Wireless sensor networks: A survey on recent developments and potential synergies

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Wireless Sensor Networks: recent developments and potential synergies

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Abstract Wireless sensor network (WSN) has emerged as one of the most promising technologies for the future. This has been enabled by advances in technology and availability of small, inexpensive, and smart sensors resulting in cost effective and easily deployable WSNs. However, researchers must address a variety of challenges to facilitate the widespread deployment of WSN technology in real-world domains. In this survey, we give an overview of wireless sensor networks and their application domains including the challenges that should be addressed in order to push the technology further. Then we review the recent technologies and testbeds for WSNs. Finally, we identify several open research issues that need to be investigated in future.

Our survey is different from existing surveys in that we focus on recent developments in wireless sensor network technologies. We review the leading research projects, standards and technologies, and platforms. Moreover, we highlight a recent phenomenon in WSN research that is to explore synergy between sensor networks and other technologies and explain how this can help sensor networks achieve their full potential. This paper intends to help new researchers entering the domain of WSNs by providing a comprehensive survey on recent developments.

Keywords Wireless sensor network · IEEE 802.15.4 · Platforms · Synergy

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1 Introduction

In recent years there has been a world-wide interest in Wireless Sensor Networks (WSNs). It will not be an exaggeration to consider WSNs as one of the most researched areas in the last decade. Here is a sampling from the literature as summarized in [1–9]. With several applications and business opportunities arising every day, the WSN market is forecast to rise from $0.45 billion in 2012 to $2 billion in 2022 [10, 11]. Figure 1 shows the forecasted rise in revenues from the WSN market for the period of 2010-2014.

A WSN can be defined as a network of tiny devices, called sensor nodes, which are spatially distributed and work cooperatively to communicate information gathered from the monitored field through wireless links. The data gathered by the different nodes is sent to a sink which either uses the data locally or is connected to other networks, for example, the Internet (through a gateway). Figure 2 illustrates a typical WSN.

WSN technology offers numerous advantages over conventional networking solutions, such as, lower costs, scalability, reliability, accuracy, flexibility, and ease of deployment that enable their use in a wide range of diverse applications. With advancements in technology and sensors getting smarter, smaller, and cheaper, billions of wireless sensors are being deployed in numerous applications. Some of the potential application domains are military, environment, healthcare, and security. In military, sensor nodes can be used to detect, locate or track enemy movements. In case of natural disasters, sensor nodes can sense and detect the environment to forecast disasters in advance. In healthcare, sensor nodes can help in monitoring a patient's health. In security, sensors can offer vigilant surveillance and increase alertness to potential terrorist attacks. It will not be far fetched to say that eventually WSNs will enable the automatic monitoring of forest fires, avalanches, hurricanes, failure of country wide utility equipment, traffic, hospitals, etc. The wide range of potential WSN applications make WSN a rapidly growing multi-billion dollar market, but this requires a further major progress in WSN standards and technologies to support new applications [10].

Though WSNs enable new applications and new possible markets, the requirements set by these applications put several design constraints on them. The monitored environment plays an important role in determining the network size, topology and deployment. For example, if the monitored environment is a large region inaccessible by humans then an ad-hoc deployment of nodes is preferred over a pre-planned deployment. Similarly, outdoor environments require a large number of nodes to cover a large area whereas fewer nodes are sufficient for indoor environments to form a network in a limited space [12]. Moreover, a WSN has several resource constraints that include a limited amount of energy, short communication range, low bandwidth, and limited processing capacity and storage in each node.

The objective of research in WSN is to address the above mentioned design and resource constraints by introducing new design concepts, improving existing protocols, and developing new algorithms. WSN is a promising tech-

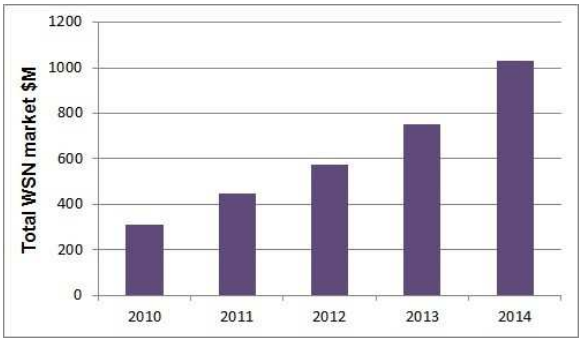

Fig. 1 WSN market 2010-2014 ($ Millions) [10].

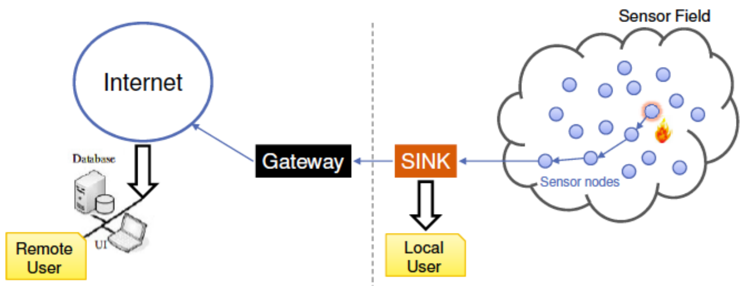

Fig. 2 Wireless Sensor Network (WSN) [42].

nology with a great potential to transform our world if we can solve some research issues. Several surveys exist in the literature on different research domains in WSN such as routing techniques [7,13,14], MAC protocols [15–17], congestion control [18,19], data collection [20–22], energy conservation [23,24], localization [25–27], security [28–30], and applications [3,31–41].

We would like to add that target application driven development of technologies results in a *Silo approach* . This leads to solutions that are effective for targeted applications, but are narrow in approach and do not explore a wider optimisation space. This inhibits eventual cost reductions that come with mass production and widespread use of a technology. On the other hand, there are other driving forces such as, research and exploration of new ideas, cross layer solutions, disruptive technologies and synergy with other fields, that can break this silo approach and lead to global advancement of technology and cost reductions. In a parallel to the above thought, we first describe some technologies, applications and then move towards exploring synergies between different fields and discuss some research ideas in this paper.

The rest of the paper is structured as follows. We give a general overview of WSNs including unique features and different types of WSNs in section 2. In section 3, we describe WSN standards and technologies. Section 4 presents potential applications and some recent deployments. In section 5, we review leading research projects in the domain of WSN. Section 6 presents some popular and significant testing platforms. Section 7 explores potential synergies between WSN and other existing and emerging technologies. Section 8 describes open research issues, and we conclude in section 9.

2 Wireless Sensor Networks

A Wireless sensor network (WSN) consists of wireless sensor nodes or motes, which are devices equipped with a processor, a radio interface, an analog-to-digital converter, sensors, memory and a power supply. The processor provides the mote management functions and performs data processing. The sensors attached to the mote are capable of sensing temperature, humidity, light, etc. Due to bandwidth and power constraints, motes primarily support low data units with limited computational power and a limited sensing rate. Memory is used to store programs (instructions executed by the processor) and data (raw and processed sensor measurements). Motes are equipped with a low-rate (10-100 kbps) and short-range (less than 100m) wireless radio, e.g., IEEE 802.15.4 radio to communicate among themselves. Since radio communication consumes most of the power, the radio must incorporate energy-efficient communication techniques. The power source commonly used is rechargeable batteries. Since motes can be deployed in remote and hostile environments they must use little power and must employ built-in mechanisms to extend network lifetime. For example, motes may be equipped with effective power harvesting methods, such as solar cells, so they may be left unattended for years.

Sensor nodes can be deployed in an ad-hoc or a pre-planned manner. An ad-hoc deployment is good for large uncovered regions where a network of a very large number of nodes can be deployed and left unattended to perform monitoring and reporting functions. Network maintenance such as managing connectivity and detecting failures is difficult in such a WSN due to large number of nodes. On the other hand, pre-planned deployment is good for limited coverage where fewer nodes are deployed at specific locations with the advantage of lower network maintenance and management cost.

2.1 Unique features of WSN: Challenges and Requirements

The collaborative nature of WSNs brings several advantages over conventional wireless ad-hoc networks, including self-organization, rapid deployment, flexibility, and inherent intelligent-processing capability. However, the unique features of WSN present new challenges in hardware design, communication protocols, and application design. A WSN technology must address these challenges to realize the numerous envisioned applications. This requires modifying legacy protocols for conventional wireless ad-hoc networks or designing new effective communication protocols and algorithms [5].

Table 1 lists important challenges and corresponding required mechanisms to address them in WSN. Sensor nodes have resource constraints including

Table 1 Challenges vs. Required mechanisms in WSN.

