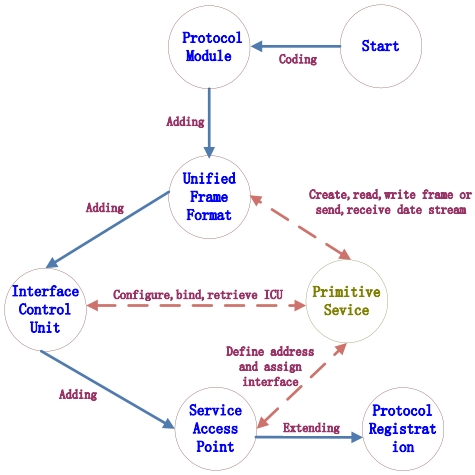

Figure 7 workflow of Extending Security Protocol.

The workflow to add a security protocol to the simulation platform is illustrated in Figure 7.

Step 1: Design the unified frame format to encapsulate all kinds of security protocols, as shown in Figure 8.

Figure 8 Unified Frame Format.

The type of protocol denotes the sort of security protocols; the address of module denotes the SAP of security protocols; the frame number field includes the serial number of frames; the control field is used to implement certain control functions; raw data field carries the original security protocol packets.

Step 2: As illustrated in Figure 9, design the standard ICU between security protocol modules and other modules for exchange of management information.

Figure 9 Interface Control Unit.

The management interface denotes the address through which the management frame could be sent and received; the status code denotes the current state of management; the operation code is used to identify different management operation, such as adding or deleting operation; the registration info denotes the protocol name, type and address; the result field is used to inform the results of operations.

Step 3: Mark security protocol modules with designed ASP and register them in a database.

Step 4: Code the security protocol module, configure its data stream port and connect it with the Security Protocol Simulation Interface.

VI. Platform Validation

In this section, we implement the simulation platform for WLAN security protocols in OPNET and demonstrate its correctness, feasibility and universality through extending and simulating two concrete security protocols—WEP and EAP-TLS.

1) Platform implementation

First, we modify the OPNET built-in modules and implement the new protocol modules in the process layer of OPNET. These modifications and implementations mainly include three parts denoted by ①, ② and ③ in Figrue10. Part①: modify the data stream management function in Wireless_Lan_Mac module to control the security protocol data stream; Part②: code the Security Protocol Simulation Interface and their sub-modules to fulfill the function of identifying, scheduling and managing security protocols; Part③: write programs to implement the Protocol module to be tested. These new added and modified modules correspond to the DSMM, SPISM and MPES modules respectively.

Second, we add the Security Protocol Simulation Interface module and the Protocol module to the WLAN nodes in OPNET and define the logical relationship between these modules, as shown in Figure 10.

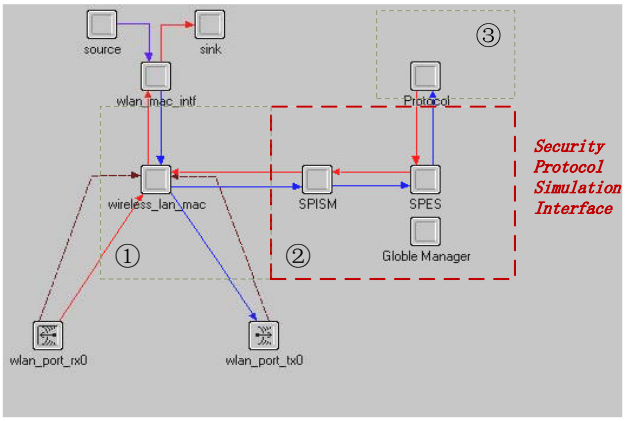

Figure 10 Logical Structure of Simulation Platform.

2) Evaluation criteria

To exactly evaluate the simulation platform, three evaluation criteria are established:

Feasibility: If a simulation platform could accept input by rule, successfully perform simulation process, output right results and fulfill functions of modules, it can be considered to be feasible.

Correctness: we can compare the results of a simulation platform with actual test results. If the difference between the two results is slight and in an acceptable rang, the simulation platform can be considered to be correct.

Universality: If various kinds of protocol modules could be added by a unified extension interface to a simulation platform without modifying other communication modules, the simulation platform can be considered to be universal.

3) Validation of Feasibility

A. Protocol extension

First, we code the protocol module of WEP in OPNET according to the standard IEEE 802.11[15]. Second, we extend and embed it into the simulation platform. Finally, we debug and install it.

B. Simulation scenarios

A typical IEEE 802.11 network, illustrated in Figure 15, is set up, This network consists of two Basic Service Sets(BSSs). BSS1 is composed of Station A, Station B and AP_A; BSS2 is composed of Station C and AP_B. Two BSSs are connected by Bridge forming an ESS. In detail, Station B keeps on sending data packets to Station A and Station C, and hands off periodically between the two BSSs during first 20 minutes of simulation. In this network, all wireless nodes adopt the standard 802.11a[15] and four scenarios are developed.

Scenario 1 is named authentication_1, in which each node has an authentication function. The pre-shared key between Station B and AP_A is identical; and another pair of keys between Station B and AP_B is the same too.

Scenario 2 is named authentication_2, in which each node has an authentication function. The pre-shared key between Station B and AP_A is identical; however, another pair of keys between Station B and AP_B is not the same.

Scenario 3 is named authentication_3, in which each node has an authentication function. The pre-shared key between Station B and AP_A differs; and another pair of keys between Station B and AP_B is not the same either.

Scenario 4 is named non_authentication, in which all nodes consist of OPNET built-in modules that do not have an authentication function.

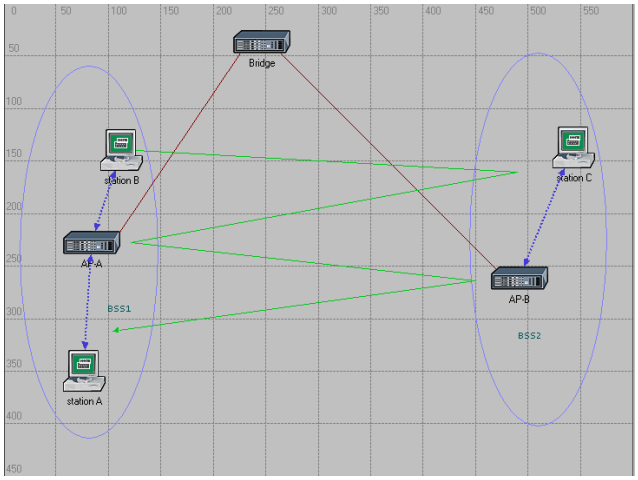

Figure 11 Typical Simulation Scenario of WLAN.

C. Simulation and collection of statistics

The task of simulation utilizes the optimized simulation kernel and continues for 30 minutes. During simulation, four kinds of statistics are collected: rate of dropping data packets of Station B, average receiving rate of data packets of Station A, throughput of MAC module of Station A, overall transmission delay of data packets from Station B to Station A, all of which are illustrated in Figure 12- 15 respectively.

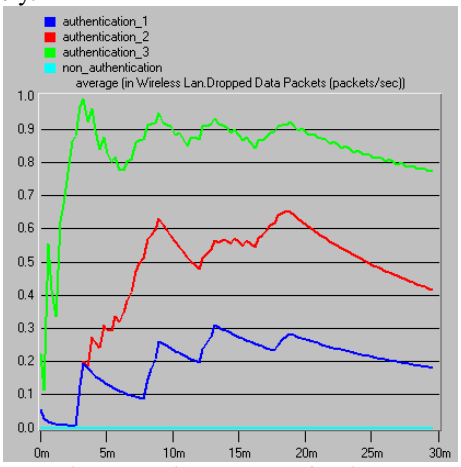

Figure 12 Packet Drop Rate of Station B.

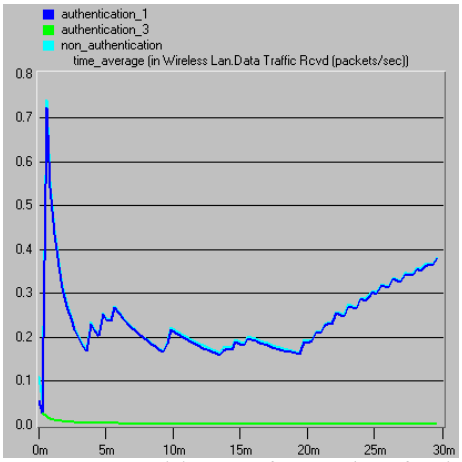

Figure 13 Average Receiving Rate of Data Packets of Station A.

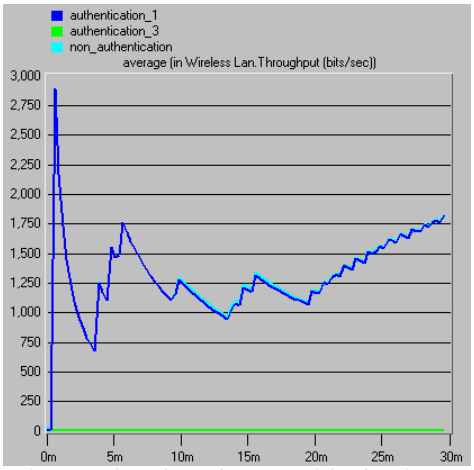

Figure 14 Throughput of MAC Module of Station A.

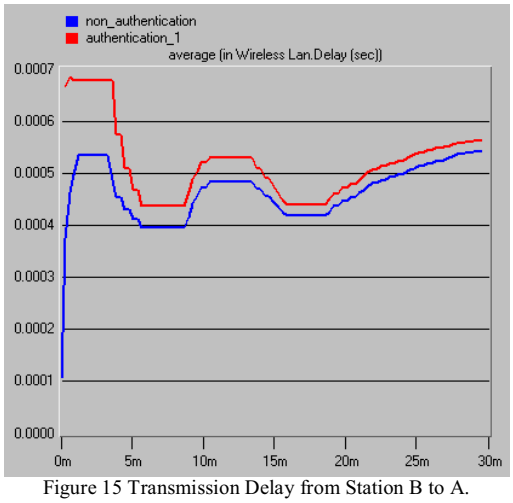

Figure 15 Transmission Delay from Station B to A.

D. Analysis

According to the proposed simulation architecture, the simulation platform for WLAN security protocols, based on OPNET, is implemented. Meanwhile, under the direction of the proposed extension method, the WEP security protocol

is embedded into our platform and the corresponding simulation statistics and results are obtained. It is demonstrated that the architecture and method have practical significance and can be referred as a principle to set up security protocol simulation platforms. Furthermore, it is also validated that the simulation platform possesses certain characteristic of feasibility. Detailed analysis is as follows.

