Energy-Efficient Routing Protocols in Wireless Sensor Networks: A Survey

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***Abstract*—The distributed nature and dynamic topology of Wireless Sensor Networks (WSNs) introduces very special requirements in routing protocols that should be met. The most important feature of a routing protocol, in order to be efficient for WSNs, is the energy consumption and the extension of the network's lifetime. During the recent years, many energy efficient routing protocols have been proposed for WSNs. In this paper, energy efficient routing protocols are classified into four main schemes: *Network Structure*, *Communication Model*, *Topology Based* and *Reliable Routing*. The routing protocols belonging to the first category can be further classified as *flat* or *hierarchical*. The routing protocols belonging to the second category can be further classified as *Query-based* or *Coherent and non-coherent-based* or *Negotiation-based*. The routing protocols belonging to the third category can be further classified as *Location-based* or *Mobile Agent-based*. The routing protocols belonging to the fourth category can be further classified as *QoS-based* or *Multipath-based*. Then, an analytical survey on energy efficient routing protocols for WSNs is provided. In this paper, the classification initially proposed by Al-Karaki, is expanded, in order to enhance all the proposed papers since 2004 and to better describe which issues/operations in each protocol illustrate/enhance the energy-efficiency issues.**

***Index Terms*—Routing Protocols, Energy Efficiency, Wireless Sensor Networks.**

I. Introduction

A WSN is a collection of wireless nodes with limited energy capabilities that may be mobile or stationary and are located randomly on a dynamically changing environment. The routing strategies selection is an important issue for the efficient delivery of the packets to their destination. Moreover, in such networks, the applied routing strategy should ensure the minimum of the energy consumption and hence maximization of the lifetime of the network [1].

One of the first WSNs was designed and developed in the middle of the 70s by the military and defense industries. WSNs were also used during the Vietnam War in order to support the detection of enemies in remote jungle areas. However, their implementation had several drawbacks including that the large size of the sensors, the energy they consume and the limited network capability.

Manuscript received 21 May 2011; revised 8 December 2011 and 16 March 2012.

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Digital Object Identifier 10.1109/SURV.2012.062612.00084

Since then, a lot of work on the WSNs field has been carried out resulting in the development of the WSNs on a wide variety of applications and systems with vastly varying requirements and characteristics. At the same time, various energy-efficient routing protocols have been designed and developed for WSNs in order to support efficient data delivery to their destination. Thus, each energy-efficient routing protocol may have specific characteristics depending on the application and network architecture.

The WSNs may be used in a variety of everyday life activities or services. For example a common application of WSNs is for monitoring. In the area of monitoring, the WSN is deployed over a region in order to monitor some phenomenon. A practical use of such a network could be a military use of sensors to detect enemy intrusion. In case that the sensors detect an event (change on heat or on the blood pressure) then the event is immediately reported to the base station, which decides the appropriate action (send a message on the internet or to a satellite). A similar area of use may be the monitoring of the air pollution, where the WSNs are deployed in several cities to monitor the concentration of dangerous gases for citizens. Moreover, a WSN may be used for forest fires detection to control when a fire has started. The nodes will be equipped with sensors to control temperature, humidity and gases which are produced by fire in the trees or vegetation.

In addition to the above, an important area of use is the healthcare sector. this area the WSNs may offer significant cost savings and enable new functionalities that will assist the elderly people living along in the house or people with chronic diseases on the daily activities. In wired systems, the installation of enough sensors is often limited by the cost of wiring. Previously inaccessible locations, rotating machinery, hazardous or restricted areas, and mobile assets can now be reached with wireless sensors.

Moreover, the use of WSNs on agriculture may benefit the industry frees the farmer from the maintenance of wiring in a difficult environment. The gravity feed water systems can be monitored using pressure transmitters to monitor water tank levels, pumps can be controlled using wireless I/O devices and water use can be measured and wirelessly transmitted back to a central control center for billing. The water industry may be benefited for power or data transmission can be monitored using industrial wireless I/O devices and sensors powered using solar panels or battery packs.

The main contribution of this paper is to provide an exhaustive survey on the energy-efficient routing protocols for WSNs as well as their classification into four main categories: Network Structure, Communication Model, Topology Based and Reliable Routing Schemes. We focus on the techniques these protocols use in order to route messages, taking into consideration the energy they consume and how they achieve to minimize this consumption and extend the lifetime of the network. Moreover, we discuss the strengths and weaknesses of each protocol providing a comparison among them including some metrics (scalability, mobility, power usage, route metric, periodic message type, robustness) in order for researchers and practitioners to understand the various techniques and thus helping them to select the most appropriate one based on their needs. Also, in this paper the classification initially proposed by Al-Karaki, is expanded, in order to enhance all the proposed papers since 2004 and to better describe which issues/operations in each protocol illustrate/enhance the energy-efficiency issues.

This paper is organized as follows: In section 2, the related work in the survey of routing protocols for WSNs is presented. In section 3, the real deployment and energy consumption in WSNs is presented. In section 4, the energy-efficient route selection policies are described. In section 5, the routing techniques and their classification into four main categories, *Structure*, *Communication Model*, *Topology Based* and *Reliable Routing*, are analyzed and discussed. The routing protocols belonging to the first category can be further classified as *Flat* or *Hierarchical*. The routing protocols belonging to the second category can be further classified as *Query-Based* or *Coherent and Non-Coherent Based* or *Negotiation-Based*. The routing protocols belonging to the third category can further classified as *Location-based* or *Mobile Agent-based*. The routing protocols belonging to the fourth category can be further classified as *QoS-based* or *Multipath-based*. In Section 6, we describe and compare the protocols that belong to the *Network Structure* scheme. In section 7, the protocols that belong to the *Communication Model* scheme are described and compared. In Section 8, we describe and compare the protocols that belong to the *Topology Based* scheme. In section 9, the protocols that belong to the *Reliable Routing* scheme are described and compared. In section 10, the route selection factors and the future research directions are discussed. Finally, in section 11, we conclude the paper.

II. Related Work

There is a large number of current works, as well as efforts that are on the go, for the development of routing protocols in WSNs. These protocols are developed based on the application needs and the architecture of the network. However, there are factors that should be taken into consideration when developing routing protocols for WSNs. The most important factor is the energy efficiency of the sensors that directly affects the extension of the lifetime of the network. There are several surveys in the literature on routing protocols in WSNs and an attempt is made to present below and discus the existing differences between them and our work.

In [2], the authors make a comprehensive survey on design issues and techniques for WSNs (2002). They describe the physical constraints of sensor nodes and the proposed protocols concern all layers of the network stack. Moreover, the possible applications of sensor networks are discussed. However, the paper does not make a classification for such routing protocols and the list of discussed protocols is not meant to be complete, given the scope of the survey. Our survey is more focused on the energy efficiency on WSNs providing at the same time a classification of the existing routing protocols. We also discuss a number of developed energy-efficient routing protocols and provide directions to the readers on selecting the most appropriate protocol for their network.

In [3], a survey on routing protocols in WSNs is presented (2004). It classifies the routing techniques, based on the network structure, into three categories: flat, hierarchical, and location-based routing protocols. Furthermore, these protocols are classified into multipath-based, query-based, negotiation-based, and QoS-based routing techniques depending on the protocol operation. It presents 27 routing protocols in total. Moreover, this survey presents a good number of energy-efficient routing protocols that have been developed for WSNs and was published in 2004. It also presents the Routing Challenges and Design Issues that have to be noticed when using WSNs. Thus, limited energy supply, limited computing power and limited bandwidth of the wireless links connecting sensor nodes are described. Also, the authors try to highlight the design tradeoffs between energy and communication overhead savings in some of the routing paradigm, as well as the advantages and disadvantages of each routing technique. On the contrary, in our work we focus on the energy efficiency issues in WSNs. We provide details and comprehensive comparisons on energy efficient protocols that may help researchers on their work. Also, in this paper we expand the classification initially proposed by Al-Karaki in order to enhance all the proposed papers since 2004 and to better describe which issues/operations in each protocol illustrate/enhance the energy-efficiency issues.

The survey in [4] discusses few routing protocols for sensor networks (24 in total) and classifies them into data-centric, hierarchical and location-based (2005). Although it presents routing protocols for WSNs it does not concentrate on the energy efficient policies. On the contrary, we focus mainly on the energy-efficient routing protocols discussing the strengths and weaknesses of each protocol in such a way as to provide directions to the readers on how to choose the most appropriate energy-efficient routing protocol for their network.

In [5], authors provide a systematical investigation of current state-of-the-art algorithms (2007). They are classified in two classes that take into consideration the energy-aware broadcast/multicast problem in recent research. The authors classify the algorithms in the MEB/MEM (minimum energy broadcast/multicast) problem and the MLB/MLM (maximum lifetime broadcast/multicast) problem in wireless ad hoc networks. Typically, the two main energy-aware metrics that are considered are: minimizing the total transmission power consumption of all nodes involved in the multicast session and maximizing the operation time until the battery depletion of the first node involved in the multicast session. Moreover, each node in the networks is considered to be equipped with an omni-directional antenna which is responsible for sending and receiving signals.

The survey in [6], presents a top-down approach of several applications and reviews on various aspects of WSNs (2008).

It classifies the problems into three different categories: internal platform and underlying operating system, communication protocol stack, network services, provisioning, and deployment. However, the paper neither discusses the energy efficient routing protocols developed on WSNs nor provides a detailed comparison of the protocols. Our work is a dedicated study on energy-efficient routing protocols and provides directions to the readers on selecting the most appropriate protocol for their network.

In [7], the authors present a survey that is focused on the energy consumption based on the hardware components of a typical sensor node (2009). They divide the sensor node into four main components: a sensing subsystem including one or more sensors for data acquisition, a processing subsystem including a micro-controller and memory for local data processing, a radio subsystem for wireless data communication and a power supply unit. Also the architecture and power breakdown as the solution to reduce power consumption in wireless sensor networks is discussed. They provide the main directions to energy conservation in WSNs. The paper is focused on the description of the characteristics and advantages of the taxonomy of the energy conservation schemes. The protocols are classified into duty-cycling, data-driven and mobility based. In the next protocols, more details and discussion are presented of this classification. Moreover, they provide observations about the different approaches to energy management and highlight that the energy consumption of the radio is much higher than the energy consumption due to data sampling or data processing. However, many real applications have shown the power consumption of the sensor is comparable to, or even greater than, the power needed by the radio. They conclude that the sampling phase may need a long time especially compared to the time needed for communications, so that the energy consumption of the sensor itself can be very high as well. Also they observe an increasing interest towards sparse sensor network architecture. In our work, we basically focus on the energy-efficient protocols and we discuss the strengths and weaknesses of each protocol that can provide directions to the readers about the most appropriate energy-efficient routing protocol for their network.

In [8], the design issues of WSNs and classification of routing protocols are presented (2009). Moreover, a few routing protocols are presented based on their characteristics and the mechanisms they use in order to extend the network lifetime without providing details on each of the described protocols. Also, the authors do not present a direct comparison of the discussed protocols. In our work we do not only focus on the energy-efficient protocols but we also discuss the strengths and weaknesses of each protocol in such a way as to provide directions to the readers on how to choose the most appropriate energy-efficient routing protocol for their network.

The paper in [9] presents the challenges in the design of the energy-efficient Medium Access Control (MAC) protocols for the WSNs (2009). Moreover, it describes few MAC protocols (12 in total) for the WSNs emphasizing their strengths and weaknesses, wherever possible. However, the paper neither discusses the energy-efficient routing protocols developed on WSNs nor provides a detailed comparison of the protocols. Our survey is concentrated on the energy-efficient routing protocols discussing the strengths and weaknesses of each protocol in such a way as to provide directions to the readers on how to choose the most appropriate energy-efficient routing protocol for their network.

In [10], few energy-efficient routing techniques for Wireless Multimedia Sensor Networks (WMSNs) are presented (2011). Also the authors highlight the performance issues of each strategy. They outline that the design challenges of routing protocols for WMSNs followed by the limitations of current techniques designed for non-multimedia data transmission. Further, a classification of recent routing protocols for WMSNs is presented. This survey discusses some issues on energy efficiency in WSNs. However, it is mostly based on the energy efficient techniques combining QoS Assurance for WMSNs.

Although, there is a good number of surveys for sensor networks, or routing and MAC algorithms for WSNs ([2], [3], [4], [5], [6], [7], [8], [9] and [10]), this paper provides an analytical survey emphasizing on the energy-efficient routing protocols in WSNs. Our survey is focused on the energy-efficient routing protocols in WSNs that can provide directions to the readers on how to choose the most appropriate energy-efficient routing protocol for their network. Moreover, our work reflects the current state of the art in routing research by including a comprehensive list of recently proposed routing protocols. Moreover, we discuss the strengths and weaknesses of each protocol making a comparison between them including some metrics (scalability, multipath, mobility, power usage, route metric, periodic message type, robustness and QoS support).

III. REAL DEPLOYMENT AND ENERGY CONSUMPTION IN WSNS

A. *Real Deployments in WSNs*

The research and development of routing protocols in WSNs were initially driven by defense applications. This has resulted in the development of many WSN systems like acoustic tracking of low-flying aircraft or Remote Battlefield Sensor System (REMBASS). In [11], a WSN that offers battle field surveillances services is presented. Also in [12] the application of WSNs to the intrusion detection problem and the related problems of classifying and tracking targets is presented.

However, in the recent years the WSNs offer a well defined and easy way to offer services to a lot of daily sectors of people paying a great attention to healthcare services [13]. In [14] a sensor and actuator network in smart homes for supporting elderly and handicapped people is studied. Also in [15] an application for smart home monitoring has also been described. Also there is a lot of effort on developing more complicating WSN systems concluding to frameworks and make them available to a larger set of applications [16], [17], [18], [19].

Sensor networks consist of a small or large amount of nodes called sensor nodes. These nodes are varying in size and based on their size the sensor nodes work efficiently in different fields. WSNs have such sensor nodes which are specially designed in such a typical way that they include a microcontroller which controls the monitoring, a radio transceiver for generating radio waves, different types of

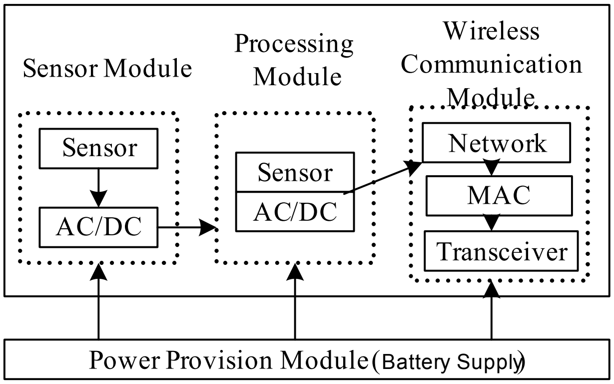

Fig. 1. The architecture of a WSN node.

wireless communicating devices and also equipped with an energy source such as battery. The entire network works simultaneously by using sensors of different dimensions and by using a routing algorithm they are mainly focused on providing delivery data from the source to the destination nodes.

B. Energy Consumption Models for WSN nodes

The WSN nodes consist of several modules as shown in figure 1: Sensor Module, Processing Module, Wireless Communication Module and Power Supply Module. These components work together in order to make the sensor operational in a WSN environment. Thus, in order to evaluate the energy consumption of a WSN node, it is important to study the energy consumption of its components.

There are a few attempts to propose and discus about models for energy efficiency WSNs. Most of them are based on sensor node power consumption model, while at the same time the impact of the sensor node device hardware and external radio environment are considered. However, in real deployments the separation of the power consumption of each hardware component and the impact of the external radio environment should be considered.

In particular, the authors in [20] present a realistic power consumption model for WSN devices by incorporating the characteristics of a typical low power transceiver (2006). This work proves that for typical hardware configurations and radio frequency environments, whenever single hop routing is possible it should be preferred as it is more power efficient than multi-hop routing.

In [21], an energy model specifically built for use for on-line accounting is presented. This model of the communication system appears to be relatively simple, only two states for the microcontroller and the radio chip are considered (2007). On the other hand, in [22] the authors present an energy model divided into a set of finite state machines that represent the states and transitions of a sensor node's hardware (2008). With this model and its application in on-line energy accounting, it is possible to get a more detailed and more precise view on the energy consumption in a sensor network than before. Data gathered from the online accounting can be used to tune the energy consumption of sensor node applications automatically at run-time.

In addition, in [23] a general energy consumption model of WSNs devices based on the actual hardware architecture is proposed (2007). In order to achieve this, the authors utilize the measured energy consumption performance of the actual hardware components and implement a realistic CSESM (Communication Subsystem Energy Consumption Model) of WSNs devices. This can reflect the energy consumption in various functioning states and during transitions between states of the devices. In this model the energy consumption of the communication stage is considered to be influenced by the receive module (Rx), the transmit module (Tx), the voltage regulator (VR), the crystal oscillator (XOSC), the bias generator (BG), and the frequency synthesizer (FS).

Another model related to energy consumption of the sensor CPU (Central Processing Unit) is presented in [24] (2010). It's a probabilistic model which evaluates the energy consumption for CPU of wireless sensor node. This model in order to evaluate the CPU energy consumption it calculates the power spend on standby, powerup, idle and active state of the CPU. The total amount of this CPU consumption along with the spend time conclude to the energy consumption.

A more up to date approach regarding the energy consumption of the WSN nodes is presented in [25] (2011). More detailed, the energy consumption of the wireless sensor nodes based on fig.1 depends on its components and is summarized on the following:

- *Sensor Module*. The energy consumption of sensor module is due to a few numbers of operations. This includes signal sampling, AD (Analogue to Digital) signal conversion and signal modulation. Also the energy consumption of this module is related to the sense operation of the node (periodic, sleep/wake, etc.). For example in periodic mode the energy consumption is modeled as

$$\mathbf{E}_{sensor} = \mathbf{E}_{on-off} + \mathbf{E}_{off-on} + \mathbf{E}_{sensor-run} \quad (1)$$

  In this relation the $E_{on\text{-}off}$ is the one time energy consumption of closing sensor operation, $E_{off\text{-}on}$ is the one time energy consumption of opening sensor operation and $E_{sensor\text{-}run}$ is the energy consumption of sensing operation that is equal to the the working voltage multiplied by the current of sensors and the time interval of sensing operation.
- *Processing Module*. The main activities of this module are the sensor controlling, the protocol communication and data processing. In most cases this module supports three operation states (sleep, idle, run). The Processor energy consumption, denoted as E_{cpu} is the sum of the state energy consumption $E_{cpu\text{-}state}$ and the state-transition energy consumption $E_{cpu\text{-}change}$ where i=1,2,..m is the processor operation state and m is the number of the processor state, j=1,2,..n, is the is the type of state

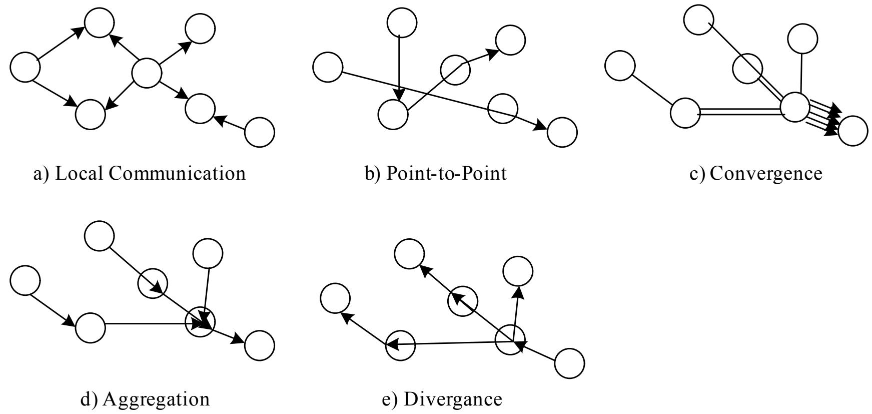

Fig. 2. The traffic patterns in WSNs.

transition and n is the number of the state-transition.

$$\mathbf{E}_{cpu} = \mathbf{E}_{cpu-state} + \mathbf{E}_{cpu-change} = \sum_{i=1}^{m} \mathbf{P}_{cpu-state}(i)\mathbf{T}_{cpu-state}(i) + \sum_{j=1}^{n} \mathbf{N}_{cpu-change}(j)\mathbf{e}_{cpu-change}(j) \quad (2)$$

On this relation, $P_{cpu\text{-}state}(i)$ is the power of state *i* that can be found from the reference manual, $T_{cpu\text{-}state}(i)$ is the time interval in state *i* which is a statistical variable. $N_{cpu\text{-}change}(j)$ is the frequency of state transition *j* and $e_{cpu\text{-}change}(j)$ is the energy consumption of one-time state transition *j*.

- *Wireless Communication Module*. The total power consumption for transmitting PT and for receiving PR, is denoted as

$$\mathbf{P}_T(d) = \mathbf{P}_{TB} + \mathbf{P}_{TRF} + \mathbf{P}_A(d) = \mathbf{P}_{T0} + \mathbf{P}_A(d) \quad (3)$$

$$\mathbf{P}_R = \mathbf{P}_{RB} + \mathbf{P}_{RRF} + \mathbf{P}_L = \mathbf{P}_{R0} \quad (4)$$

Where $P_A(d)$ is the power consumption of the power amplifier which is a function of the transmission range *d*. The $P_A(d)$, will depend on many factors including the specific hardware implementation, DC bias condition, load characteristics, operating frequency and P_A output power, P_{Tx} [26]. The PTB, PTRF, PRB, PRRF and P_L do not depend on the transmission range.

- *Power Supply Module*. The power module of the nodes is related to the manufacturer and the model of each node. For example, a wireless sensor node LOTUS and node IRIS developed by MEMSIC, are both supplied by two AA batteries, while the current draw on receive mode is 16mA and on transmit for Tx value -17dBm, -3dBm, +3dBm consumes 10mA, 13mA and 17mA respectively. On the other hand, the known node MICA2, which is also supplied by two AA batteries, on transmit with maximum power it consumes 27mA and has an average receive of 10mA. Also on the sleep mode it consumes less than 0.001 mA. A real deployment example where MICA sensors are used is presented in [27]. In this deployment a detailed study of the power requirements of the MICA node for different operations is presented.

C. Traffic Patterns in WSNs

In difference to traditional networks, the WSNs exhibit unique asymmetric traffic patterns. This is mainly faced due to the function of the WSN which is to collect data, sensor nodes persistently send their data to the base station, while the base station only occasionally sends control messages to the sensor nodes.

Moreover, the different applications can cause a wide range of traffic patterns. The traffic of WSNs can be either single hop or multi-hop. The multi-hop traffic patterns can be further divided, depending on the number of send and receive nodes, or whether the network supports in-network processing, into the following (figure 2):

- *Local Communication*. It is used to broadcast the status of a node to its neighbors. Also it is used to transmit the data between the two nodes directly.
- *Point-to-Point*. Routing. It is used to send a data packet from an arbitrary node to another arbitrary node. It is commonly used in a wireless LAN environment.
- *Convergence*. The data packets of multiple nodes are routed to a single base node. It is commonly used for data collection in WSNs.
- *Aggregation*. The data packets can be processed in the relaying nodes and the aggregate value is routed to the base node rather than the raw data.
- *Divergence*. It is used to send a command from the base node to other sensor nodes.

It is interesting to investigate the traffic patterns in WSNs along with the mobility of the nodes, as node mobility has been utilized in a few WSN applications such as healthcare monitoring. One of the first attempts on doing this is provided in [28]. However, there is still an ongoing research area that will gather great attention on the following years.

IV. Energy Efficient Route Selection Policies

Energy efficiency is a critical issue in WSNs. The existing energy-efficient routing protocols often use residual energy, transmission power, or link distance as metrics to select an optimal path. In this section, the focus is on energy-efficiency in WSNs and the route selection policies with novel metrics in order to increase path survivability of WSNs. The novel metrics result in stable network connectivity and less additional route discovery operations.

The devices used in a WSN are resource constrained, they have a low processing speed, a low storage capacity and a limited communication bandwidth. Moreover, the network has to operate for long periods of time, but the nodes are battery-powered, so the available energy resources limit their overall operation. To minimize energy consumption, most of the device components, including the radio, should be switched off most of the time. Another important characteristic is that sensor nodes have significant processing capabilities in the ensemble, but not individually. Nodes have to organize themselves, administering and managing the network all together, and this is much harder than controlling individual devices. Furthermore, changes in the physical environment, where a network is deployed, make also nodes experience wide variations in connectivity and thus influencing the networking protocols.

The main design goal of WSNs is not only to transmit data from a source to a destination, but also to increase the lifetime of the network. This can be achieved by employing energy-efficient routing protocols. Depending on the applications used, different architectures and designs have been applied in WSNs. The performance of a routing protocol depends on the architecture and design of the network, and this is a very important feature of WSNs. However, the operation of the protocol can affect the energy spent for the transmission of the data.

The main objective of current research in WSNs is to design energy-efficient nodes and protocols that could support various aspects of network operations. In 2000 and 2002, the PicoRadio project [29] at Berkeley and AMPs project [30] at MIT, respectively, focused on the energy-constrained radios and their impact on the ultra-low-power sensing and networking.

The initial efforts to develop energy-efficient sensors are mostly driven by academic institutions. However, the last decade a number of commercial efforts have also appeared (a lot of them based on some of the above academic efforts), including companies such as Crossbow, Sensoria, Worldsens, Dust Networks and Ember Corporation. These companies provide the opportunity to purchase sensor devices ready for deployment in a variety of application scenarios along with various management tools for programming, maintenance, and sensor data visualization.