Challenges	Required mechanisms
Resource constraints	Efficient use of resources
Dynamic and extreme environment conditions	Adaptive network operation
Data redundancy	Data fusion and localized processing
Unreliable wireless communication	Reliability
No global identification (ID) for sensor nodes	Data-centric communication paradigm
Prone to node failures	Fault tolerance
Large scale deployment	Low-cost small-sized sensors with self-configuration and self-organization

limited energy, limited memory and computational capacities. The limited energy supplies of the sensor nodes in the network impose lifetime constraints on the WSN. The problem of limited resources can be addressed by using them efficiently. Energy efficient operation is required to maximize the network lifetime by implementing energy efficient protocols, e.g., energy-aware routing on network layer, energy-saving mode on MAC layer, etc. Efficient use of limited memory in sensors is required by taking into account the memory consuming issues like routing tables, data replication, security, etc.

Dynamic network topologies and harsh environment conditions may cause sensor-node failures and performance degradation. This requires WSN to support adaptive network operation including adaptive signal-processing algorithms and communication protocols to enable end-users to cope with dynamic wireless-channel conditions and varying connectivity.

The communication in WSN is unreliable due to error prone wireless medium with high bit error rates and variable-link capacity. Thus, a WSN should be reliable in order to function properly and depending on the application requirements, the sensed data should be reliably delivered to the sink node. WSNs are usually prone to unexpected node failures due to different reasons like nodes may run out of energy or might be damaged (in extreme environment conditions), or wireless communication between two nodes can be permanently interrupted. This requires WSNs to be robust to node failures. In WSN, fault tolerance can be improved through a high level of redundancy by deploying additional nodes than required if all nodes functioned properly. In case of high density deployment, sensor observations can be highly correlated in the space domain. Data fusion and localized processing are required to address the data redundancy such that only necessary information is delivered to the end-user and communication overhead can be reduced.

Since WSNs may contain a large number of sensor nodes, the employed architectures and protocols must be able to scale to sizes of thousands or more. Moreover, a large scale deployment of WSN requires low-cost and small-sized sensor nodes. A WSN should be able to self-organize itself as the network topology may change due to reasons like node failure, mobility, and large scale deployments. In addition, new nodes may need to join the network, for example, to replace failed nodes, thus, a WSN must be self-reconfiguring. It can be expensive to give a unique address for each node (address-centric paradigm) especially when thousands of nodes are deployed in the application. Global identification for sensors in a WSN lead to large overhead. Moreover, due to limited memory and computational power it is not advisable to depend on a single sensor node's contents. Thus, WSNs are required to use the data-centric paradigm which focuses on data generated by a group of sensors.

2.2 Types of WSNs

Presently many WSNs are deployed on land, underground and underwater. They face different challenges and constraints depending on their environment. We present five types of WSNs [12] as shown in Figure 3.

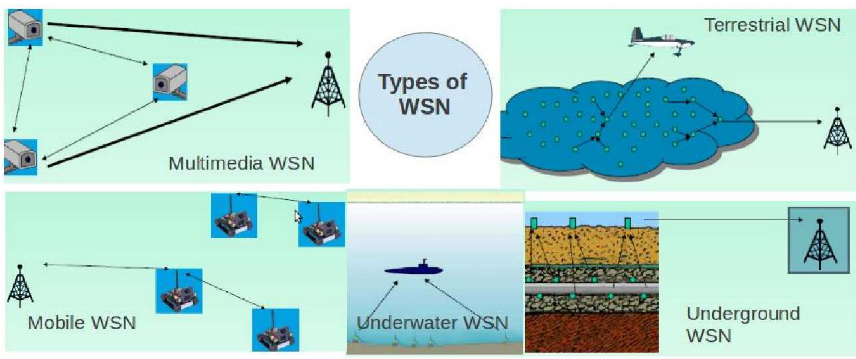

Fig. 3 Types of WSN [43].

Terrestrial WSN: consists in a large number (hundreds to thousands) of low-cost nodes deployed on land in a given area, usually in an ad-hoc manner (e.g., nodes dropped from an airplane). In terrestrial WSNs [2], sensor nodes must be able to effectively communicate data back to the base station in a dense environment. Since battery power is limited and usually non-rechargeable, terrestrial sensor nodes can be equipped with a secondary power source such as solar cells. Energy can be conserved with multi-hop optimal routing, short transmission range, in-network data aggregation, and using low duty-cycle operations. Common applications of terrestrial WSNs are environmental sensing and monitoring, industrial monitoring, and surface explorations.

Underground WSN: consists of a number of sensor nodes deployed in caves or mines or underground to monitor underground conditions [44, 45]. In order to relay information from the underground sensor nodes to the base station, additional sink nodes are located above ground. They are more expensive than terrestrial WSNs as they require appropriate equipments to ensure reliable communication through soil, rocks, and water. Wireless communication is a challenge in such environment due to high attenuation and signal loss. Moreover, it is difficult to recharge or replace the battery of nodes buried underground making it important to design energy efficient communication protocol for prolonged lifetime. Underground WSNs are used in many applications such as agriculture monitoring, landscape management, underground monitoring of soil, water or mineral, and military border monitoring.

Underwater WSNs: consists of sensors deployed underwater, for example, into the ocean environment [46, 47]. Such nodes being expensive, only a few nodes are deployed and autonomous underwater vehicles are used to explore or gather data from them. Underwater wireless communication uses acoustic waves that presents various challenges such as limited bandwidth, long propagation delay, high latency, and signal fading problems. These nodes must be able to self-configure and adapt to extreme conditions of ocean environment. Nodes are equipped with a limited battery which cannot be replaced or recharged requiring energy efficient underwater communication and networking techniques. Applications of underwater WSNs include pollution monitoring, under-sea surveillance and exploration, disaster prevention and monitoring, seismic monitoring, equipment monitoring, and underwater robotics.

Multi-media WSN: consists of low cost sensor nodes equipped with cameras and microphones, deployed in a pre-planned manner to guarantee coverage [48]. Multi-media sensor devices are capable of storing, processing, and retrieving multimedia data such as video, audio, and images. They must cope with various challenges such as high bandwidth demand, high energy consumption, quality of service (QoS) provisioning, data processing and compressing techniques, and cross-layer design. It is required to develop transmission techniques that support high bandwidth and low energy consumption in order to deliver multi-media content such as a video stream. Though QoS provisioning is difficult in multi-media WSNs due to variable link capacity and delay, a certain level of QoS must be achieved for reliable content delivery. Multi-media WSNs enhance the existing WSN applications such as tracking and monitoring.

Mobile WSN: consists of mobile sensor nodes that can move around and interact with the physical environment [12]. Mobile nodes can re-position and organize themselves in the network in addition to be able to sense, compute, and communicate. A dynamic routing algorithm must, thus, be employed unlike fixed routing in static WSN. Mobile WSNs face various challenges such as deployment, mobility management, localization with mobility, navigation and control of mobile nodes, maintaining adequate sensing coverage, minimizing energy consumption in locomotion, maintaining network connectivity, and data distribution. Primary examples of mobile WSN applications are monitoring (environment, habitat, underwater), military surveillance, target tracking, search and rescue. A higher degree of coverage and connectivity can be achieved with mobile sensor nodes compared to static nodes.

3 WSN standards and technologies

The process of standardization in the field of WSN has been very active in the last years. As compared to some well known wireless communication standards such as IEEE 802.11 [49] and IEEE 802.15 [50], the standard IEEE 802.15.4 [51] is specifically designed for low power, low data rate and low-cost wireless sensor communication. In comparison, Wi-Fi (IEEE 802.11) provides higher data throughput and range, but it consumes more energy resulting in a crucial disadvantage for WSNs. Bluetooth Low Energy (BLE) [52] is considered as an attractive technology for WSN applications demanding higher data rates, but short range. Most of the WSN technologies operate in the ISM band (Industrial, Scientific and Medical radio band), which were internationally reserved for the use of RF (Radio Frequency) electromagnetic fields for industrial, scientific and medical purposes other than communications.

The choice of technology to be used should be based on the target application as every WSN application has different requirements on the communication system. While some applications need a very low latency, others need a high secure connection or a long battery life. The development of new technologies is pushing WSN into new areas of application. While ISA100 [53] and WirelessHART [54] technologies make WSNs a more viable possibility in traditional manufacturing environments, technologies like Bluetooth low energy, ZigBee green power, Wi-Fi direct and EnOcean [55] will drive growth into areas such as; medical devices, healthcare, automotives, energy efficient buildings, sports and agriculture. In this section, we describe the potential WSN standards and technologies. In addition to the standard technologies, some commercial non-standard technologies like ANT [56] are also considered. A comparative study of emerging and existing radio technologies for WSNs is provided in Table 2.