Figure 12 shows the packet drop rate of Station B in each Sub-Scenario. The results are arranged in descending order: Sub-Scenario3, Sub-Scenario2, Sub-Scenario1, and Sub-Scenario4(does not have dropped packets). Because Station B, in Sub-Scenario 3, can not succeed in authenticating with any AP for different session key pre-shared between them, it discards all the data packets, and its packet drop rate is highest. In contrast, Station B in Sub-Scenario 4 does not drop any data packets, because it does not have the authentication function. In Sub-Scenario 1, Station B successfully completes the authentication with both APs, and sends and receives data packets normally. Therefore, the number of data packets it drops is the smallest. In addition, as illustrated in Figure 12, four peaks are appeared in Sub-Scenario1, 2,3, respectively. This is because that Station B hands off four times during the first 20 minutes simulation time and then requires re-authenticating with the corresponding AP.

As seen from Figure 13 and Figure 14, the average data receiving rate and throughput of Station A in Sub-Scenario 3 are zero, which demonstrates that it does not receive any data packets under these conditions. On the contrary, Station A can receive data packets in Sub-Scenario 1 and 4. The reason is that Station B cannot send out any data packets in Sub-Scenario 3 due to the failure in the authentication. However, in Sub-Scenario 1 and 4, the data packets sent from Station B could be received by Station A. Furthermore, the average data receiving rate and throughput of Station A in Sub-Scenario 1 are nearly the same with and yet a little lower than those in Sub-Scenario 4. This is because Station B, in Sub-Scenario 1, will drop some normal data packets during the authentication procedure, whereas it will not perform authentication in Sub-Scenario 4.

Figure 15 shows that the transmission delay of data packets in Sub-Scenario 1 is far larger than that in Sub-scenario 3 during the initial phase of simulation, and that the difference between them dwindles to a relatively constant afterwards. The reason is that more time will be spent at the beginning of simulation due to the authentication procedure. Afterwards, because of the process of encryption and decryption, the overall transmission delay of data packets in Sub-Scenario 1, during the next simulation time, is larger than that in Sub-scenario 4; and their difference is almost constant.

In conclusion, with WEP embedded into the simulation platform, it can accept input by rule, successfully perform simulation process, and output reasonable results, which clearly demonstrate that the simulation platform proposed possesses the characteristics of feasibility.

4) Validation of Correctness

We plan to test the WLAN security protocol EAP-TLS in a practical test-bed we established, and obtain relative results which would be compared with the simulation results in order to validate the correctness of the proposed simulation platform.

A. Protocol extension

First, we code the protocol module of EAP-TLS in OPNET and in the practical test- bed respectively. Second, we extend and embed it into the simulation platform and the test- bed. Finally, we debug and install it.

B. Simulation scenarios

A typical IEEE 802.11 network, illustrated in Figure 16, is set up. This network consists of eight Stations, two APs, two Bridges and one AS which is connected with AP1 and AP2 by wire; all wireless nodes adopt the standard 802.11 and EAP-TLS security protocol. In detail, Station1 is supplicant, AP1 is authenticator and AS is authentication server; Station1 initiates authentication request retransmitted to AS by AP1, and perform standard authentication process with AS. The Station1's attribute is shown in Figure 17.

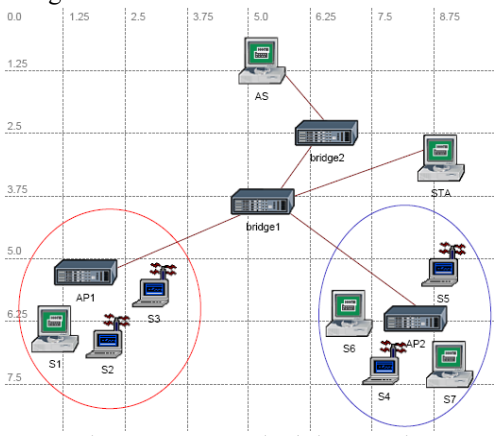

Figure 16 EAP-TLS Simulation Scenario

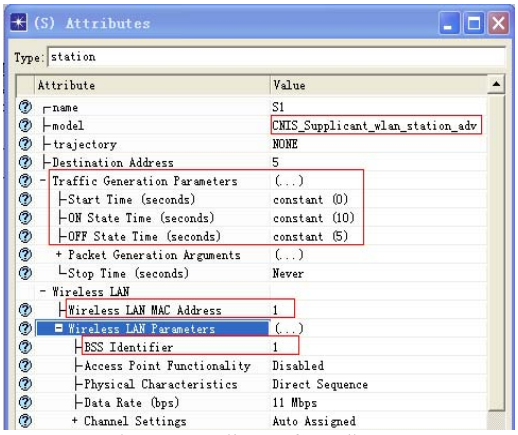

Figure 17 Attributes of Supplicant-1

C. Practical test-bed

As illustrated in Figure 18, a practical WLAN security protocol test-bed is set up in our lab, the topology of which is similar to the topology in Figure 16. More detailed parameters of the test-bed are as follows.

a) Supplicant
Hardware: LINKSYS Wireless-G USB wireless NIC
Software: Windows XP, WPA_supplicant 0.5.10
b) AP
Hardware: LINKSYS Wireless-B PCI wireless NIC
Software: Linux2.6, Hostap drivers, Hostapd 0.5.10
c) AS:
Hardware: Broadcom NetLink(TM) Ethernet NIC
Software: Linux2.6, FreeRadius 2.1.1

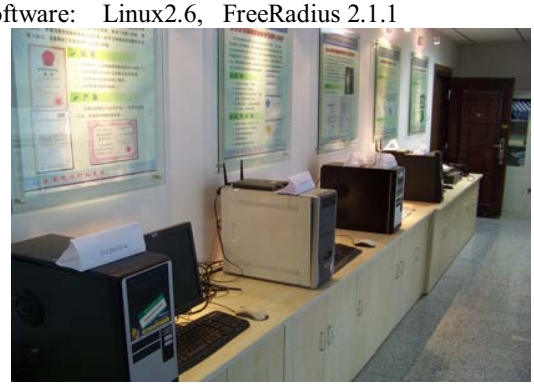

Figure 18 EAP-TLS Test Scenario

D. Simulation and test data

To contrast simulation data with practical test data, detailed information in every round of protocol, including transmission delay, propagation delay and processing overload, is precisely recorded.

In practical test scenarios, protocol packets are captured in NIC to obtain the difference between the packets' sending time and receiving time. In one case, the difference refers to the span of time when a packet enters the NIC and another packet of next round of protocol departs from the same NIC. In another case, it refers to the span of time when a packet departs from the NIC and another packet of next round of protocol is received at the same NIC. At the same time, breakpoints are inserted in the testing program and variables are set to record the packets' processing time, i.e. MAC protocol processing time, which includes encapsulation and dencaplulation, encryption and decryption and protocol FSM operations.

In simulation scenarios, the packets' receiving time and sending time are recorded in transmit-receive module of OPNET.

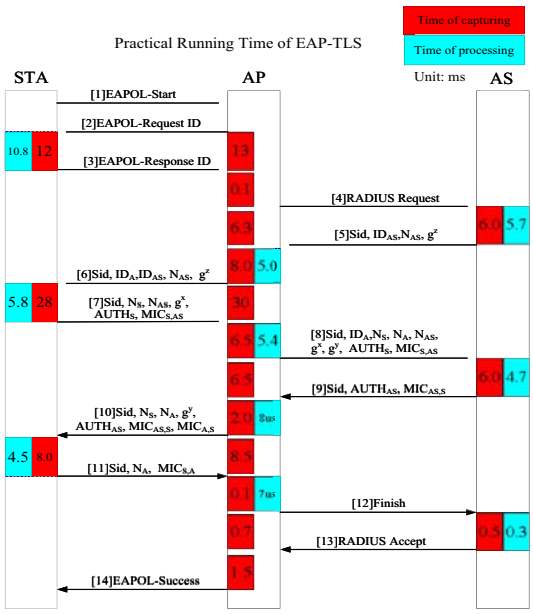

Figure 19 Practical Running Time of EAP-TLS

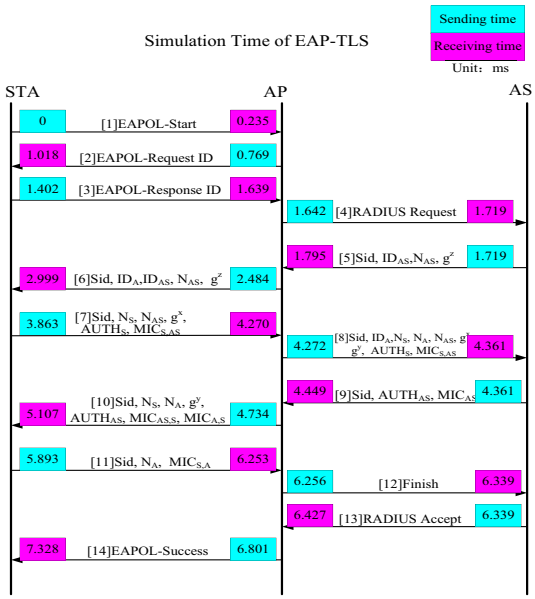

Figure 20 Simulation Time of EAP-TLS

The practical running time of EAP-TLS in test-bed and the simulation time of it in proposed simulation platform are shown in Figure19 and Figure 20 respectively. In Figure19, the time of capturing refers to the difference

between the packets' sending time and receiving time. The time of processing refers to the protocol's processing time. In Figure20, the sending time denotes the time when a packet departs from the transmit module of OPNET, and the receiving time denotes the time when a packet enters the receive module of OPNET.

E Analysis

It can be learned from the principles of communication and Media Access Control that there are several time-consuming states in one round of protocol exchange.

T0：Delay of MAC protocol operation

T1：Delay of sending

T2：Delay of propagation

T3：Delay of receiving

T4：Delay of resolving and dencapsulating

T5：Delay of processing protocol packets (verifying signature and decrypting and so on)

T6：Delay of forming new packets (computing signature, Hash, and encrypting and so on)

T7：Delay of encapsulating

T8：Delay of ACK

In practical test scenarios, because of the adoption of WLAN standard topology and protocol configuration, the practical running time of EAP-TLS includes following time-consuming states:

$T_{run} = T0 + T1 + T2 + T3 + T4 + T5 + T6 + T7$ (+ *T8*)

Because the responding ACK and the processing packets are the simultaneous performance of operations, T8 is not counted in the Trun. Moreover, we also discover that during the running of protocol, the delay of processing packets accounts for the majority of the total running time which is not same as what we have commonly thought — the majority of the total running time mainly consists of the delay of sending, receiving and propagation.

In simulation scenarios, due to the lack of modeling CPU' computing capacity and RAM' storage capacity, the delay of resolving, processing and encapsulating protocol packets are not counted in the total simulation time which includes following time-consuming states:

$T_{simulate} = T0 + T1 + T2 + T3 + T8$

Apart from the delay of processing packets, the simulation time is almost same as the practical running time, i.e. the difference between them is slight and in an acceptable rang, which clearly demonstrates that the proposed simulation platform can be considered to be correct.