In parallel to the development of the hardware of the sensors, and in order to provide energy-efficient solutions, the development of routing protocols that will require less energy, resulting in the extension of the network lifetime, is an ongoing research area. The simplest idea is to greedily switch to lower mode whenever possible. The problem is that the time and power consumption required to reach higher modes is not negligible. So, techniques and protocols that would consider energy efficiency and transmit packets through energy-efficient routing protocols and thus prolonging the lifetime of the network, are required.

Most of the energy consumption, in WSNs, is spent on three main activities: sensing, data processing and communication. All these factors are important and should be considered when developing protocols for WSNs. The communication of the sensor nodes is the major component of the energy consumption. Thus, the on-going research in WSNs is mostly concentrated on designing protocols that use the less possible energy during the communication of the nodes.

The potential task of the protocols is not only to find the lowest energy path from a source to a destination, but also to find the most efficient way to extend the network's lifetime. The continuous use of a low energy path frequently leads to energy depletion of the nodes along this path and in the worst it case may lead to network partition.

There are some terms related to the energy efficiency on WSNs that are used to evaluate the performance of the routing protocols and here are the most important ones [31]:

- *Energy per Packet*. This term is referred to the amount of the energy that is spent while sending a packet from a source to a destination.
- *Energy and Reliability.* It refers to the way that a tradeoff between different application requirements is achieved. In some applications, emergency events may justify an increased energy cost to speed up the reporting of such events or to increase the redundancy of the transmission by using several paths.
- *Network Lifetime*. There is none universally agreed definition for the network lifetime. In many cases the term network lifetime corresponds to the time when the first node exhausts its energy, or when a certain fraction of the network's nodes is dead, or even when all nodes are dead. In some other cases it may be reasonable to measure the network lifetime by application-specific parameters, such as the time when the network can no longer relay the video. However, the importance of a WSN is to be operational and able to perform its tasks during its use. In WSNs, it is important to maximize the network lifetime, which means to increase the network survivability or to prolong the battery lifetime of nodes. The common practice in networks is to use the shortest routes to transfer the packets. This could result the death of the nodes along the shortest path. Since in a WSN every node has to act as a relay in order to forward the message, if some nodes die sooner, due to the lack of energy, it is possible that other nodes will not be able to communicate any more. Hence, the network will get disconnected, the energy consumption is not balanced and the lifetime of the whole network is seriously affected. Therefore, a combination between the shortest path and the extension of the network lifetime is the most suitable routing metrics to be used in WSNs. Moreover, the lifetime of a node is effectively determined by its battery life. The main drainage of battery is due to transmitting and receiving data among nodes and the processing elements.
- *Average Energy Dissipated*. This metric is related to the network lifetime and shows the average dissipation of energy per node over time in the network as it performs various functions such as transmitting, receiving, sensing and aggregation of data.

- *Low Energy Consumption*. A low energy protocol has to consume less energy than traditional protocols. This means that a protocol that takes into consideration the remaining energy level of the nodes and selects routes that maximize the network's lifetime is considered as low energy protocol.
- *Total Number of Nodes Alive*. This metric is also related to the network lifetime. It gives an idea of the area coverage of the network over time.
- *Total Number of Data Signals Received at BS*. This metric is equivalent to the energy saved by the protocol by not transmitting continuously data packets (hello messages), which are not required.
- *Average Packet Delay*. This metric is calculated as the average one-way latency that is observed between the transmission and reception of a data packet at the sink. This metric measures the temporal accuracy of a packet.
- *Packet Delivery Ratio*. It is calculated as the ratio of the number of distinct packets received at sinks to the number originally sent from source sensors. This metric indicates the reliability of data delivery.
- *Time until the First Node Dies*. This metric indicates the duration for which all the sensor nodes on the network are alive. There are protocols in which the first node on the network runs out of energy earlier than in other protocols, but manages to keep the network operational much longer.
- *Energy Spent per Round*. This metric is related to the total amount of energy spent in routing messages in a round. It is a short-term measure designed to provide an idea of the energy efficiency of any proposed method in a particular round.
- *Idle Listening*. A sensor node that is in idle listening mode, does not send or receive data, it can still consume a substantial amount of energy. Therefore, this node should not stay in idle listening mode, but should be powered off.
- *Packet Size*. The size of a packet determines the time that a transmission will last. Therefore, it is effective in energy consumption. The packet size has to be reduced by combining several packets into one large packet or by compression.
- *Distance*. The distance between the transmitter and receiver can affect the power that is required to send and receive packets. The routing protocols can select the shortest paths between nodes and reduce energy consumption.

The selection of the energy efficient protocols in WSNs is a really critical issue and should be considered in all networks. There are several policies for energy-efficient route selection. The most known is called "Call Packing". This policy routes new calls on heavily-loaded rather than lightly-loaded links. The advantage of call packing is that it favors high-bandwidth calls; but its main disadvantage is that it calls up some links completely, and thus reducing the connectivity of the network. The load balancing policy, in contrast to call balancing, tries to spread the load evenly among the links. This policy decides to route new calls on lightly loaded paths rather than on heavily loaded ones.

A third policy, called "the min-hop policy", routes a call on the minimum-hop path that meets the energy efficiency requirements. This type of policy has traditionally been useful in energy-efficient WSNs.

The load-balancing policy is a good performing policy in all topologies, and the call packing policy is the worst in all topologies. In most cases, the difference between the load balancing and minimum-hop policies is very small. The relative performance of call packing to load balancing is worse in sparsely connected networks, as opposed to densely connected networks.

Moreover, there are schemes for multi-hop routing. Two of these schemes are compared in [32]. The first maximizes the minimum lifetime of the nodes, while the second one minimizes total energy consumption. The simulation results in [32] consider the transmission energy and the circuit energy spent in transmission, as well as the receiver energy. The comparison reveals that multihop routing is preferred by the first scheme when the ratio of transmission energy to circuit energy is low and by the second scheme when this ratio is high. In order to balance the load, the first scheme limits the range of multi-hop routing. Following, we examine some energy-efficient routing protocols.

A. Efficient Minimum-Cost Routing

Routing algorithms, which are closely associated with dynamic programming, can be based on different network analyses and graph theoretic concepts in data communication systems including maximal flow, shortest-route, and minimum-span problems. The Shortest Path routing schemes figure out the shortest path from any given node to the destination node. If the cost, instead of the link length, is associated with each link, these algorithms can also compute the minimum cost routes. These algorithms can be centralized or decentralized.

The usual way of routing in WSNs is to route packets on the minimum-cost path from the source to the destination (sink or base station). In case that the nodes generate data constantly and the bandwidth is constrained, then routing data on the minimum-cost paths can overload wireless links close to the base station. Therefore, a routing protocol must take into consideration the wireless channel bandwidth limitation, otherwise, it might route the packets over highly congested links and paths. This will lead to an increase of congestion, increased delay and packet losses, which in turn will cause retransmission of packets, and thereby increasing energy consumption.

The efficient Dijkstra algorithm, which has polynomial complexity, and the Bellman-Ford algorithm, which finds the path with the least number of hops are the two very well-known and well-defined algorithms for shortest path routing.

Following, some of the existing efficient minimum-cost routing algorithms are discussed.

1) Efficient Minimum-Cost Bandwidth-Constrained Routing (MCBCR) in WSNs: The EMCBCR routing protocol proposed in [33] at 2000, is a simple, scalable and efficient solution to the minimum cost routing problem in WSNs. It is a protocol which finds the most appropriate routes for transferring data from sensor nodes to base stations and thus reducing to the minimum the entire cost of routing, while guaranteeing that the load on each wireless link does not overrun its capacity. The protocol is derived from a combinatorial optimization problem, known as the minimum cost flow problem in the operations research literature. This protocol is highly scalable because polynomial-time minimum cost flow algorithms are used. Simulation results have shown that the proposed protocol MCBCR has good performance and achieves long network lifetime [33].

2) A Scalable Solution to Minimum-Cost Forwarding (SSMCF) in Large Sensor Networks: Fan Ye *et al.* [34] at 2001, studied the problem of minimum cost messages delivery from any given source to the interested client user (called a sink) along the minimum-cost path in a large sensor network. When the field is established, the message, that carries dynamic cost information, flows along the minimum cost path in the cost field. The intermediate nodes forward the message only if they find themselves to be on the optimal path, based on dynamic cost states. The intermediate nodes to maintain explicit forwarding path states are not required in this design. This algorithm requires only a few simple operations and scales to any network size.

Their design was based on the following three goals:

- *Optimality:* To achieve minimum cost forwarding, while the design of the most data forwarding protocols is based on a chosen optimality criterion.
- *Simplicity:* To reduce to the minimum the number of the performed operations as well as the states which are maintained at each sensor node participating in data forwarding.
- *Scalability:* The solution has to scale to large network size, since unconstrained scale is an inherent feature of a sensor network.

This approach requires constant time and space complexities at each node, and scales to large network size.

B. Minimum Network Overhead

The overhead energy is a substantial component of energy consumption at sensor nodes in a WSN. Negligence of the overhead energy in energy-efficient routing decisions might result in non-optimal energy usage. Routing algorithms should be focused on the overhead energy which is consumed, and therefore wasted, at each hop of data transmission through the wireless network. The use of shorter multi-hop links appears as a more advantageous solution, if only the transmission energy is considered as the communication cost.

However, because of other energy-dissipating activities on the sensor nodes, such as, reception of relayed messages, sensing and computation tasks, a considerable overhead energy might be consumed while forwarding a message, some dissipation models, proposed at 2002, 2005, 2008 respectively, are presented in [35], [36], [37]. Therefore, multi-hopping is sometimes a disadvantage in wireless sensor networks. Recent research has recently focused on minimizing WSNs overhead by taking into account various factors, such as, the energy consumed at sensing the environment, computing the collected information, relaying messages, and transmitting data at each hop through the WSN.

C. Challenging Factors Affecting the Energy-Efficient Routing Protocols Design Issues

WSNs, despite their innumerable applications, suffer from several restrictions concerning, mainly, limited energy deposits, limited processing power, and limited bandwidth of the wireless links connecting sensor nodes. One of the most significant design goals of WSNs is to go through data communication while trying, at the same time, to contribute to the longevity of the network and to preclude connectivity abasement through the use of aggressive energy management techniques. The design of energy-efficient routing protocols in WSNs is influenced by many factors. These factors must get over before efficient communication can be achieved in WSNs.

Here is a list of the most common factors affecting the routing protocols design [38]:

- *Node Deployment:* It is an application-dependent operation affecting the routing protocol performance, and can be either deterministic or randomized.
- *Node/Link Heterogeneity:* The existence of heterogeneous set of sensors gives rise to many technical problems related to data routing and they have to be overcome.
- *Data Reporting Model:* Data sensing, measurement and reporting in WSNs depend on the application and the time criticality of the data reporting. Data reporting can be categorized as either time-driven (continuous), event-driven, query-driven, and hybrid.
- *Energy Consumption Without Losing Accuracy:* In this case, energy-conserving mechanisms of data communication and processing are more than necessary.
- *Scalability:* WSNs routing protocols should be scalable enough to respond to events, e.g. huge increase of sensor nodes, in the environment.
- *Network Dynamics:* Mobility of sensor nodes is necessary in many applications, despite the fact that most of the network architectures assume that sensor nodes are stationary.
- *Fault Tolerance:* The overall task of the sensor network should not be affected by the failure of sensor nodes.
- *Connectivity:* The sensor nodes connectivity depends on the random distribution of nodes.
- *Transmission Media:* In a multi-hop WSN, communicating nodes are linked by a wireless medium. One approach of MAC design for sensor networks is to use TDMA-based protocols that conserve more energy compared to contention-based protocols like CSMA (e.g., IEEE 802.11).
- *Coverage:* In WSNs, a given sensor's view of the environment is limited both in range and in accuracy; it can only cover a limited physical area of the environment.
- *Quality of Service:* Data should be delivered within a certain period of time. However, in a good number of applications, conservation of energy, which is directly related to network lifetime, is considered relatively more important than the quality of data sent. Hence, energy-aware routing protocols are required to capture this requirement.
- *Data Aggregation:* Data aggregation is the combination

of data from different sources according to a certain aggregation function, e.g. duplicate suppression.

V. Routing Techniques in WSNs - Classification

Routing in WSNs may be more demanding than other wireless networks, like mobile ad-hoc networks or cellular networks for the following reasons:

- Sensor nodes demand careful resource management because of their severe constraints in energy, processing and storage capacities.
- Almost all applications of WSNs require the flow of sensed data from multiple sources to a particular base station.
- Design requirements of a WSN depend on the application, because WSNs are application-specific.
- The nodes in WSNs are mostly stationary after their deployment which results in predictable and non-frequent topological changes.
- Data collection is, under normal conditions, based on the location, therefore, position awareness of sensor nodes is important. The position of the sensor nodes is detected by using methods based on triangulation e.g. radio strength from a few known points. For the time being, it is possible to use Global Positioning System (GPS) hardware for this purpose. Moreover, it is favorable to have solutions independent of GPS for the location problem in WSNs [39].
- In WSNs, there is a high probability that collected data may present some undesirable redundancy which is necessary to be exploited by the routing protocols to improve energy and bandwidth utilization.

Because of all these disparities, several new routing mechanisms have been developed and proposed to solve the routing problem in WSNs. These routing mechanisms have taken into account the inherent features of WSNs along with the application and architecture requirements. A high efficient routing scheme will offer significant power cost reductions and will improve network longevity. Finding and maintaining routes in WSNs is a major issue since energy constraints and unexpected changes in node status (e.g., inefficiency or failure) give rise to frequent and unforeseen topological alterations. Routing techniques proposed in the literature for WSNs employ some well-known routing tactics, suitable for WSNs, to minimize energy consumption. In this paper, we expand the classification initially proposed by Al-Karaki in [3]. Thus, the routing protocols can be classified into four main schemes: Network Structure Scheme, Communication Model Scheme, Topology Based Scheme and Reliable Routing Scheme (figure 3). Also, the presented classification can be viewed as four different approaches to classify the protocols, rather than four parallel classes.

A. Network Structure

The structure of a network can be classified according to node uniformity. The nodes in some networks are considered to be deployed uniformly and be equal to each other, or other networks make distinctions between different nodes. More specifically, the main attribute of the routing protocols belonging to this category is the way that the nodes are connected and they route the information based on the networks architecture. This addresses two types of node deployments, nodes with the same level of connection and nodes with different hierarchies. Therefore, the schemes on this category can be further classified as follows:

- *Flat Protocols:* All the nodes in the network play the same role. Flat network architecture presents several advantages, including minimal overhead to maintain the infrastructure between communicating nodes.
- *Hierarchical Protocols:* The routing protocols on this scheme impose a structure on the network to achieve energy efficiency, stability, and scalability. In this class of protocols, network nodes are organized in clusters in which a node with higher residual energy, for example, assumes the role of a cluster head. The cluster head is responsible for coordinating activities within the cluster and forwarding information between clusters. Clustering has the potential to reduce energy consumption and extend the lifetime of the network. They have high delivery ratio and scalability and can balance the energy consumption. The nodes around the base station or cluster head will deplete their energy sources faster than the other nodes. Network disconnectivity is a problem where certain sections of the network can become unreachable. If there is only one node connecting a part of the network to the rest and fails, then this section would cut off from the rest of the network.

B. Communication Model

The Communication Model adapted in a routing protocol is related to the way that the main operation of the protocol is followed in order to route packets in the network. The protocols of this category can deliver more data for a given amount of energy. Also in terms of dissemination rate and energy usage the protocols of this class can perform close the theoretical optimum in point-to-point and broadcast networks. The problem with Communication Model protocols is that they do not have high delivery ratio for the data that are sent to a destination. Thus, they do not guarantee the delivery of data.

The protocols on this scheme can be classified as follows:

- *Query-Based Protocols:* The destination nodes propagate a query for data (sensing task) from a node through the network and a node having this data sends the data, which matches the query, back to the node, which in turn initiates the query.
- *Coherent and Non-Coherent-Based Protocols:* In coherent routing, the data is forwarded to aggregators after a minimum processing. In non-coherent data processing routing, nodes locally process the raw data before it is sent to other nodes for further processing.
- *Negotiation-Based Protocols:* They use meta-data negotiations to reduce redundant transmissions in the network.

C. Topology Based Protocols

Topology-based protocols use the principle that every node in a network maintains topology information and that the main

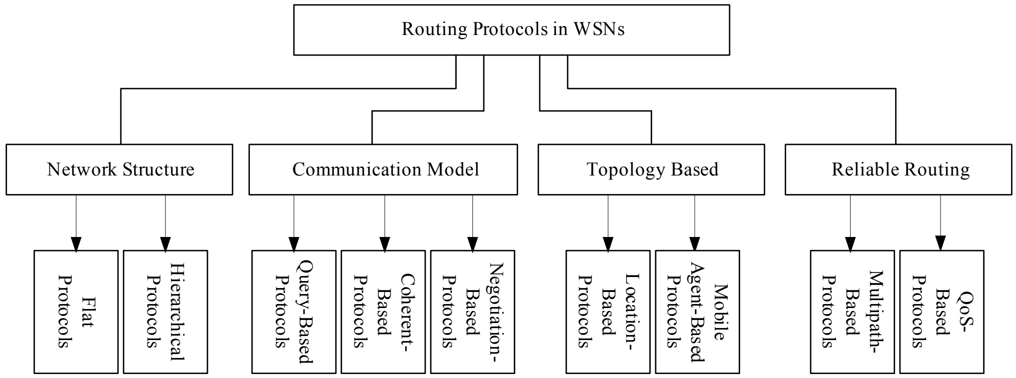

Fig. 3. Classification of routing protocols in WSNs.

process of the protocol operation is based on the topology of the network. The protocols on this scheme can be further classified as follows:

- *Location-based Protocols:* They take advantage of the position information in order to relay the received data to only certain regions and not to the whole WSN. The protocols of this class can find a path from a source to a destination and minimize the energy consumption of the sensor nodes. They have limited scalability in case that the nodes are mobile. Also a node must know or learn about the locations of other nodes.
- *Mobile Agent-based Protocols:* The mobile agent protocols are used in WSNs to route data from the sensed area to the destination and this is an interesting sector. The mobile agent systems have as a main component a mobile agent, which migrates among the nodes of a network to perform a task autonomously and intelligently, based on the environment conditions. Mobile agent protocols may provide to the network extra flexibility, as well as new capabilities in contrast to the conventional WSN operations that are based on the client-server computing model.

D. Reliable Routing Protocols

The protocols on this scheme are more resilient to route failures either by achieving load balancing routes or by satisfying certain QoS metrics, as delay, energy, and bandwidth. The nodes of the network may suffer from the overhead of maintaining routing tables and the QoS metrics at each sensor node. The protocols are classified as follows:

- *Multipath-Based Protocols:* They achieve load balancing and are more resilient to route failures.
- *QoS-Based Protocols:* The network has to balance between energy consumption and data quality. Whenever a sink requests for data from the sensed nodes in the network, the transmission has to meet specific level of quality.

E. Comparison of the Routing Categories

The main attribute of the protocols belonging to the Network Structure is the way the nodes are connected and exerts an influence on the routing of the information. For example, in a hierarchical structure the lower level nodes transit the information to upper lever nodes, resulting to a balanced energy structure of the network.

However, in the Communication Model, the main characteristic of the protocols is the way that a routing decision is made up, without mainly based on the structure of the network. Thus, a well defined technique, for example the negotiation of the nodes with each other before transmitting data is considered, to route the information from the source to the destination.

Moreover, there are some protocols that apart from the Communication Model that they use for the data transmission, they take into consideration the topology of the network. They operate without any routing tables, by periodically transmitting HELLO messages to allow neighbors to know their positions.

A set of these protocol use mobile agents in order to move the data processing elements to the location of the sensed data may reduce the energy expenditures of the nodes. Finally, there is a category of protocols that apart of the energy efficiency they tend to provide reliable routing of the data. They achieve this either by providing multiple path from the source to the destination or by applying QoS on their main routing activity.

It should be noted that some of the protocols described below, may fall to one or more of the above routing categories, but only discussed once to category that they mainly fit.

Also, the Tables II, III, IV, V, VI, VII, VIII, IX and X summarize the advantages and disadvantages of each protocol described in the paper. Moreover, some metrics for each protocol, that may be useful for the reader, are presented. These metrics are the following:

- *Scalability.* The scalability refers to the ability of the protocol to handle growing amounts of work in a graceful manner. This means that the performance of the protocol will be stable for both small and large networks.
- *Mobility.* The mobility refers to the ability of the protocol to work in case that the nodes are mobile.
- *Route Metric.* The route metric refers to the form of routing which attempts to send packets of data over a network in such a way that the path taken from the sending node to the recipient node is the most efficient. Thus, this path may be the shortest path, which minimizes the energy consumed by nodes, or the path that maximizes

the network's lifetime and takes into consideration the remaining energy of the nodes.

- *Periodic Message Type*. The periodic message type is the messages that the nodes exchange in order to have an up to date view of the nodes that are alive on the network.
- *Robust*. A protocol that performs well even in cases of unordinary conditions, for example in sudden changes of the topology of the network, is considered as robust protocol.

VI. Network Structure Scheme

A. Flat Networks Routing Protocols

In general, Flat Networks Routing Protocols for WSNs can be classified, according to the routing strategy, into three main different categories: Pro-active protocols, Re-active protocols and Hybrid protocols [40]. All these protocols differ in many ways and do not present the same characteristics, although they have been designed for the same underlying network.

According to another classification found in the literature, Flat Networks routing protocols for WSNs can be categorized as Table-driven and Source-initiated (or Demand-driven) respectively (Pro-active and Re-active routing protocols). The following sections discuss these protocols and classify them according to their characteristics.

1) Pro-active or Table-Driven Routing Protocols: Pro-active (or table-driven routing protocols) work in a way similar to wired networks: based on the periodically exchanging of routing information between the different nodes, each node builds its own routing table which can be used to find a path to a destination. Each node is required to maintain one or maybe more tables by storing routing information. They also respond to any changes in network topology by sending updates throughout the wireless network and thus maintaining a consistent network view. Therefore, when a path to some destination is needed at a node, or a packet needs to be forwarded, the route is already known and there is no extra delay due to route discovery. However, keeping the information up-to-date, it may require a lot of bandwidth, which is sparse, and extra battery power, which is limited in WSNs. The information may still be out-of-date. Following, some of the existing table-driven routing protocols are discussed.

a) Wireless Routing Protocol (WRP): The WRP protocol is a table-based routing protocol, which inherits the properties of the distributed Bellman-Ford algorithm [41]. The WEP maintains an up-to-date view of the network by using a set of tables to maintain more accurate information. The tables that are maintained by a node are the following ones: Distance Table (DT), Routing Table (RT), Link Cost Table (LCT), and a Message Retransmission List (MRL).

Each entry of the MRL contains the following:

- A sequence number of the update message,
- A retransmission counter,
- An acknowledgement-required flag vector with one entry per neighbor and
- A list of updates sent in the update message. Mobile nodes inform each other of any link changes by means of update messages.

An update message is transmitted only among neighboring nodes and contains a list of updates (such as, the destination, the distance to the destination, and the forerunner of the destination) and a list of responses indicating which mobile nodes should acknowledge the updates. In the case of the loss of a link between any two nodes, the nodes transmit update messages to their neighbors. Following, the neighbors change their distance table entries and check for new paths among other nodes. Any new paths are relayed back to the original nodes so that they can update their tables accordingly.

In WRP, each node is focused on performing consistency checks of predecessor information reported by all its neighbors. This can minimize looping situations and can provide faster route convergence when a link failure event occurs. In general, WRP has fast convergence and involves few table updates. But it demands large memory and great processing power from nodes in the WSN, due to the complexity of maintenance of multiple tables. Thus, it suffers from limited scalability and is not suitable for large mobile networks.

b) The Topology Dissemination Based on Reverse-Path Forwarding Protocol (TBRPF): The TBRPF protocol transmits only the differences between the previous network state and the current network state [42], [43]. This results in smaller routing messages, that can be sent more frequently. This means that the routing tables of the nodes are more up-to-date. TBRPF protocol applies the concept of reverse-path forwarding to broadcast link-state updates in the reverse direction along the spanning tree formed by the minimum-hop paths from all sensor nodes to the source of the update. The information received through these broadcast trees can be used to compute the minimum-hop paths that form the trees themselves. Since minimum-hop paths have been computed, each source node broadcasts link-state updates for its outgoing links along a minimum-hop tree rooted at the source and a separate broadcast tree is created for each source.

The protocol stores the following information at each node of the network:

- A topology table, consisting of all link-states stored at the node and
- A list of neighbor nodes
- For each node: a parent, a list of children and the sequence number of the most recent link-state update.

The main idea in TBRPF is to broadcast topology updates in reverse direction along this tree. Meanwhile, modifying is based on the new topology information, received along the tree. The broadcast of a link-state update originated at a source is accepted by another node if it is received from the parent of that node and if it has a larger sequence number than the corresponding link-state entry in the topology table. The topology table is updated and then forwarded to all children of the node only if the link-state update is accepted.

The properties of TBRPF Protocol are:

- It is a pro-active protocol
- It uses a minimum-hop spanning tree to broadcast link-state updates
- The minimum-hop spanning tree is rooted to the update of the source
- The minimum-hop tree is maintained with info received by the tree itself

- Each node is provided with full topology information
- Multiple paths to destinations are possible

Periodic topology updates are sent less frequently than other protocols of this category. These updates are large messages which ensure that each node eventually can learn the whole topology. The TBRPF is not suitable for networks with low mobility (e.g. stationary battery-powered sensor networks). The lack of loop-freedom causes packet loss and waste of bandwidth.