3.1 IEEE 802.15.4 standard

IEEE 802.15.4 [51] is a standard defined by IEEE 802.15.4 Working Group for data communication devices operating in Low Rate Wireless Personal Area Networks (LR-WPANs). It provides low cost, short-range, low power and low data-rate communication for sensor networks. It targets wireless sensor applications which require short range communication to maximize battery life. The standard specifies the lowest two layers of the protocol stack; the physical (PHY) and medium access control (MAC) layers, based on the OSI model as shown in Figure 4. The upper layers and interoperability sub-layers of the protocol stack are separately defined by other architectures such as 6LoWPAN [57], ZigBee [58], ISA100.11a [53], and WirelessHART [54]. Table 3 provides a technical comparison between the key IEEE 802.15.4-based WSN standards.

Table 2 WSN standards and technologies.

	IEEE 802.15.4 (ZigBee)	UWB IEEE 802.15.4a	Blue-tooth	BLE	Z-wave	ANT	Wavenis	Dash7	EnOcean
Frequency (ISM)	868/915 MHz; 2.4 GHz	3.1-10.6 GHz	2.4 GHz	2.4 GHz	sub-1 GHz	2.4 GHz	868, 915, 433 MHz	433 MHz	868;315 MHz
Max Data rate	250 kbps	110 Mbps	3 Mbps	1 Mbps	40 kbps	1 Mbps	100 kbps	200 kbps	125 kbps
Range	100 m	10 m	10-100 m	200 m	30 m		1-4 km	2 km	300 m
Battery life	Days-years	Multi-year		Months -years	Multi-year	Year	Multi-year	Multi-year	Battery -less
Network topology	Star, P2P, Mesh		P2P	P2P	Mesh	Star, P2P Tree Mesh	P2P		
Power consu-mption	Low	Low	Low	Ultra-low	Low	Ultra-low	Ultra-low	Low	Ultra-low
Open	✓	✓	✓	✓	✓	X	✓	✓	✓
IPv6	✓			✓	✓		✓		
Target Market/ Applic-ation	Smart-meter, Smart grid devices	Real-time monitor and track location (Indoor)	Consumer electronics	Health fitness, Smart devices	Home autom-ation, security, consumer electronics	Health Fitness Heart-rate monitor, Speed sensors	M2M, Smart meter, Telemetry, Home automation	Mobile payments, Smart meter, Supply chain,	Building, Industrial Automation self-powered sensors, switches

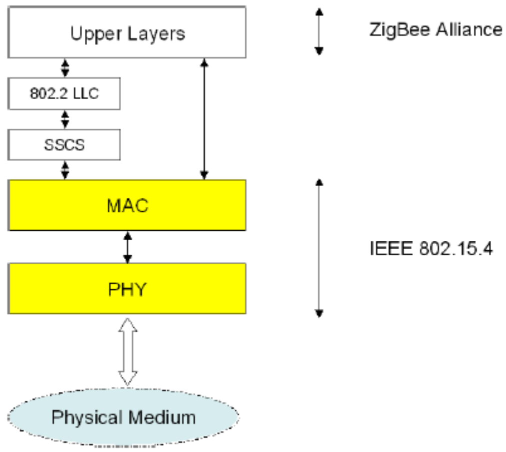

Fig. 4 IEEE 802.15.4 protocol stack. Upper layers: ZigBee, 6LowPAN, etc.[59].

Table 3 Key IEEE 802.15.4-based WSN standards.

Standard	Topology	Battery life (days)	Network nodes	Max Throughput	Range (m)
ZigBee	Mesh	100-1000+	255	250 Kbps	10-100
6LoWPAN	Mesh	100-365+	65536	250 Kbps	1-100
WirelessHART	Mesh	760+	200	250 Kbps	1-100
ISA100.11a	Mesh, Star	1000+		250 Kbps	100

The IEEE 802.15.4 standard defines two types of network nodes: full-function device (FFD) and reduced-function device (RFD). RFDs are very basic nodes with little processing and memory resources. They can only act as end-systems in the network and communicate with FFDs. Whereas FFDs are able to fully implement the standard. FFDs can act as coordinators (Personal Area Networks (PAN) or full network coordinators) and communicate with both FFDs and RFDs. IEEE 802.15.4 supports two types of network topologies; star and peer-to-peer topology for communication between network devices as shown in Figure 5. In the star topology, all the devices communicate with a central controller (FFD) while the peer-to-peer topology allows more complex network formations to be implemented, such as mesh networking topology. A peer-to-peer network can be ad-hoc, self-organizing, and self-healing. Star topology is preferred when coverage area is small and low latency is required by the WSN application. Whereas peer-to-peer topology is suitable for a large coverage area where latency is not a critical issue.

The original 2003 version supports 868/915 MHz low bands with data rates of 20 and 40 kbps, and 2.4 GHz high bands with a rate of 250 kbps. The current

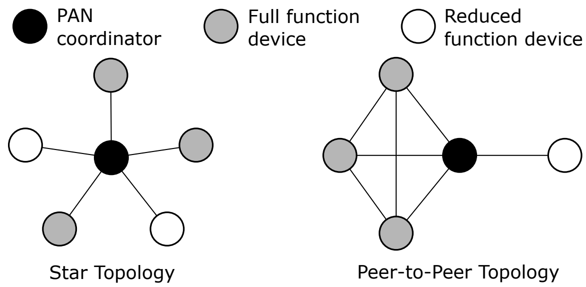

Fig. 5 IEEE 802.15.4-compliant network topologies: star and peer-to-peer topology.

version of the IEEE standard is 802.15.4-2006. It improves the maximum data rates of up to 100 and 250 kbps for the 868/915 MHz bands.

3.1.1 ZigBee

ZigBee is a low-cost and low power wireless communication technology used in embedded applications. The ZigBee standard is maintained by ZigBee Alliance [58]. Its main contribution is providing mesh networking capabilities to 802.15.4 applications. Usually, to deploy Zigbee, additional equipments such as a Zigbee coordinator and a Zigbee router are required in addition to the Zigbee end-device. Standard ZigBee node needs an 802.15.4/IP gateway to communicate with an IP network. Hence, ZigBee is good for WSN applications that do not require to interface with IP devices. However, the new ZigBee IP specification provides an IPv6-based wireless mesh networking solution. It enriches IEEE 802.15.4 by adding network and security layers and an application framework, offering a scalable architecture with end-to-end IPv6 networking.

3.1.2 6LoWPAN

The 6LoWPAN standard (RFC 4944) [57] has been defined by IETF to adapt IPv6 communication on top of IEEE 802.15.4 networks. 6LoWPAN refers to IPv6 over Low power Wireless Personal Area Networks. It enables IPv6 packets communication over low power and low rate IEEE 802.15.4 links and assures interoperability with other IP devices. 6LowPAN devices can communicate directly with other IP-enabled devices. IP for Smart Objects (IPSO) Alliance [60] is promoting the use of 6LowPAN and embedded IP solutions in smart objects. 6LoWPAN provides an adaptation layer, new packet format, and address management to enable such devices to have all the benefits of IP communication and management. Since IPv6 packet sizes are much larger than the frame size of IEEE 802.15.4, the adaptation layer is introduced between MAC layer and the network layer to optimize IPv6 over IEEE 802.15.4. The adaptation layer provides mechanisms for IPv6 packet header compression, fragmentation and reassembly allowing IPv6 packets transmission over IEEE 802.15.4 links.

3.1.3 WirelessHART

WirelessHART [54], released in 2007, is a wireless communications standard suitable for industrial applications such as process measurement and control applications. It adds wireless capabilities to the HART protocol while maintaining compatibility with existing HART devices. A WirelessHART network consists of wireless field devices, gateways, process automation controller, host applications, and network manager. Field devices are connected to process or plant equipment and communicate with the host applications through gateways. The process automation controller serves as a single controller for continuous process. The network manager is responsible for configuring the network, scheduling communication between devices, managing routes, and monitoring network health. WirelessHART operates in the 2.4 GHz ISM band and to prevent interference from other applications, it uses frequency hopping with blacklisting of bad channels and has a high reliability in challenging environments. The key features are its reliability, security, energy efficiency, compatibility with existing devices and it enables mesh networking.