5) Validation of Universality

In the previous sections, two types of WLAN security protocols, WEP and EAP-TLS, are added by the designed unified extension interface to the proposed simulation platform without modifying other communication modules, and reasonable and similar results are obtained from the simulation and the practical test, which definitely shows that the proposed simulation platform possesses the characteristics of universality.

VII. CONCLUSION

In this paper, we propose a novel simulation platform for WLAN security protocols and investigate its architecture design, simulation interface and protocol extension method. The simulation platform provides a universal, flexible and extensible simulation solution for the evaluation of WLAN security protocols. Furthermore, based on the architecture and the method, we also implement the simulation platform in OPNET and validate its feasibility, correctness and universality through simulating and testing concrete security protocols. The results show that the platform has characteristics of correctness, universality and extensibility.

VIII. ACKNOWLEDGMENT

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On-Demand QoS Multicast Routing for Triple-Layered LEO/HEO/GEO Satellite IP Networks

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***Abstract*—In this paper, for the sake of better global coverage, we introduce a novel triple-layered satellite network architecture including the Geostationary Earth Orbit (GEO), the Highly Elliptical Orbit (HEO), and the Low Earth Orbit (LEO) satellite layers, which provides the near-global coverage with 24 hour uninterrupted over the areas varying from 75° S to 90° N. On the basis of this satellite network architecture, we propose an on-demand QoS multicast routing protocol (ODQMRP) for satellite IP networks using the concept of logical locations to isolate the mobility of LEO and HEO satellites. In ODQMRP, we present two strategies, i.e., the parallel shortest path tree (PSPT) strategy and the least cost tree (LCT) strategy, to create the multicast trees under the condition that the QoS requirements, containing the delay constraint, and the available bandwidth constraint, are guaranteed. The PSPT and LCT strategy minimize the path delay and the path cost of the multicast trees, respectively. Simulation results demonstrate that the performance benefits of the proposed ODQMRP in terms of the end-to-end tree delay, the tree cost, and the failure ratio of multicasting connections by comparison with the conventional non-QoS shortest path tree (SPT) strategy.**

***Index Terms*—Satellite networks, multicast routing, quality of service, low earth orbit (LEO), highly elliptical orbit (HEO), geostationary earth orbit (GEO).**

I. INTRODUCTION

SATELLITE networks have a wide range of potential applications in data communications and the Internet, mobile and personal communications, voice and telephony networks, broadcast and multicast of digital content, and so on [1]. There is no doubt that satellite networks will be an integral part of the newly emerging Next Generation Networks (NGN) [2] and the evolution of Future Networks (FN) [3], and also play a critical role in realizing the "global village" concept of the world [4]. The impetus to the NGN, even the revolutionary FN, which satellite networks provide can be summarized as follows [4]–[6].

- Global connectivity anywhere and anytime.
- Cost-effective broadcast/multipoint services.
- World-wide direct and ubiquitous access to diversified environments, even remote, inaccessible areas.
- Connectivity in geographical areas where the terrestrial infrastructure has been damaged.
- Very flexible bandwidth-on-demand capabilities.
- Alternative channels for connections for which the bandwidth demands and traffic characteristics are unpredictable.
- Flexible network configuration and capacity allocation
- On-demand multimedia (integrated voice, data, and video) communications, such as distance learning, distributed software updates, telemedicine, and electronic commerce, etc.

Due to the rapidly and regularly changing network topology caused by the high mobility of satellites [7], routing in satellite networks faces great challenges. Previous routing schemes for ATM or ATM-type switches on-board satellites are designed based on the connection-oriented mechanisms that satellite networks own. The integration of the concept of virtual path connections (VPC) and a modified traditional routing scheme is introduced in [8], [9] to tackle the time-variant topology. In [10], a Finite State Automation (FSA) is used to model the Low Earth Orbit (LEO) satellite networks, and the routing problem is treated as a set of link assignment problems using a combinatorial optimization method. The handover rerouting protocol is presented in [11] to maintain the optimality of the initial route without performing a routing algorithm after inter-satellite handovers. In [12], the probabilistic routing protocol (PRP) is investigated to reduce the number of rerouting attempts for the dynamic network topology.

However, with the great popularity of the Internet and the rapid development of the NGN in terrestrial networks, satellite networks will be required to provide connectionless service and transport IP-based traffic. Routing strategies for IP or IP-like switches on-board satellites have also been extensively studied. The

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DARTING algorithm [13] is devised to gear the periodic exchange of topology update messages until there is demand of delivering data messages. Nevertheless, the performance evaluation in [14] demonstrates that the DARTING algorithm requires a much higher overhead and has higher instability at network update periods. In [15], based on the geographic-based addresses, a distributed routing protocol is proposed to direct satellites to route packets in the direction that most reduces the remaining distance to the destination. The datagram routing algorithm (DRA) in [16], using the concept of logical locations of the LEO satellites, is introduced to forward the packets with the minimum propagation delay. In [17], the Multi-Layered Satellite Routing (MLSR) algorithm calculates routing tables efficiently using the collected delay measurements periodically. The Satellite Grouping & Routing Protocol (SGRP) [18] forwards the packets on minimum delay paths regardless of the satellite mobility, and distributes the routing table calculation for LEO satellites to multiple Medium Earth Orbit (MEO) satellites.

With the explosive growth of Internet-based multimedia applications, such as push media, file distribution and caching, multimedia conferencing, multi-player games, chat groups, and so on [19], multicasting constitutes an important service to perform the simultaneous distribution of the same multicasting packets from a single source node to a group of destinations in the satellite IP networks. Multicast routing is one of the key technologies in the multicasting service for satellite networks. In recent years, many conventional multicast routing protocols for terrestrial networks have been proposed [20]–[22] and effectively employed. In terms of the conditions of networks, the multicast routing protocols can be categorized into two types: a) "wired" multicast routing protocols; such as the Distance Vector Multicast Routing Protocol (DVMRP) [23], the Core Based Tree (CBT) [24], the Internet Group Management Protocol (IGMP) [25], the Multicast Extensions for OSPF (MOSPF) [26], etc; b) wireless multicast routing protocols, such as the Multicast Ad hoc On-Demand Distance Vector (MAODV) [27], the Associativity-Based Ad hoc Multicast (ABAM) [28], the On-Demand Multicast Routing Protocol (ODMRP) [29], the Core-Assisted Mesh Protocol (CAMP) [30], etc. However, these existing multicast routing protocols can not be very well suited for satellite IP networks.

At present, only a few multicast routing schemes in the literature have been developed for satellite IP networks. In [31], using the DRA [16] to create the multicast trees, a multicast routing algorithm for LEO satellite IP networks is introduced, which minimizes the end-to-end delay for real time multimedia services. The bandwidth-efficient multicast routing mechanism [32] based on rectilinear Steiner trees for LEO satellite IP networks minimizes the total bandwidth and gains the limited overhead. Two multicast routing algorithms based on the dynamic approximate center (DAC) core selection method, i.e., the core-cluster combination-based shared tree (CCST) algorithm and the weighted CCST algorithm, are presented in [33]. The former significantly decreases the average tree cost, and the latter reduces the average end-to-end propagation delay. The distributed multicast routing protocol in [34] aims to minimize the total cost of the multicast trees in multi-layered satellite IP networks, including Geostationary Earth Orbit (GEO), MEO, and LEO layers. On the whole, the multicast routing schemes proposed for satellite IP networks in the literature can be divided into two categories: a) multicast routing for single-layered satellite IP networks; b) multicast routing for multi-layered satellite IP networks.

In addition, the future media rich applications such as media streaming, content delivery distribution and real time broadband access require satellite networks that inherently offer greater bandwidth and user level quality of service (QoS) guarantees [35]. In this regard, one of the challenges for multicasting communications in satellite networks is to design the QoS multicast routing protocols. QoS-aware multicast routing aims to find a multicast tree rooted from the source node, which not only spans to all the destination nodes, but also meet the QoS requirements. To our knowledge, some QoS unicast routing schemes for satellite networks have been proposed, such as the hierarchical & distributed QoS routing protocol (HDRP) [36], the distributed QoS routing [37], the AntNet-based multi-QoS routing [38], the Predictive Routing Protocol (PRP) [39], etc. However, there is no QoS multicast routing protocol so far specifically developed for satellite IP networks.

In general, a combination of different layers of satellite constellations, such as GEO, LEO, MEO, and Highly Elliptical Orbit (HEO) satellite constellations, to build up a solid satellite network with multiple layers, can yield a much better performance than these layers individually [17], e.g., higher efficiency in the spectrum usage, flexible user's access and networking configuration, larger transmission capacity, strong invulnerability. Currently, the multi-layered satellite networks mainly make use of the combinations of different layers of GEO, LEO, MEO satellite constellations, namely, a) the double-layered satellite networks including the LEO/MEO architecture [8], [18], [40], and the LEO/LEO architecture [41], b) the conventional LEO/MEO/GEO architecture [17], [34]. However, the existing multi-layered satellite networks can not provide the coverage over the special regions or the areas of high latitudes. In this paper, for the sake of better "global coverage", we take into account the demand of satellite communications over the special regions, e.g., the high-latitude areas, and present a triple-layered LEO/HEO/GEO satellite network architecture. On the basis of the novel hierarchical satellite network architecture, we adopt the concept of logical locations to isolate the mobility of LEO and HEO satellites and propose an on-demand QoS multicast routing protocol (ODQMRP) for satellite IP networks. In ODQMRP, the link state information piggybacked by each satellite is exchanged through the link state report process, and the network topology is acquired by the source node through the route discovery and route reply process. Furthermore, we introduce two strategies to

create the multicast trees under the condition that the QoS requirements are guaranteed, i.e., the parallel shortest path tree (PSPT) strategy and the least cost tree (LCT) strategy. The PSPT and LCT strategy minimize the path delay and the path cost of the multicast trees, respectively. We also have evaluated the performance of our proposed ODQMRP under different strategies, i.e., PSPT and LCT, via computer simulations. Simulation results demonstrate that the performance benefits of ODQMRP in terms of the end-to-end tree delay, the tree cost, and the failure ratio of multicasting connections in contrast with the conventional shortest path tree (SPT) strategy.

The remainder of the paper is organized as follows. Section II introduces the triple-layered LEO/HEO/GEO satellite network architecture. In Section III, we present the formulation of the problem, and a description of ODQMRP is proposed in detail in Section IV. Section V evaluates the performance of our proposed ODQMRP. We conclude the paper in Section VI.