2) Re-active or Source-Initiated On-Demand Routing Protocols: A different approach from table-driven routing is the source-initiated on-demand routing. Unlike pro-active (table-driven) routing protocols, re-active protocols (on-demand protocols) only start a route discovery procedure when needed [44]. When a route from a source to a destination is needed, a kind of global search procedure is started. This task does not request the constant updates to be sent through the network, as in pro-active protocols, but this process does cause delays, since the requested routes are not available and have to be found. In some cases, the desired routes are still in the route cache maintained by the sensor nodes. When this is the case, there is no additional delay since routes do not have to be discovered. The whole process is completed as soon as a route is found or all possible route combinations have been examined.

Following, some of the existing on-demand routing protocols are discussed.

a) Temporarily Ordered Routing Algorithm (TORA): The TORA Algorithm is a highly adaptive loop-free distributed routing algorithm [45]. It is based on the concept of link reversal. In TORA, each node i knows its own height and the height of each directly connected neighbor j [46]. Thus, the control messages are localized to a very small set of nodes near the occurrence of a topological change in order for this protocol to provide energy efficiency. It marks each link as upstream or downstream based on whether the height of its neighbor is greater or less than its own height. Nodes are assigned heights based on their location with respect to the destination. When a node gets a data packet, it always forwards it into the downstream direction (figure 4). Thus packets find their way to the destination flowing down from tall nodes located far away from the destination to short nodes located near it.

The main advantage of TORA is that it was designed to minimize the communication overhead associated with adapting to network topological changes and thus, to minimize the energy consumption. In addition it supports multiple routes and multicast. However, TORA does not incorporate multicast into its basic operation.

b) Gossiping: Gossiping and broadcasting are two problems of information dissemination described for a group of individuals connected by means of a communication network [47]. In gossiping, every person in the network knows a unique item of information and needs to communicate it to everyone else. In broadcasting, one individual has an item of information which needs to be communicated to everyone else. Actually, gossiping is a derivative of flooding where nodes do not broadcast but send the incoming packets to a randomly selected neighbor. Although this approach avoids the implosion problem by just having one copy of a message at any node, it takes long to propagate the message to all sensor nodes in the network.

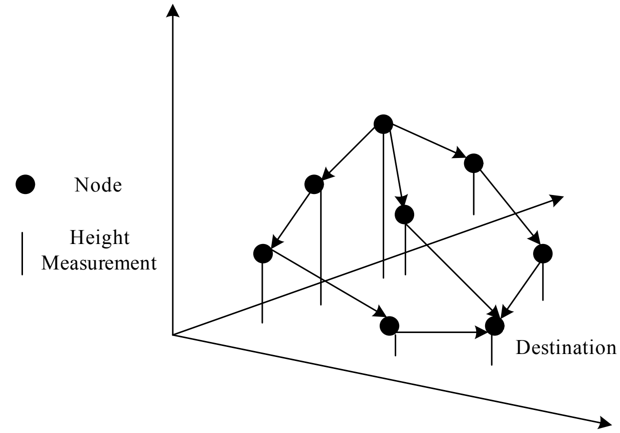

Fig. 4. The TORA is always forwards packets into the downstream direction (redrawn from [46]).

c) Flooding: Flooding is an old and very simple technique which can be also used for routing in WSNs [48]. In flooding, copies of incoming packets are sent by every link except the one by which the packets arrived. This procedure generates an enormous amount of superfluous traffic. Flooding is an extremely robust technique but as long as there is a route from source to destination the delivery of the packet is guaranteed.

Flooding is a reactive technique, and does not require costly topology maintenance and complex route discovery algorithms.

However, it has several drawbacks, which are:

- *Implosion:* Implosion is a situation where duplicated messages are broadcasted to the same node.
- *Overlay:* If two nodes share the same under observation region, both of them may sense the same stimuli at the same time. As a result, neighbor nodes receive duplicated messages.
- *Resource blindness:* The flooding protocol does not take into consideration all the available energy resources. An energy resource-aware protocol must take into account the amount of energy which is available to them all the time.

Flooding has two interesting characteristics which arise from the fact that all possible routes are tried:

- As long as there is a route from source to destination, the delivery of the packet is guaranteed.
- One copy of the packet will arrive by the quickest possible route.

Flooding is an extremely robust technique and would be particularly suitable for a *battlefield* situation. The second property might be useful for *route learning*.

Moreover, flooding consumes much energy, as for each data packet, all the nodes that are in the broadcast domain will receive packets that they will forward it to their neighbors. Thus, they require a large amount of power that causes a prohibitively short network lifetime.

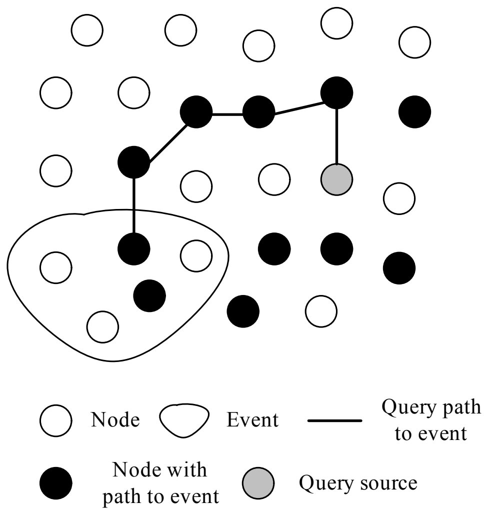

Fig. 5. Rumor Routing Protocol (redrawn from [50]).

There have been some protocols developed that use flooding as a part of their routing [49].

d) Rumor Routing (RR): The Rumor Routing is a compromise between flooding queries and flooding event notifications [50]. The main idea of this protocol is to create paths that lead to each event (figure 5), unlike event flooding which creates a network-wide gradient field. Thus, in case that a query is generated it can be then sent on a random walk until it finds the event path, instead of flooding it throughout the network. As soon as the event path is discovered it can be further routed directly to the event. On the other hand, if the path cannot be found, the application can try re-submitting the query or flooding it.

The Rumor Routing can be a good method for delivering queries to events in large networks according to a wide range of conditions (energy requirements lower than the alternatives). It is designed to be tunable to different application requirements, while it can be adjusted to support different query to event ratios, successful delivery rates, and route repair. Furthermore, it is able to handle node failure gracefully, degrading its delivery rate linearly with the number of failed nodes.

e) Energy-aware Temporarily Ordered Routing Algorithm (E-TORA): The E-TORA is an alteration of TORA and its main focus is to minimize the energy consumption of the nodes [51]. The classic TORA chooses the routes with the least hops as long as the network topology doesn't change. This may cause to the nodes that are on the main route heavy load. Also if some routes repeatedly include the same node, the node will run out of its energy much earlier than the other nodes. Thus, the use of nodes in the shorter path without considering their power leads to the decrease of the network lifetime.

Thus, E-TORA was proposed in [51] to solve this problem. E-TORA takes into consideration the level of power of each node and avoids using nodes with low energy. In addition, the energy consumption of nodes is balanced in order to avoid that some nodes exhaust their energy earlier if they are used too frequently.

In case that a node with no directed links and with a route-required flag requires a route to the destination, it broadcasts a QUERY packet and sets its route-required flag. When a node i receives a QUERY it reacts as follows:

- If node *i* has no downstream links and its route-required flag is un-set, it re-broadcasts the QUERY packet and sets its route-required flag.
- If node *i* has no downstream links and the route-required flag is set, it discards the QUERY packet.

Thus, E-TORA takes into consideration the energy left on the nodes in order to use nodes with more power and extends the lifetime of the network.

3) Comparison between Pro-active and Re-active Protocols: The main differences between pro-active and re-active protocols may be summarized as follows [52], [53]:

- Proactive protocols require a lot of routing information and maintain routing information independently of the need for communication. Whereas, reactive protocols are on demand and require less amount of routing information for each node and thus less energy consumption for the sensor nodes.
- In proactive protocols there is no latency in route discovery, so they are suitable for real time traffic. In reactive protocols there is a delay due to route discovery, which is called route acquisition delay which may not be appropriate for real time communication.
- Pro-active protocols waste bandwidth and energy to periodic updates in comparison to reactive protocols that do not require periodic updating and so they save energy and bandwidth during inactivity.
- The proactive protocols update routes and tables continuously. In reactive protocols a route can be found on demand.
- Proactive protocols need to obtain and maintain the routing information for all the nodes in a network. They require a large capacity to keep network information current. In reactive protocols intermediate nodes do not have to make routing decisions. There is no need to have information about nodes.
- Proactive protocols send update messages throughout the network periodically or when the topology changes. There is no need to send the update message when topology changes in case of reactive protocol.
- Proactive protocols are good for heavy loads but not good enough for light loads while reactive protocols are good for light loads and collapse during large loads.
- Proactive protocols are never bursty but reactive protocols can be bursty as there is congestion during high activity.
- If routing information changes frequently, then the proactive protocols would not exert any impact on the packet delivery, but as far as reactive protocols concerns, if routing information changes frequently, as this is the obvious case in MANETs, and if route discoveries are needed for those changed routes, then reactive protocols may result in a large volume of messaging overhead, since route recoveries require a global broadcast on demand.

In Table I, a comparison between Pro-active and Re-active Protocols is presented.

TABLE I
COMPARISON BETWEEN PRO-ACTIVE AND RE-ACTIVE PROTOCOLS

	Pro-active Protocols	**Re-active Protocols**
On demand protocols		X
Update routes continuously	X	
Route acquisition delay		X
Periodic updating	X	
Maintain the routing information for all nodes in the network	X	
Send update messages when the topology changes		X
Proper for heavy loads	X	
Bursty		X
Result in a large volume of messaging overhead	X	

The availability of routing information is a key advantage of table-driven routing protocols, because faster routing decisions - and consequently less delay in route setup process - can be made, than in the case of on-demand routing protocols [54]. On the other hand, this important advantage of table-driven routing protocols requires periodic routing updates to keep the routing tables up-to-date, which in turn costs higher signaling traffic than the required on-demand routing protocols. Moreover, this makes the sensor nodes to spend more energy of their periodic update messages. However, for other functions like path reconfiguration after link failures, there are variations between the protocols of each class. For example, TORA is an on-demand routing protocol. At the same time, TORA uses local route maintenance schemes which reduce signaling overhead.

4) Hybrid Routing Protocols: Hybrid protocols combine the advantages of both pro-active and re-active routing protocols; they locally use pro-active routing and inter-locally use re-active routing. This is partly based on the following two assumptions: a) Most communication in WSNs takes place between nodes that are close to each other, and b) Changes in topology are only important if they happen in the vicinity of a node. When a link fails or a node disappears on the other side of the network, it affects only the local neighborhoods; nodes on the other side of the network are not affected.

a) Zone Routing Protocol (ZRP): The ZRP is a hybrid routing scheme that combines not only the advantages of pro-active but also the advantages of re-active protocols in a hybrid scheme [55]. According to this scheme, the network is divided into zones and the zones proactively maintain the topology of the zone, however, there is no periodic exchange of the topology change throughout the network. The neighboring nodes are informed only at periodic intervals. If there is need for ZRP to search for a particular node, then it initiates the route query and broadcasts it to the neighboring sensor nodes. Whenever a sensor node's link state is changed, a notice will be sent as far as zone radius hops away (i.e., the zone of this node). Hence, a node always knows how to reach another node in the same zone. This also limits the number of updates triggered by a link state change. On the other hand, the inter-zone routing uses a scheme, when a node needs a route to a node outside its zone; it performs a border casting by sending a RREQ (Route REQuest) to each node on the "border" of this zone. On receiving such a packet at a border node, it first checks its intra-zone routing table for existence of a route to the requested destination node. If so, a RREP (Route REPly) can be sent; otherwise, it performs another border casting in its zone. This is repeated until a route is found.

The main advantage of ZRP is that it requires a small amount of routing information at each node, so it produces much less routing traffic than a pure reactive or proactive scheme [56]. However, it experiences excessive delays and overhead due to many useless control packets that are sent in the network. Therefore, the load of network is increased resulting in a decrease of network performance.

In Table II, Flat Routing Schemes Comparison is presented. The protocols TBRPD, TORA, Gossiping, E-TORA and ZRP are efficient in case that the nodes are moving. Moreover, protocols TBRPF, RR and ZRP are really robust, mainly due to the fact that they use periodic hello messages to discover live nodes in the network. On the other hand, E-TORA and ZRP do not use the shortest path as the other protocols, but they select the best route based on energy of the nodes. Moreover, TORA, Gossiping, RR and E-TORA are more scalable than the other protocols of this scheme.

Finally, in Flat Protocols a few protocols can partially be included, that are mainly classified and described in details in the categories on the below. These protocols are: OGF and HGR.

B. Hierarchical Networks Routing Protocols

Unlike flat protocols, where each node has its unique global address and all the nodes are peers, in hierarchical protocols nodes are grouped into clusters. Every cluster has a cluster head the election of which is based on different election algorithms. The cluster heads are used for higher level communication, reducing the traffic overhead. Clustering may be extended to more than just two levels having the same concepts of communication in every level. The use of routing hierarchy has a lot of advantages. It reduces the size of routing tables providing better scalability.

1) Low-Energy Adaptive Clustering Hierarchy (LEACH): The LEACH protocol is a hierarchical protocol in which most nodes transmit to cluster heads [57], [58].

The operation of the LEACH protocol consists of two phases:

- The Setup Phase. In the Setup Phase, the clusters are organized and the cluster heads are selected. The cluster heads aggregate, compress and forward the data to the base station. Each node determines whether it will become a cluster head, in this round, by using a stochastic algorithm at each round. If a node becomes a cluster head for one time, it cannot become cluster head again for P rounds, where P is the desired percentage of cluster heads. Thereafter, the probability of a node to become a cluster head in each round is 1/P. This rotation of cluster heads leads to a balanced energy consumption to all the nodes and hence to a longer lifetime of the network.
- The Steady State Phase. In the Steady State Phase, the data is sent to the base station. The duration of the steady state phase is longer than the duration of the setup phase

TABLE II
FLAT ROUTING SCHEMES COMPARISON

Scheme	Advantages	Drawbacks	Scalability	Mobility	Route Metric	Periodic Message Type	Robust
WRP	It eliminates looping situations and provides faster route convergence when a link failure occurs.	It is not suitable for highly dynamic and also for a very large wireless network.	Limited	Limited	Shortest Path	Table exchange	Low
TBRPF	Periodic topology updates are sent less frequently than other protocols of this category	It is not suitable for networks with low mobility	Limited	Good	Shortest Path	Hello messages	Good
TORA	It minimizes the communication overhead, supports multiple routes and multicast	It does not incorporate multicast into its basic operation	Good	Good	Shortest Path	IMEP Control	Low
Gossiping	It avoids the implosion problem and enquire very little or no structure to operate	It takes long to propagate the message to all sensor nodes in the network	Good	Good	Random	None	Good
Flooding	It is a simple and robust technique	It may broadcast duplicated messages are to the same node	Limited	Low	Shortest Path	None	Good
RR	It is able to handle node failure gracefully, degrading its delivery rate linearly with the number of failed nodes	It may deliver duplicated messages to the same node	Good	Low	Shortest Path	Hello messages	Good
E-TORA	It minimizes the energy consumption and results to the balance of the energy consumption of nodes	It does not incorporate multicast into its basic operation	Good	Good	The best route	IMEP Control	Low
ZRP	It produces low routing traffic	It experiences excessive delays	Limited	Good	The best route	Hello messages	Good

in order to minimize overhead. Moreover, each node that is not a cluster head selects the closest cluster head and joins that cluster. After that the cluster head creates a schedule for each node in its cluster to transmit its data.

The main advantage of LEACH is that it outperforms conventional communication protocols, in terms of energy dissipation, ease of configuration, and system lifetime/quality of the network [59]. Providing such a low energy, wireless distributed protocol will help pave the way in a WSN. However, LEACH uses single-hop routing where each node can transmit directly to the cluster-head and the sink. Therefore, it is not recommended for networks that are deployed in large regions. Furthermore, the dynamic clustering may results to extra overhead, e.g. head changes, advertisements etc., which may diminish the gain in energy consumption.

2) Low-Energy Adaptive Clustering Hierarchy Centralized (LEACH-C): The LEACH-C utilizes the base station for cluster formation, unlike LEACH where nodes self-configure themselves into clusters [60]. Initially in the LEACH-C, the Base Station (BS) receives information regarding the location and energy level of each node in the network. After that, using this information, the BS finds a predetermined number of cluster heads and configures the network into clusters. The cluster groupings are chosen to minimize the energy required for non-cluster-head nodes to transmit their data to their respective cluster heads.

The improvements of this algorithm compared to LEACH are the following:

- The BS utilizes its global knowledge of the network to produce clusters that require less energy for data transmission.
- Unlike LEACH where the number of cluster heads varies from round to round due to the lack of global coordination among nodes, in LEACH-C the number of cluster heads in each round equals a predetermined optimal value.

3) Power-Efficient Gathering in Sensor Information Systems (PEGASIS): The PEGASIS protocol is a chain-based protocol and an improvement of the LEACH [61]. In PEGASIS each node communicates only with a nearby neighbor in order to send and receive data. It takes turns transmitting to the base station, thus reducing the amount of energy spent per round. The nodes are organized in such a way as to form a chain, which can either be accomplished by the sensor nodes themselves, using a greedy algorithm starting from some node, or the BS can compute this chain and broadcast it to all the sensor nodes.

In [61] a simulation is performed in a network that has 100-random located nodes. The BS is placed at a remote distance from all the other nodes. Thus, for a 50m x 50m plot, the BS is located at (25, 150) so that the BS is at least 100m far away from the closest sensor node. In order to construct the chain, it is assumed that all nodes have global knowledge of the network and that a greedy algorithm is employed. Thus, the construction of the chain will start from the far away node to the closer node. If a node dies, the chain is reconstructed in the same manner to bypass the dead node.

In general, the PEGASIS protocol presents twice or more performance in comparison with the LEACH protocol [62], [63]. However, the PEGASIS protocol causes the redundant data transmission since one of the nodes on the chain has been selected. Unlike LEACH, the transmitting distance for most of the nodes is reduced in PEGASIS. Experimental results show that PEGASIS provides improvement by factor 2 compared to LEACH protocol for 50m x 50m network and improvement by factor 3 for 100m x 100m network. The PEGASIS protocol, however, has a critical problem that is the redundant transmission of the data. The cause of this problem is that there is no consideration of the base station's location about the energy of nodes when one of nodes is selected as the head node.

4) Threshold sensitive Energy Efficient sensor Network protocol (TEEN): The TEEN is a hierarchical protocol designed for the conditions like sudden changes in the sensed attributes such as temperature [64]. The responsiveness is important for time-critical applications, in which the network is operated in a reactive mode. The sensor network architecture in TEEN is based on a hierarchical grouping where closer nodes form clusters and this process goes on the second level until the sink is reached.

In this scheme the cluster-head broadcasts to its members the Hard Threshold (HT) and the Soft Threshold (ST). The HT is a threshold value for the sensed attribute. It is the absolute value of the attribute beyond which, the node sensing this value must switch on its transmitter and report to its cluster head. The ST is a small change in the value of the sensed attribute which triggers the node to switch on its transmitter and transmit. The nodes sense their environment continuously. The first time a parameter from the attribute set reaches its hard threshold value, the node switches on its transmitter and sends the sensed data. The sensed value is stored in an internal variable in the node, called the sensed value (SV).

The main advantage of TEEN is that it works well in the conditions like sudden changes in the sensed attributes such as temperature. On the other hand, in large area networks and when the number of layers in the hierarchy is small, TEEN tends to consume a lot of energy, because of long distance transmissions. Moreover, when the number of layers increases, the transmissions become shorter and overhead in the setup phase as well as the operation of the network exist.

5) Adaptive Threshold sensitive Energy Efficient sensor Network (APTEEN): The APTEEN is an improvement of TEEN and aims at both capturing periodic data collections and reacting to time-critical events [65]. As soon as the base station forms the clusters, the cluster heads broadcast the attributes, the threshold values and the transmission schedule to all nodes. After that the cluster heads perform data aggregation, which has as a result to save energy.

The main advantage of APTEEN, compared to TEEN, is that nodes consume lees energy. However, the main drawbacks of APTEEN are the complexity and that it results in longer delay times.

6) Virtual Grid Architecture Routing (VGA): The VGA combines data aggregation and in-network processing to achieve energy efficiency and maximization of network lifetime [66]. The overall scheme can be divided into two phases, clustering and routing of aggregated data. In the clustering phase, sensors are arranged in a fixed topology as most of the applications require stationary sensors. Inside each cluster a cluster-head, known as local aggregator, performs aggregation. A subset of this Local Aggregators (LA) is selected to perform global or in-cluster aggregation and its members are known as master aggregator (MA). In the data aggregation phase, some heuristic are proposed which may give simple, efficient and near optimal solution. An example of a heuristic is that LA nodes form groups which may be overlapping. Thus, the reading of members in a group can be correlated.

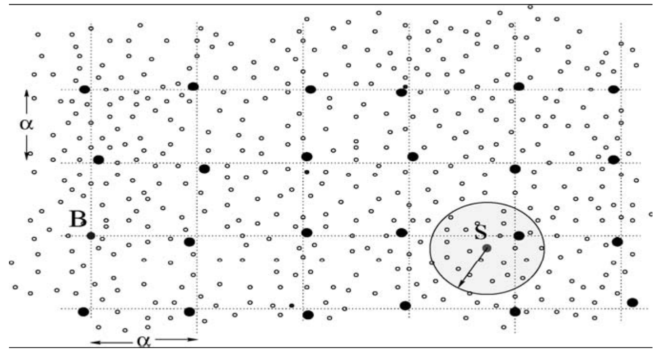

Fig. 6. One source B and one sink S (redrawn from [67]).

The main advantage of this protocol is that it may achieve energy efficiency and maximization of network lifetime, but the problem of optimal selection of local aggregators as master aggregators is NP-hard problem.

7) Two-Tier Data Dissemination (TTDD): The TTDD assumes that the sensor nodes are stationary and location aware and sinks are allowed to change their location dynamically [67]. At the time that an event is sensed by nearby sensors, one of them becomes the source that will generate data reports. After that the virtual grid structure is built, initiated by source node and chooses itself as a start crossing point of a grid. It sends a data announcement message to its four different adjacent crossing points using greedy geographical forwarding. The message only stops once it reaches to a node that is closest to the crossing point. This process continues until the message reaches boundary of the network.

In figure 6, an example is presented for the construction of the grid. In this case, one source B and one sink S and a two-dimensional sensor field are considered. The source B divides the field into a grid of cells. Each cell is an x square. A source itself is at one crossing point of the grid. It propagates data announcements to reach all other crossings.

The TTDD can be used for multiple mobile sinks in a field of stationary sensor nodes. The main drawback is that each source node builds a virtual grid structure of dissemination points to supply data to mobile sinks.

8) Base-Station Controlled Dynamic Clustering Protocol (BCDCP): The BCDCP sets up clusters based on the main idea that they will be balanced [68]. In order to achieve this, the base station, before constructing the routing path, receives information on the current energy status from all the nodes in the network. Based on this feedback, the base station first computes the average energy level of all the nodes. Then the base station chooses a set of nodes whose energy levels are above the average value.

In addition to the above, at each cluster, the head clusters are serve an approximately equal number of member nodes between each others in order to achieve the following:

- avoid cluster head overload,
- uniform placement of cluster heads throughout the whole sensor field and

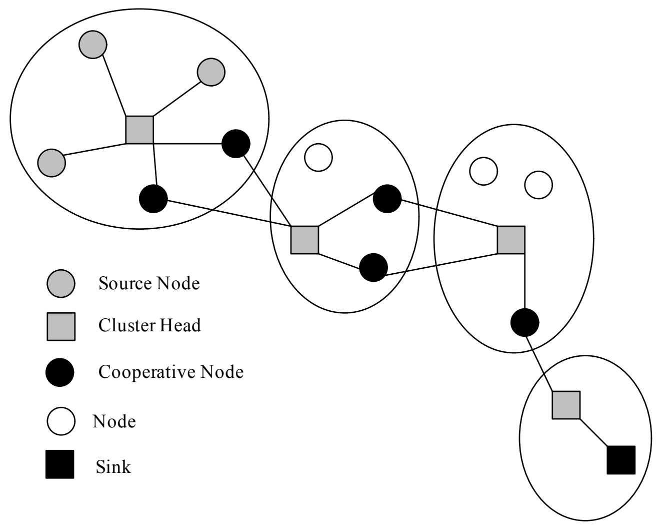

Fig. 7. Multihop virtual MIMO protocol (redrawn from [69]).

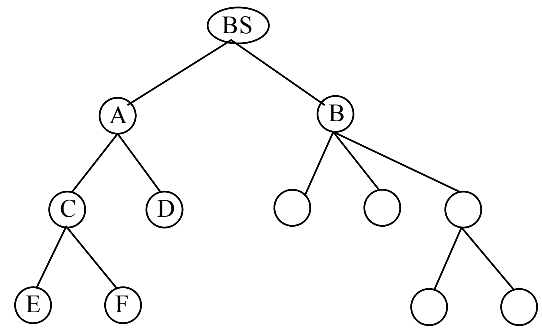

Fig. 8. A three-level cluster hierarchy (redrawn from [71]).

- utilize a clusterhead-to-clusterhead (CH-to-CH) routing to transfer the data to the base station.