3.1.4 ISA100.11a

ISA100.11a standard [53] is developed by the ISA100 standards committee which is a part of the International Society of Automation (ISA) organization. Its main application is in industrial automation and to meet the needs of industrial applications, it supports various network topologies, such as star and mesh networking. A ISA100.11a WSN consists of field devices, gateways, and handheld devices. Field devices are responsible for gathering sensor data and some of them can also provide routing functionalities. The gateways ensure connection between the WSN and the user application and also support interoperability with existing standards, such as WirelessHART by translating and tunneling information between the networks. Handheld devices support device installation, configuration and maintenance. One of the key features of ISA100.11a is the low latency or fast response time of 100ms. ISA100.11a uses only the 2.4 GHz ISM band with frequency hopping to increase reliability and prevent interference from other wireless networks.

3.2 IEEE 802.15.4a - Ultra Wideband

Ultra Wideband (UWB) is a Radio Frequency (RF) communication technology in which the information is transmitted through a series of very short impulses emitted in periodic sequences [61]. A UWB signal can be defined as a signal with instantaneous spectral occupancy in excess of 500 MHz or a fractional bandwidth of more than 20%. UWB has been a proposed technology for the IEEE 802.15.4a standard which provides an alternative physical layer for low rate WPAN and is an amendment to IEEE 802.15.4. The advantages of UWB include its spectral efficiency, ability to transmit high data rates with low power, high precision ranging and location capability, and ability to cope with multipath environments. However, UWB is not suitable for communication over longer distances or measuring data from unsafe zone because of high peak energy of pulses. Impulse Radio-UWB (IR-UWB) [62] that relies on ultra-short (nanosecond scale) waveforms is a promising UWB technique for WSN applications.

3.3 Bluetooth and Bluetooth Low Energy (BLE)

Bluetooth is a wireless technology for short-range and cheap devices intended to replace the cables in WPANs. It operates in the 2.45 GHz ISM band and uses frequency hopping to combat interference and fading. Bluetooth can cover a communication range of 10-100 m and allows data rate up to 3 Mbps. It was standardized as IEEE 802.15.1, but the standard is no longer maintained. Currently, Bluetooth is managed by the Bluetooth Special Interest Group, which adopted Bluetooth Core Specification Version 4.0 in 2010.

Bluetooth v4.0 [63] is the most recent version. It introduced Bluetooth Low Energy (BLE) technology [52] that enables new low-cost Bluetooth Smart devices to operate for months or years on tiny, coin-cell batteries. Potential markets for BLE-based devices include healthcare, sports and fitness, security, and home entertainment. BLE operates in the same 2.45 GHz ISM band as classic Bluetooth, but uses a different set of channels. Instead of Bluetooth's 1-MHz wide 79 channels, BLE has 2-MHz wide 40 channels. As compared to classic Bluetooth, BLE is intended to provide considerably reduced power consumption and lower cost, with enhanced communication range. BLE allows 1 Mbps data rates with 200 m range and has two implementation alternatives; single-mode and dual-mode. Single-mode BLE devices support only new BLE connections, whereas dual-mode devices support both classic Bluetooth as well as new BLE connections and have backward-compatibility.

3.4 Z-wave

The Z-Wave is a low powered RF-based wireless communications technology designed specifically for remote control applications in residential and light commercial environments. It was developed by Zensys [64] and is currently, supported by Z-Wave Alliance [65]. Z-Wave's main advantage with respect to IEEE 802.15.4-based technologies is that it operates in sub-1 GHz band (around 900 MHz); unaffected to interference from Wi-Fi and other wireless technologies (Bluetooth, ZigBee, etc.) in the crowded 2.4-GHz range. The 868 MHz band used by Z-Wave in Europe is limited by European regulations to operate at or under 1% duty cycle, that can be sufficient for most of the control applications. Z-Wave technology supports mesh networking, operable data rates of 9.6 kbps and 40 kbps and maximum outdoor range of 30 m.

3.5 ANT technology

ANT [56] is a proprietary technology that features a wireless communication protocol stack for ultra-low power networking applications. It is designed to run using low cost, low power micro-controllers and transceivers operating in the 2.4 GHz ISM band. ANT supports various topologies including peer-to-peer, star, tree and other types of mesh networking in personal area networks (PAN) suited for sports, fitness, wellness and home health applications. It is also suited for local area networks (LAN) in homes and industrial automation applications. ANT is energy-efficient and provides a data rate of 1 Mbps, which is much higher than that of IEEE 802.15.4 (250 kbps). However, it lacks interoperability. This can be addressed by adding ANT+, an interoperability function to the base ANT protocol to make it interoperable. ANT+ enabled fitness monitoring devices, such as heart rate monitors, speed monitors, and weight scales can all work together to assemble and track performance metrics.

3.6 Wavenis technology

Wavenis is an ultra-low-power and long-range wireless technology developed by Coronis [66] for WSN applications in which communication ability and device autonomy present conflicting requirements. It was originally developed as a proprietary technology, and is now promoted by the Wavenis Open Standard Alliance. Wavenis-based devices are used in Telemetry, industrial automation, remote utility meter monitoring, home healthcare, access control and cold-chain monitoring. Its key features include reliability, power savings, network coexistence, and robustness against interferers. Wavenis operates worldwide in the 868, 915 and 433 MHz ISM bands. Its data rates are programmable, from 4.8 kbps to 100 kbps. Most Wavenis applications communicate at 19.2 kbps.

3.7 Dash7

Dash7 [67] is an open source, ultra low-power and long-range wireless sensor networking technology based on the ISO 18000-7 open standard. It operates in the 433 MHz ISM unlicensed band. It is promoted by the DASH7 Alliance that focuses on the interoperability among Dash7 devices. The DASH7 network uses a new concept called BLAST (Bursty, Light, Asynchronous, Transitive) technology that makes it best suited to the uses that have bursty, asynchronous communication between devices. Dash7 system devices are portable and upload-centric, so there is no need to manage devices by fixed infrastructure (i.e., base stations). The main characteristics of Dash7 include a multi-year battery life, communication range of up to 10 km, low latency for connecting with moving objects, security support, data rate of up to 200 kbps, and real-time location precision within 4 m. The major applications of Dash7 include supply chain management, inventory management, mobile payments, manufacturing and warehouse optimization, hazardous material monitoring, advanced location based services, smart meter, and building automation.

3.8 EnOcean technology

EnOcean is an emerging WSN technology that is promoted by EnOcean Alliance. The EnOcean wireless standard [55] is optimized for solutions with ultra-low power consumption and energy harvesting. The battery free EnOcean technology brings together wireless sensing and energy harvesting to enable energy harvester-powered WSNs. The goal of EnOcean's energy harvesting wireless sensor technology is to draw energy from the surroundings, for example, from motion, pressure, light or differences in temperature and convert that into energy that can be used electrically. Thus, combining miniaturized energy harvesters and highly efficient wireless technology enable designing WSN that is supplied via energy harvesting. EnOcean provides wireless sensor solutions for buildings and industrial automation. It uses 868 MHz and 315 MHz and supports transmission range of up to 30 m indoor and 300 m outdoor. EnOcean products available in the market include battery-less self-powered wireless sensors and switches. Battery-less EnOcean modules with energy harvesting are available which reduce the life cycle cost as they are maintenance free.

4 Application domains and deployments

WSNs have been adopted in a large number of diverse application domains. It is envisioned that in future everyday objects will be embedded with sensors to make them smart. Smart objects can explore their environment, communicate with other smart objects, and interact with humans.

A taxonomy of WSN applications is shown in Figure 6. In general, WSN applications can be of two types: monitoring and tracking. As shown in the taxonomy (Figure 6), the leading application domains of WSNs include military and crime prevention, environment, health (Body Area Networks), industry and agriculture, and urbanisation and infrastructure. Military operations involving force protection with unattended ground sensors formed into intelligent networks around forward operating bases are receiving much attention. VigilNet [68] is an integrated sensor network system for energy-efficient surveillance missions. Another interesting example is networked mines called self-healing minefields that automatically rearrange themselves to ensure optimal coverage. Body Area Networks (BANs) integrated with soldier communication systems are also a key application, as vital health functions can be monitored when soldiers enter hazardous areas. In addition, the homeland security sector is showing great interest in WSNs for critical infrastructure monitoring (utilities, airports, etc), border protection, incident detection and crisis management. In the health sector, BANs for health applications are one of the emerging markets for WSNs. Figure 7 illustrates a Wireless Body Area Network of intelligent sensors for patient monitoring [35,69,70]. In environmental

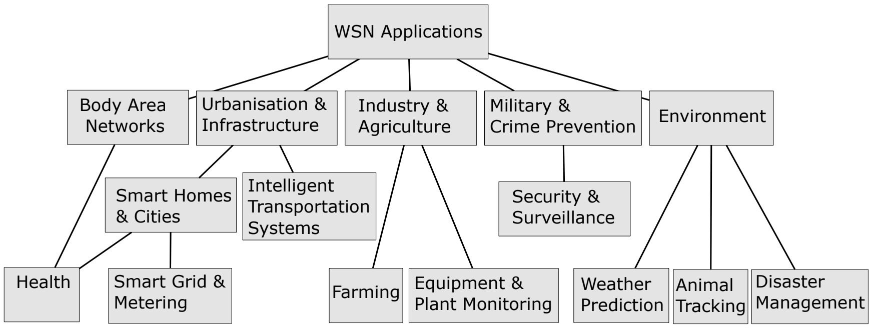

Fig. 6 Taxonomy of WSN applications.