II. Triple-Layered Satellite Network Architecture

The triple-layered satellite network architecture consists of a GEO constellation, several LEO and HEO constellations, and some fixed terrestrial gateways. The terrestrial gateways are in the coverage areas of GEO and LEO satellites and assumed to be the sources and destinations of multicasting communications and provide the interconnection to other ground wired/wireless networks. The circular coverage area on the Earth surface, i.e., the footprint of a single satellite, is the union of the cell-like areas covered by the spot beams of that satellite. The proposed satellite network architecture is illustrated in Fig. 1.

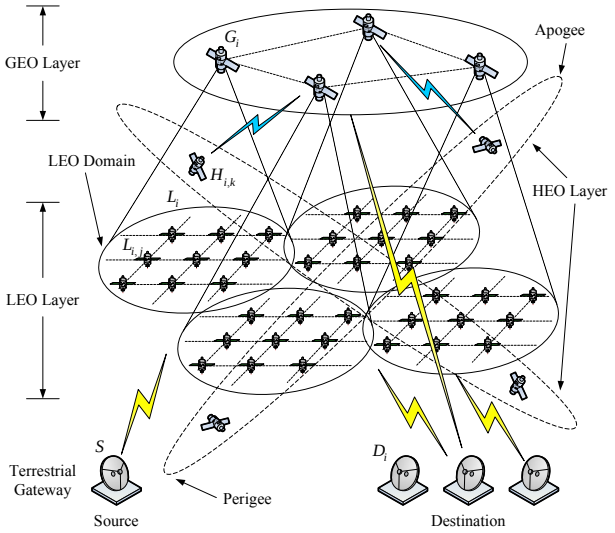


Figure 1. Triple-layered LEO/HEO/GEO satellite network architecture.

A. Satellite Layers and Links

The hierarchical satellite network architecture is divided into three layers in terms of the corresponding constellations.

1) GEO Layer: The GEO layer is composed of a GEO constellation which achieves the full coverage in the region of equator. The GEO satellites within a GEO constellation orbit the Earth at an altitude of about 36000 km and the angular velocity matches the Earth's rate of rotation. Assume that the total number of GEO satellites is N_G and a GEO satellite is denoted by G_i, $i = 1, \cdots, N_G$.

2) LEO Layer: The LEO layer is composed of several LEO constellations which cover the entire globe. The LEO satellites within a LEO constellation move with high velocities at altitudes typically with the range from 500 km to 1500km above the surface of the Earth. Note that the LEO satellites in different LEO constellations have the same orbital altitude. Assume that the total number of satellites in LEO layer is N_L and a LEO satellite is denoted by $L_{i,j}$, which is in the coverage area of the GEO satellite G_i. The logical location concept [16] is used to resolve the problems caused by the mobility of LEO satellites. Assume that Walker star pattern constellation [42] is applied in the LEO layer to organize the LEO satellites.

3) HEO Layer: The HEO constellations are introduced to provide coverage to selected areas of the globe, e.g. Earth's polar regions, over which most GEO satellites lack. The HEO layer is composed of all HEO satellites in the satellite network. The HEO satellites within a HEO constellation have an orbit elliptical in shape with the perigee altitude approaching 500 km and the apogee altitude about 50000 km above the ground. The satellite period varies from 8 to 24 hours. Assume that the total number of satellites in HEO layer is N_H and a HEO satellite is denoted by $H_{i,k}$, which is in the coverage area of the GEO satellite G_i.

Three types of duplex links are maintained in the network. Satellites are connected to each other within the same layer via Inter-Satellite Links (ISLs), while the communication between satellites (e.g. GEO and LEO satellites) in different layers is completed via Inter-Orbital Links (IOLs). Note that coverage for communication services from HEO satellites is only provided when HEO satellites are moving very slowly relative to the globe while in the vicinity of apogee. For that reason, assume that the communication between GEO satellites and HEO satellites is accomplished via IOLs when HEO satellites are moving near apogee, while the communication between HEO satellites cannot be maintained through ISLs in our architecture. The terrestrial gateways can be directly connected to LEO satellites and GEO satellites via User Data Links (UDLs).

B. Satellite Domains

Taking the logical locations of satellites into account, we introduce satellite domains to organize the satellites in a hierarchical manner in order to isolate the mobility of satellites from upper layer, i.e., GEO layer.

1) LEO Satellite Domains: A LEO satellite domain L_i is the set of logical locations of LEO satellites that are within the coverage of a GEO satellite G_i. This GEO satellite G_i can just communicate with the LEO satellites through IOLs within a LEO satellite domain that is in the

coverage of G_i. Furthermore, the GEO satellite G_i is called the manager of the LEO satellite domain L_i. In terms of LEO layer, ISLs can be categorized into two types, i.e., intra-domain ISLs and inter-domain ISLs. Note that the LEO satellites are connected to their adjacent neighbors over the grid points in the same layer via intra-domain ISLs. Here, $L_i = \{L_{i,j} \mid j = 1, \cdots, \mathcal{S}(L_i)\}$, where $\mathcal{S}(\cdot)$ is a size function that generates the total number of all satellites in a satellite domain.

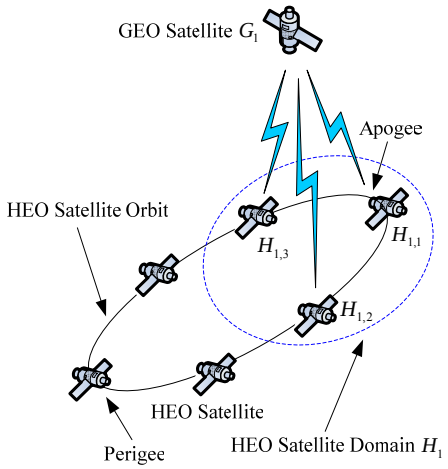


Figure 2. A partial view of a HEO satellite domain.

2) HEO Satellite Domains: A HEO satellite domain H_i is the set of logical locations of HEO satellites that are within the coverage of a GEO satellite G_i. Note that different GEO satellites may have the same HEO satellite domains. For that reason, all the satellites in a HEO satellite domain have the IOLs with a certain number of GEO satellites that cover the same HEO satellite domain. The GEO satellite G_i is also called the manager of the HEO satellite domain H_i. Here, $H_i = \{H_{i,k} \mid k = 1, \cdots, \mathcal{S}(H_i)\}$. Assume that half of the HEO satellites within a HEO constellation in the same orbit have IOLs with a GEO satellite at time instant. A partial view of a HEO satellite domain is depicted in Fig. 2, where a GEO satellite G_1, a HEO constellation and a HEO satellite domain H_1 containing three HEO satellites, i.e., $H_{1,1}$, $H_{1,2}$, $H_{1,3}$, are illustrated.

III. Problem Formulation

A. Definitions

Definition 1. The topology of satellite network based on our architecture is modeled as a connected directed graph $G = (V, E)$, where V is the set of nodes representing the satellites and terrestrial gateways in our architecture and $E \subseteq V \times V$ is the set of links connecting the nodes, i.e., ISLs, IOLs and UDLs.

Definition 2. Let the terrestrial gateway $S \in V$ denote a source node of a multicasting communication, and other terrestrial gateways constitute a non-empty finite set of destination nodes, i.e., $D \subseteq V - \{S\}$, called a multicast group. A *multicast tree* $T = (V_T, E_T)$, for $V_T \subseteq V$ and $E_T \subseteq E$, is a subtree of the graph $G = (V, E)$ rooted from S, which includes all of the nodes of D and an arbitrary subset of $V - D$.

Definition 3. The *link state* of a link l is composed of delay $\mathcal{D}(l)$, available bandwidth $\mathcal{B}(l)$ and cost $\mathcal{C}(l)$, for $l \in E$, where $\mathcal{D}(l): E \to \boldsymbol{R}^+$, $\mathcal{B}(l): E \to \boldsymbol{R}^+$ and $\mathcal{C}(l): E \to \boldsymbol{R}^+$ are delay function, available bandwidth function and cost function, respectively. Note that the delay $\mathcal{D}(l)$ of a link l contains three delay components: a) radio propagation delay, b) queuing delay, and c) protocol processing delay.

Definition 4. The *available path bandwidth* $B(P)$ of a path P is the minimum bandwidth of the links along the path, i.e.,

$$B(P) = \arg\min\{\mathcal{B}(l_i) \mid l_i \in P, i = 1, \cdots, \mathcal{PL}(P)\} \tag{1}$$

where $\mathcal{PL}(\cdot)$ is a function that returns the number of links in the path P.

Definition 5. The *available tree bandwidth* $B(T)$ of a multicast tree T is the minimum bandwidth of the links in the multicast tree, i.e.,

$$B(T) = \arg\min\{\mathcal{B}(l_i) \mid l_i \in T, i = 1, \cdots, \mathcal{TL}(T)\} \tag{2}$$

where $\mathcal{TL}(\cdot)$ is a function that returns the number of links in the tree T.

Definition 6. The *path delay* $D(P)$ of a path P is the sum of the delay of the links on the path, i.e.,

$$D(P) = \sum_{i=1}^{\mathcal{PL}(P)} \mathcal{D}(l_i) \tag{3}$$

Definition 7. The *tree delay* $D(T)$ of a multicast tree T is the maximum delay of the paths from source node S to the destination nodes of D on the multicast tree, i.e.,

$$D(T) = \arg\max\{D(P_{S \to D_i}) \mid i = 1, \cdots, |D|\} \tag{4}$$

where $P_{S \to D_i}$ denotes a feasible path from the source node S to destination node D_i, and $|D|$ denotes the number of destination nodes.

Definition 8. The *path cost* $C(P)$ of a path P is defined as the product of the available path bandwidth and the path delay of the path P, i.e.,

$$C(P) = B(P) \times D(P) \tag{5}$$

Definition 9. The *least cost path* $P^*_{A \to B}$ from node A to node B is defined as a path that satisfies

$$C(P^*_{A \to B}) = \arg\min\{C(P^i_{A \to B}) \mid i = 1, \cdots, \mathcal{PN}(P_{A \to B})\} \tag{6}$$

where $P_{A \to B}$ denotes a feasible path from the node A to the node B, and $\mathcal{PN}(\cdot)$ is a function that returns the number of feasible paths from the node A to the node B.

Definition 10. The *tree cost* $C(T)$ of a multicast tree T is defined as the product of the available tree bandwidth and the tree delay of the multicast tree T, i.e.,

$$C(T) = B(T) \times D(T) \quad (7)$$

B. Problem Statement

Our problem is: given a satellite network $G = (V, E)$, a source node *S*, a multicast group *D*, a delay bound Δ and a bandwidth bound Ω, respectively, to construct a multicast tree $T = (V_T, E_T)$ which spans *S* and *D* such that the tree cost defined in (7) is minimized under the condition that the accumulated available tree bandwidth and tree delay of the multicast tree *T* satisfy the following required QoS constraints

- Delay constraint: $D(T) \le \Delta$;
- Bandwidth constraint: $B(T) \ge \Omega$.