Also, in the BCDCP the base station is considered to be a high-energy node with a large amount of energy supply.

9) Multihop Virtual Multiple Input Multiple Output (MIMO): In the Multihop Virtual MIMO the data are collected by multiple source nodes and transmitted to a remote sink by multiple hops [69]. The sensor nodes are organized into clusters (figure 7). The cluster head broadcasts the data to the cluster nodes that belong to the specific cluster. An Additive White Gaussian Noise channel (a channel model in which the only impairment to communication is a linear addition of wideband or white noise with a constant spectral density expressed as watts per hertz of bandwidth and a Gaussian distribution of amplitude) with a squared power path loss is assumed in such a transmission due to the short intracluster transmission range. Next, the cluster nodes encode and transmit the data to the cluster head in the next hop according to the orthogonal Space-Time Block Code (STBC).

In order to improve the energy saving performance, the Multihop Virtual MIMO presents that the average attenuation of the channel between each cluster node and cluster head can be estimated during the formation of the clusters, so it uses an equal Signal to Noise Ratio (SNR) policy to allocate the transmit power due to its spectral efficiency and simplicity.

10) Hierarchical Power Aware Routing (HPAR): The HPAR is a power aware routing protocol that divides the network into a group of sensors called zones [70]. Each zone is a group of geographically close sensor nodes and is treated as an entity. Thus the first step of this protocol is to format the clustered zones. The next step is the function of routing scheme to decide how a message is routed across other zones hierarchically so that battery life of nodes in the system is maximized. This can be done by a message that is routed along a path with a maximum power over all minimum remaining powers. This path is called max-min path. The main idea of making such a decision is that it may be possible that a path with high residual power has more energy consumption than the minimum energy consumption path. This scheme presents an approximation algorithm called max-min ZPmin algorithm. The algorithm first finds a path with least power consumption by applying Dijkstra algorithm. It then finds a second path that maximizes the minimal residual power in the network. The protocol then tries to optimize both solution criteria.

The main advantage of this protocol is that it takes into consideration both the transmission power and the minimum battery power of the node in the path. In addition, it makes use of zones to take care of the large number of sensor nodes. On the other hand, the discovery of the power estimation may consult on the overhead to the network.

11) Sleep/Wake Scheduling Protocol: The sleep/wake scheduling protocol conserves energy as it puts the radio to sleep during idle times and wake it up right before message transmission/reception [71]. The important part for a sleep/wake protocol is the synchronization between the sender and the receiver, so that they can wake up simultaneously to communicate with each other. The existing synchronization schemes achieve precise synchronization immediately after the exchange of synchronization messages, although there is still random synchronization error because of the non-deterministic factors in the system. These errors have as consequence the clock disagreement to grow with time and be comparable to the actual message transmission time. Thus, in [71] an optimal sleep/wake scheduling algorithm is proposed. It achieves a message capture probability threshold with minimum energy consumption. Moreover, multi-hop communication is considered.

The sleep/wake scheduling protocol is organized into cluster hierarchy and each cluster consists of a single cluster head and multiple cluster members. The most important issue, in this protocol, is that a cluster member can also be a cluster head in one cluster. In figure 8, C is the cluster head of E, but it is also a member of A. The member nodes are synchronized in the synchronization interval and in the transmission interval each member node transmits in a TDMA manner and sends one message to the cluster heads every T seconds.

12) Grid Based Data Dissemination (GBDD): In GBDD the size of the cell is determined by dual radio range of a sensor node [72]. Unlike TTDD, where the source initiates grid construction, in GBDD the sink that first was interested in sending or receiving data starts the grid construction process. This node is set as the crossing point (CP) of the grid and its geographical coordinates (x,y) become the starting point for the formation of grid cells. The RH and RL are the transmission ranges of every sensor node while working in high power radio mode and low power radio mode respectively. The cell of the grid is a square and each side is of size a.

13) Extending Lifetime of Cluster Head (ELCH): In ELCH the sensors vote for their neighbors in order to elect suitable cluster heads [73]. This protocol achieves to consume low energy and thus extending the life of the network utilizing a hybrid protocol, which combines the cluster architecture, with multi-hop routing. This protocol presents two phases:

- *Setup Phase*. In this phase, the cluster formation and the cluster-head selection are performed. The nodes vote their neighbor sensors. The most voted sensor becomes the cluster-head.
- *Steady-State Phase*. In this phase, the creation of clusters, the forwarding to the head and forwarding to the sink are performed. The clusters are formed in a way that they consist of one cluster-head and some sensors. These sensors have been chosen based on their location. This means that the sensors located in a radius less than the radio radius are selected. Then, the time slot TDMA for each cluster member in each round is used. In addition, each cluster-head maintains a table with maximum power for each node at each selection round. As soon as the above are completed the data transmission can start.

As soon as the clusters have been organized, the cluster heads can form a multi-hop routing backbone. The data are forwarded directly to the cluster head by each node. Moreover, for the communication between the cluster heads and the sink, a multihop routing is adopted. This technique can minimize the transmission energy and the network can be more balanced in terms of energy efficiency.

14) Novel Hierarchical Routing Protocol Algorithm (NHRPA): The NHRPA algorithm can adopt the suitable routing technology for the nodes that is relative to the distance of nodes to the base station, the density of nodes distribution and the residual energy of nodes [74]. A glance at the computation cost indicates that the proposed routing algorithm in dealing nodes mainly requires loop operations, judgment operations, and assignment operations. Moreover, the initialization process of the node is performed once during the period of deploying sensor networks. By selecting suitable threshold value, he NHRPA can balance varying concerns among different demand situations, such as security and energy concerns.

15) Scaling Hierarchical Power Efficient Routing (SHPER): he SHPER protocol supposes the coexistence of a base station and a set of homogeneous sensor nodes [75]. These nodes are randomly distributed within a delimited area of interest. The base station is located a long distance away from the sensor field. Both the base station and the set of the sensor nodes are supposed to be stationary. Also the base station is able to transmit with high enough power to all the network nodes, due to its unlimited power supply.

The operation of SHPER protocol consists of two phases: initialization and steady state phase. In the first phase the base station broadcasts a TDMA schedule and requests the nodes to advertise themselves. The nodes transmit their advertisements and the relative distances among them are identified. After that the base station randomly elects a predefined number of high and low level cluster heads and broadcasts the IDs of the new cluster heads and the values of the thresholds. In the steady state phase the cluster head defines the mostly energy efficient path to route its messages to the base station.

The main advantage of this protocol is that it performs the cluster leadership by taking into account the residual energy of nodes and energy balance is achieved and the power depletion among the nodes is performed in a more even way. Moreover, the data routing is based on a route selection policy which takes into consideration both the energy reserves of the nodes and the communication cost associated with the potential paths. However, it does not support the mobility of the nodes.

16) Distributed hierarchical agglomerative clustering (DHAC): The main idea in the DHAC is that a node needs the knowledge of only one hop neighbor to build the clusters [76]. The steps in the DHAC to form clusters are the following:

- Obtain input data set and build resemblance matrix. In this step each node elects itself as a cluster head and exchanges the information via HELLO messages to its neighbors.
- Execute the DHAC algorithm. In this phase each cluster establishes its own local resemblance matrix and the minimum coefficient can be easily found. In addition, each cluster then determines its minimum cluster head.
- Cut the hierarchical cluster tree. In case that a predefined upper bound size of clusters is reached, the control conditions correspond to the step of cutting the hierarchical cluster tree.
- Control the minimum cluster size. The next is to generate the clusters by running DHAC, the minimum cluster size can also be used to limit the lower bound of cluster size by performing the procedure ”MERGE CLUSTERS”.
- Choose CHs. To choose the CHs, the DHAC choose the lower id node between the two nodes that join the cluster at the first step. The CH chosen does not require extra processing.

Following, the DHAC uses the sequence of nodes merging into the current cluster as the schedule. Each cluster member gets its assigned role and starts to send data to CH in turns.

Moreover, there are also others hierarchical protocols apart from the above that have been proposed for WSNs [77], [78], [79], [80], [81].

In Table III, Hierarchical Routing Schemes Comparison is presented. Thus, for example protocols: LEACH, LEACH-C, PEGASIS, TEEN, APTEEN, VGA, MIMO, Sleep/Wake, GBDD, NHRPA, SHPER and DHAC are more robust than the others of this category. Moreover, protocols PEGASIS, VGA, GBDD, ELCH and TTDD use the greedy route policy selecting nodes in order to achieve the energy efficiency of the nodes. In addition to this, LEACH, LEACH-C, PEGASIS, TEEN, APTEEN, VGA, MIMO, Sleep/Wake, GBDD, NHRPA, SHPER and DHAC are more scalable than the other protocols of this scheme.

Finally, in Hierarchical Protocols a few protocols can partially be included, that are mainly classified and described in details in the categories on the below. These protocols are: GEM, HMRP and CBMPR.

C. Comparison of Flat and Hierarchical Protocols

The simulation results in [41] show that WRP provides about 50 percent improvement in the convergence compared to the Bellman-Ford. A protocol that reduces its complexity, compared to WRP, is TORA. In TORA, the first node at the network runs out of power at 205sec and all the nodes at the network die at 800sec. The simulation results in [82] show that TORA was found to have a worse delivery ratio and better delay, ranging from 0,0025 to 0,00125 seconds, compared to WRP.

However, E-TORA compared to TORA can balance effectively energy consumption of each node and increase evidently the lifetime of the network [51]. Moreover, the first node at the network runs out of power at 210sec.

On the other hand, the simulation results in [48] show that Flooding has a delivery ratio up to 100 percent and the delay varies from 100ms to 180ms. However, the TBRPF achieves up to a 98 percent reduction in communication cost in a 20-node network and the ZRP can reduce up to 95 percent the control packets compared to Flooding.

One of the most popular protocol, the gossip, requires very little or no structure to operate [47]. This makes it particularly appealing to apply in dynamic systems, where topology changes are common. Therefore, it seems particularly well fit to operate in wireless self-organizing networks.

Another protocol, the RR delivers 98.1 percent of all queries, with an average cost of 92 cumulative hops per query or about 1/40 of a network flood and can achieve significant savings over event flooding [50]. If the number of queries per event is less than ten, a smaller setup cost is better than a smaller per-query delivery cost. On the other hand, if we need to deliver more queries for example 40, a larger investment in path building yields will provide better results. The delivery is guaranteed, as undelivered queries are flooded.

A protocol that is really popular, the LEACH, can reduce the total number of transmissions, compared to that of direct communication. Moreover, the first node at the network runs out of power at 230sec and all the nodes at the network die at 700sec. However, LEACH-C outperforms LEACH in terms of energy efficiency. The first node at the network runs out of power at 525sec and all the nodes at the network die at 600sec. Moreover, the PEGASIS performs better than LEACH by about 100 percent to 300 percent when 1 percent, 20 percent, 50 percent and 100 percent of nodes die for different network sizes and topologies [62], [63].

Also, TEEN outperforms LEACH and LEACH-C in terms of energy efficiency [64]. The first node at the network runs out of power at 600sec and all the nodes at the network are dead at 2000sec. Also the performance of APTEEN lies between TEEN and LEACH with respect to energy consumption and longevity of the network [65]. TEEN only transmits time-critical data while sensing the environment continuously. To overcome the drawbacks of TEEN, the APTEEN has a periodic data transmission.

In addition, the BCDCP has a more desirable energy expenditure curve than those of LEACH, LEACH-C and PEGASIS [68]. Also BCDCP reduces overall energy consumption and improves network lifetime compared to LEACH, LEACH-C and PEGAGSIS. Moreover, the first node at the network runs out of power at 820sec and all the nodes at the network are dead at 900sec.

The SHPER outperforms TEEN concerning the mean energy consumption by 9.88 percent (the distance between the base station and the node is 100m), 18.77 percent (the distance between the base station and the node is 200m), 26.23 percent (the distance between the base station and the node is 300m) [75].

Also TTDD increases the energy gradually but sublinearly as the number of sinks increases and for a specific number of sinks (e.g., 4 sinks), energy consumption increases almost linearly as the number of sources increases [67]. Moreover, the delay ranges from 20msec to 80msec and the delivery ratio can be up to 90 percent. The TTDD is compared to Directed Diffusion and the results show that TTDD scales better than Directed Diffusion to the number of sources. If there are 1 or 2 sources, Directed Diffusion uses less energy, but if there are more than 2 sources, TTDD consumes much less energy. However, the GBDD has 43 percent overall energy savings compared to TTDD. Moreover, GBDD shows 30 percent improvement compared to TTDD in average delay computed across all source-sink pairs for a data packet to reach the destination.

Moreover, two protocols, compared to LEACH, are the MIMO and the ELCH. The MIMO, outperforms LEACH in terms of energy consumption. The first node at the network runs out of power at 700sec [69]. The ELCH outperforms LEACH in terms of energy efficiency and the first node at the network runs out of power at 270sec [73].

The NHRPA outperforms TEEN and Direct Diffusion in terms of packet latency and average energy consumption [74]. More specifically, the average energy consumption in LEACH varies from 3.884mJ (with 1 percent cluster head) to 0.904mJ (with 20 percent cluster head) compared to NHRPA, it varies from 0.949mJ to 0.524mJ.

The HPAR performs better than 80 percent of optimal for 92 percent of the experiments and performs within more than 90 percent of the optimal for 53 percent of the experiments and the sleep/wake can achieve at least 0.73 of the optimal performance [70].

The DHAC outperforms LEACH and LEACH-C in terms of energy consumption. Moreover, the first node at the network runs out of power at 600sec and all the nodes at the network are dead at 1100sec. While the sink moves further, the network lifetime of LEACH-C decreases very quickly compared to DHAC. Also DHAC gains much better performance when the network has light traffic [76].

VII. Communication Model Scheme

A. Query-Based Routing Protocols

In Query-based routing protocols, the destination nodes propagate a query for data (sensing task) from a node through the network and a node having this data sends the data which matches the query back to the node, which initiates the query [83]. These queries are usually described in natural language, or in high-level query languages. For example, client C1 may submit a query to node N1 and ask: Are there moving vehicles in battle space region 1? All the nodes have tables consisting of

TABLE III
HIERARCHICAL ROUTING SCHEMES COMPARISON

Scheme	Advantages	Drawbacks	Scalability	Mobility	Route Metric	Periodic Message Type	Robust
LEACH	Low energy, ad-hoc, distributed protocol	It is not applicable to networks deployed in large regions and the dynamic clustering brings extra overhead	Good	Fixed BS	Shortest Path	None Good	
LEACH-C	The energy for data transmission is less than LEACH	Overhead	Good	Fixed BS	The best route	None	Good
PEGASIS	The transmitting distance for most of the node is reduced	There is no consideration of the base station's location about the energy of nodes when one of the nodes is selected as the head node	Good	Fixed BS	Greed route selection	None	Good
TEEN	It works well in the conditions like sudden changes in the sensed attributes such as temperature	A lot of energy consumption and overhead in case of large network	Good	Fixed BS	The best route	None	Limited
APTEEN	Low energy consumption	Long delay	Good	Fixed BS	The best route	IMEP Control	Good
VGA	It may achieve energy efficiency and maximization of network lifetime	The problem of optimal selection of local aggregators as master aggregators is NP- hard problem	Good	No	Greedy route selection	None	Good
TTDD	It can be used for multiple mobile sinks in a field of stationary sensor nodes	The source node builds a virtual grid structure of dissemination points to supply data to mobile sinks	Low	No	Greedy route selection	None	Good
BCDCP	Low energy consumption	The performance gain decreases as the sensor field area becomes small	Limited	No	The best route	None	Limited
MIMO	The energy saving and QoS provisioning	It may results in suboptimal system performances	Good	No	The data bits collected by multiple source nodes will be transmitted to a remote sink by multiple hops	None	Limited
HPAR	It takes into consideration both the transmission power and the minimum battery power of the node in the path. In addition, it makes use of zones to take care of the large number of sensor nodes	The discovery of the power estimation may result on the overhead to the network	Low	No	It initially selects the shortest path and then tries to optimize it based on the total energy consumption	None	Good
Sleep/Wake	It identifies the bottleneck and significantly extends the network lifetime	Synchronization and scheduling will both affect the overall system performance	Good	No	The best route	None	Limited
GBDD	It ensure continuous data delivery from source nodes to sink	It consumes more energy when the speed is very high	Good	Limited	If valid grid is present, sink discovers closest corner node	None	Good
ELCH	It can minimize the transmission energy and the network can be more balanced in terms of energy efficiency	If the number of the members of each cluster in the environment exceeds from a certain amount it will have a negative effect on the network operation	Limited	Fixed BS	It selects the node with maximum remaining power	None	Good
NHRPA	Low energy consumption	packet latency	Good	Fixed BS	The best route	None	Good
SHPER	Energy balance of the network	It does not support mobility	Good	Fixed BS	The best route	None	Good
DHAC	The longer network lifetime	The performance is worse as the network traffic is getting high	Good	No	The best route	Hello messages	Limited

the sensing tasks queries that they receive and send data which matches these tasks when they receive it. Directed diffusion is an example of this type of routing. In directed diffusion, the BS (Base Station) node sends out interest messages to sensors. As the interest is propagated throughout the sensor network, the gradients from the source back to the BS are set

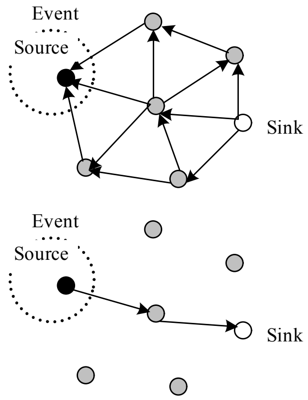

Fig. 9. a) Interest propagation, b) Initial gradients set up, c) Data delivery along reinforced path (redrawn from [84]).

up. When the source has data for the interest, the source sends the data along the interests' gradient path. To lower energy consumption, data aggregation (e.g., duplicate suppression) is performed enroute.

1) Directed Diffusion (DD): In Direct Diffusion all nodes are application-aware [84]. The DD can select empirically good paths and use the techniques of caching and processing data in-network in order to achieve the minimization of energy consumption. The DD consists of several elements [84], figure 9:

- *Naming*. The task descriptions are named using a list of attribute-value pairs. These attributes may be the type of data, the interval of transmission data, the duration etc.
- *Interests and Gradients*. The task description specifies an interest for data matching the attributes. These data, sent as a response to interests, are named using a similar naming scheme. The gradients are set up within the network and are designed to draw "events", for example data that match the interest requirements. Every node in the network maintains an interest cache. Each item in the cache corresponds to a distinct interest. Also, the interest entry contains several gradient fields up to one per neighbor.
- *Data Propagation*. In case that a sensor node detects a target, it searches for its interest cache for a matching interest entry. Thus, if it finds one, it computes the highest requested event rate among all its outgoing gradients.
- *Reinforcement*. Events start flowing towards the originators of interests along multiple paths. The sensor network reinforces one, or a small number of these paths.

The evaluation and the performance results in [84] show that directed diffusion has the potential for significant reduction of energy efficiency for the sensor nodes and the extension of the network lifetime. Even with relatively unoptimized path selection, it outperforms an idealized traditional data dissemination scheme like omniscient multicast. Moreover, the diffusion mechanisms are stable.

2) COUGAR approach: The COUGAR views the network as a huge distributed database system [85]. The key idea is to use declarative queries in order to abstract query processing from the network layer functions such as selection of relevant sensors and so on. COUGAR utilizes in-network data aggregation to obtain more energy savings. The abstraction is supported through an additional query layer. This lies between the network and application layers. COUGAR incorporates architecture for the sensor database system where sensor nodes select a leader node to perform aggregation and transmit the data to the BS. The BS is responsible for generating a query plan, which specifies the necessary information about the data flow and in-network computation for the incoming query and send it to the relevant nodes. The query plan also describes how to select a leader for the query. The architecture provides in-network computation ability that can provide energy efficiency in situations when the generated data is huge [86]. COUGAR provides network-layer independent methods for data query.

The main advantage of the COUGAR is that it provides energy efficiency when generated data is huge. On the other hand, the main disadvantages of the COUGAR are the overhead of the additional query layer for the energy consumption and storage, the complexity of the synchronization in network data computation and the dynamic maintenance of leader nodes to prevent failure.

3) ACtive QUery forwarding In sensoR nEtworks (ACQUIRE): The ACQUIRE is similar to COUGAR [87]. The ACQUIRE views the network as a distributed database where complex queries can be further divided into several sub queries. The Base Station (BS) node sends a query, which is then forwarded by each node receiving the query. During this, each node tries to respond to the query partially by using its pre-cached information and then forwards it to another sensor node. If the pre-cached information is not up-to-date, the nodes gather information from their neighbors within a look-ahead of d hops. Once the query is being resolved completely, it is sent back through either the reverse or shortest-path to the BS. Hence, ACQUIRE can deal with complex queries by allowing many nodes to send responses. Note that directed diffusion may not be used for complex queries due to energy considerations as directed diffusion also uses flooding-based query mechanism for continuous and aggregate queries.

The ACQUIRE is ideal for one-shot and complex queries for response which may be provided by many nodes. It provides efficient querying by adjusting the value of the look-ahead hop parameter. However, if the parameter is equal to the network size, the traffic behaves similar to flooding. On the other hand, the query has to travel more hops if the setting is too small.

In Table IV, the Query-Based Routing Schemes Comparison is presented. Thus, protocols DD and COUGAR select the path with the less energy consumption, while ACQUIRE selects the shortest path in order to minimize the energy consumption. Moreover, DD and COUGAR can support limited mobility of the nodes. Also DD is more scalable than COUGAR and ACQUIRE.

Finally, in Query-Based Protocols a few protocols can partially be included, that are mainly classified and described in details in the categories on the below. These protocols are: RR, SPIN-PP, SPIN-EC, SPIN-BN and SPIN-RL.

TABLE IV
QUERY-BASED ROUTING SCHEMES COMPARISON

Scheme	Advantages	Drawbacks	Scalability	Mobility	Route Metric	Periodic Message Type	Robust
DD	It extends the network lifetime	It can not be used for continuous data delivery or event-driven applications	Good	Limited	The best path	Query messages	Low
COUGAR	It provides energy efficiency when generated data is huge	Overhead, complexity of the synchronization in network data computation	Limited	No	The best path	Query messages	Low
ACQUIRE	It is ideal for one-shot and complex queries for response which may be provided by many nodes	Flooding	Limited	Limited	Shortest Path	Query messages	Low

B. Coherent and Non-Coherent-Based Routing Protocols

In WSNs the processing of the data is required at the node level. The sensor nodes make a collaborative effort to process the data within the sensor network. The routing mechanism which initiates the data processing module is proposed in [88]. This mechanism is divided into two categories:

- *Coherent Data Processing-Based Routing:* This category is an energy efficient mechanism where only the minimum processing is done by the sensor node. Time stamping, duplicate suppression are the tasks accomplished in minimum processing. After the minimum processing, the data is forwarded to the aggregators.
- *Non Coherent Data processing-based routing [89]:* In this category the sensor nodes locally process the actual data and then send it to the other nodes for further processing. The nodes that perform further processing are called the aggregators. There are three phases of data processing in non-coherent routing. (a) Target detection, data collection, and preprocessing, (b) Membership declaration, and (c) Central-node election. In target detection stage, an event is detected; its information is collected and pre-processed. In the membership declaration phase, the sensor node chooses to participate in a cooperative function and declare this intention to all neighbors. In the central node election stage, a central node is chosen to perform more refined information processing.

1) Single Winner Algorithm (SWE): In the SWE, a single aggregator node is elected for complex processing [90]. This node is the CN (Central Node) and is selected based on the energy reserves and computational capability of that node. In order to select the CN each node broadcasts an elect message and announces itself as a CN candidate. In response to the first batch of elect messages, the nodes that have already received them, will start comparing the proposed CN candidates with itself and respond with a second batch of elect messages that carries the result of this initial comparison. The second batch of message passing will generate further exchange of messages. The message that presents a better candidate, is recorded in the registry and then can be forwarded to all neighbors, otherwise the message is discarded.

In figure 10, the continuing exchange, forwarding and discarding phase of elect messages, is presented and show how the information of the winning candidates are sent in the network. Together with this diffusion process, a minimum-hop spanning tree rooted at the winning candidate will gradually increase until it completely covers the network.

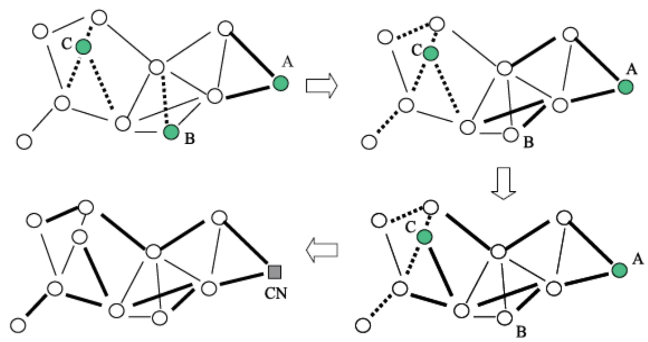

Fig. 10. SWE Election Process (redrawn from [88]).

2) Multiple Winner Algorithm (MWE): In the MWE, a simple extension to SWE is proposed [90]. When all nodes are sources and send their data to the central aggregator node, a large amount of energy will be consumed; hence, this process has a high cost. The energy cost may be lower only if there will be a limit to the number of sources that can send data to the central aggregator node. Instead of keeping a record of only the best candidate node (master aggregator node), each node will keep a record of up to n nodes of those candidates. The MWE process makes each sensor in the network to have a set of minimum-energy paths to each Source Node (SN). After that, SWE is used to find the node that yields the minimum energy consumption. This node can then serve as the central node for coherent processing.