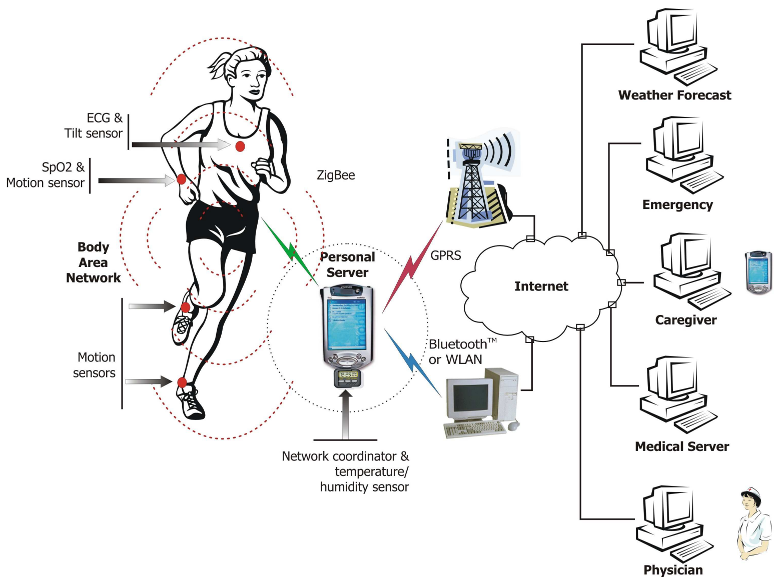

Fig. 7 Wireless Body Area Network (BAN) of Intelligent Sensors for Patient Monitoring[69].

applications, sensor networks are increasingly used to monitor nature. Some examples of environmental monitoring applications include Great Duck Island [71]; a sensor network deployment for habitat monitoring, biodiversity mapping; to observe wildlife, flood detection, forest fire detection, and precision agriculture. Furthermore, in the civil sector, WSNs have generated a lot of interest from their smart infrastructure applications, such as smart grids, smart energy metering, smart transport and traffic management, smart roads, etc. Structural health monitoring enables detecting the health status of structures using a network of accelerometers and strain gages.

Several real applications have been deployed and with the advancement in technology, new application areas keep emerging. Here we describe some examples of the recently deployed WSN applications which have been tested

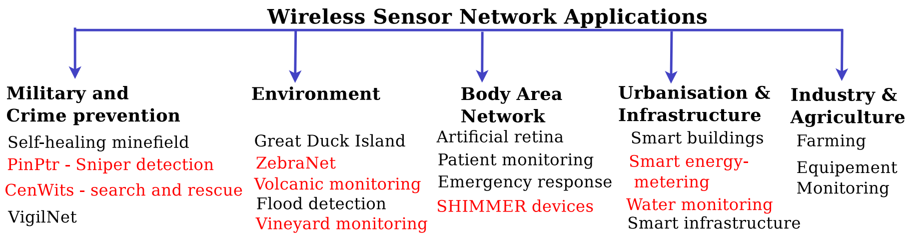

Fig. 8 Examples of WSN applications deployed in real environment.

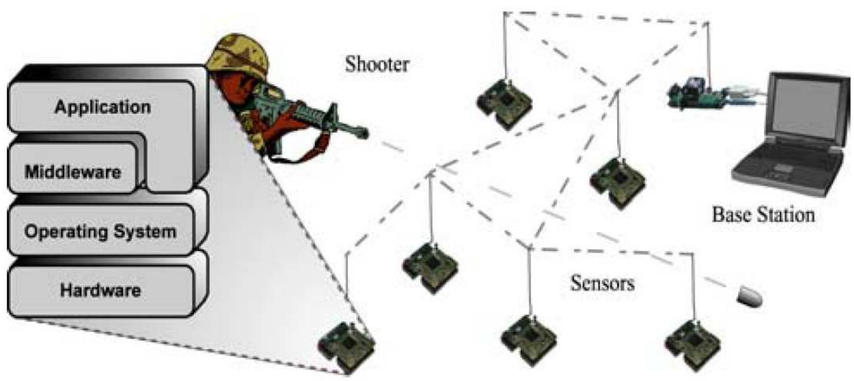

Fig. 9 System architecture in the counter-sniper application PinPtr[72].

in the real environment (Figure 8).

PinPtr: is a counter-sniper system developed to detect and locate shooters [72] as shown in Figure 9. The ad-hoc acoustic sensor network detects the muzzle blast and the acoustic shock wave that originate from the sound of gunfire. Sensors route their measurements to the base station to compute the shooter's location. The arrival times of the acoustic events at different sensor nodes are used to determine the trajectory of the bullet and estimate the location of the shooter.

CenWits: is a search-and-rescue system designed to determine an approximate small area where search-and-rescue efforts can be concentrated [73]. The system consists of mobile sensors worn by subjects (people), access points that collect information from these sensors and GPS receivers, and location points to provide location information to the sensors. The subject determines its current location by using the GPS receivers and location points. The key concept of this sensor-based tracking system is to use the witnesses to convey the movement and location information of the subject to the outside world.

ZebraNet: is a sensor-based tracking system developed to track animal migrations. ZebraNet [74] consists of a mobile sensor network created by attaching

Fig. 10 The ZebraNet sensor collar, attached to a Zebra [74].

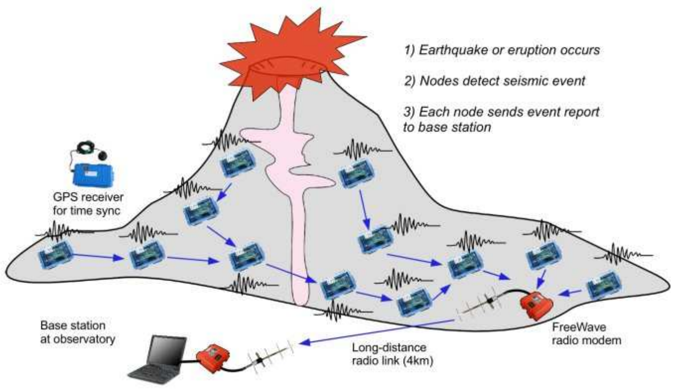

Fig. 11 Volcan Reventador deployment for volcano monitoring [76].

special collars equipped with a low-power GPS system to the necks of zebras to monitor their movement patterns and behavior as shown in figure 10. The system was deployed at the Sweetwaters game reserve in central Kenya to study the effects and reliability of the collar and to collect movement data. GPS is used to take positional readings which are sent multi-hop across zebras to the base station. The movement data collected through the base station can be used for analysis to better understand the zebra movements during the day and night.

Volcanic monitoring: A wireless sensor network of 16 sensor nodes equipped with seismo-acoustic sensors was deployed on Volcan Reventador in northern Ecuador to monitor volcanic eruptions [75]. The network collected seismic and acoustic data on volcanic activity over 3 km and transmitted the collected data through a multi-hop routing and over a long-distance radio link to a base station at the volcano observatory. Figure 11 illustrates the volcano monitoring sensor network architecture in Volcàn Reventador deployment [76]. The network observed 230 eruptions and other volcanic events over three weeks, generating useful data that enabled to evaluate the performance of large-scale sensor networks for collecting high-resolution volcanic data.

Vineyard monitoring: Intel Corporation and Intel Research Berkeley Labs have deployed a WSN in a vineyard to collect and interpret the gathered data [77]. In addition, the network uses data to make decisions, for example, to detect the presence of parasites and enable the use of the appropriate kind of insecticide. Data collection in the wireless vineyard relies on data mules, that are small devices carried by people (or dogs), which communicate with the nodes and collect data. The focus is on reliable information collection as well as active decision-making based on gathered data.