IV. On-Demand QoS Multicast Routing Protocol

Our proposed on-demand QoS multicast routing protocol (ODQMRP) is mainly composed of five parts, namely, link state report, route discovery, route reply, route maintenance and multicast tree creation. We now discuss the operation of the proposed protocol in detail.

A. Link State Report

In the link state report process, the available bandwidth and the delay of each link $l \in E$ in the satellite network $G(V, E)$ are established and the related link state information is recorded in each node. The link state report process is initiated whenever a source node (i.e., a source terrestrial gateway) receives a QoS request from the application layer for setting up a multicasting connection with a multicast group *D* and the given delay and bandwidth bound constraints, i.e., Δ and Ω. The source terrestrial gateway initially generates a report request (REPORT_REQ) message and then transmits the REPORT_REQ message to a GEO satellite via a UDL. When receiving the REPORT_REQ message, the GEO satellite follows the steps below to complete the link state report process.

1) Link State Report Request: The link state report request process can be described as follows.

(a) The GEO satellite forwards the REPORT_REQ message to other adjacent GEO satellites (i.e., the neighbors of the GEO satellite) via ISLs.

(b) When the REPORT_REQ message are received by all the GEO satellites in the GEO layer, each GEO satellite sends the REPORT_REQ message to the LEO and HEO satellites within its covered LEO satellite domain and HEO satellite domain through IOLs.

(c) In the LEO layer, the LEO satellite floods the REPORT_REQ message to other LEO satellites within the same LEO satellite domain via intra-domain ISLs and across different domains via inter-domain ISLs.

(d) The members of the multicast group *D* (i.e., $|D|$ destination terrestrial gateways) receive the REPORT_REQ message from the GEO and LEO satellites via UDLs.

2) Link State Interaction: After all the nodes in the satellite network acquire the REPORT_REQ message, the link state interaction process is initiated. The link state interaction process can be described as follows.

(a) The members of the multicast group *D* transmit a state report (STATE_REPORT) message to the GEO/LEO satellites through the reverse UDLs. The format of the STATE_REPORT message is illustrated in Fig. 3. The "Type" refers to the message type and is set to 1 for the STATE_REPORT message. The fields "Available Bandwidth" and "Delay" record the available bandwidth and the delay between a node and its downstream node over the corresponding link. The pair < Node Address, State Report Sequence Number > uniquely identifies the STATE_REPORT message. The "State Report Sequence Number" is monotonically incremented whenever a node issues a new STATE_REPORT message to its downstream node and can be used to check the duplicate copies of an old STATE_REPORT message for the downstream node. In other words, when a downstream node receives a STATE_REPORT message, if it has already received a STATE_REPORT message with the same "Node Address" and "State Report Sequence Number", it drops the redundant STATE_REPORT message in order to reduce the communication load. The "Downstream Node Address" identifies the downstream node, and the "Reserved" is set to 0 for ignoring and non-zero for receiving. When receiving the STATE_REPORT messages from the destination terrestrial gateways, the GEO and LEO satellites acquire the link state information, i.e., the available bandwidth and the delay between the GEO satellites or LEO satellites and the destination terrestrial gateways.

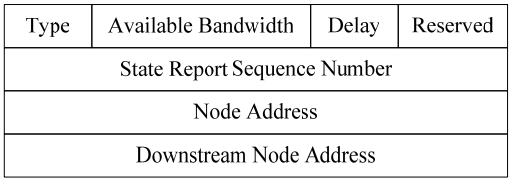


Figure 3. The STATE_REPORT message format.

(b) In the LEO layer, the LEO satellite receives the STATE_REPORT message from the upstream node (i.e., the destination terrestrial gateway) and then issues its STATE_REPORT message to other LEO satellites within the same LEO satellite domain via intra-domain ISLs and across different domains via inter-domain ISLs.

(c) The LEO satellites in the same LEO satellite domain transmit their STATE_REPORT messages via IOLs to their manager, the GEO satellite.

(d) In the GEO layer, the GEO satellite sends its STATE_REPORT messages to other adjacent GEO satellites via ISLs. When exchanging their link state information, the GEO satellite delivers

the corresponding STATE_REPORT messages to the HEO satellites within its covered HEO satellite domain through IOLs and also to the source terrestrial gateway through UDLs.

B. Route Discovery

Our proposed QoS multicast routing protocol is an "on demand". The nodes neither maintain any routing information nor participate in any periodic routing table exchanges when there is no QoS multicast routing call received by the multicast source.

The route discovery is initiated by the source terrestrial gateway when the link state report process is completed. According to the QoS multicast routing request, the source node initiates the route discovery by flooding a route request (RREQ) message to its neighbor nodes. The RREQ message inherits the modified format of RREQ message in traditional Ad hoc On-Demand Distance Vector (AODV) routing protocol [43] and the format of the RREQ message is depicted in Fig. 4(a). The "Type" refers to the message type and is set to 2 for the RREQ message. The fields "Ω" and "Δ" denote the given bandwidth bound and delay bound, respectively and prevent unnecessary network-wide dissemination of RREQ messages. The pair < Source Address, RREQ ID > uniquely identifies the RREQ message. The "RREQ ID" is monotonically increasing whenever the source node issues a new RREQ message to its neighbor nodes and can be used to check the duplicate copies of an old RREQ message for the neighbor nodes. The "Multicast Group Address List" indicates the set of destination nodes and the "Path" records the routing information. The "Accumulated Delay" records the sum of delay along the path. Furthermore, the "Reserved" has the same meaning with that in the STATE_REPORT message.

Type	Ω	Δ	Reserved
RREQ ID			
Multicast Group Address List			
Source Address			
Path			
Accumulated Delay			

(a) RREQ message format

Type	Ω	Δ	Reserved
RREP ID			
Destination Address			
Source Address			
Path Set			
Lifetime			

(b) RREP message format

Figure 4. The RREQ and RREP message format.

When an intermediate node receives a RREQ message, it checks two items to decide whether to reflood the newly received RREQ message.

(a) Whether there is enough available bandwidth $\mathcal{B}(l')$ over the link l' between the last hop node and itself according to the link state information, i.e., whether there exists $\mathcal{B}(l') \geq \Omega$. If $\mathcal{B}(l') < \Omega$, it means that there is no available bandwidth to meet the QoS requirements for establishing the connection through that link and the node drops the RREQ message.

(b) Whether the sum of the value of the "Accumulated Delay" and the delay $\mathcal{D}(l')$ over the link l' meets the delay bound constraint, i.e., $AD + \mathcal{D}(l') \leq \Delta$, where AD denotes the value in the field "Accumulated Delay". If $AD + \mathcal{D}(l') > \Delta$, it means that the delay requirement cannot be guaranteed and the node drops the RREQ message.

Otherwise, if the RREQ message is received by the node for the first time, the node enters its own address to the field "Path" and inputs the value of $(AD + \mathcal{D}(l'))$ into the field "Accumulated Delay", and then disseminates the RREQ message out. Note that this intermediate node is also called the forwarding node. If the newly received RREQ message with the pair < Source Address, RREQ ID > was received before, it means that there exists another path from the source to the node. The node records this path information and discards the RREQ message.

C. Route Reply

This operation in the route discovery process will be repeated node by node until the delay bound or available bandwidth bound cannot be guaranteed. Eventually, a RREQ message will arrive at a destination terrestrial gateway and the destination node will also check two items described in the route discovery process to determine whether the QoS constraints are satisfied. If so, the destination node will wait for a certain timeout T_1 to receive multiple copies of the RREQ messages. Note that each copy indicates a possible path. Then the destination node creates a route reply (RREP) message including all the information about the multiple possible paths reaching it and sends the RREP message back to the source node. Meanwhile, the destination node can also act as an intermediate node and continues to forward the RREQ message until the QoS constraints are not guaranteed.

The format of the RREP message is shown in Fig. 4(b). The "Type" refers to the message type and is set to 3 for the RREP message. The pair < Destination Address, RREP ID > uniquely identifies the RREP message and the "RREP ID" is monotonically increasing whenever the destination node sends a new RREP message back to the source node. The "Destination Address" is the address of the destination node that has received the RREQ message. The "Lifetime" denotes a value of a pre-defined timeout T_2 for which the nodes receiving the RREP message consider the route to be valid, and the "Path Set" is the set of multiple possible paths from the source node to the destination node. In the field "Path Set", each path is marked with the information of accumulated delay and available bandwidth from the source node to the destination node. The values of other entries in the RREP message are consistent with the corresponding entries in the RREQ message.

After a pre-defined timeout T_2, i.e., the value of the "Lifetime" field, the source node does not receive any more RREP messages and the route discovery and route reply process terminate. When the source node receives all the RREP messages, it gets a partial topology from it

to the multicast group in the satellite network $G=(V,E)$. Figure 5 gives an example of a partial topology generated of the satellite network by the route discovery and route reply process, where the nodes in the partial topology are denoted by the corresponding notations described in our architecture, and the given delay bound is set to $\Delta=1200$ ms and bandwidth bound is set to $\Omega=100$ Mb/s. The integer parameters along the links are represented as (*delay*, *available bandwidth*), where the units of the parameters are ms and Mb/s, respectively. Our multicast tree creation strategies are dependent on this partial topology and the global topology of the satellite network is not necessary for the source node. Furthermore, the source node may have multiple parallel paths to some destination nodes, e.g., the two possible paths in Fig. 5 shown as follows.

$$\begin{cases} S \to L_{4,3} \to L_{4,4} \to G_4 \to G_3 \to L_{3,9} \to D_3 & \text{path 1} \\ S \to L_{1,2} \to L_{1,5} \to G_1 \to G_2 \to L_{2,5} \to L_{2,4} \to L_{3,8} \to L_{3,5} \to D_3 & \text{path 2} \end{cases}$$

where the delay and available bandwidth of path 1 are 620 ms and 120 Mb/s, respectively, and the delay and available bandwidth of path 2 are 817 ms and 100 Mb/s, respectively. Obviously, as shown in Fig. 5, the destination node may also serve as a forwarding node, e.g., the path from S to D_1 shown as follows.

$$\text{path 1} \to L_{3,6} \to L_{2,3} \to L_{2,2} \to L_{3,1} \to D_1 \qquad \text{path 3}$$

where the destination node D_3 in path 3 is the forwarding node, and the delay and available bandwidth of path 3 are 775 ms and 100 Mb/s, respectively.