In Table V, a Coherent and non-Coherent Routing Schemes Comparison is presented. The protocol SWE is more scalable than MWE, while MWE computes a set of minimum-energy paths to each node.

C. Negotiation-Based Routing Protocols

Negotiation-based routing protocols or Sensor Protocols for Information via Negotiation (SPIN) is among the early works to pursue a data-centric routing mechanism.

TABLE V
COHERENT AND NON-COHERENT-BASED ROUTING SCHEMES COMPARISON

Scheme	Advantages	Drawbacks	Scalability	Mobility	Route Metric	Periodic Message Type	Robust
SWE	It builds a minimum-hop spanning tree	It is a complex protocol	Good	No	Shortest Path	Hello messages	Low
MWE	Each sensor in the network has a set of minimum-energy paths to each source node	Long delay and low scalability	Low	No	Shortest Path	Hello messages	Low

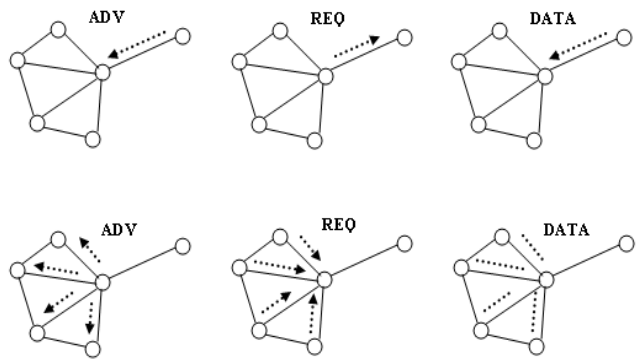

Fig. 11. Spin protocol and ADV, REQ, and DATA packets (redrawn from [91]).

The SPIN family of protocols rests upon two basic ideas [91].

- First, to operate efficiently and to conserve energy, sensor applications need to communicate with each other about the data that they already have and the data they still need to obtain.
- Second, nodes in a network must monitor and adapt to changes in their own energy resources to extend the operating lifetime of the system.

The main idea of SPIN is to name the data using high level descriptors or meta-data [92]. They use meta-data negotiations to reduce redundant transmissions in the network. Therefore, if a node has some data, then, first of all, it will advertise by sending an advertise packet that it has sensed an event or receives a data from another node and if some other node has received the advertised packet and is interested in that data then it will send a request packet and upon receiving the request packet the node will send the actual data in the data packet (figure 11). So SPIN is a 3-stage protocol, ADV, REQ, and DATA. SPIN provides scalability in a sense that each node needs to know only its single-hop neighbors, so, any changes in the topology would be local. The problem with SPIN is that it does not guarantee delivery of data, like considering a situation when an interested node is very far from the advertised, then that interested node will not get any data if nodes between these two nodes are not interested in the data. SPIN is based on data-centric routing.

The following protocols belong to SPIN family of protocols:

1) SPIN for Point to Point Communication (SPIN-PP): This protocol has been designed to perform optimally for point-to-point communication [93]. In SPIN-PP, two nodes may have exclusive communication with each other without any interference from the other nodes. Thus, the cost of communication for one node to communicate with n nodes is n times more expensive than communicating with one node. This protocol is a simple 3-way handshake protocol and the main characteristic of it is that energy is not considered to be a constraint. When a node has some new data, it advertises this new data using the ADV messages to its neighbors. As soon as, a neighboring node receives this advertisement, this node checks the meta-data and check if it already has the data item or not. If it does not, it sends an REQ message back requesting for the data item. The originating node that will receive the REQ message will send DATA messages containing the missing data to the requesting node.

The advantages of this protocol are its simplicity, its implosion avoidance and the minimal start-up cost. The disadvantages of this protocol are that it does not guaranty the delivery of the data and that it consumes unnecessary power.

2) SPIN with Energy Conservation (SPIN-EC): In this protocol, the sensor nodes communicate using the same 3-way handshake protocol as in SPIN-PP but there is an energy-conservation heuristic added to it [93]. If a node receives an advertisement, it will not send out an REQ message if it does not have enough energy to transmit an REQ message and receives the corresponding DATA message.

The properties of SPIN-EC are summarized as follows [94]:

- It adds simple energy-conservation heuristic to the SPIN-PP protocol.
- When energy is abundant, SPIN-EC acts as SPIN-PP protocol.
- Whenever energy comes close to low-energy threshold, it adapts by reducing its participation.
- The node will only participate in the full protocol if it believes that it has enough energy to complete the protocol without reaching below the threshold value.
- It does not prevent nodes from receiving messages such as ADV or REQ below its low-energy threshold, but prevents the nodes to handle a DATA message below the threshold.

3) SPIN for Broadcast Networks (SPIN-BC): This protocol was designed for broadcast networks in which the nodes use a single shared channel to communicate [93]. In this protocol, a node sends out a message and all the other nodes within a certain range of the sender receive it. A node, which has received an ADV message, does not immediately respond with an REQ message, but wait for a certain time before sending out the REQ message. In case that a different node receives the REQ message, it cancels its own request, in order to avoid redundant requests for the same message. After the advertising node receives an REQ message, it sends the data message only once because it is a broadcast network even though it might have got multiple requests for the same message.

The SPIN-BC is better than SPIN-PP for broadcast networks by using cheap, one-to-many communications, meaning that all messages are sent to broadcast address and processed by all the nodes that are within transmission range of the sender.

4) SPIN with Reliability (SPIN-RL): This protocol makes two changes to the above SPIN-BC protocol [93]. First each SPIN-RL node keeps track of which advertisements it hears from which nodes and if it does not receive the data within a certain period of time, it sends out the request again. The important point of this protocol is that nodes have a limit on the frequency with which they resend the data messages. After having sent out a data message, a node will wait for a certain period of time before it responds to other requests for the same data message.

The SPIN-RL is a reliable version of SPIN-BC which disseminates data through a broadcast network even in the cases that a network loses packets or communication is asymmetric.

In Table VI, Negotiation-Based Routing Schemes Comparison is presented. The protocols SPIN-PP, SPIN-EC, SPIN-BC and SPIN-RL support mobility of the nodes, while all of these protocols communicate with their neighbors only in case that they have data to send, minimizing the energy spent on periodic messages. Moreover, all the protocols SPIN-PP, SPIN-EC, SPIN-BC and SPIN-RL are scalable and robust and their performance is independed of the network size.

Finally, in Negotiation-Based Protocols a few protocols can partially be included, that are mainly classified and described in details in the categories on the below. These protocols are: VGA and SAR.

D. Comparison of Query, Negotiation and Coherent, non-Coherent Based Protocols

In DD, the first node at the network runs out of power at 90sec and all the nodes in the network are dead at 200sec. On the other hand, the COUGAR has a query optimizer generates an efficient query plan for in-network query processing, which can vastly reduce resource usage and thus extend the lifetime of a sensor network [85].

The ACQUIRE for a very small amortization factor c $0.001 \leq c \leq 0.01$, the optimal look-ahead d is as high as possible (d=10). On the other hand, for $0.08 \leq c \leq 0.9$, the most energy efficient strategy is to just request information from the immediate neighbors (d=1). The results also show that there are values of c in the range from [0.001, 0.1] such that each of 1, 2...10 is the optimal look-ahead value [87].

The MWE process has a longer delay and a lower scalability than that for non-coherent processing networks [90].

Moreover, the SPIN uses approximately a factor of 3.5 less energy than Flooding and the delivery ratio is up to 95 percent. The average energy dissipated in SPIN-PP and SPIN-EC is 17msec and 16msec accordingly. On the other hand, the average energy dissipated in SPIN-BC and SPIN-RL is 40msec [93].

VIII. Topology Based Scheme

A. Location-Based Routing Protocols

In this section, the basics of location-aided or position-based routing, through methods proposed for WSNs, is presented. This type of protocols acknowledges the influence of physical distances and distribution of nodes to areas as significant to network performance.

Location-based routing protocols are based on two principal assumptions:

- It is assumed that every node knows its own network neighbors positions.
- The source of a message is assumed to be informed about the position of the destination.

This technique for localized broadcasting of queries in geo-aware sensor networks makes use of the existing query routing tree and does not involve the creation of any additional communication channels. These algorithms require nodes to periodically transmit HELLO messages to allow neighbors to know their positions. The location-based routing technique is very interesting because it operates without any routing tables. Furthermore, once the position of the destination is known, all operations are strictly local, that is, every node is required to keep track only of its direct neighbor.

The main disadvantages of such algorithms are:

- Efficiency depends on balancing the geographic distribution versus occurrence of traffic.
- Any dependence of performance with traffic load thwarting the negligence of distance may occur in overload.

1) Distance Routing Effect Algorithm for Mobility (DREAM): The DREAM is a proactive protocol and each Mobile Node (MN) maintains a location table for all other nodes in the network [95]. To maintain the table, each MN transmits location packets to nearby MNs in the sensor network at a given frequency and to faraway MNs in the sensor network at another lower frequency. Since faraway MNs appear to move more slowly than nearby MNs, it is not necessary for a MN to maintain up-to-date location information for faraway MNs. Thus, by differentiating between nearby and faraway MNs, DREAM attempts to limit the overhead of location packets.

So, in case that a node S needs to send a message m to a recipient node R, it refers to its location table in order to retrieve its location information. After that, S selects from among its neighbors those nodes that are in the direction of R and forwards m to them. This is repeated for each of these nodes, forwarding the message to those nodes in the direction of R until R is reached. It is, thus, crucial to select the neighbors of a given node in a certain direction range in such a way that it is guaranteed that R can be found with a given probability p, $0<p<1$, following routes in that direction.

Its advantage is that the data packet transmission is efficient since an end-to-end route is always available; the end-to-end delay is small. Its disadvantage is the waste of network bandwidth.

2) Geographic and Energy Aware Routing (GEAR): Unlike previous geographic routing protocols, GEAR does not use greedy algorithms to forward the packet to the destination [96]. Thus, it differs in how they handle communication holes.

TABLE VI
NEGOTIATION-BASED ROUTING SCHEMES COMPARISON

Scheme	Advantages	Drawbacks	Scalability	Mobility	Route Metric	Periodic Message Type	Robust
SPIN-PP	simplicity, implosion avoidance and the minimal start up cost	It does not guaranty the delivery of the data and consumes unnecessary power	Good	Yes	Each node sends data to its single-hop neighbors	Node with data advertises to all its neighbors	Good
SPIN-EC	Whenever energy comes close to low-energy threshold, it adapts by reducing its participation	It does not prevent nodes from receiving messages such as ADV or REQ below its low-energy threshold	Good	Yes	Each node sends data to its single-hop neighbors	Node with data advertises to all its neighbors	Good
SPIN-BC	It is better than SPIN-PP for broadcast networks by using cheap, one-to-many communications	It has to wait for a certain time before sending out the REQ message	Good	Yes	Each node sends data to its single-hop neighbors	Node with data advertises to all its neighbors	Good
SPIN-RL	It disseminates data through a broadcast even in the cases that a network loses packets or communication is asymmetric	Time consuming	Good	Yes	Each node sends data to its single-hop neighbors	Node with data advertises to all its neighbors	Good

The GEAR uses energy aware and geographically informed neighbor selection heuristics to route a packet towards the target region. This protocol uses an energy aware neighbor selection heuristic to route the packet towards the target region.

Two main characteristics of this protocol are the following:

- When a closer neighbor to the destination exists GEAR picks a next-hop node among all neighbors that are closer to the destination.
- When all neighbors are further away, there is a hole. GEAR picks a next-hop node that minimizes some cost value of this neighbor.

The main advantage of the GEAR is that each node knows its own location and remaining energy level, and its neighbors locations and remaining energy levels through a simple neighbor hello protocol. Also it attempts to balance energy consumption and thereby increase network lifetime.

3) Graph Embedding for Routing (GEM): The GEM is a location based routing protocol that tries to assign labels to the sensor nodes uniquely in a distributed manner [97]. The nodes can route messages knowing only the labels of their immediate neighbors. In GEM, virtual coordinates are used instead of actual physical coordinates.

This algorithm consists of two components that are the following:

- The Virtual Polar Coordinate Space (VPCS). The first step to build the VPCS, is to embed a ringed tree. To build the spanning tree, a root node should be defined. After that, each node is assigned an angle range, which can be used to assign angles to its sub-trees. Each node splits its angle range into its children based on the size of the sub-tree of each child. For each sub-tree its centre-of-mass and average position of all the nodes are computed and propagated to the parent of that tree.
- The Virtual Polar Coordinate Routing (VPCR). The VPCR routes from any node to any point in the VPCS. A point is defined by a level and angle.

The main advantage of GEM is that it allows messages to be efficiently routed through the network, while each node only needs to know the labels of its neighbors. Also it is robust to dynamic networks, works well in the face of voids and obstacles, and scales well with network size and density. On the other hand, it overloads nodes that are at low levels of the tree.

4) Implicit Geographic Forwarding (IGF): In the location-based protocols, routing depends on up-to-date local neighborhood tables [98]. In contrast, the IGF allows a sender to determine a packet's next-hop online in real-time. By combining lazy-binding and location-address semantics, IGF becomes a pure state free protocol, which does not depend on the knowledge of the network topology or the presence/absence of other nodes. This characteristic of being state-free is valuable to the highly dynamic sensor networks, as it supports fault tolerance and makes protocols robust to real-time topology shifts or node state transitions. Thus, this protocol can eliminate costly communication that would otherwise be required to maintain neighbourhood state information for routing. In addition, this protocol enhances the decision making process by incorporating increased distance toward the destination (IDTD) and energy remaining (ER) metrics into the route selection process.

The properties of IGF are summarized as follows:

- It has robust performance when nodes migrate or transit into and out of sleep states.
- Shorter end-to-end latency compared to schemes that must update system state prior to sending.
- The distance and energy aware forwarding.
- The distribution of the workload.
- The decoupling of routing from energy conserving protocols.

In [98] a simulation of this protocol, regarding the energy consumption, is presented. The scenario of Many-to-Many flows where the Sleep Percentage to nodes is set at 33 percent

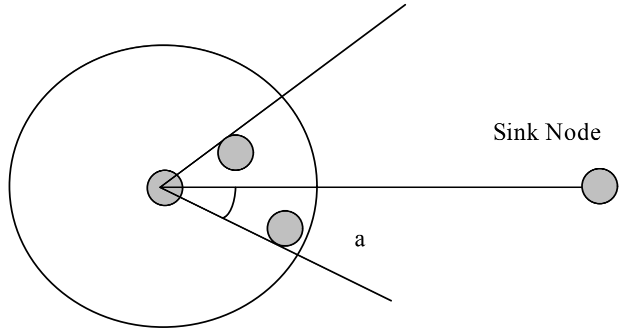

Fig. 12. Data packet dissemination model (redrawn from [99]).

for varied Toggle Periods is examined. The IGF works well in terms of energy conservation when the Toggle Period is below 18 seconds.

5) Scalable Energy-efficient Location Aided Routing (SELAR): The SELAR combines the energy consumption along with the location information in order to route packets [99]. The first step of this protocol is the sink node to flood its location information to its neighbor nodes. After that, all the nodes at the network flood their location and energy information to their neighboring nodes. They also include the location of the sink node as a reference. After that initial exchange of the above information, only energy information needs to be updated, as the network is rather static.

In order for this protocol to save energy, the control packets travel one hop. In addition to that, data packets are sent by individual nodes that calculate candidate neighbor nodes in their forwarding zone, which zone is the area formed by the angle a in the direction of the sink node and the area of coverage of the sending node (figure 12). The node initially sets the angle a of the zone to min alpha $(15)^0$ and increases it in steps until a number of neighboring sensor nodes are found, it is predefined, or until the angle reaches a max value that may be for example $(90)^0$, in order to make sure that the data packet is always forwarded in the direction of the sink. In case that no candidate node is found in the forwarding zone, then SELAR uses gossiping in order to discover a route, making it more robust.

The main advantage of this protocol is that, among the available candidate nodes in the forwarding zone, it selects the node with the highest energy level in order to provide a uniform dissipation of energy. However, this algorithm does not work well in case of a network that its nodes are often changing location.

6) Greedy Distributed Spanning Tree Routing (GDSTR): The GDSTR can find the shortest routes and generates low maintenance traffic [100]. The major contribution of this protocol is the definition of a new kind of spanning tree, which is a hull tree. A hull tree is a spanning tree where each node has an associated convex hull that contains within it the locations of all its descendant nodes in the tree. The hull trees are built by aggregating convex hull information that can be used to avoid paths that will not be productive; instead, they are able to traverse a significantly reduced subtree, consisting of only the nodes with convex hulls that contain the destination point.

The main drawback of GDSTR compared to the other geographic routing protocols is that it faces the problem of the local dead ends where greedy forwarding fails. Most of the existing geographic routing algorithms plane the node connectivity graph and then uses the right-hand rule to route around the resulting faces, in order to handle the dead ends. The GDSTR handles this situation differently by switching instead to routing on a spanning tree until it reaches a point where greedy forwarding can again make progress. In order to choose a direction on the tree, that is most likely to make progress towards the destination, each GDSTR node maintains a summary of the area covered by the sub-tree below each of its tree neighbors.

The main advantages of GDSTR are that it achieves lower path and hop stretch than existing geographic face routing algorithms and that it is simpler and easier to understand and implement. While GDSTR requires only one tree for correctness, it uses robustness to give it an additional forwarding choice.

7) Minimum Energy Relay Routing (MERR) - Location: The MERR is based on the idea that the distance between two nodes that transmit data is very important [101]. This distance is closely related to the energy consumed on the entire path, from the source to the base station, that contains, in some cases, a large number of nodes. Thus, in MERR each sensor seeks locally for the downstream node within its maximum transmission range whose distance is closest to the characteristic distance.

As soon as a sensor has decided to use the next hop, it adjusts its transmission power to the lowest possible level such that the radio signal can just be received by the respective node. This can minimize the energy consumption. If the distances between each pair of sensors are all greater than the characteristic distance, each sensor will select its direct downstream neighbor as the nexthop node.

We present an example for the selection of the optimal routing path in figure 13. The first step of this protocol (1, 2 and 3 points at the figure) is to select the relays 4, 2, and base station. The resulting path from 5 to 4 then to 2 then to BS approximates the optimal case and is used in step 4) to route data from sensor 5 to the base station.

The MERR works well in case that the sensors are deployed over a linear topology and sends data to a single control center. The main advantage of this approach is that it distributes the energy consumption of the sensors uniformly to the network sensors. On the other hand, minimizing transmit energy means that it chooses the nearest neighbor as router. Thus, a large amount of energy is wasted in case that the nodes happen to be very close to each other.

8) On-demand Geographic Forwarding (OGF): The OGF is a cross-layer protocol that employs an explicit contention scheme to establish a next-hop node [102]. In case that a sender needs to send a packet, it looks up the forwarding table in order to learn if an entry exists to the designation node. If the next-hop information is available, the source node unicasts the packet to the specified next-hop sensor. If the next-hop ID in the entry is a special code called passive, which does not allow the sender to forward packets for other sensors except itself, then the sender goes into the void handling

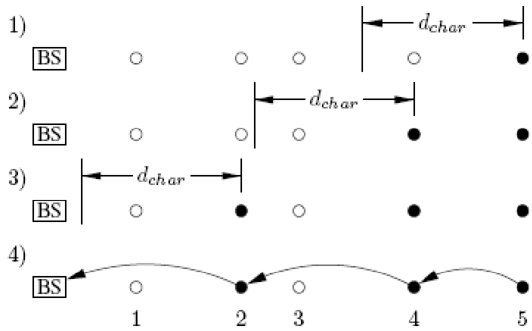

Fig. 13. Selection of the optimal routing path (redrawn from [101]).

mode directly. On the other hand, if there is no next-hop entry available, the sender initiates a contention to establish its next-hop sensor. In case that no next-hop sensor is located in the forwarding area during the contention period, the sender switches to the void handling mode. Otherwise, a next-hop node is established to receive the data packet from the sender. The sender updates the forwarding table by inserting a new entry after successfully delivering the data packet.

The operation of this protocol is based on the actual demands of the application, data traffic, and network dynamics. The simulations results in [102] show that OGF exhibits a superior performance in terms of energy consumption, scalability, and void handling. Additionally, OGF is viable for efficient data delivery in the targeted sensor networks.

9) Partial-partition Avoiding Geographic Routing-Mobile (PAGER-M): The PAGER-M uses the location information of sensors and the base station to assign a cost function to each sensor node, which is close to the Euclidean length of a sensor node's shortest path to the base station [103]. A packet is forwarded to the base station using greedy forwarding whenever possible [104]. Greedy forwarding may fail at a concave node (local minimum) that has no closer neighbor to the base station. To avoid this situation, when a packet reaches sensor nodes near a concave node, the packet is forwarded to a neighbor following the high-cost to low-cost rule.

The test results in [103] show that PAGER-M achieves high delivery ratio, low routing overhead and low energy consumption. The energy efficiency of PAGER-M comes from its low control overhead and low path length. This energy efficiency of PAGER-M proves that is suitable for WSNs with mobile nodes. On the other hand, PAGER-M does not require a node to memorize the past traffic/path; in this sense, it is a stateless location-based routing protocol.

10) Hybrid Geographic Routing (HGR): In [105], a novel hybrid geographic routing (HGR) scheme that combines both distance and direction based strategies in a flexible manner is proposed. In this protocol the main operation of a node is to define the priority as the next hop. This priority is considered as Q_i. The greater the projected progress of node i is, the larger Q_i becomes, whereas the lower deviation angle between the line that connects z with i and the line that connects z with j is, the larger Q_i becomes. Different forms for Q_i can be defined in order to combine both the distance and direction based routing criteria.

The simulation results show that HGR can achieve delivery ratio that in most cases reaches 100 percent and low end-to-end delay may be met.

Moreover, there are also others location-based protocols apart from the above that have been proposed for WSNs [106], [107], [108], [109], [110].

In Table VII, Location-Based Routing Schemes Comparison is presented. Therefore, DREAM, IGF, PAGER-M and HGR can support the mobility of the nodes, while at the same time they keep the energy consumption of the nodes in low levels. Moreover, GEM and GDSTR try to minimize energy consumption of the nodes by selecting the shortest path to route the information. On the other hand, GEM, IGF, MERR, OGF and HGR in order to minimize energy consumption do not use periodic messages. Moreover, GEM, OGF, PAGER-M and HGR are more scalable than the other protocols of this scheme. Also, DREAM has limited robust.

Finally, in Location-Based Protocols a few protocols can partially be included, that are mainly classified and described in details in the categories on the below. These protocols are: TTDD, COUGAR and ACQUIRE.

B. Mobile Agent-based Protocols

In most cases, the application-specific nature of WSNs requires the sensor nodes to have multiple capabilities. Thus, it is impractical for sensors to store all the programs needed in the local memory and run every possible application, due to the tight memory constraints.

One of the main research areas, related to WSNs is the design, development and deployment of mobile agent systems [111]. The mobile agent systems have as main component a mobile agent, software or program, which migrates among the nodes of a network to perform a task autonomously and intelligently, based on the environment conditions. Mobile agent systems employ migrating codes in order to facilitate flexible application re-tasking, local processing, and collaborative signal and information processing. This may provide to the network extra flexibility, as well as new capabilities in contrast to the conventional WSN operations that are based on the client-server computing model.

Thus, the design of mobile agents and the development of protocols in WSNs that are used to route data from the sensed area to the destination is a really interesting sector. In [111] the design issue of mobile agents in WSNs are presented. The agent's design can be divided in the following:

- *Architecture*. The architecture is based on the topology of the network and is further divided in flat or hierarchical.
- *Itinerary planning*. The itinerary is the route followed during mobile agent migration. The itinerary planning is related to the selection of the set of the source nodes, to be visited by the mobile agent, and the determination of a source-visiting sequence in an energy-efficient manner. The itinerary planning is divided in static, dynamic or hybrid.
- *Middleware system design*. Mobile agents are often implemented as middleware. Middleware is used to bridge the gap between the operating system and high-level components and to facilitate the development and deployment of applications.

TABLE VII
LOCATION-BASED ROUTING SCHEMES COMPARISON

Scheme	Advantages	Drawbacks	Scalability	Mobility	Route Metric	Periodic Message Type	Robust
DREAM	Efficient data packet transmission	The waste of network bandwidth	Limited	Good	The paths that minimize total power consumption	Control messages	Limited
GEAR	It attempts to balance energy consumption and thereby increases the network lifetime	The periodic table exchange	Limited	Limited	The best route	Hello messages	Good
GEM	It allows messages to be efficiently routed through the network, while each node only needs to know the labels of its neighbors	It overloads nodes that are at low levels of the tree	Good	Limited	Shortest Path	None	Good
IGF	Robust performance, distribution of the workload	It depends on the up to date local neighbor tables	Limited	Good	The best route	None	Good
SELAR	It selects the node with the highest energy level in order to provide a uniform dissipation of energy	It does not work well in case of a network that its nodes are changing location often	Limited	Limited	The route that nodes have the highest power	Control messages	Good
GDSTR	It finds the shortest routes and generates low maintenance traffic	Overhead to the network	Limited	No	Shortest Path	Hello messages	Good
MERR	It distributes the energy consumption of the sensors uniformly to the network sensors	It wastes energy in case that the nodes are close to each other	Limited	Low	The paths that minimize total power consumption	None	Good
OGF	It exhibits a superior performance in terms of energy consumption, scalability, and void handling	It depends on the up to date local neighbor tables	Good	Limited	The best route	None	Good
PAGER-M	It achieves high delivery ratio, low routing overhead and low energy consumption	Stateless location-based routing protocol	Good	Good	The shortest path using greedy algorithm	Hello messages	Good
HGR	It combines both distance and direction based strategies in a flexible manner	It does not guarantees delay	Good	Good	The paths that minimize total power	None	Good

- *Agent cooperation*. Mobile agents can work either as single processing units or as a distributed collection of components. The requirement to provide the means for agent cooperation is an important consideration in WMS design to reduce energy consumption in the WSN.