SHIMMER devices: are wearable sensors that can store patient data such as identification, history, and treatments [78]. Shimmer devices are equipped with wireless medical sensors, vibration sensors, and other devices that may be used to monitor and treat patients in various medical scenarios. These wearable sensor nodes can record and transmit patient data in real-time. In general, existing health care and patient monitoring can be significantly improved from prototype designs developed for health monitoring applications such as infant monitoring, alerting the deaf, blood pressure monitoring and tracking, and fire-fighter vital sign monitoring.

Water monitoring: The Non-intrusive Autonomous Water Monitoring System (NAWMS) [79] is a novel easy-to-install and self-calibrating water monitoring system developed for homes using distributed WSNs. It uses wireless vibration sensors attached to the water pipes to provide real-time water usage information at different locations of the water pipe system, thus enabling to improve the efficiency of homes. The water utility companies only provide total water usage in a house, which makes it difficult to determine the individual sources that contribute to the total consumption. The NAWMS system localizes the wastage in water usage and alerts residents about more efficient usage. Thus, using NAWMS, the water usage in each pipe of the plumbing system of the house can be monitored at a low cost.

Smart metering: The smart grid and energy sector focus on reducing the energy consumption as well as using renewable energy, such as wind, solar, tidal, and geothermal power in order to reduce the high costs of energy and promote green energy. A smart grid delivers energy (electricity, gas, water) from suppliers to consumers using digital technology and renders the weaknesses of conventional electrical grids by using smart meters. Smart Metering forms the foundation of the smart grid. It includes sensors and sensor networks that enable remote monitoring by using sensors at multiple places along the grid, e.g., at transformers and substations or at customers' homes [80]. Smart metering is advantageous for both energy suppliers and consumers. It provides an accurate profiling for forecasting, purchasing and balancing of energy to energy suppliers. At the same time, it enables domestic and industrial consumers to monitor energy consumption in real-time, reduce waste and save carbon and helps in promoting best energy consumption practices. Many governments are promoting smart grid to address energy independence and global warming issues. The European Union has launched *The 2009 Electricity Directive* to ensure that every household in the EU is fitted with smart meters by 2022.

Target tracking and parameter estimation: applications involve many different levels of complexities and different blocks in system design. The application can vary from just tracking a single spatial phenomenon, such as average road speeds to more complex scenarios, such as tracking multiple heterogeneous and mobile targets [81] with multiple time varying parameters. Some applications for such tracking capabilities include *Military applications* involving tracking different persons, vehicles and objects, such as bullets (as in Pinptr example provided before) and objects can have heterogeneous shapes and velocities. *Wildlife applications* (e.g., ZebraNet) include tracking the number and kinds of animals and vehicles in a large area to observe the wildlife and prevent poaching. In general, the applications for such capabilities are numerous. Since such capabilities require advanced costly devices, it is challenging to do with many low cost, low performance sensors with simple functions, that are distributed randomly. This requires highly-effective intelligent collaboration among sensor nodes, energy efficiency and dynamic reconfigurability to adapt to the characteristics of mobile targets. This also requires *signal processing* for estimating parameters and state of the targets from the sensed data and some existing works have used particle filters [82]. Further, there is the problem of source separation, for example, if similar objects are moving close to each other then how to track them separately.

There can be two types of solution; centralized and decentralized. Centralized solutions contain a fusion center that processes the collected data. However, centralized approach suffers from scalability issues as well as congestion at the fusion center and it is not robust against node failures due to a single bottleneck. Thus, many researchers have been attracted to designing decentralized tracking algorithms. This typically involves algorithm to build consensus through cooperation among different nodes and innovation that involves processing the obtained data to get more meaning out of the raw and local data [83]. Another problem is to adapt to the mobile object being tracked, which involves dynamic reconfiguration of WSN [84].

5 Positioning in the industry and leading research projects

Though the research in the field of WSN is about a decade old, this is considered as a new research area as reflected in the rise in WSN research and development budgets every year. The focus is on developing new communication protocols and management services to meet the specific requirements of sensor nodes such as limited power, processing capacity and storage. Some hot research topics in WSN are related to topology creation, control and maintenance. We describe here some leading research projects and work in the domain of WSNs (Table 4).

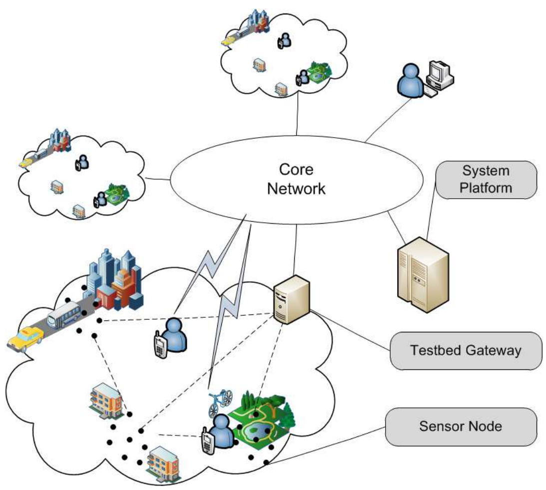

Fig. 12 A high-level architecture of SmartSantandar city.

Smart Santander Project [85]: has developed a state of the art smart city in the Spanish port city of Santander [86]. It aims at designing, deploying and validating a platform composed of sensors, actuators, cameras and screens in Santander to offer useful information to residents. In this project, 750 Waspmotes [87] have been deployed in different locations within the city to monitor different parameters, such as noise, temperature, luminosity, CO and free parking slots. The relevant data gathered by the sensors is transmitted to the central platform. The residents of the city can obtain information about their environment and other useful information, such as bus routes, shopping information using their smartphone application called *Pulse of the City* . In addition to supporting applications and services for future Smart Cities, the project envisions the deployment of 20,000 sensors in four European cities. A high-level architecture of SmartSantandar city is shown in figure 12.

CodeBlue and Mercury projects: The CodeBlue [88] project at Harvard University focuses on WSNs for medical applications in disasters such as pre-hospital and in-hospital emergency care, disaster response, and stroke patient rehabilitation. Another project is Mercury [78] that focuses on wearable sensors that monitor vital signs of patients throughout their daily lives. One current example of wearable sensors is SHIMMER devices that can record and transmit physiological and kinematic data in real-time.

GlacsWeb project [89]: develops technology to monitor glacier behavior using sensor networks. Custom sensor probes are placed in, on and under glaciers to monitor the drifting behavior of glaciers by aggregating temperature, pressure, stress, weather and sub-glacial movement data gathered by sensors. The information gathered helps in understanding the dynamics of glaciers as well as global warming [90, 91].

eDIANA project [92]: aims at achieving energy efficient buildings through innovative solutions based on networked embedded systems [93]. The focus is on having higher efficiency in terms of usage of scarce energy resources and better awareness for the citizen as well as service and infrastructure owners. The project aims to realize this through the deployment of the eDIANA platform integrated with intelligent embedded devices in the buildings to optimize total energy consumption, production and storage, and improve efficiency.

European WSN projects WiSeNts [94], e-SENSE [95], CRUISE [96]: are dedicated to provide solutions related to technology, architecture, and communication protocols for embedded systems. WiSeNts focuses on integrating the existing research in the fields of embedded systems, ubiquitous computing and WSNs to support Cooperating Objects. E-SENSE project concentrates on capturing ambient intelligence through WSNs by means of interaction between body sensor networks, object sensor networks and environmental sensor networks. CRUISE is a European Network of Excellence project that deals

Table 4 Leading research projects in the domain of WSNs.

Project	**Scope**	**Description**
Smart Santander Project [85]	Smart city	Smart City project in Santander city to monitor noise, temperature, luminosity, CO, free parking slots. Residents can obtain bus routes, tourist, shopping information using smartphone application.
CodeBlue [88] Mercury [78] projects	Healthcare	- Emergency care, disaster response, stroke patient rehabilitation - Design wearable sensors to monitor vital signs of patients
GlacsWeb project [89]	Environment study	Monitor glacier behaviour using WSNs. Understand dynamics of glaciers and global warming.
eDIANA project [92]	Embedded systems	Energy efficient buildings. Deploys eDIANA platform integrated with intelligent embedded devices in the buildings to optimize energy consumption and improve efficiency.
European projects WiSeNts [94] e-SENSE [95] CRUISE [96]	Ambient computing, Embedded systems	- WiSeNts integrates existing research in embedded systems, ubiquitous computing and WSNs to support Cooperating Objects. - e-SENSE aims to capture ambient intelligence through WSNs by interaction between body sensor networks, object sensor networks, environmental sensor networks. - CRUISE is European Network of Excellence project. It deals with a wide range of WSN scenarios and Apps.
MOSAR [97]	Healthcare	Deployment of large scale WSN to gather dynamics of interactions between patients-patients, patients-medical staff and medical-medical staff to combat antimicrobial resistance of bacteria.

with a wide range of scenarios and applications of WSNs.