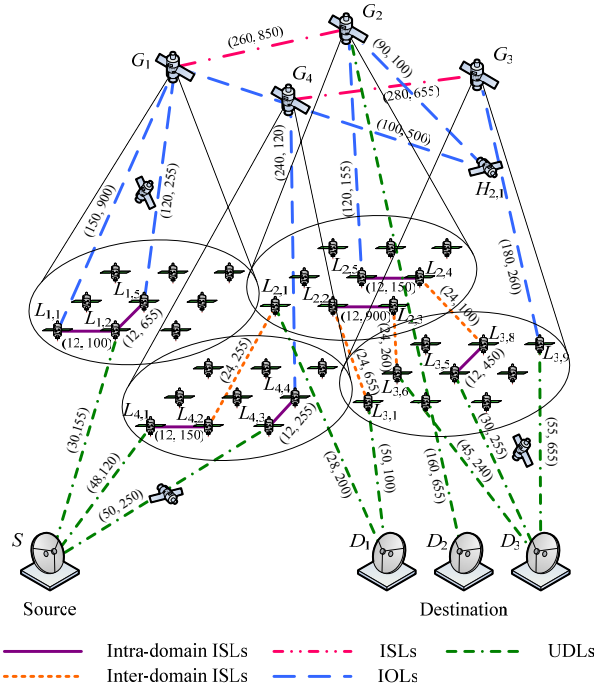


Figure 5. An example of a partial network topology generated by route discovery and route reply process.

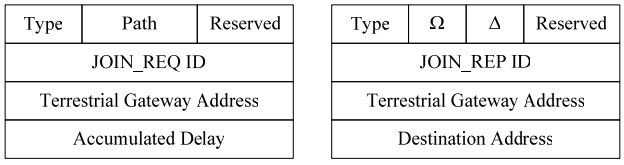
D. Route Maintenance

1) Joining Multicast Group: The joining multicast group process is initiated whenever a new terrestrial gateway wants to join a multicast group. The new gateway firstly creates a STATE_REPORT message where the "Node Address" is filled with the gateway's address, i.e., the destination address, and then transmits the STATE_REPORT message to the GEO/LEO satellites through the UDLs. Through the link state interaction process, the nodes with the corresponding links in the satellite network acquire the link state information. Then the new gateway broadcasts a join request (JOIN_REQ) message with the format depicted in Fig. 6(a). The "Type" refers to the message type and is set to 4 for the JOIN_REQ message. The pair < Terrestrial Gateway Address, JOIN_REQ ID > uniquely identifies the JOIN_REQ message and the "JOIN_REQ ID" is monotonically increasing whenever the new gateway node floods a new JOIN_REQ message to its neighbor nodes. The values of other entries in the JOIN_REQ message are consistent with the corresponding entries in the RREQ message.

When an intermediate node receives a JOIN_REQ message, it checks two items described in the route discovery process to decide whether to reflood the newly received JOIN_REQ message. The new gateway will send multiple JOIN_REQ messages out within a pre-defined timeout T_3 and the JOIN_REQ messages are flooded until they arrive at a desitination node of the multicast group. The destination node firstly will wait for a certain timeout T_4 to receive multiple copies of the JOIN_REQ messages. Secondly, according to the field "Path" information, it will check two items described in the route discovery process to determine whether the QoS constraints are satisfied. If so, the destination node creates a join reply (JOIN_REP) message including all the information about the multiple possible paths reaching it and sends the JOIN_REP message back to the new gateway. Note that this destination node serves as a forwarding node and the source node does not know the information about this new terrestrial gateway.

The format of the JOIN_REP message is shown in Fig. 6(b). The "Type" refers to the message type and is set to 5 for the JOIN_REP message. The pair < Destination Address, JOIN_REP ID > uniquely identifies the JOIN_REP message and the "JOIN_REP ID" is monotonically increasing whenever the destination node sends a new JOIN_REP message back to the new gateway node. The values of other entries in the JOIN_REP message are consistent with the corresponding entries in the RREP message.

After a pre-defined timeout T_5, the new gateway node does not receive any more JOIN_REP messages and the joining multicast group process terminates.



(a) JOIN_REQ message format (b) JOIN_REP message format

Figure 6. The JOIN_REQ and JOIN_REP message format.

2) Leaving Multicast Group: The leaving multicast group process is initiated whenever a destination terrestrial gateway wants to leave a multicast group. The destination terrestrial gateway firstly sends out multiple join negative acknowledgement (JOIN_NAK) messages to its neighbor nodes and then deletes all the routing information of the neighbor nodes. The format of the JOIN_NAK message is shown in Fig. 7. The pair < Terrestrial Gateway Address, JOIN_NAK Sequence Number > uniquely identifies the JOIN_NAK message. The "Type" refers to the message type and is set to 6 for the JOIN_NAK message. The "JOIN_NAK Sequence Number" is monotonically incremented whenever the destination terrestrial gateway issues a new JOIN_NAK message to its neighbor node.

When receiving a JOIN_NAK message, a neighbor node checks whether it has an upstream node or a downstream node. If so, the neighbor node prunes the link from the destination terrestrial gateway and deletes the routing information of the destination terrestrial gateway, and then transmits the JOIN_NAK message out to notify that the destination terrestrial gateway has been leaving the multicast group. Otherwise, the neighbor node will check whether it is a member of the multicast group. If so, the neighbor node just prunes the link from the destination terrestrial gateway. Otherwise, the neighbor node becomes a non-forwarding node and withdraws from the QoS multicasting communications.

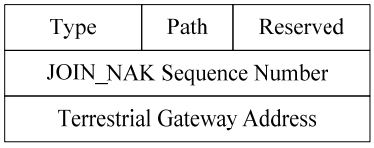


Figure 7. The JOIN_NAK message format.

E. Multicast Tree Creation

The multicast tree creation process is activated by the source node at the end of the route discovery and route reply process. As mentioned previously, the source node has maintained multiple parallel paths from itself to several destination nodes in the multicast group. Consequently, the main goal of the source node is to select one of the parallel paths to set up a connection, and then proceed to create a multicast tree. Here, we present two strategies to construct the multicast tree under the condition that the QoS requirements are guaranteed, namely, the parallel shortest path tree (PSPT) strategy and the least cost tree (LCT) strategy.

1) Parallel Shortest Path Tree Strategy: In the PSPT strategy, we will not apply the classic Dijkstra's algorithm [44], i.e., the *Shortest Path Tree* (SPT), to find the path, and further to produce the multicast tree. However, we will employ the results of the route discovery and route reply process, i.e., the multiple parallel paths from the single source to the destination nodes, which are recorded in the field "Path Set" in the RREP message. Here, we consider that the PSPT possesses the shortest delay for the reason that each path from the source node to the destination node in the multicast group is a path with the shortest path delay.

The basic idea of the PSPT strategy works as follows. In the case of a received RREP message from a destination node D_i, $i=1,\cdots,|D|$, the source node initially checks whether the field "Path Set" contains multiple parallel paths. Assume that the "Path Set" from a destination node D_i is denoted by PS_i. If so, according to the RREP message, the source node computes the path delay $D(P_{i,j})$ of each path $P_{i,j}$, $j=1,\cdots,|PS_i|$, and then compares $D(P_{i,j})$ to select a path $P_{i,j}^*$ with the shortest path delay, i.e.,

$$D(P_{i,j}^*)=\arg\min\{D(P_{i,j})|i=1,\cdots,|D|, j=1,\cdots,|PS_i|\} \quad (8)$$

Therefore, the path $P_{i,j}^*$ is selected as a path form the source node to the destination node D_i for setting up a multicasting connection. Note that the bandwidth constraint of the path $P_{i,j}^*$ is also guaranteed. If the field "Path Set" contains just one path, the source node employs this path to establish a connection. This operation will proceed until the source node acquires $|D|$ paths with the shortest path delay. Then the multicast tree is constructed and the source node starts the multicasting session.

2) Least Cost Tree Strategy: The PSPT strategy can bring the minimum path delay in the multicast tree, but not optimize the path cost in the multicast tree. The LCT strategy takes into consideration both of the QoS requirements, i.e., the delay bound Δ and the bandwidth bound Ω, in order to reduce the path cost, further to optimaize the tree cost.

The basic idea of the LCT strategy works as follows. When receiving a RREP message from a destination node D_i, $i=1,\cdots,|D|$, the source node gets the information of accumulated delay and available bandwidth from the source node to this destination node along a path $P_{i,j}$, $j=1,\cdots,|PS_i|$, i.e., the path delay $D(P_{i,j})$ and the available path bandwidth $B(P_{i,j})$. Therefore, the source node can compute the path cost $C(P_{i,j})=B(P_{i,j})\times D(P_{i,j})$ for the path $P_{i,j}$, and then compare $C(P_{i,j})$ to select a path $P_{i,j}^*$ with the least path cost, i.e.,

$$C(P_{i,j}^*)=\arg\min\{C(P_{i,j})|i=1,\cdots,|D|, j=1,\cdots,|PS_i|\} \quad (9)$$

After a pre-defined timeout T_2, the source node gains all the information about the paths with least path cost from itself to each destination node in the multicast group.

Afterwards, the source node follows the steps below to create a multicast tree.

(a) Construct two node sets $K = \{S\} \bigcup D$ and $H_0 = \{S\}$.

(b) Start with a subtree $T_0 = (V_0, E_0)$, where $V_0 = \{S\}$ and $E_0 = \varnothing$.

(c) For $\alpha = 1, \cdots, |D|$, the source node finds a node in $K - H_{\alpha-1}$, i.e., a destination node D_i, such that the path cost from the source node to D_i is minimum among all the paths with the least path cost, namely, $D_i = \arg\min\{C(P^*_{i,j}) | i = 1, \cdots, |D|, j = 1, \cdots, |PS_i|\}$. Construct the subtree $T_\alpha = (V_\alpha, E_\alpha)$ by adding the path $P^*_{i,j}$ between the source node and D_i to T_α, i.e., set $V_\alpha = V_{\alpha-1} \bigcup \{\text{nodes in } P^*_{i,j}\}$ and $E_\alpha = E_{\alpha-1} \bigcup \{\text{links in } P^*_{i,j}\}$. Meanwhile, set $H_\alpha = H_{\alpha-1} \bigcup \{D_i\}$.

When the multicast tree is created, the source node starts the multicasting session.

V. Performance Evaluation

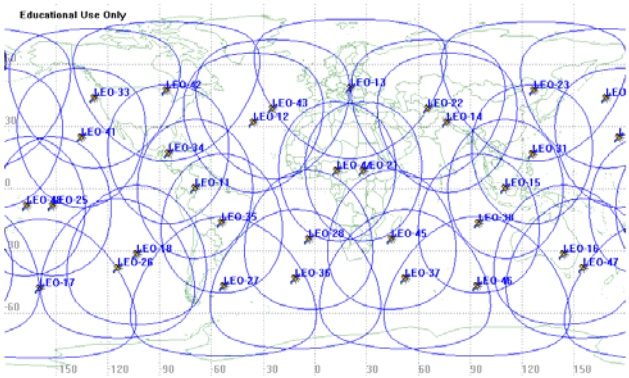
In this section, we evaluate the performance of ODQMRP under different strategies, i.e., PSPT and LCT, by comparing them with the conventional non-QoS SPT [44] strategy via computer simulations using STK 6.0 and NS-2.