In most cases applying mobile agent systems in WSNs may lead to reduce bandwidth consumption and high flexibility on the network. Moving the data processing elements to the location of the sensed data may reduce the energy expenditures of the nodes. However, finding the optimal itinerary is NP-hard and a lot of efforts are on going.

1) Multi-agent based Itinerary Planning (MIP): In [112], a multi-agent based itinerary planning (MIP) protocol is presented. In most scenarios, single agent based itinerary planning (SIP) protocols are developed and operate on mobile agent systems. However, using SIP protocols in a large scale network may lead to high delay rates and unbalanced load. Thus, the use of a Multi agent itinerary planning (MIP) protocol is important to be used.

The basic idea of the protocol proposed in [112] is to distribute each source's impact factor to other source nodes. For example, considering n as the source number, then each source will receive n-1 impact factors from other nodes and one from itself. After that the accumulated impact factor is calculated and the location of the source with the largest accumulated impact factor is selected.

The simulation results prove that the energy consumption of MIP algorithm is higher than SIP algorithms in case that the source number is small. However, this algorithm is designed for use when source number is large. Thus, based on the results when the source number is 40, the energy consumption of MIP algorithm is much better that those of SIP algorithms.

2) Itinerary Energy Minimum for First-source-selection (IEMF) and Itinerary Energy Minimum Algorithm (IEMA): In [113], an Itinerary Energy Minimum for First-source-selection (IEMF) algorithm is proposed. Then, the Itinerary Energy Minimum Algorithm (IEMA), an iterative version of IEMF, is presented.

In the IEMF algorithm the first activity is to select an arbitrary source node v as a tentative S[1] and the remaining source set is considered as by V - {v}. The next, action is to set *v* as the start point the determination of the itinerary for the n - 1 source nodes in V - {v} is evaluated by visiting in sequence the remaining n-1 source nodes. The following action is to obtain the entire itinerary sequence starting from the sink. Thus, every source in V is selected as tentative S[1] and the itinerary is established. The final action of the IEMF is selecting the itinerary that has the minimum energy cost.

However, IEMA, apart from selecting the S[1], this algorithm seeks to optimize the remaining itinerary to a certain degree.

The simulation results have demonstrated that IEMF provides high energy efficiency while it can achieve delivery ratio up to 90 percent. However, the limitation of utilizing a single agent to perform the whole task makes the algorithm unscalable with a large number of source nodes to be visited.

In Table VIII, Mobile Agent-based Routing Schemes Comparison is presented. In this table, the IEMF/IEMA described to have limited scalability and its performance is decreased as the number of nodes is increased. On the other hand, MIP consumes less energy as the number of nodes in the network increases.

C. Comparison of Location and Multi Agent-based Protocols

The simulation results in [95] show that DREAM outperforms the Network Structure schemes, WRP and TORA in terms of average energy consumption. It has a delivery ratio up to 80 percent and an end-to-end delay up to 50msec.In addition, SELAR outperforms Flooding, Gossiping and DREAM in terms of network lifetime and the amount of data delivery. SELAR is able to deliver up to 2.5 and 4 times more packets than Flooding [99].

Also, the simulation results in [101] show that MERR achieves power savings of up to 80 percent compared to minimum transmission energy routing and can deliver packets with a ratio up to 95 percent. However, the simulation results in [100] show that GDSTR routes packets along shorter paths than the other algorithms, and is thus likely to deliver packets faster and with less consumption of radio resources. However, this can minimize the network's lifetime.

The IGF can deliver packets with a ratio close to 100 percent [98]. The IGF has the best results concerning the energy consumption when the toggle period sleep/wake is below 18 seconds. However, OGF outperforms IGF and Direct Diffusion in terms of energy consumption [102]. OGF has an average energy dissipated up to 50msec. It can deliver more than 90 percent of the packets even under a high sensor failure rate such as 0,6.

The PAGER-M achieves an average delivery ratio greater than 99 percent with beacon interval 3-4 seconds [103]. PAGER-M has an average energy dissipated up to 10msec. The maximum energy usage among all nodes is 57.44mJ for diffusion. Also, the bit rate is 250 bits/sec, which demonstrates the extremely low data rate requirements of sensor networks.

The GEAR is more efficient than Flooding [96]. It achieves energy balancing by taking alternative path; therefore, it is not surprising that it increases the path length by 25 percent to 45 percent over all packets delivered. Also in GEM the live nodes at the network are 500 from 0 to 6000 packets that are sent and get into 0 at 7500 packets [97].

The simulation results in [112] show that if the source number is 40, the energy consumption of MIP algorithm is much better that those of SIP algorithms. Moreover, the simulation results in [113] have demonstrated that IEMF provides high energy efficiency while it can achieve delivery ratio up to 90 percent.

IX. Reliable Routing Scheme

A. Multipath Based Routing Protocols

Multi-path routing is an interesting outing method for wireless sensor networks. The multi-path routing has the advantage to achieve load balancing and is more resilient to route failures [114]. There are a lot of multi-path routing protocols that belong to this scheme for wireless sensor networks and the performance evaluations of them may show that they take advantage of the lower routing overhead, the lower end-to-end delay and the alleviate congestion in comparison with single-path routing protocols. We describe below the routing protocols of this category.

1) Routing On-demand Acyclic Multipath (ROAM): The ROAM presents an on-demand distance-vector algorithm called Routing On-demand Acyclic Multipath (ROAM) [115]. It uses a concept called feasible distance to maintain routes and loop freedom. ROAM detects network partitions by requiring nodes to send update messages to neighboring routing whenever there is a change in distance to a certain destination.

In ROAM, each router maintains a distance table, a routing table and a linkcost table. The distance table is a matrix containing the distance between two neighbors at a router. The routing table at router is a column vector containing, for each destination, the distance to the destination node, the feasible distance, the reported distance, the successor, the query origin flag and the timestamp. The link-cost table lists the costs of links to each known adjacent neighbor. When a router gets a data packet that is to be delivered to a destination for which it has no entry in its routing table, it starts a diffusing search. The diffusing search propagates from the source out on a hop by hop basis, until it reaches a router that has an entry for the requested destination. As soon as it reaches this entry the router replies with its distance to it. At the end of the search, the source obtains a finite distance to the destination. If the there is no route to the destination all the nodes in the same connected component determine that the destination is unreachable.

The ROAM informs routers when a destination is unreachable and prevents routers from sending unnecessary search packets, in order to find paths to an unreachable destination. Since the algorithm requires the exchanges of state information between nodes, it is more suitable for use in static networks or networks with limited mobility. The main disadvantage of this algorithm is that it needs to send periodic update in order to be informed about the active nodes.

TABLE VIII
MOBILE AGENT-BASED ROUTING SCHEMES COMPARISON

Scheme	Advantages	Drawbacks	Scalability	Mobility	Route Metric	Periodic Message Type	Robust
MIP	It can consume less energy when the number of nodes of the network is large	High delay	Limited	Good	The paths that minimize the total power consumption	None	Good
IEMF/IEMA	This protocol seeks to optimize the remaining itinerary to a certain degree	It is unscalable with a large number of source nodes to be visited	Limited	Good	The paths that minimize total power	None	Good

2) Label-based Multipath Routing (LMR): The LMR broadcasts a control message throughout the network for a possible alternate path [116]. During the process, labels are assigned to the paths the message passes through. The label information is used for segmented backup path search if a disjoint path is not achievable. The LMR is designed to use only the localized information to find disjoint paths or segments to protect the working path. With one flooding, LMR can either find disjoint alternate paths or several segments to protect the working path.

In LMR, after the nodes, on the working path, have reinforced one of their links, as the link to form a working path, they broadcast a label message to the rest of their neighbors. Both, the reinforcement and label messages, take an integer, termed label. The value of the label is increased by 1 by each working node which then broadcasts a new label message. Every working node should remember this value as its own node label. The label messages are forwarded towards the source along all the paths which the exploratory data messages pass through. A node receiving two or more label messages will forward the one with smaller label value only. The idea is to make the label message from the node closer to the sink go as far as possible so that the disjoint paths are possible to be found.

The working nodes do not forward the label messages from any other nodes. Every node should remember all labels it has seen and the associated neighbors they are coming from. If a node receives multiple label messages with the same label value from different neighbors, only the first one is recorded to find a shortest backup path. The label information can reduce the routing overhead and backup path setup delay. However, to find the possible alternate paths, LMR incurs overhead, a flooded label message, and a label reinforce message and a backup exploratory message.

3) GRAdient Broadcast (GRAB): The GRAB, is designed specifically for robust data delivery in order to deal with the unreliable nodes and fallible wireless links [117]. It builds and maintains a cost field by propagating advertisement (ADV) packets in the network. As soon as a node receives an ADV packet containing the cost of the sender, it calculates its cost by adding the link cost between itself and the sender to the sender's advertised cost. It compares this cost to the previously recorded one and sets the new cost as the smaller of the two. As it obtains a cost smaller than the old one, it broadcasts an ADV packet containing the new cost. GRAB controls the width of the band by the amount of credit carried in each data message, allowing the sender to adjust the robustness of the data delivery.

The advantage of GRAB is that it relies on the collective efforts of multiple nodes to deliver data, without dependency on any individual ones and it is really robust. On the other hand, It may have overhead by sending redundant data.

4) Hierarchy-Based Multipath Routing Protocol (HMRP): The HMRP employs a hierarchical concept to construct an entire sensor network [118]. Each sensor node (involving the sink node) just needs to broadcast the layer construction packet once and maintain its own CIT (Candidates Information Table). When a sensor node disseminates a data packet, it only needs to know which parent node to transfer, without to maintain the whole path information. This can reduce the overhead of the sensor node. Although HMRP has to compute some information to record in the CIT of the sensor node, the energy expense is less than transmission and reception. Furthermore, HMRP supports multipath data forwarding, without using the fixed path. The energy consumption will be distributed and the lifetime of the network will be prolonged. Finally, HMRP can support for multiple sink nodes situation.

HMRP has many candidate paths to disseminate data packets to the sink. The data aggregation mechanism is present in each node apart from the leaf nodes reducing the energy consumption in the networks. The proposed system was designed according to the following objectives:

- Scalability. The sensing area may include hundreds or thousands, sensor nodes. The HMRP could be suitable for a small or large sensing scale, since the communication overhead among sensor nodes is very low.
- Simplicity. The sensors have restricted computing capability and memory resources. Therefore, this approach attempts to minimize the numbers of operations performed, and the states maintained at each node, which only has to maintain its candidate parents' information table to determine the routing path.
- System Lifetime. These networks should operate for as long as possible, the recharging of the battery of nodes may be inconvenient or impossible. Therefore, data aggregation and energy-balanced routing are adopted to decrease the number of messages in the network to extend its network lifetime.

5) Cluster-Based Multi-Path Routing (CBMPR): The CBMPR combines cluster-based routing and multi-path rout-

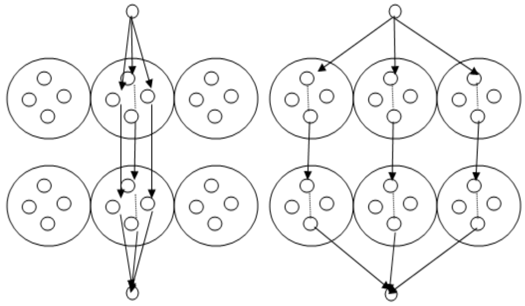

Fig. 14. Multiple Paths established with conventional multi-path routing protocol, Multiple Paths established with CBMPR (redrawn from [119]).

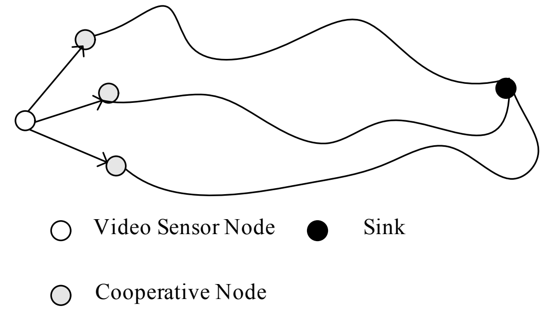

Fig. 15. Illustration of DGR-based multipath video transmission.

ing efficiently [119]. The CBMPR makes use of cluster network to find multiple paths, that provide independent paths, decrease routing control overhead and improve the networks scalability.

As in all the hierarchical protocols, CBMPR sets cluster heads and member nodes. The nodes in the networks send HELLO messages regularly. A cluster member adds its IP address; a cluster head adds the IP address of its cluster member, into its HELLO message. A cluster head keeps tracks of all the IP addresses of its cluster member in its routing table. Moreover, the cluster head keeps a neighbor table, which contains all the IP addresses of its neighbor cluster head.

The CBMPR is a mutlipath protocol as it sets up multiple paths from the source node to the destination node. These paths can be classified into optimal path, shortest path and so on, according to the hop number (h), accumulated delay (d) and bandwidth (b) included in the paths messages received by source.

Based on the above mentioned, the main steps of this protocol are the following:

- The first step is to calculate the path weight value w=b/ln(dh) according to the hop number (h), accumulated delay (d) and bandwidth (b) included in the paths messages.
- The next step is the utilization M-for-N diversity coding technique (reconstruct the original Xbit information packet, provided that at least N blocks will reach the destination) to solve the inherent unreliability of the network by adding extra information overhead to each packet. The data packet is fragmented into smaller blocks.
- Finally, according to the weight value of the path, it distributes the blocks over the available paths. As the weight value of the path is growing, more blocks are distributed over the path. The data load is distributed over multiple paths in order to minimize the packet drop rate, achieve load balancing, and improve end-to-end delay.

The figure 14 shows an example of multiple paths which will suffer less interference by choosing routing paths through different clusters.

The main advantage of CBMPR over conventional multipath routing is the less interference and is simple. Each path in the CBMPR just passes through the heads of clusters, resulting in a simple cluster level hop-by-hop routing. This makes CBMPR convenient and simple reducing the burden of interference calculation needed at every intermediate node. Even though the CBMPR can mitigate the interference problem efficiently, path-joining problems may be occurred because path joining can be easily created while choosing cluster-by-cluster link. However, the data packet that is fragmented into smaller blocks must be reassembled at the destination node, it may lead to error and increase control overhead.

6) Directional Geographical Routing (DGR): In [120], a novel multipath routing protocol DGR is presented. This protocol is a very interesting solution to the problem of real time video streaming over a bandwidth and energy constrained WSN from a small number of dispersed video sensor nodes (VNs) to a sink by combining forward error correction (FEC) coding.

In DGR an active Video Sensor Node (VN) broadcast to its direct neighbors a packet concatenating all the data and FEC packets of a video frame. As soon as these nodes receive the concatenated packet broadcasted by the VN, they select their own payload according to the identifiers and the sequence numbers of the corresponding packets of these nodes, in the concatenated packet. Then these nodes unicast the assigned packets to the sink via the respective individual paths.

An example of this architecture is presented in figure 15, where the multipath routing layer sets up 3 paths between the source and the sink. Moreover, each path uses a different initial direct neighbor. This architecture in combination with the shortest path routing along with the number of successful frame deliveries during the period that the nodes are alive, is a promising and useful scheme that can efficient route the video traffic of the network.

The simulation results demonstrate that DGR can offer low delay that is around to 0.05msec, substantially longer lifetime and better received video quality. Also the average video peak signal to noise ratio can be improved by up to 3dB.

7) Directional Controlled Fusion (DCF): In [121], a directional control fusion (DCF) algorithm is presented. The main ability of the DCF is the jointly consideration of data fusion and load balancing. Also a key parameter in DCF named multipath fusion factor can provide the trade-offs between multipath-converging and multipath-expanding in order to satisfy specific QoS requirements from various applications.

In DCF one source node is selected as the reference source per round based on some criteria (maximum of the remaining energy, distance from the center of the target region, or distance to the sink). The first step is for every source node to start a Reference-Source-Selection-Timer (RSSTimer). At the RSSTimer a random value to each timer based on a specific criterion is set. In this step a small value of RSSTimer indicates that a source has higher eligibility as the reference source. The next step is the monitoring of the RSS-Timer. The source whose this value expires first will be selected as the reference source and will broadcast an election notification message within the target region. When other source nodes receive this message, they will cancel their RSS-Timers and know the reference source's location piggybacked in the message. The next step is the reference source to initiate the construction of the reference path and the side sources to transmit the control packets.

8) Routing Protocol for Low power and Lossy Networks (RPL): RPL is an IPv6 routing protocol for WSNs proposed by the ROLL working group in the IETF [122]. The basic ingredient of RPL is the Destination Oriented DAG (DODAG). A Destination Oriented DAG is a DAG rooted at a single root node, which is a node with no outgoing edge.

In the converged state, each router in the WSN has identified a stable set of parents, on a path towards the root of the DODAG, as well as one among these as its preferred parent. Each router, which is part of a DODAG, will emit DODAG Information Object (DIO) messages, using link-local multicasting, indicating its respective Rank in the DODAG. Upon having received a number of such DIO messages, a router will calculate its own rank such that it is greater than the rank of each of its parents, and it will start emitting DIO messages. Thus, the DODAG formation starts at the root, and spreads gradually to cover the whole network. The root can trigger "global recalculation" of the DODAG by way of increasing a sequence number in the DIO messages.

RPL provides a mechanism to disseminate information over the dynamically-formed network topology. The dissemination enables minimal configuration in the nodes, allowing nodes to operate mostly autonomously.

The minimal set of inrouter state required in a WSN router running RPL is the following (figure 16):

- the identifier of the DODAG root,
- the address and rank of the preferred parent,
- the configuration parameters shared by the DODAG root and
- the maximum rank that the WSN router has itself advertised

Moreover, there are also others multipath-based protocols apart from the above that have been proposed for WSNs [123], [124].

In Table IX, Multipath-Based Routing Schemes Comparison is presented. As shown from table IX, protocols LMR, HMRP, DGR and DCF do not use periodic messages in order to minimize energy consumption. Moreover, DGR do not support mobility of the nodes, while ROAM, HMRP and GBMPR perform better in case that the nodes are not mobile. Moreover, LMR, GRAB, HMRP, DGR, DCF and RPL are more scalable than the other protocols of this scheme. Also, LMR, GRAB, DGR, DCF and RPL are more robust than the orther protocols of this scheme.

Finally, in Multipath-Based Protocols a few protocols can partially be included, that are mainly classified and described in details in the categories on the below. These protocols are: TBRPF, TORA, TTDD, MIMO, Sleep/Wake, ELCH, DD, MWE and MMSPEED.

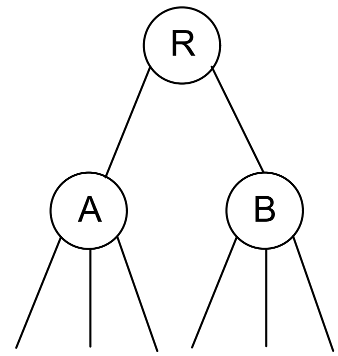

Fig. 16. The multiple nodes in the LLN coordinate over a backbone and expose the same DAGID.

B. QoS-Based Routing Protocols

In QoS-based routing protocols, the network has to balance between energy consumption and data quality [125], [126]. In particular, the network has to satisfy certain QoS metrics, e.g., delay, energy, bandwidth, etc. when delivering data to the BS. In the best-effort routing the main concerns are the throughput and average response time. QoS routing is usually performed through resource reservation in a connection-oriented communication that meet the QoS requirements for each individual connection. While many mechanisms have been proposed for routing QoS constrained real-time multimedia data in wire-based networks, they cannot be directly applied to WSNs due to the limited resources, such as bandwidth and energy that a sensor node has.

1) Sequential Assignment Routing (SAR): The SAR is one of the first routing protocols for WSNs that introduces the notion of QoS in the routing decisions [127]. Routing decision in SAR depends on three factors: energy resources, QoS on each path, and the priority level of each packet. To avoid single route failure, a multi-path approach is used and localized path restoration schemes are used. The objective of SAR algorithm is to minimize the average weighted QoS metric throughout the lifetime of the network.

2) SPEED Protocol: Another QoS routing protocol for WSNs that provides soft real-time end-to-end guarantees is SPEED, which can provide congestion avoidance when the network is congested [128]. The routing module in SPEED is called Stateless Geographic Non-Deterministic forwarding (SNFG) and works with four other modules at the network layer SPEED maintains a desired delivery speed across sensor networks with a two-tier adaptation included for diverting traffic at the networking layer and locally regulating packets sent to the MAC layer. It consists of the following components (figure 17):

- An API (Application Programming Interface).
- A delay-estimation scheme.
- A neighbor-beacon-exchange scheme.
- A Nondeterministic Geographic Forwarding (NGF) algorithm.

TABLE IX
MULTIPATH-BASED ROUTING SCHEMES COMPARISON

Scheme	Advantages	Drawbacks	Scalability	Mobility	Route Metric	Periodic Message Type	Robust
ROAM	It can inform routers when a destination is unreachable and prevents routers from sending unnecessary search packets	It needs to send Hello messages to maintain the active nodes	Limited	Limited	Any path	Hello messages	Limited
LMR	The label information can reduce the routing overhead and backup path setup delay	It may have an overhead in order to find the possible alternate paths	Good	Good	Any path	None	Good
GRAB	It relies on the collective efforts of multiple nodes to deliver data, without dependency on any individual ones	It may have overhead by sending redundant data	Good	Good	Set of disjoint paths that satisfy QoS requirement	Hello messages	Good
HMRP	Scalability, simplicity, and system lifetime	It broadcasts the layer construction packet once	Good	Low	Any path	None	Limited
CBMPR	Low interference, simplicity	Path joining problems may be occurred	Limited	Low	The best path	Hello messages	Limited
DGR	It is a very interesting solution to the problem of real time video streaming	It is optimized for video traffic	High	No	The path with different initial direct neighbor	None	High
DCF	It provides the trade-offs between multipath-converging and multipath-expanding	It selects one source node as the reference source per round	High	High	The best path	None	Good
RPL	Low energy consumption	It supports only unicast traffic	Good	Good	Shortest Path	DIO messages	Good

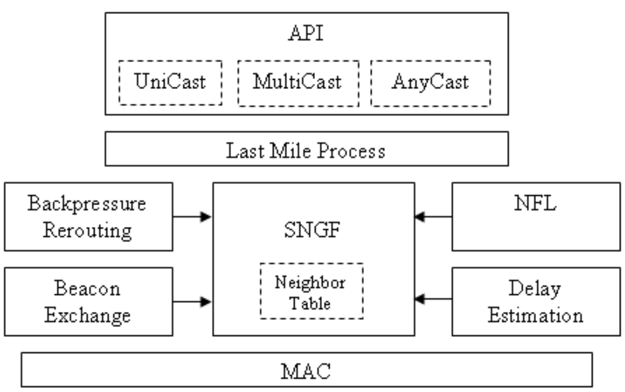

Fig. 17. Speed Protocol (redrawn from [127]).

- A Neighborhood Feedback Loop (NFL).
- Backpressure Rerouting.
- Last mile processing.

Under heavy congestion, SPEED has slightly higher energy consumption mainly because SPEED delivers more packets to the destination than the other protocols when heavily congested. The main advantage of SPEED is that it performs better in terms of end-to-end delay and miss ratio. However, SPEED does not consider energy consumption in its routing protocol. Therefore, for more realistic understanding of SPEED's energy consumption, there is a need to compare it to a routing protocol that is energy-aware.

3) Multi-Path and Multi-SPEED (MMSPEED) Protocol: The MMSPEED is developed for probabilistic QoS guarantee in WSNs. The QoS provisioning is performed in two domains [129]:

- Timeliness domain. This can be accomplished by guaranteeing multiple packet delivery speed options.
- Reliability domain. This can support various reliability requirements by probabilistic multipath forwarding.

These mechanisms for QoS provisioning are realized in a localized way without global network information by employing localized geographic packet forwarding augmented with dynamic compensation, which compensates for local decision inaccuracies as a packet travels towards its destination.

The main advantage of MMSPEED is that it guarantees end-to-end requirements in a localized way, which is desirable for scalability and adaptability to large scale dynamic sensor networks. It can provide QoS differentiation in both reliability and timeliness domains and significantly improves the effective capacity of a sensor network in terms of number of flows that meet both reliability and timeliness requirements.

4) Multimedia Geographic Routing (MGR): In [130], a new architecture called mobile multimedia sensor network (MMSN) and a routing scheme called Mobile Multimedia Geographic Routing (MGR) are presented. In this architecture the mobile multimedia sensor node (MMN) is exploited to enhance the sensor network's capability for event description. The proposed protocol is designed to minimize the energy consumption and satisfy constraints on the average end-to-end delay of specific applications in MMSNs.