MOSAR [97]: is an European project for Mastering hospital Antimicrobial Resistance and its spread into the community. The MOSAR project intends to integrate and coordinate the research activities of physicians and scientists from several European institutions to combat the antimicrobial resistance of bacteria responsible for major and emerging nosocomial infections in hospitals. The project aims to achieve this through the deployment of a large scale sensor network to gather the dynamics of the interactions between patients-patients, patients-medical staff and medical-medical staff.

6 WSN platforms

The first commercial WSN platforms appeared in the late 1990s. The most important platform was Crossbow's Rene mote that evolved later to the popular Mica platform, which evolved further to the Mica2 and MicaZ platforms. The Crossbow mote platforms had been popular primarily due to their open source policy. Today, various commercial platforms with different characteristics in terms of computing resources, sensor interfaces, software architecture, are available, which allow to cope with a wide spectrum of applications [98].

WSN platforms consist of sensor nodes deployed in a controlled environment and are designed to support experimental research in a real-world setting. The availability of such testing platforms provide researchers a way to test their protocols, algorithms, network issues and applications as researchers can configure, run, and monitor their experiments remotely. Though several WSN platforms have been designed, usually they are geared toward specific projects and have specific features. Furthermore, there is a growing interest in large scale heterogeneous WSN testbeds in the context of Future Internet for the deployment of new technologies. The design and deployment of testbeds should consider user requirements to allow easy and flexible access to large number of users.

In this section, we present the significant features required for a general-purpose WSN testbed in Table 5, especially from the perspective of the users in terms of the ability to control and analyse the WSN experiments. Open software and open access platform are preferred over closed or proprietary platform as the testbed software must be ready for future extensions, especially in the context of Future Internet. We survey state of the art, open access WSN platforms and highlight their salient features. The testbeds are classified in three categories depending on their deployment; *1) outdoor, 2) indoor, and 3) indoor and outdoor.* A comparison of open access WSN testbeds is given in Table 6, at the end of the section. In addition, Table 7 compares the WSN testbeds in terms of desirable features.

Table 5 Characteristics of the WSN testbeds from the users' perspective.

Characteristics	**Description**
Interaction with users	Transparent access to testbed for users. Web-interface access to users. Analysis tools. Easy installation and automated resource reservation system.
Scale	Network size (number of sensor nodes) should be large for a real world deployment scenario.
Heterogeneity	Support for heterogeneous nodes. Interoperable with other testbeds.
Mobility	Support for mobile nodes, robots, mobile devices.
Federation	Testbed federation enables experiments at (large) scale. Reduces deployment cost.
Software (SW) Reuse	Provides software that can be reused to operate third-party testbeds.

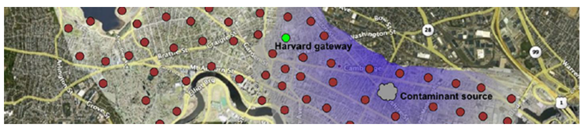

Fig. 13 CitySense: Conceptual deployment of sensor nodes in Cambridge[99].

6.1 Outdoor testbeds

CitySense [99]: is an open urban-scale WSN testbed that deploys 30 outdoor nodes (target is 100 nodes) on buildings and streetlights around the Cambridge city. It is a mesh like testbed with high power radios and embedded PCs. Its nodes support various sensors for monitoring weather conditions and air quality. Figure 13 illustrates the conceptual deployment of sensor nodes.

6.2 Indoor testbeds

TWIST [100, 101]: is a scalable and flexible testbed for indoor deployment of WSNs at the Technical University of Berlin. TWIST deploys 204 nodes (102 TmoteSky and 102 eyesIFX) and provides basic services like node configuration, network-wide programming, out-of-band extraction of debug data and gathering of application data. The testbed is deployed hierarchically in 3 tiers; servers, super nodes and sensor nodes. The significant features of TWIST are; self-configuration capability, use of hardware with standardized interfaces and open-source software. The testbed is open to the registered users.

Tutornet [102]: is a tiered WSN testbed at University of Southern California. It consists of 3 tiers; testbed servers, gateway stations (Stargates), and sensor nodes as shown in Figure 14. Currently, the testbed deploys 13 stargates and 104 motes (91 TmoteSky and 13 MicaZ). The motes are attached to the gateway stations via USB connections. One stargate together with several motes form a cluster. Presently, there are 13 clusters and the motes can be pro-

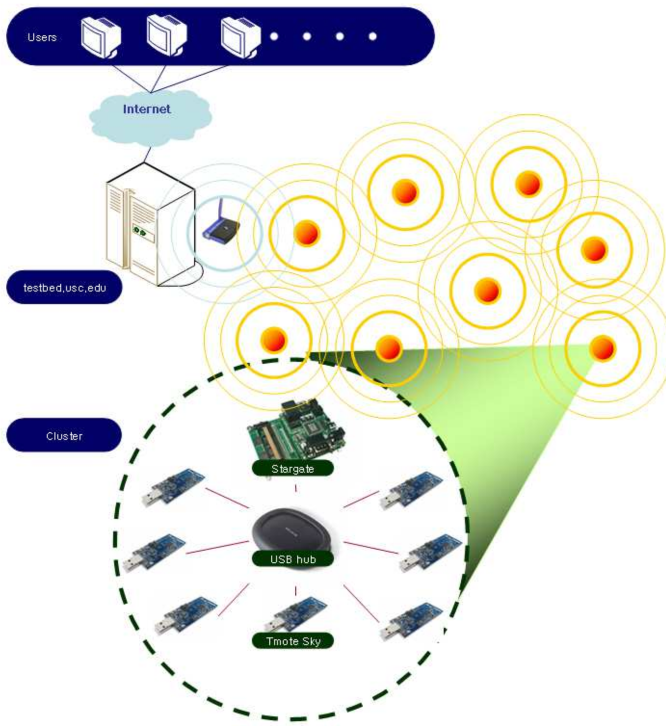

Fig. 14 Tutornet: 3-tiered WSN testbed.

grammed remotely. Access to the testbed is allowed to the authenticated users.

MoteLab [103]: is an open access indoor WSN testbed deployed at Harvard University. The testbed is accessible for development and testing of sensor network applications via a web-based interface. Registered users can upload and associate executable files with motes to create and schedule an experiment to be run on MoteLab. In addition, some tools are provided via the web interface to view data while the experiment is running. MoteLab aims to facilitate research in sensor network programming environments, communication protocols, system design, and applications. The testbed currently features 190 TMote Sky sensor nodes. The motes consist of MSP430 processor running at 8MHz, 10KB of RAM, 1Mbit of Flash memory and a Chipcon CC2420 radio operating at 2.4GHz with an indoor range of 100 meters. Each node includes sensors for light, temperature, and humidity. Nodes run the TinyOS [104] operating system and are programmed in the NesC [105] programming language.

Mobile Emulab [106]: is a robotic testbed developed for mobile WSNs to evaluate mobility-related protocols and applications. It consists of robots which carry a Stargate (small computer) and Mica2 mote [107]. The robots operate on battery power which lasts up to 3 hours and use 802.11b for com-

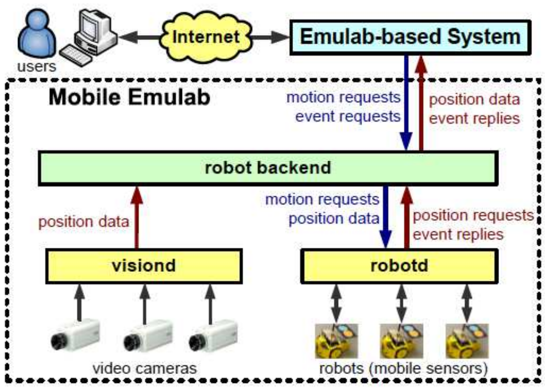

Fig. 15 The software architecture of Mobile Emulab [108].

munication with radios set to 900 MHz. There are two drive wheels operating at a maximum speed of 2 m/s that manage the motion and steering of the robot. In order to detect obstructions, six infrared proximity sensors are placed on all sides of the robot. Users can create experiments through a web interface and schedule events to control the movement of the robots remotely. Figure 15 shows the software architecture of mobile Emulab testbed.