In our empirical study, three performance metrics, i.e., a) the end-to-end tree delay, b) the tree cost, and c) the failure ratio of multicasting connections, are used to evaluate the performance of the proposed ODQMRP with PSPT (denoted by ODQMRP-PSPT), ODQMRP with LCT (denoted by ODQMRP-LCT), and the traditional SPT strategy.

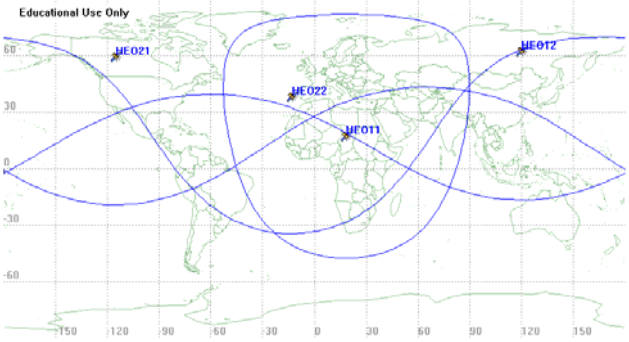
A. Simulation Setup

In our simulations, the constellation parameters of the triple-layer satellite network are given in Table I. The performance of coverage from the proposed triple-layer satellite network is illustrated in Fig. 8. According to Fig. 8, the proposed triple-layered satellite network can offer coverage over the areas varying from 75° S to 90° N with 24 hour uninterrupted. We use the non-uniform distribution [34] to determine the positions of the terrestrial gateways, including the source node and the multicast group. Moreover, we assume that the capacity of all ISLs, IOLs, and UDLs are set to 655 Mb/s, each outgoing link has a buffer space of 20 MB.

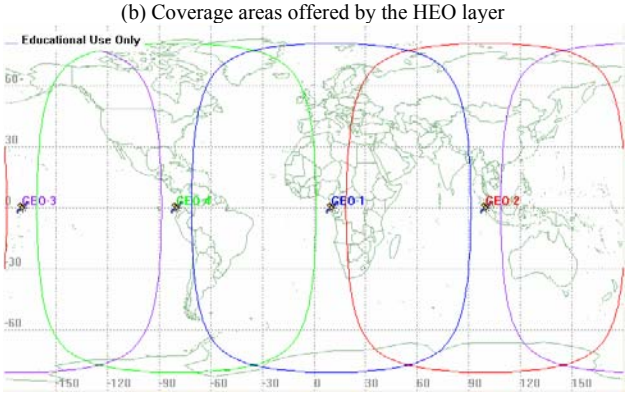
In order to describe the QoS requirements for different application services, we present three different QoS application types, namely, the QoS classes, representing three multicasting scenarios. The multicasting sessions are assigned randomly to one of these QoS classes defined in Table II.



(a) Coverage areas offered by the LEO layer



(b) Coverage areas offered by the HEO layer



(c) Coverage areas offered by the GEO layer

Figure 8. Illustration of near-global coverage from the satellite network using the proposed triple-layered LEO/HEO/GEO architecture.

TABLE I. Parameters for Triple-Layered Satellite Networks.

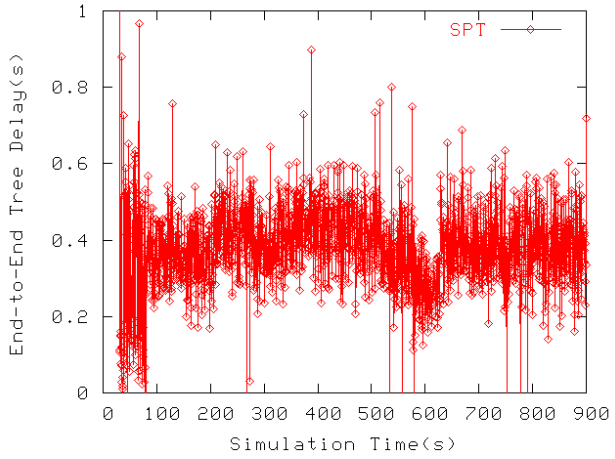
Parameters	LEO Layer	HEO Layer	GEO Layer
Type of orbit	LEO Recursive orbit	HEO Recursive orbit	GEO
Altitude	1262km	27000km(A) 800km(P)	35786km
Orbital period	6628s	8h	24h
Number of satellites	32	4	4
Number of orbital planes	4	2	1
Orbit inclination angle	48°	63.4°	—
Minimum elevation angle	—	10°	5°
Constellation type	Walker star	Draim	—
Semi-major axis	—	20278km	—
Eccentricity	—	0.646	—
Argument of perigee	—	270°	—
Phase factor	1	—	—
Ascending node longitude	—	90° E	—

TABLE II. QOS CLASSES AND REQUIREMENTS

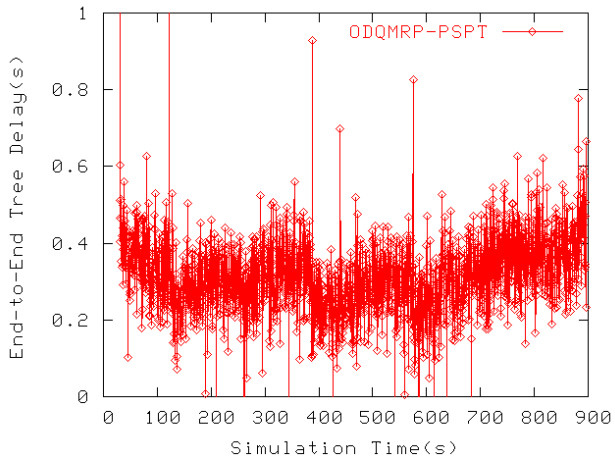
QoS Classes	Delay Requirements	Available Bandwidth Requirements	Application Types
Class 0	600 ms	155 Mb/s	High-speed data on-demand
Class 1	400 ms	256 Mb/s	High-resolution color images
Class 2	200 ms	32 Mb/s	Video teleconferencing

B. Simulation Results and Analysis

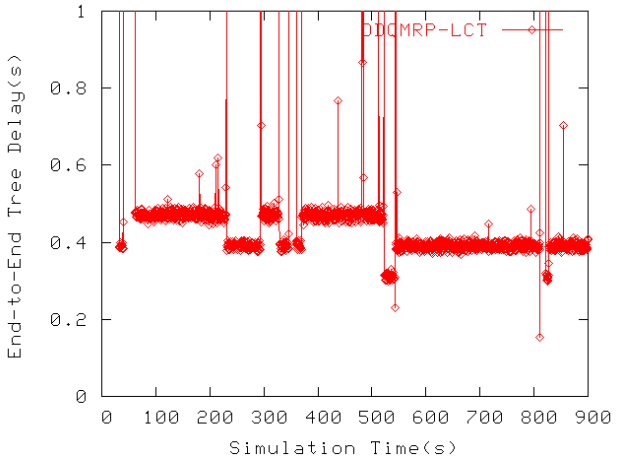
1) Performance Comparison of End-to-End Tree Delay: In the first set of experiments, we observe the end-to-end tree delay of the SPT strategy and the proposed ODQMRP, and the multicast group size is set to 50. Figure 9(a), (b), and (c) depict the performance of the end-to-end tree delay of the SPT strategy, the ODQMRP-PSPT, and the ODQMRP-LCT, under the QoS Class 0, respectively. It can be easily seen that the end-to-end tree delay of the SPT strategy and the ODQMRP-PSPT vary a lot in the range of 0.2 s to 0.6 s, with the increase of the simulation time. However, as the simulation time increases, the end-to-end tree delay of the ODQMRP-LCT remains almostly steady with the range of 0.4 s to 0.6 s. Overall, since the ODQMRP-LCT mainly optimizes the tree cost, we observe that the end-to-end tree delay of the SPT strategy and the ODQMRP-PSPT are slightly smaller than that of the ODQMRP-LCT.



(a) The end-to-end tree delay of the SPT.



(b) The end-to-end tree delay of the ODQMRP-PSPT.



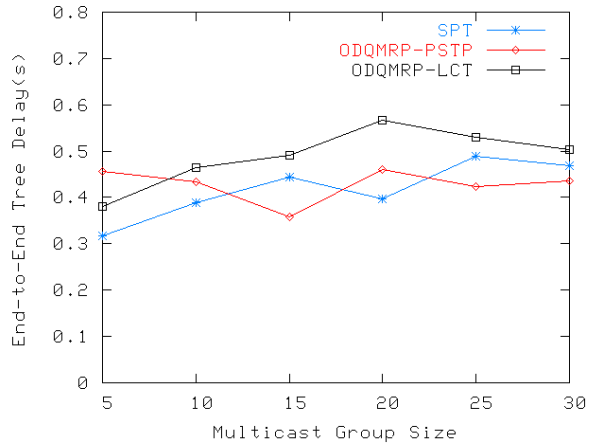
(c) The end-to-end tree delay of the ODQMRP-LCT.

Figure 9. Performance comparison of the end-to-end tree delay of the SPT strategy and the proposed ODQMRP under QoS Class 0.

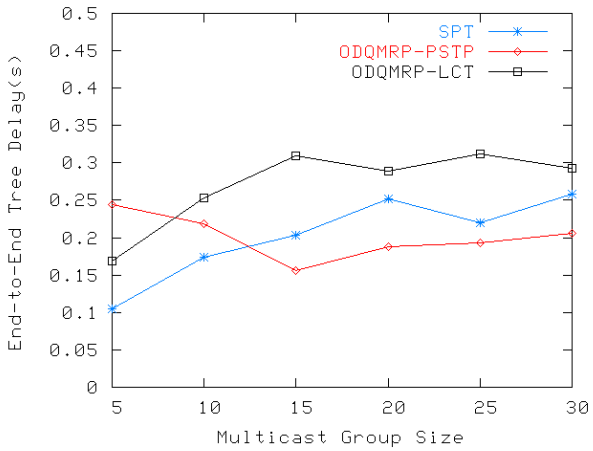
2) Performance Comparison Under Different QoS Classes: In this set of experiments, we compare the performance of the SPT strategy, the ODQMRP-PSPT, and the ODQMRP-LCT, in terms of the performance metrics, i.e., the end-to-end tree delay, the tree cost, and the failure ratio.

Figure 10 shows the comparison of the end-to-end tree delay versus the multicast group size between the SPT strategy and the proposed ODQMRP for different QoS Classes. In Fig. 10(a), (b), and (c), we can obviously see that the end-to-end tree delay of the SPT strategy and the ODQMRP-PSPT are a little lower than that of the ODQMRP-LCT with the range of 10 to 30 of the multicast group size for the reason that the SPT strategy and the ODQMRP-PSPT aim at optimizing the end-to-end tree delay. Furthermore, the SPT strategy finds the path based on the minimum path delay during the route discovery and reply, whereas the proposed ODQMRP-PSPT constructs the multicast tree using the minimum tree delay after the process of the route discovery and reply.