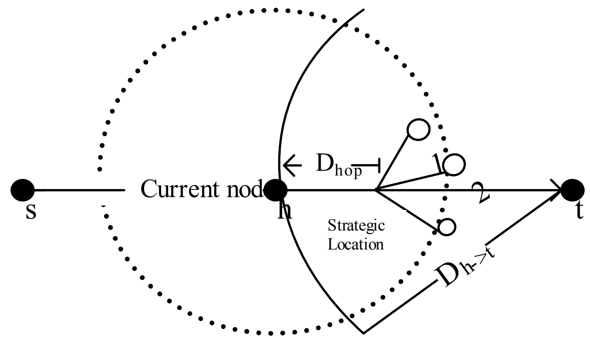

Fig. 18. The Strategic Location Selection in MGR.

In this protocol, the main concern is to treat the delay guaranteeing as the goal with top priority for the QoS provisioning. Then, the protocol continues the attempts to minimize the energy consumption and to enlarge the lifetime of sensors. This motivates to exploit the energy delay tradeoffs for the design of this protocol.

Thus, the protocol's main operation is to select the ideal location of current node's next hop. In order to achieve this, MGR calculate the desired hop distance for next hop selection (Dhop), by dividing the distance from current node to the sink node ($Dh \to t$), with the desired hop count from current node to the sink node ($Hh \to t$).

Based on Dhop calculation, the strategic location of MGR is decided as in figure 18.

The simulation results in [130] show that for delay set to 0.035s, the MGR guarantees the QoS delay in the most cases. In addition to that MGR saves about 30 percent energy consumption and extends the network lifetime when compared to classical geographic routing.

Moreover, there are also others hierarchical protocols apart from the above mentioned that have been proposed for WSNs [131], [132], [133], [134], [135].

In Table X, a QoS-Based Routing Schemes Comparison is presented. Therefore, SAR, SPEED and MMSPEED can provide energy efficient routing with guarantee quality of service considering that the nodes are not mobile. On the other hand, MGR can be more scalable than the others protocols as it can use mobility of the nodes.

Finally, in QoS-Based Protocols a few protocols can partially be included, that are mainly classified and described in details in the categories on the above. These protocols are: MIMO, Sleep/Wake, GRAB, DGR and DCF.

C. Comparison of Multipath and QoS Based Protocols

The LMR is efficient with local multicast and reduces the average number of messages by 1/2D (D is the average node degree) [116]. Moreover, in a network of 400 nodes, in case of unicast, the maximum overhead packet number is 500 while in case of multicast the maximum overhead packet number is 4500.

The HMRP, compared to LEACH and PEGASIS, improves the lifetime (75 percent of the nodes are alive) of LEACH by 200 percent and of PEGASIS by 8 percent [118]. HMRP displays a reduction in energy consumption of 35 percent over LEACH.

The GRAB can successfully deliver over 90 percent of packets with relatively low energy cost, even under the adverse conditions of 30 percent node failures compounded with 15 percent link message losses [117]. For different packet loss rates, the energy remains almost constant around 16054, increasing less than 6 Joules as the packet loss rate grows from 5 to 50 percent. However, The CBMPR increases throughput about 5 8 percent for each additional path, finally reaching at 20 24 percent at four paths.

In the simulation results in [122], RPL shows that for the given topology, 90 percent of paths have a path length of 4 hops or less with an ideal shortest path routing methodology, whereas in RPL Point-to-Point (P2P) routing, 90 percent of the paths will have a length of no more than 5 hops. This result indicates that despite having a non-optimized P2P routing scheme, the path quality of RPL is close to an optimized P2P routing mechanism for the topology in consideration. Moreover, RPL support IPv6 that will be used in all the future networks.

The SAR offers less power consumption than the minimum-energy metric protocol [127]. SAR maintains multiple paths from nodes to Base Station. This ensures fault-tolerance and easy recovery, but the protocol suffers from the overhead of maintaining the tables and states at each sensor node especially when the number of nodes is huge.

The end-to-end delay for the SPEED varies from 10msec to 140msec for a congestion rate from 0ps up to 100ps [128]. Also SPEED manages to deliver 95 percent of its packets to the destination. However, the MMSPEED can provide clear service differentiation in the reliability domain and both flow groups in the simulation can meet their own reliability requirements up to 20 flows [129]. On the other hand, in SPEED protocol, two flow groups are mixed up with no differentiation and it makes flow group 1 to miss reliability requirement of 0.7 for 18 flows and more. Also, MMSPEED may lead to more energy consumption due to more complex computation and longer frame with overhead bits.

The simulations results show that the ROAM outperforms TORA in terms of energy efficiency [115].

X. Future Research Directions

All routing protocols have the same general goal that is to share network reachability information among routers and achieve this in a variety of ways. Thus, they may send a complete routing table to other routers or send specific information on the status of directly connected links.

Alternative routing protocols may send periodic HELLO packets to maintain their status with peer routers or may include advanced information such as a subnet mask or prefix length with route information. The most of the routing protocols share dynamic (learned) information, but in some cases, static configuration information is more appropriate.

However, the major goals for developing routing protocols for WSNs are the following:

- Improvement of network survivability, availability (up time) and service.
- Increase of the sensor network battery life time.
- Guarantee of connectivity under various mission scenarios schemes.

TABLE X
QOS-BASED ROUTING SCHEMES COMPARISON

Scheme	Advantages	Drawbacks	Scalability	Mobility	Route Metric	Periodic Message Type	Robust
SAR	Low power consumption. It maintains multiple paths to destination	Overhead of maintaining the tables and states at each sensor node especially when the number of nodes is huge	Limited	No	The path that minimizes the average weighted QoS metric throughout the lifetime of the network	Hello messages	Low
SPEED	It performs well in terms of end-to-end delay and miss ratio	It does not perform well in heavy congestion	Limited	No	The path that is the Stateless Geographic Non-Deterministic	Hello messages	Low
MMSPEED	It can provide QoS differentiation in both reliability and timeliness domains and significantly improves the effective capacity of a sensor network	In a high load network, it is unable to meet end to end delay requirements	Limited	No	The path that is the Stateless Geographic Non-Deterministic	Hello messages	Low
MGR	It minimizes the energy consumption and satisfy constraints on the average delay	It treats the delay guaranteeing as the goal with top priority	Good	Good	The path with that minimizes the delay	None	Low

- Efficient energy consumption control.
- Minimization of the transfer delay of the mission critical information.
- Reduction of complexity.
- Improvement of WSN performance.

Routing protocols differ in their scalability and performance characteristics. Many routing protocols are designed for small internet works. There are routing protocols that work best in a static environment and have a hard time converging to a new topology when changes occur. However, there are routing protocols that are meant for connecting interior campus networks, and others are meant for connecting different enterprises. The above sections provide more information on the different characteristics of routing protocols.

The WSNs have several restrictions, such as limited energy supply, limited computing power, and limited bandwidth of the wireless links connecting sensor nodes. One of the main design goals of WSNs is to carry out data communication while trying to prolong the lifetime of the network and prevent connectivity degradation by employing aggressive energy management techniques. Many factors influence the design of routing protocols in WSNs. For example, network deployment, network dynamic, data delivery model and data aggregation are major WSNs system design issues and the factors that influence WSN routing design are: energy consumption, scalability and QoS.

Depending on the application and the size of the network, different architectures and design goals-constraints have been considered for sensor networks. It is clear that the performance of a routing protocol is closely related to the architectural model.

The most important factors that influence the selection of a routing protocol are:

- *Network Dynamics:* The main components in a sensor network are the sensor nodes, sink and monitored events. In the most of the network architectures sensor nodes are assumed to be stationary. On the other hand, supporting the mobility of sinks or cluster-heads is sometimes necessary. Routing messages sent or received from nodes are more challenging since route stability becomes an important optimization factor, in addition to energy, bandwidth etc. The sensed event can be dynamic or static and this depends on the application. Thus, in a target detection application, the event is dynamic, but forest monitoring for early fire prevention is a static event.
- *Node Deployment:* This affects the performance of the routing protocol. The deployment may be deterministic or self-organizing. In deterministic situations, the sensors are placed manually and all the data are routed through pre-defined paths. In self-organizing systems, the sensor nodes are scattered randomly and create an infrastructure in an ad hoc manner.
- *Energy Considerations:* The set up of a route is greatly influenced by energy considerations. Since the transmission power of a wireless radio depends on distance squared or even higher order in the presence of obstacles, multi-hop routing will consume less energy than direct communication. However, multi-hop routing may add significant overhead for topology management and medium access control. In Contrast, direct routing performs well enough if all the nodes are very close to the sink.
- *Data Delivery Models:* The data delivery model to the sink, depending on the application of the sensor network, can be continuous, event-driven, query-driven and hybrid. In the continuous delivery model, each sensor sends data periodically. In event-driven and query-driven models, the transmission of data is triggered when an event occurs or a query is generated by the sink. Moreover, there are some networks that apply a hybrid model using a combination of continuous, event-driven and query-driven data delivery. The routing protocol is based on the data delivery model, especially with regard to the

minimization of energy consumption and route stability.

- *Node Capabilities:* In a sensor network, different functionalities can be associated with the sensor nodes. In most networks, a node can be dedicated to a particular special function such as relaying, sensing and aggregation, as engaging the three functionalities at the same time on a node might quickly drain the energy of that node.
- *Data Aggregation/Fusion:* The sensor nodes might generate similar packets from multiple nodes that can be aggregated so that the number of transmissions would be reduced. Data aggregation is the combination of data from different sources. This can be fulfilled by using functions such as suppression, min, max and average. These functions can be performed either partially or fully in each sensor node. The computation can be less energy consuming than communication and substantial energy savings can be obtained through data aggregation. This technique can achieve energy efficiency and traffic optimization in a number of routing protocols. In many network architectures all aggregation functions are assigned to more powerful and specialized nodes.

In the recent years a large number of energy efficient routing protocols for the WSNs have been developed. However, there is still a lot of work that has to be done, not only in the area of energy efficiency but also, in other areas. Some factors that should be examined when developing a routing protocol may be the following:

- *Energy Balanced Network*. When developing an energy efficient routing protocol the load balancing of the energy that the sensors consume should be one of the main targets of the protocol. This means that the routing protocols need to minimize the energy consumption of the network by selecting not only the shortest routes but also the routes that will lead to the extension of the network lifetime.
- *Network Security*. An important factor, apart from energy consumption, is the security that the protocols can offer to protect against eavesdropping and malicious behavior and more advanced schemes to be developed.
- *Nodes Mobility*. The nodes in the WSN were assumed to be static. In the last years there is an increased interest in applications that support the mobility of the users. An example of this is the medical care applications where the mobile sensors are attached to the patients and need to send continues data from the patient to the doctor. There are some protocols that cover this, but still there is a lot of scope for future research in this area.
- *Performance Evaluation on Real Environment*. The most of the protocols for the WSNs have been evaluated through simulations. However, it is important to evaluate the performance of these protocols in real environments with a lot of users.
- *Real-Time Application and QoS*. It is an ongoing need to develop real-time application that will offer high level of QoS to the end users. Thus, it is important for the scientists to make a lot of efforts to develop routing protocols that will offer QoS to real-time applications.
- *Integration of Fixed with Mobile Networks*. Most of the applications, for example in health care monitoring, require the data collected from the sensor nodes to be transmitted to a server so that the doctor may access and make a diagnosis or send medication to the patients. In this case the routing requirements of each environment are different, further research is necessary for handling this kind of situations.
- *QoS routing protocols*. The QoS is important in the delivery of the data in critical applications such as healthcare. Thus, the development of routing protocols that consider both energy efficiency and accurate delivery of data will help on this direction.

Although, many of the proposed algorithms have been evaluated by using simulation tools i.e. NS2, Sensor Toolkit, many of them might be implemented in real deployments i.e. Implicit Geographic Forwarding (IGF) [98] in military networks, The Topology Dissemination Based on Reverse-Path Forwarding Protocol (TBRPF) [42], [43], Energy-aware Temporarily Ordered Routing Algorithm (E-TORA) [51] and COUGAR [85] approach in health systems.

Also, the algorithms Two-Tier Data Dissemination (TTDD) [67], Column-Row Location, Routing On-demand Acyclic Multipath (ROAM) [115], Single Winner Algorithm (SWE) [90] and Multiple Winner Algorithm (MWE) [90], since they don't perform well in mobile environments, can be further studied and improved in order to overcome these low or limited mobility and minimize the energy consumption drawbacks.

An analytical summary of the classification of the routing protocols may be found in Table XI.

In the paper, each protocol is described in detail once in the main category that it belongs. However, the most of the above described routing protocols, due to their characteristics may be partially belong in more than one category. For example, based on its main characteristics, TTDD can be classified as hierarchical-based. However, this protocol may perform in some cases as location-based or multipath-based protocol. Thus, in the Table XI, TTDD is classified as hierarchical-based (bold X), location-based (normal X) and multipath-based (normal X).

XI. Conclusion

In our days the WSNs have greatly expanded playing an important role for the data efficient selection and their delivery. The energy efficiency is a very important issue for the networks especially for WSNs which are characterized by limited battery capabilities. The complexity and reliance of corporate operations on WSNs require the use of energy-efficient routing techniques and protocols, which will guarantee the network connectivity and routing of information with the less required energy.

In this paper, we concentrate on the energy efficient protocols that have been developed for WSNs. We classify them in *flat, hierarchical, query-based, coherent and non- coherent-based, negotiation-based, location-based, mobile agent-based, multipath-based, QoS-based.*

The flat protocols may be an ideal solution for a small network with fixed nodes. However, in a large network they

TABLE XI
CLASSIFICATION OF ROUTING PROTOCOLS

	Flat Protocols	Hierarchical Protocols	Query Based Protocols	Coherent and Non-Coherent	Negotiation Based Protocols	Location Based Protocols	Mobile Agent-Based Protocols	Multipath Based Protocols	QoS Based Protocols
WRP	**X**								
TBRPF	**X**							X	
TORA	**X**							X	
Gossiping	**X**								
Flooding	**X**								
RR	**X**		X						
E-TORA	**X**								
ZRP	**X**								
LEACH		**X**							
LEACH-C		**X**							
PEGASIS		**X**							
TEEN		**X**							
APTEEN		**X**							
VGA		**X**			X				
TTDD		**X**				X		X	
BCDCP		**X**							
MIMO		**X**						X	X
HPAR		**X**							
Sleep/Wake		**X**						X	X
GBDD		**X**							
ELCH		**X**						X	
NHRPA		**X**							
SHPER		**X**							
DHAC		**X**							
DD			**X**					X	
COUGAR			**X**			X			
ACQUIRE			**X**			X			
SWE				**X**					
MWE				**X**				X	
SPIN-PP			X		**X**				
SPIN-EC			X		**X**				
SPIN-BN			X		**X**				
SPIN-RL			X		**X**				
DREAM						**X**			
GEAR						**X**			
GEM		X				**X**			
IGF						**X**			
SELAR						**X**			
GDSTR						**X**			
MERR						**X**			
OGF	X					**X**			
PAGER-M						**X**			
HGR	X					**X**			
MIP							**X**		
IEMF/IEMA							**X**		
ROAM								**X**	
LMR								**X**	
GRAB								**X**	X
HMRP		X						**X**	
CBMPR		X						**X**	
DGR								**X**	X
DCF								**X**	X
RPL								**X**	
SAR									**X**
SPEED									**X**
MMSPEED								X	**X**
MGR									**X**

become infeasible because of link and processing overhead. The hierarchical protocols try to solve this problem and to produce scalable and efficient solutions. They divide the network into clusters and to efficiently maintain the energy consumption of sensor nodes and perform data aggregation and fusion in order to decrease the number of transmitted messages to the sink. The clusters are formatted based on the energy reserve of sensors and sensor's proximity to the cluster head. Thus, hierarchical protocols are suitable for sensor networks with heavy load and wide coverage area. On the other hand, the location based protocols may be useful for high dynamic networks as they do not need a state in routers nor in packet header and do not cause flood in the search. They use location information in order to calculate the distance among nodes, thus minimizing the energy consumption and extend the lifetime of the network.

The negotiation based protocols can perform close to the theoretical optimum in both point-to-point and broadcast networks. On the other hand, they can not guarantee the successful delivery of data. The multipath protocols maintain multiple paths from nodes to sink. This ensures fault tolerance and easy recovery but as they need to find multiple paths they suffer from the overhead of maintaining the tables and states at each sensor node especially. On the other hand, in Query-based routing protocols, the destination nodes send a query for data from a node through the network and the node having this data sends these data back to the destination nodes. Query-based routing is used to networks with dynamic network topologies such as WSNs. A feature of route-query protocols is the support for multiple route replies. The problem of the accurate delivery of the data from the source to the destination is solved by QoS protocols. They ensure optimized QoS metrics such as delay bound, energy efficiency, and low bandwidth consumption while achieving energy efficiency in WSNs applications. The coherent-based routing protocol is an energy efficient mechanism where only the minimum processing is done by the sensor node. At non-coherent data processing based on routing, the sensor nodes locally process the actual data and then send to the other nodes for further processing.

The application of each scheme in a WSN has its advantages and disadvantages, as Tables II, III, IV, V, VI, VII, VIII and IX depict. Therefore, further investigation in order to develop a scheme that will extend the lifetime of the WSNs is needed in order to improve the energy consumption of the sensors on the network.

With the penetration of next generation wireless mobile networks and personal communication systems and the exploitation of the sensor architectures a new type of scheme has been occurred, the mobile agent based. Mobile agent-based routing protocols have as main component a mobile agent, software or program, which migrates among the nodes of a network to perform a task autonomously and intelligently, based on the environment conditions. However, since these agents present different characteristics in terms of coverage, bandwidth and delay, routing is a critical process and should be taken under careful consideration in order to ensure the continuity of connections and the energy consumption of the nodes.

Therefore, the application of the proper routing protocol will increase the network lifetime and at the same time it will ensure the network connectivity and efficient data delivery.

REFERENCES

[1] Nikolaos A. Pantazis, Dimitrios D. Vergados, "A Survey on Power Control Issues in Wireless Sensor Networks," *IEEE Communications Surveys*, 2007, Vol. 9, Issue 4, pp. 86-107.

[2] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, "Wireless Sensor Networks: A Survey," *Computer Networks*, 2002, Vol. 38, Issue 4, pp. 399-422.

[3] Al-Karaki, A. Kamal, "Routing Techniques in Wireless Sensor networks: A Survey," *Security and Networks*, 2004, Vol. 11, Issue 6, pp. 6-28.

[4] K. Akkaya, M. Younis, "A Survey on Routing Protocols for Wireless Sensor Networks," *Ad Hoc Network, Elsevier*, 2005, Vol. 3, Issue 3, pp. 325-349.

[5] S. Guo, O. Yang, "Energy-Aware Multicasting in Wireless Ad hoc Networks: A Survey and Discussion," *Computer Communications, Elsevier*, 2007, Vol. 30, Issue 9, pp. 21292148.

[6] J. Yick, B. Mukherjee, D. Ghosal, "Wireless Sensor Network Survey," *Computer Networks*, 2008, Vol. 52, Issue 12, pp. 2292-2330.

[7] G. Anastasi, M. Conti, M. Francesco, A. Passarella, "Energy Conservation in Wireless Sensor Networks: A survey," *Ad Hoc Networks*, 2009, Vol. 7, Issue 3, pp. 537-568.

[8] R .V. Biradar, V. C.Patil, S. R. Sawant, R. R. Mudholkar, "Classifiacation and Comparison of Routing Protocols in Wireless Sensor Networks," *Special Issue on Ubiquitous Computing Security Systems*, 2009, Vol. 4, Issue 2, pp. 704-711.

[9] R. Yadav, S. Varma, N. Malaviya, "A Survey of MAC Protocols for Wireless Sensor Networks," *UbiCC Journal*, 2009, Vol. 4, Issue 3, pp. 827-833.

[10] S. Ehsan, B. Hamdaoui, "A Survey on Energy-Efficient Routing Techniques with QoS Assurances for Wireless Multimedia Sensor Networks," *IEEE Commun. Surveys Tuts.*, 2011, Vol. 14, Issue 2, pp. 265-278.

[11] E. Shi, A. Perrig, "Designing Secure Sensor Networks," *IEEE Wireless Commun.*, 2004, Vol. 11, Issue 6, pp. 38-43.

[12] A. Basharat, N. Catbas, M. Shah, "A Framework for Intelligent Sensor Network with Video Camera for Structural Health Monitoring of Bridges," *In Proc. 3rd IEEE International Conference on Pervasive Computing and Communications (PerCom)*, Hawaii, 2005, pp. 385-389.

[13] J. Paek, K. Chintalapudi, R. Govindan, J. Caffrey, S. Masri, "A Wireless Sensor Network for Structural Health Monitoring: Performance and Experience," *In Proc. 2nd IEEE Workshop on Embedded Networked Sensors EmNetS-II*, Syndey Australia, 2005, pp. 1-10.

[14] S. Dengler, A. Awad, F. Dressler, "Sensor/Actuator Networks in Smart Homes for Supporting Elderly and handicapped People," *In Proc. 21st International Conference on Advanced Information Networking and Applications Workshops*, Niagara Falls, 2007, Vol. 2, pp. 863-868.

[15] S. Li, "Wireless Sensor Actuator Network for Light Monitoring and Control Application," *In Proc. IEEE Consumer Communications and Networking Conference*, Las Vegas, 2006, Vol. 2, pp. 974-978.

[16] C. Lombriser, N. Bharatula, D. Roggen, G. Troster, "On-Body Activity Recognition in a Dynamic Sensor Network," *In Proc. 2nd International Conference on Body Area Networks (BodyNets)*, Florence, Italy, June 2007, Vol. 17, pp. 1-6.

[17] P. Gibbons, B. Karp, Y. Ke, S. Nath, S. Seshan, "IrisNet: AN Architecture for a Worldwide Sensor Web," *IEEE Pervasive Computing*, 2003, Vol. 2, Issue 4, pp. 22-33.

[18] M. Srivastava, M. Hansen, J. Burke, A. Parker, S. Reddy, G. Saurabh, M. Allman, V. Paxson, D. Estrin, "Wireless Urban Sensing System," *CENS Technical Report 65*, 2006, pp. 1-20.

[19] A. Dunkels, R. Gold, S. Marti, A. Pears, M. Uddenfeldt, "Janus: An Architecture for Flexible Access to Sensor Nnetwork," *In Proc. 1st ACM Workshop on Dynamic Interconnection of Networks*, Cologne, Germany, 2005, pp 48-52.

[20] Q. Wang, M. Hempstead, W. Yang, "A Realistic Power Consumption Model for Wireless Sensor Network Devices," *In Proc. 3rd Annual IEEE Communications Society on Sensor and Ad Hoc Communications and Networks*, Reston, 2006, Vol. 1, pp. 286-295.

[21] A. Dunkels, F. Osterlind, N. Tsiftes, Z. He, "Software-Based On-Line Energy Estimation for Sensor Nodes," *In Proc. 4th workshop on Embedded Networked Sensors*, New York, USA, 2007, pp. 28-32.

[22] S. Kellner, M. Pink, D. Meier, E. Blass, "Towards a Realistic Energy Model for Wireless Sensor Networks," *In Proc. 5th Annual Conference on Wireless on Demand Network Systems and Services*, Garmisch, 2008, pp. 97-100.

[23] Q. Wang, W. Yang, "Energy Consumption Model for Power Management in Wireless Sensor Networks," *In Proc. 4th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks*, SanDiego, 2007, pp. 142-151.

[24] A. Shareef, Y. Zhu, "Energy Modeling of Wireless Sensor Nodes Based on Petri Nets," *In Proc. 39th International Conference on Parallel Processing*, San Diego, 2010, pp. 101-110.

[25] H. Zhou, D. Luo, Y. Gao, D. Zuo, "Modeling of Node Energy Consumption for Wireless Sensor Networks," *Wireless Sensor Network*, 2011, Vol. 3, Issue 1, pp. 18-23.

[26] T. Lee, "The Design of CMOS Radio-Frequency Integrated Circuits," *Cambridge University Press*, 1998.

[27] A. Mainwaring, J. Polastre, R. Szewczyk, D. Culler, J. Anderson, "Wireless Sensor Networks for Habitat Monitoring," *In Proc. 1st International Workshop on Wireless Sensor Networks and Applications*, Atlanta, 2002, pp. 88-97.

[28] P. Wang, I. Akyildiz, "Effects of Different Mobility Models on Traffic Patterns in Wireless Sensor Networks," *In Proc. IEEE Global Communications Conference Exhibition and Industry Forum (GLOBECOM)*, Miami, 2010, pp. 1-5.

[29] J. M. Rabaey, M. J. Ammer, J. L. da Silva, D. Patel, S. Roundy, "PicoRadio Supports Ad hoc Ultralow Power Wireless Networking," *IEEE Computer*, 2000, Vol. 33, Issue 7, pp. 4248.

[30] A. P. Chandrakasan, R. Min, M. Bhardwaj, S. Cho, A. Wang, "Power Aware Wireless Microsensor Systems," *Keynote paper at ESSCIRC*, Florence, Italy, 2002, pp. 47-54.

[31] L. Alazzawi, A. Elkateeb, "Performance Evaluation of the WSN Routing Protocols Scalability," *Journal of Computer Systems, Networks, and Communications*, 2008, Vol. 14, Issue 2, pp. 1-9.

[32] S.C. Ergen, P. Varaiya, "On Multi-Hop Routing for Energy Efficiency," *IEEE Commun. Lett.*, 2005, Vol. 9, Issue 10, pp. 880-881.

[33] J. Chang,, L. Tassiulas, "Energy Conserving Routing in Wireless Ad-Hoc Networks," *In Proc. International Conference on Computer Communications*, Tel-Aviv, Israel, 2000, pp. 22-31.