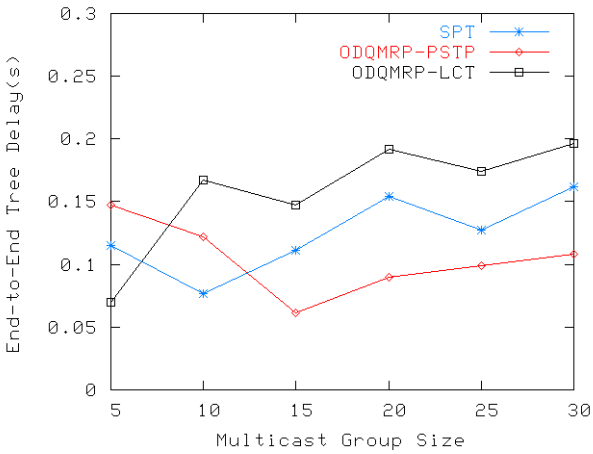
Moreover, in Fig. 10(b) and (c), it can be seen that the end-to-end tree delay of the proposed ODQMRP-PSPT is superior to that of the SPT strategy with the growth of the size of the multicast group, which means that the proposed ODQMRP-PSPT is more suitable for the applications with the greater demand on delay, for example, the video teleconferencing.



(a) QoS Class 0.



(b) QoS Class 1.

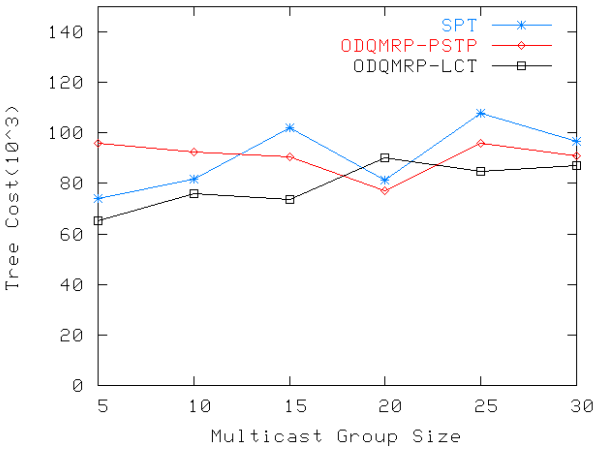


(c) QoS Class 2.

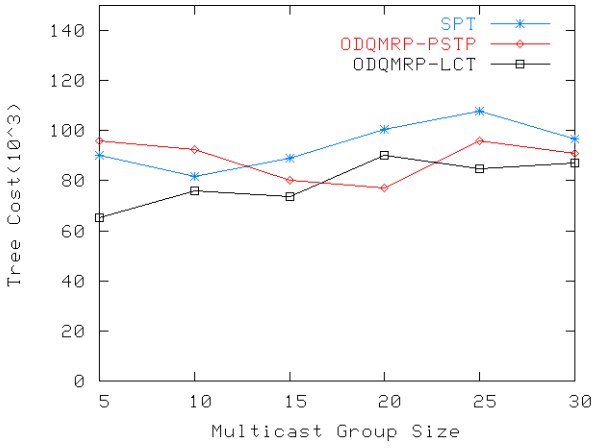
Figure 10. Performance comparison of the end-to-end tree delay of the SPT strategy and the proposed ODQMRP under different QoS Classes.

Figure 11 demonstrates the comparison of the tree cost versus the multicast group size between the SPT strategy and the proposed ODQMRP for different QoS Classes. In Fig. 11(a), (b), and (c), in terms of overall performance, the tree cost of the proposed ODQMRP-LCT is better than that of the ODQMRP-PSPT and the SPT strategy. This can be explained by the fact that the proposed ODQMRP-LCT focuses on the optimization of the tree cost in the construction of the multicast tree under the condition that the QoS constraints, i.e., the delay requirement and the available bandwidth requirement, are guaranteed. However, the SPT strategy or the proposed ODQMRP-PSPT only optimizes the delay constraint, although the proposed ODQMRP-PSPT takes the available bandwidth requirement into account.

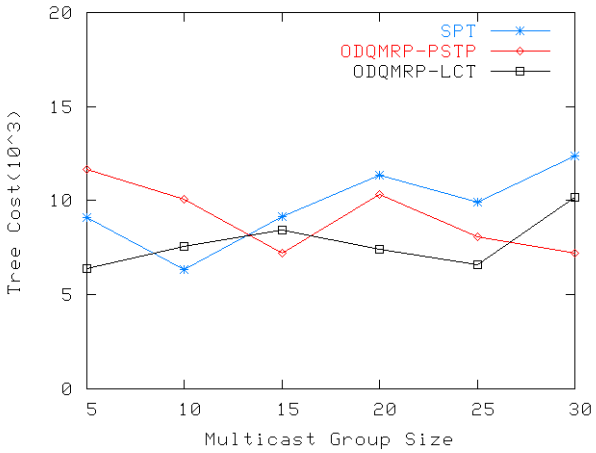
Moreover, the tree cost of the proposed ODQMRP-PSPT is superior to that of the SPT strategy with the range of 15 to 30 of the multicast group size, which indicates that the performance of the proposed ODQMRP-PSPT is better than that of the SPT strategy as the increase of the size of the multicast group.



(a) QoS Class 0.



(b) QoS Class 1.

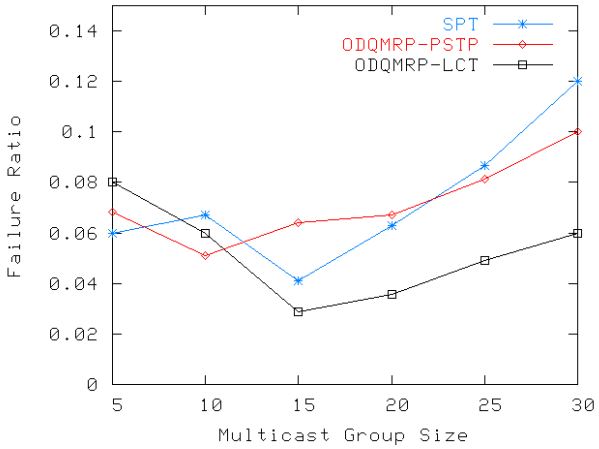


(c) QoS Class 2.

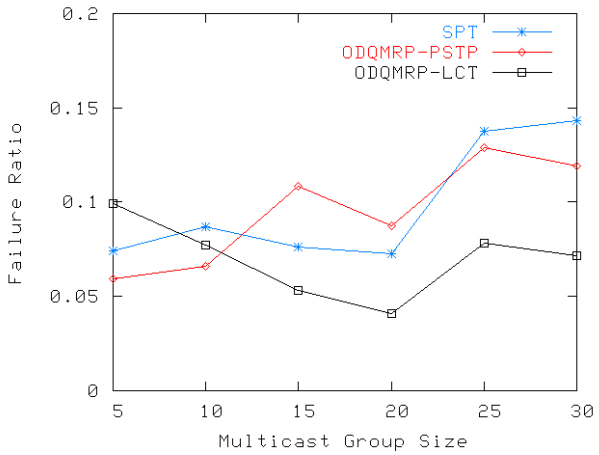
Figure 11. Performance comparison of the tree cost of the SPT strategy and the proposed ODQMRP under different QoS Classes.

Figure 12 compares the failure ratio of multicasting connections versus the multicast group size between the SPT strategy and the proposed ODQMRP for different QoS Classes. In Fig. 12(a), (b), and (c), we can observe that the performance of the failure of multicasting connections of our proposed ODQMRP-LCT and ODQMRP-PSPT surpasses that of the SPT strategy in terms of the overall performance, which demonstrates that as the multicast group size increases, the success ratio of the QoS multicasting requests of the proposed ODQMRP is superior to that of the SPT strategy. For that reason, the proposed ODQMRP can easily establish the QoS multicasting connections. This can be explained by the fact that the proposed the SPT strategy does not take into account the available bandwidth constraint, which results in the higher possibility in the failure of QoS multicasting connections.

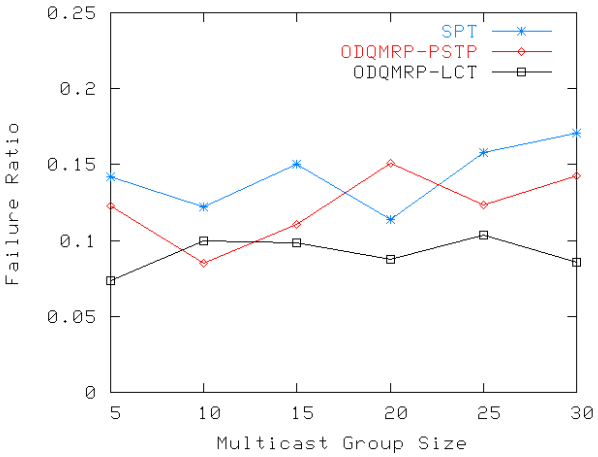
Furthermore, from Fig. 12(a) and (c), it can be easily seen that the failure ratio of multicasting connections of the proposed ODQMRP-LCT is much lower than that of the SPT strategy and the ODQMRP-PSPT in the range of 15 to 30 of the multicast group size. This illustrates that the proposed ODQMRP-LCT is more appropriate to the applications with the less available bandwidth, for example, the video teleconferencing and high-speed data on-demand.



(a) QoS Class 0.



(b) QoS Class 1.



(c) QoS Class 2.

Figure 12. Performance comparison of the failure ratio of the SPT strategy and the proposed ODQMRP under different QoS Classes.

VI. Conclusions

In this paper, aiming at the difficulty to provide the coverage over the special regions or the areas of high latitudes by the existing hierarchical satellite networks, we introduce a novel triple-layered LEO/HEO/GEO satellite network architecture including three satellite layers, i.e., the LEO layer, the HEO layer, and the GEO layer, which provides the near-global coverage with 24 hour uninterrupted over the areas varying from 75° S to 90° N. On the basis of this novel architecture, we propose an on-demand QoS multicast routing protocol (ODQMRP) for satellite IP networks by employing the concept of logical locations to isolate the mobility of LEO and HEO satellites. In the proposed ODQMRP, we present two strategies, i.e., the PSPT strategy and the LCT strategy, to create the multicast trees under the condition that the QoS constraints, containing the delay requirement, and the available bandwidth requirement, are both guaranteed. Moreover, the main goal of the PSPT strategy and the LCT strategy is to minimize the path delay and the path cost of the multicast trees, respectively. Simulation results demonstrate that the performance benefits of ODQMRP in terms of three performance metrics, i.e., the end-to-end tree delay, the tree cost, and the failure ratio of multicasting connections in contrast with the traditional non-QoS guaranteed shortest path tree (SPT) strategy.

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