[34] Y. Fan, A. Chen, L. Songwu, L. Zhang, "A Scalable Solution to Minimum Cost Forwarding in Large Scale Sensor Networks," *In Proc. 10th International Conference on Computer Communications and Networks*, Scottsdale, Orlando, USA, 2001, pp. 304309.

[35] Y. J. Zhai, R. Govindan, D. Estrin, "Residual Energy Scans for Monitoring Wireless Sensor Networks," *In Proc. IEEE Wireless Commun. and Networking Conference (WCNC'02)*, Orlando, USA, 2002, Vol. 1, pp. 356-362.

[36] R. Mini, M. Machado, A. Loureiro, B. Nath, "Prediction-Based Energy Map for Wireless Sensor Networks," *Ad Hoc Networks*, 2005, Vol.3, Issue 2, pp. 235-253.

[37] D. Guidoni, R. Mini, A. Loureiro, "Creating Small-World Models in Wireless Sensor Networks," *In Proc. 19th IEEE International Symposium on Personal Indoor and Mobile Radio Communications*, Cannes, France, 2008, pp. 1-6.

[38] L. Junhai, X. Liu, Y. Danxia, "Research on Multicast Routing Protocols for Mobile ad-hoc Networks," *Computer Networks*, 2008, Vol. 52, Issue 5, pp. 988-997.

[39] A. Savvides, C. Han, M. Srivastava, "Dynamic Fine-Grained Localization in Ad-Hoc Networks of Sensors," *In Proc. 7th ACM Annual International Conference on Mobile Computing and Networking (MobiCom)*, Italy, 2001, pp. 166-179.

[40] P. Arce, J. Guerri, A. Pajares, O. Lazaro, "Performance Evaluation of Video Streaming Over Ad Hoc Networks Using Flat and Hierarchical Routing Protocols," *Book:Mobile Networks and Applications*, 2008, pp. 324-336.

[41] S. Murphy, L. Aceves, "An Efficient Routing Protocol for Wireless Networks," *Mobile Networks and Applications, ACM Journal*, USA, Hingham, 1996, Vol. 1, Issue 2, pp. 183-197.

[42] B. Bellur, R. Ogier, "A Reliable, Efficient Topology Broadcast Protocol for Dynamic Networks," *In Proc. IEEE INFOCOM '99*, New York, USA, 1999, vol.1, pp.178-186.

[43] R. Ogier, F. Templin, M. Lewis, "Topology Dissemination Based on Reverse-Path Forwarding (TBRPF)," *RFC Editor 2004*.

[44] H. Pucha, S. Das, Y. Hu, "The Performance Impact of Traffic Patterns on Routing Protocols in Mobile Ad Hoc Networks," *Computer Networks*, 2007, Vol. 51, Issue 12, pp. 3595-3616.

[45] D. Park, S. Corson, "A Highly Adaptive Distributed Routing Algorithm for Mobile Wireless Networks," *In Proc. 16th Conference on Computer and Communications Societies*, Japan, 1997, pp. 1405-1413.

[46] S. Bali, "Performance Comparisons of DSR and TORA," *Wireless Networks and Mobile Computing*, South Carolina, 2001, pp. 10-15.

[47] S. Hedetniemi, A. Liestman, "A Survey of Gossiping and Broadcasting in Communication Networks," *Book:Networks*, 1998, Vol. 18, Issue 4, pp. 319-349.

[48] H. Lim, C. Kim, "Flooding in Wireless Ad Hoc Networks," *Computer Communications*, 2001, Vol. 24, Issue 3, pp. 353-363.

[49] M. Ma, Y. Yang, C. Ma, "Single-Path Flooding Chain Routing in Mobile Wireless Networks," *International Journal of Sensor Networks*, 2006, Vol. 1, issue 2, pp. 11-19.

[50] D. Braginsky, D. Estrin, "Rumor Routing Algorithm for Sensor Networks," *In Proc. 1st ACM International Workshop on Wireless Sensor Networks and Applications*, USA, Atlanta, 2002, pp. 22-31.

[51] F. Yu, Y. Li, F. Fang, Q. Chen, "A New TORA-Based Energy Aware Routing Protocol in Mobile Ad Hoc Networks," *In Proc. 3rd IEEE/IFIP International Conference in Central Asia on Internet (ICI)*, Tashkent, 2007, pp. 1-4.

[52] K. Yadav, J. Singh, B. Singla, "Proactive vs Reactive Protocols for Ad-Hoc Networks," *In Proc. World Congress on Science, Engineering and Technology*, Germany, 2008, pp. 20-25.

[53] S. Lee, Y. Yu, S. Nelakuditi, Z. Zhang, C. Chuah, "Proactive vs Reactive Approaches to Failure Resilient Routing," *In Proc. 23rd AnnualJoint Conference of the IEEE Computer and Communications Societies*, China, 2004, Vol. 1, pp. 176-186.

[54] Li Layuan, Li Chunlin, Yaun Peiyan, "Performance Evaluation and Simulations of Routing Protocols in Ad Hoc Networks," *Computer Communications*, 2007, Vol. 30, Issue 8, pp. 1890-1898.

[55] Z.J. Haas, "A New Routing Protocol for the Reconfigurable Wireless Networks," *In Proc. 6th International Conference on Universal Personal Communications Record*, San Diego, CA, 1997, Vol. 2, pp. 562-566.

[56] Z. Haas, M. Pearlman, "The Performance of Query Control Schemes for the Zone Routing Protocol," *IEEE/ACM Trans. Netw.*, USA, Piscataway, 2001, Vol. 9, Issue 4, pp. 427-438.

[57] W. Heinzelman, A. Chandrakasan, H. Balakrishnan, "Energy-Efficient Communication Protocol for Wireless Microsensor Networks," *In Proc. 33rd Hawaii International Conference on System Sciences*, HI, USA, 2000, Vol. 8, pp. 110.

[58] M. J. Handy, M. Haase, D. Timmermann, "Low Energy Adaptive Clustering Hierarchy with Deterministic Cluster-Head Selection," *In Proc. 4th International Workshop on Mobile and Wireless Communications Network*, USA, 2002, Vol. 1, pp. 368-372.

[59] D. A. Vidhate, A. K. Patil, S. S. Pophale, "Performance Evaluation of Low Energy Adaptive Clustering Hierarchy Protocol for Wireless Sensor Networks," *In Proc. International Conference and Workshop on Emerging Trends in Technology (ICWET 2010)TCET*, Mumbai, India, 2010, pp. 59-63.

[60] W. Heinzelman, A. Chandrakasan, H. Balakrishnan, "An Application-Specific Protocol Architecture for Wireless Microsensor Networks," *IEEE Trans. Wireless Commun.*, 2002, Vol. 1, Issue 4, pp. 60-70.

[61] S. Lindsey, C.Raghavendra, "PEGASIS: Power-Efficient GAthering in Sensor Information Systems," *In Proc. IEEE Aerospace Conference*, USA, Montana, 2002, Vol. 3, pp. 1125-1130.

[62] S. Jung, Y. Han, T. Chung, "The Concentric Clustering Scheme for Efficient Energy Consumption in the PEGASIS," *In Proc. 9th International Conference on Advanced Communication Technology*, Gangwon-Do, 2007, Vol. 1, pp. 260-265.

[63] L. Almazaydeh, E. Abdelfattah, M. Al-Bzoor, A. Al-Rahayfeh, "Performance Evaluation of Routing Protocols in Wireless Sensor Networks," *Computer Science and Information Technology*, 2010, Vol. 2, Issue 2, pp. 64-73.

[64] A. Manjeshwar, D. Agrawal, "Teen: A Routing Protocol for Enhanced Efficiency in Wireless Sensor Networks," *In Proc. 15th International Parallel and Distributed Processing Symposium (IPDPS'01) Workshops*, USA, California, 2001, pp. 2009-2015.

[65] A. Manjeshwar, D. Agrawal, "APTEEN: A Hybrid Protocol for Efficient Routing and Comprehensive Information Retrieval in Wireless Sensor Networks," *In Proc. International Parallel and Distributed Processing Symposium*, Florida, 2002, pp. 195-202.

[66] J.N Al-Karaki, R. Mustafa, A. Kamal, "Data Aggregation in Wireless Sensor Networks Exact and Approximate Algorithms," *In Proc. IEEE Workshop High Performance Switching and Routing 2004*, Phoenix, AZ, 2004, pp. 241-245.

[67] H. Luo, F. Ye, J. Cheng, S. Lu, L. Zhang, "TTDD: Two-Tier Data Dissemination in Large-Scale Wireless Sensor Networks," *Wireless Networks*, Springer Netherlands, 2005, Vol. 11, Issue 1, pp. 161-175.

[68] S. Muruganathan, D. Ma, R. Bhasin, A. Fapojuwo, "A Centralized Energy-Efficient Routing Protocol for Wireless Sensor Networks," *IEEE Commun. Mag.*, 2005, Vol. 43, Issue 3, pp. 8-13.

[69] Y. Yuan, Z. He, M. Chen, "Virtual MIMO-based Cross-layer Design for Wireless Sensor Networks," *IEEE Trans. Veh. Technol.*, 2006, Vol. 55, Issue 3, pp. 856-864.

[70] Q. Li, J. Aslam, D. Rus, "Hierarchical Power-aware Routing in Sensor Networks," *In Proc. DIMACS Workshop on Pervasive Networking*, California, 2001, pp. 25-27.

[71] Y. Wu, S. Fahmy, N. Shroff, "Energy Efficient Sleep/Wake Scheduling for Multi-Hop Sensor Networks: non-Convexity and Approximation Algorithm," *In Proc. 26th Annual IEEE Conference on Computer Communications (INFOCOM 2007)*, Anchorage, Alaska, 2007, pp. 1568-1576.

[72] T.P. Sharma, R.C. Joshi, Manoj Misra, "GBDD: Grid Based Data Dissemination in Wireless Sensor Networks," *In Proc. 16th International Conference on Advanced Computing and Communications (ADCOM 2008)*, Chennai, India, 2008, pp. 234-240.

[73] J. Lotf, M. Bonab, S. Khorsandi, "A Novel Cluster-based Routing Protocol with Extending Lifetime for Wireless Sensor Networks," *In Proc. 5th IFIP International Conference on Wireless and Optical*

Communications Networks (WOCN08), East Java Indonesia, Surabaya, 2008, pp. 1-5.

[74] H. Cheng, G. Yang, S. Hu, "NHRPA: A Novel Hierarchical Routing Protocol Algorithm for Wireless Sensor Networks," *China Universities of Posts and Telecommunications*, 2008, Vol. 15, Issue 3, pp. 75-81.

[75] D. Kandris, P. Tsioumas, A. Tzes, G. Nikolakopoulos, Dimitrios D. Vergados, "Power Conservation Through Energy Efficient Routing in Wireless Sensor Networks," *Sensors*, 2009, Vol. 9, Issue 9, pp. 7320-7342.

[76] C. H. Lung, C. Zhou, "Using Hierarchical Agglomerative Clustering in Wireless Sensor Networks: An Energy-efficient and Flexible Approach," *Ad Hoc Networks*, 2010, Vol. 8, Issue 3, pp. 328-344.

[77] S. Zhao, L. Tan, J. Li, "A Distributed Energy Efficient Multicast Routing Algorithm for WANETs," *Sensor Networks*, 2006, Vol. 2, Issue 2, pp. 62- 67.

[78] Y. Yang, H. Wu, H. Chen, "SHORT: Shortest Hop Routing Tree for Wireless Sensor Networks," *Sensor Networks*, 2007, Vol. 2, Issue 5, pp. 368-374.

[79] Y. Jia, L. Zhao, B. Ma, "A Hclustering-Based Routing Protocol for Wireless Sensor Networks Supporting Multiple Data Aggregation Qualities," *Sensor Networks*, 2008, Vol. 4, Issue 1, pp. 79-91.

[80] W. El-Hajj, D. Kountanis, A. Al-Fuqaha, S. Guizani, "A Fuzzy-Based Virtual Backbone Routing for Large-Scale MANETs," *Sensor Networks*, 2008, Vol. 4, Issue 4, pp. 250-259.

[81] J. Liu, X. Hong, "An Online Energy-Efficient Routing Protocol with Traffic Load Prospects in Wireless Sensor Networks," *Sensor Networks*, 2009, Vol. 5, Issue 3, pp. 185-197.

[82] S. Giannoulis, C. Antonopoulos, E. Topalis, S. Koubias, "ZRP versus DSR and TORA: A comprehensive survey on ZRP performance," *In Proc. 10th IEEE Conference on Emerging Technologies and Factory Automation*, Catania, 2005, pp. 1017-1024.

[83] N. Sadagopan, B. Krishnamachari, A. Helmy, "Active Query Forwarding in Sensor Networks," *Ad Hoc Networks*, 2005, Vol. 3, Issue 1, pp. 91-113.

[84] C. Intanagonwiwat, R. Govindan, D. Estrin, "Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks," *In Proc. 6th Annual International Conference on Mobile Computing and Networking*, Boston, Massachusetts, 2000, pp. 56-67.

[85] Y. Yao, J. Gehrke, "The Cougar Approach to In-Network Query Processing in Sensor Networks," *SIGMOD Record*, 2002, Vol. 31, Issue 3, pp. 9-18.

[86] Nikolaos A. Pantazis, Dimitrios J. Vergados, Dimitrios D. Vergados, "Increasing Intelligent Wireless Sensor Networks Survivability by Applying Energy-Efficient Schemes," *In Proc. 3rd IFIP International Conference on Artificial Intelligence Applications and Innovations, Springer IFIP (International Federation for Information Processing)*, 2006, Vol. 204, pp. 657-664.

[87] N. Sadagopan, B. Krishnamachari, A. Helmy, "Active Query Forwarding in Sensor Networks (ACQUIRE)," *Ad Hoc Networks*, 2005, Vol. 3, Issue 1, pp. 91-113.

[88] K. Sohrabi, J. Pottie, "Protocols for Self-Organization of a Wireless Sensor Network," *IEEE Pers. Commun.*, 2000, Vol. 7, Issue 5, pp 16-27.

[89] V. Jolly, S. Latifi, "Comprehensive Study of Routing Management in Wireless Sensor Networks-Part-2," *In Proc. International Conference on Wireless Networks*, Las Vegas, Nevada, USA, 2006, pp. 4962.

[90] D. Cevizovic, S. Galovic, S. Zekovic, Z. Ivic, "Boundary Between Coherent and Noncoherent Small Polaron Motion: Influence of the Phonon Hardening," *Physica B:Condensed Matter*, 2009, Vol. 404, Issue 2, pp. 270-274.

[91] J. Kulik, W. Rabiner, H. Balakrishnan, "Adaptive Protocols for Information Dissemination in Wireless Sensor Networks," *In Proc. 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking*, Massachusetts Institute of Technology, USA, Washington, 1999, pp. 174-185.

[92] F. Bokhari, "Energy-Efficient QoS-based Routing Protocol for Wireless Sensor Networks," *Parallel and Distributed Computing, Department of Computer Science, Lahore University of Management Sciences*, 2010, Vol. 70, Issue 8, pp. 849-85.

[93] C. M. Cordeiro, D. P. Agrawal, "Book: Ad hoc and Sensor Networks:Theory and Applications Edition," *World Scientific*, 2006.

[94] J. Kulik, W. Heinzelman, H. Balakrishnan, "Negotiation-Based Protocols for Disseminating Information in Wireless Sensor Networks," *Wireless Networks Journal*, 2004, Vol. 8, Issue 2, pp. 169-185.

[95] S. Basagni, I. Chlamtac, V. Syrotiuk, B. Woodward, "A Distance Routing Effect Algorithm for Mobility (DREAM)," *In Proc. 4th annual ACM/IEEE international conference on Mobile computing and networking*, USA, Texas, 1998, pp. 67-84.

[96] Y. Yu, R. Govindan, D. Estrin, "Geographical and Energy Aware Routing: A Recursive Data Dissemination Protocol for Wireless Sensor Networks," *UCLA Computer Science Department Technical Report*, 2001, pp. 1-11.

[97] J. Newsome, D. Song, "GEM: Graph EMbedding for Routing and Data-centric Storage in Sensor Networks Without Geographic Information," *In Proc. 1st International Conference on Embedded Networked Sensor Systems*, California, USA, 2003, pp. 76-88.

[98] B. Blum, T. He, S. Son, J. Stankovic, "IGF: A State-Free Robust Communication Protocol for Wireless Sensor Networks," *Technical Report CS-2003-11*, Department of Computer Science, University of Virginia, USA, 2003.

[99] G. Lukachan, M. Labrador, "SELAR: Scalable Energy-Efficient Location Aided Routing Protocol for Wireless Sensor Networks," *In Proc. 29th Annual IEEE International Conference on Local Computer Networks*, USA, Florida, 2004, pp. 694-695.

[100] B. Leong, B. Liskov, R. Morris, "Geographic Routing Without Planarization," *In Proc. 3rd Conference on Networked Systems Design and Implementation*, San Jose, CA, 2006, Vol. 3, pp. 25-39.

[101] M. Zimmerling, W. Dargie, J.M. Reason, "Energy-Efficient Routing in Linear Wireless Sensor Networks," *In Proc. 4th IEEE Internatonal Conference on Mobile Adhoc and Sensor Systems (MASS 2007)*, Italy, Pisa, 2007, pp. 1-3.

[102] D. Chen, P. Varshney, "On-demand Geographic Forwarding for Data Delivery in Wireless Sensor Networks," *Computer Communications*, 2007, Vol. 30, Issue 14-15, pp. 29542967.

[103] L. Zou, M. Lu, Z. Xiong, "PAGER-M: A Novel Location-Based Routing Protocol for Mobile Sensor Networks," *In Proc. 2007 ACM SIGMOD International Conference on Management of Data*, Beijing, China, 2007, pp. 1182-1185.

[104] I. Stojmenovic, X. Lin, "Loop-free Hybrid Single- Path/Flooding Routing Algorithms with Guaranteed Delivery for Wireless Networks," *IEEE Trans. Parallel Distrib. Syst.*, Canada, 2001, Vol. 12, Issue 10, pp. 1023-1032.

[105] M. Chen, V. Leung, S. Mao, Y. Xiao, I. Chlamtac, "Hybrid Geographical Routing for Flexible Energy-Delay Trade-Offs," *IEEE Trans. Veh. Technol.*, 2009, Vol. 58, Issue 9, pp. 4976-4988.

[106] K. Sha, J. Du, W. Shi, "WEAR: A Balanced, Fault-Tolerant, Energy-Aware Routing Protocol in WSNs," *Sensor Networks*, 2006, Vol. 1, issue 3, pp. 156-168.

[107] K. Liu, N. Abu-Ghazaleh, "Aligned Virtual Coordinates for Greedy Geometric Routing in WSNs," *Sensor Networks*, 2008, Vol. 3, Issue 4, pp. 252-265.

[108] G. Wang, L. Zhang, J. Cao, "Hole-Shadowing Routing in Large-Scale MANETs," *Sensor Networks*, 2008, Vol. 4, Issue 4, pp. 220-229.

[109] M. Chen, T. Kwon, S. Mao, V. Leung, "Spatial-Temporal Relation-Based Energy-Efficient Reliable Routing Protocol in Wireless Sensor Networks," *Sensor Networks*, 2009, Vol. 5, Issue 3, pp. 129-141.

[110] M. Al-Otaibi, H. Soliman, "Efficient Geographic Routeless Routing Protocols with Enhanced Location Update Mechanism," *Sensor Networks*, 2010, Vol. 8, Issue 4, pp. 160-171.

[111] M. Chen, S. Gonzalez, V. Leung, "Applications and Design Issues of Mobile Agents in Wireless Sensor Networks," *IEEE Wireless Commun.*, 2007, Vol. 14, Issue 6, pp. 20-26.

[112] M. Chen, S. Gonzalez, Y. Zhang, V. Leung, "Multi-agent Itinerary Planning in Wireless Sensor Networks," *Computer Science*, 2009, Vol. 22, Issue 10, pp. 584-597.

[113] M. Chen, L. Yang, T. Kwon, L. Zhou, M. Jo, "Itinerary Planning for Energy-efficient Agent Communication in Wireless Sensor Networks," *IEEE Trans. Veh. Technol.*, 2011, Vol. 60, Issue 7, pp. 1-8.

[114] M. Tarique, K. Tepe, S. Adibi, S. Erfani, "Survey of Multipath Routing Protocols for Mobile Ad Hoc Networks," *Network and Computer Applications*, 2009, Vol. 32, Issue 6, pp. 1125-1143.

[115] J. Raju, J. Garcia-Luna-Aceves, "A New Approach to on-Demand Loop-free Multipath Routing," *In Proc. 8th International Conference on Computer Communications and Networks*, Boston, MA, 1999, pp. 522-527.

[116] X. Hou, D. Tipper, J. Kabara, "Label-based Multipath Routing (LMR) in Wireless Sensor Networks," *In Proc. 6th International Symposium on Advanced Radio Technologies (ISART)*, USA, Boulder, 2004, pp. 113-118.

[117] F. Ye, G. Zhong, S. Lu, L. Zhang, "GRAdient Broadcast: A Robust Data Delivery Protocol for Large Scale Sensor Networks," *Wireless Networks (WINET)*, 2005, Vol. 11, Issue 3, pp. 285-298.

[118] Y. Wang, C. Tsai, H. Mao, "HMRP: Hierarchy-Based Multipath Routing Protocol for Wireless Sensor Networks," *Science and Engineering*, 2006, Vol. 9, Issue 3, pp. 255-264.

[119] J. Zhang, C. Jeong, G. Lee, H. Kim, "Cluster-Based Multi-Path Routing Algorithm for Multi-hop Wireless Network," *Future Generation Communication and Networking*, Korea, 2007, Vol. 1, Issue 1, pp. 67-75.

[120] M. Chen, V. Leung, S. Mao, Y. Yuan, "Directional Geographical Routing for Real-Time Video Communications in Wireless Sensor Networks," *Computer Communications*, 2007, Vol. 30, Issue 17, pp. 1-16.

[121] M. Chen, V. Leung, S. Mao, "Directional Controlled Fusion in Wireless Sensor Networks," *Mobile Network Application*, 2009, Vol. 14, Issue 2, pp. 220-229.

[122] T. Winter, P. Thubert, A. Brandt, T. Clausen, J. Hui, R. Kelsey, P. Levis, K. Pister, R. Struik, JP. Vasseur," *Internet draft, http://tools.ietf.org/html/draft-ietf-roll-rpl-18*, 2011.

[123] H. Chao, C. Chang, "A Fault-Tolerant Routing Protocol in Wireless Sensor Networks," *Sensor Networks*, 2008, Vol. 2, Issue 2, pp. 66-73.

[124] H. Soliman, M. Al-Otaibi, "Enhancing AODV Routing Protocol over Mobile ad hoc Sensor Networks," *Sensor Networks*, 2011, Vol. 10, Isuue 2, pp. 36-41.

[125] K. Akkaya, M. Younis, "Energy and QoS Routing for Wireless Sensor Networks," *Cluster Computing*, 2005, Vol. 8, Issue 2, pp. 179-188.

[126] G. Shafiullah, A. Agyei. P. Wolfs, "A Survey of Energy-Efficient and QoS-Aware Routing Protocols for Wireless Sensor Networks," *Book:Novel Algorithms and Techniques, In Telecommunications, Automation and Industrial Electronics*, 2008, pp. 352-357.

[127] K. Sohrabi, J. Gao, V. Ailawadhi, G. Pottie, "Protocols for Self-Organization of a Wireless Sensor Network," *IEEE Pers. Commun.*, 1999, Vol. 7, Issue 5, pp. 16-27.

[128] T. He, J.Stankovic, C. Lu, T. Abdelzaher, "SPEED: A Stateless Protocol for Real-Time Communication in Sensor Networks," *In Proc. 23rd International Conference on Distributed Computing Systems*, Torodo, 2003, pp. 46-55.

[129] E. Felemban, C. Lee, E. Ekici, "MMSPEED: Multipath Multi-SPEED Protocol for QoS Guarantee of Reliability and Timeliness in Wireless Sensor Networks," *IEEE Trans. Mobile Computing*, 2006, Vol. 5, Issue 6, pp. 738-754.

[130] M. Chen, M. Guizani, M. Jo, "Mobile Multimedia Sensor Networks: Architecture and Routing," *In Proc. Mobility Management in the Networks of the Future World*, Shanghai, 2011, pp. 409-412.

[131] J. Lian, K. Naik, "Skipping Technique in Face Routing for Wireless ad hoc and Sensor Networks," *Sensor Networks*, 2008, Vol. 4, Issue 1, pp. 92-103.

[132] M. Chen, T. Kwon, S. Mao, Y. Yuan, V. Leung, "Reliable and Energy-Efficient Routing Protocol in Dense Wireless Sensor Networks," *Sensor Networks*, 2008, Vol. 4, Issue 1, pp. 104-117.

[133] Y. Chen, N. Nasser, T. El Salti, H. Zhang, "A Multipath QoS Routing Protocol in Wireless Sensor Networks," *Sensor Networks*, 2010, Vol. 7, Issue 4, pp. 207-216.

[134] Y. Yang, M. Cardei, "Delay-Constrained Energy-Efficient Routing in Heterogeneous Wireless Sensor Networks," *Sensor Networks*, 2010, Vol. 7, Issue 4, pp. 236-247.

[135] M. B. Haider, S. Imahori, K. Sugihara, "Success Guaranteed Routing in Almost Delaunay Planar nets for Wireless Sensor Communication," *Sensor Networks*, 2011, Vol. 9, Issue 2, pp. 69-75.

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