Kansei [109]: testbed at Ohio State University is designed to facilitate research of networked sensing applications at scale. Kansei provides a testbed infrastructure to conduct experiments on various wireless platforms, including 802.11, 802.15.4, and 900 MHz Chipcon CC1000 radios, as well as diverse sensor node platforms (e.g., XSM, TelosB, Imote2 and Stargates). Currently, the testbed consists of 96 Kansei Nodes. Kansei is now part of the Global Environment for Network Innovation (GENI) project [110] and the Kansei testbed is being federated with the NetEye [111] testbed at Wayne State University. KanseiGenie [109] is a consortium of sensor testbeds for at-scale federated experimentation. It provides access to 700 or more motes for experiments.

NetEye [111]: is an indoor WSN testbed at Wayne State University that features 130 TelosB motes. Users can access the testbed through a web interface to create and schedule an experiment. Significant features of the testbed include FCFS (first come first served) scheduling approach for resource allocation, automatic storage and logging of data on to the server, real-time data and event injection on the fly. NetEye is being integrated with the Kansei testbed [109] as part of the GENI project.

w-iLab.t testbed [112]: consists of 200 TMoteSky motes in an indoor, laboratory environment. It is run by the IBBT iLab.t Technology Center and is located in Gent, Belgium. The w-iLab.t testbed is based on the widely used MoteLab testbed [103]. The w-iLab.t testbed is accessible to authorized users

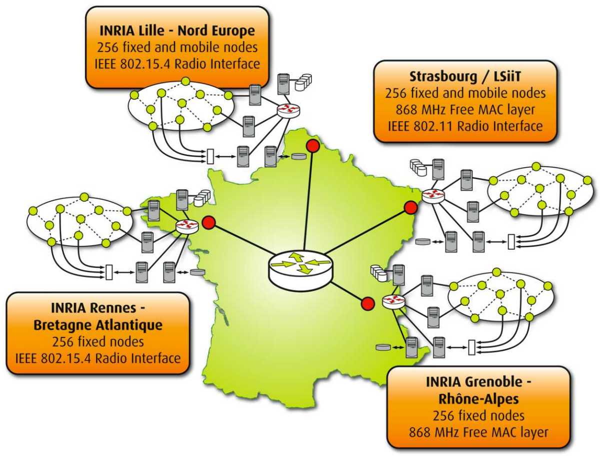

Fig. 16 SensLAB national wireless grid testbed.

via a web-interface, to schedule, upload, monitor experiment on the testbed and retrieve results. The unique features of the testbed include real-time monitoring of the power consumption and battery capacity emulation. In addition, it is possible to simulate node mobility in a repeatable way.

Planetlab [113, 114]: is an open, shared, large-scale platform for conducting real-world experiments to develop new network services and technologies. It provides support for developing, deploying, and accessing planetary-scale applications. Though PlanetLab is not dedicated to sensor networks, it is being federated with different types of testbeds including WSN testbeds. As a part of the initiative to develop testbeds for the Future Internet, the OneLab [115] initiative is extending PlanetLab Europe by federating it with other PlanetLab testbeds worldwide as well as other types of testbeds. Presently, PlanetLab consists of 1168 nodes at 550 sites worldwide in more than 40 countries. While the worldwide control center of PlanetLab (PlanetLab Central) is in Princeton, other centers are in Japan and Paris. PlanetLab Europe [116] is the European portion of the PlanetLab testbed. It consists of 349 nodes at 156 sites. Planetlab provides user accounts to persons affiliated with corporations and universities that host PlanetLab nodes.

SensLAB [117, 118]: is a large scale open WSN testbed designed for sensor network experimentation. The SensLAB testbed aims to offer an accurate and efficient scientific tool to support the design, development, tuning, and experimentation of real large-scale sensor network applications. As illustrated in Figure 16, the SensLAB platform is distributed among 4 sites in France (Lille, Grenoble, Rennes and Strasbourg) and consists of 1024 sensor nodes. Each site deploys 256 MSP430-based sensor nodes with two sites offering access to mobile nodes as well. The Strasbourg and Lille sites deploy some toy electric trains (mobile nodes) that can be controlled remotely. Within a site, a node can communicate via its radio interface with the neighbor nodes. In addition, a sensor node can be configured as a sink node and can communicate and exchange data with any other sink node of the whole SensLAB testbed or any computer on the Internet. SensLAB is accessible to the registered users through a web interface that offers services to reserve, configure and deploy experiments. The federation project F-Lab [119] is federating SensLAB with other testbeds specifically, OneLab and PlanetLab. The F-Lab project aims at developing federation mechanisms allowing OneLab users to deploy experimental services on sensor nodes on SensLAB.

CONET Integrated Testbed [120]: aims to develop a common testbed for cooperating objects. The main elements of the testbed are; 5 robotic platforms and a WSN of 40 Crossbow Mica2 nodes (static and mobile nodes). Inside CONET, the cooperating objects feature diverse sensing, computation and wireless communication capabilities. The goal of CONET is to facilitate the research, development, testing, validation and comparison of different techniques and applications regarding cooperative objects.

6.3 Indoor and Outdoor testbeds

Sensei-UU testbed [121]: is a relocatable testbed at the University of Uppsala campus. It enables users to conduct experiments with repeatable node mobility and supports heterogeneous nodes (common sensor node platforms such as TelosB as well as mobile phones such as Android-based smart phones) in diverse environments. The testbed supports a robot-based solution for mobility at walking speeds and indoor usage. Inexpensive Lego robots are used to carry sensors and to create repeatable movements.

DES-Testbed [122, 123]: is located at the Freie Universitat Berlin. It consists of 95 MSB-A2 sensor nodes and 95 wireless mesh routers equipped with up to three IEEE 802.11a/b/g network adapters. The core of the testbed, called DES-Mesh, is formed by the IEEE 802.11 network and a parallel testbed called DES-WSN is formed by the wireless sensor nodes. The testbed allows users to define, schedule, run, monitor and evaluate WSN experiments as well as Wireless Multi-hop Wireless network experiments.

WISEBED [124]: is an open large-scale WSN testbed consisting of 550 nodes (e.g. iSense, TelosB, MicaZ, Mica2, Tmote Sky, etc). It deploys some mobile nodes (e.g., iSense nodes) also with IEEE 802.15.4 as backbone. WISEBED aims to establish a large-scale network of WSNs by federating a number of testbeds. Currently, the WISEBED experimental facility consists of WSNs located at 9 locations in Europe. Each WISEBED partner maintains its own testbed with different hardware equipment and setup. The portal servers of testbed partner sites are interconnected via an overlay network. Users can ac-

Table 6 A comparison of open access WSN platforms. *FCFS: first come first served scheduling approach.*

Testbed	Type	Nodes and Scale	Significant features
Outdoor			
CitySense[99]	WSN, Mesh	30 Sensor nodes, City-scale	Monitors weather, air quality,
Indoor			
TWIST[101]	WSN	204 motes (102TmoteSky, 102 eyesIFX)	3 Tiers Tiered testbed.
Tutornet[102]	WSN	104 motes (91 TmoteSky, 13 MicaZ)	3 Tiers Tiered testbed.
MoteLab[103]	WSN	190 TmoteSky motes	FCFS with user quota, best-effort. Select topology, schedule, upload, manage, retrieve.
Mobile Emulab[106]	Mobile WSN	250 motes(Mica2, robotic nodes, 802.11b)	FCFS, Select topology, schedule, run experiment, Control robots remotely.
Kansei[109]	WSN, Mesh	96 Kansei motes (XSM, TelosB, iMote2, Robotic nodes)	FCFS, best-effort, mobility support (mobile robots) Select topology, schedule, upload, manage, retrieve.
Kansei-Genie[109]	WSN, Mesh	700 motes (XSM, TelosB, iMote2, Robotic nodes)	Heterogeneous mote platforms, Kansei is being federated with NetEye as part of GENI project.
NetEye[111]	WSN	130 TelosB motes	FCFS scheduling, web-interface to create, schedule experiment. To be integrated as part of the KansaiGeni testbed.
w-iLab.t[112]	WSN, Mesh	200 TMoteSky motes	Energy measurement, battery capacity emulation, repeatable mobility support.
Planetlab[113]	Wired	1168 wired nodes	Distributed, 550 sites (40+ countries). It is being federated with WSN testbeds (SensLab).
SensLAB[117]	WSN	1024 WSN430 nodes	Mobility support via electric toy trains. It is being federated with OneLab and PlanetLab.
CONET[120]	WSN, Robotic	WSN(40 Mica2 motes), 5 Robotic platforms	Testbed for cooperating objects, static and mobile nodes, diverse sensing, computation and wireless communication.
Indoor and Outdoor			
Sensei-UU[121]	WSN	Common sensor nodes (TelosB), Mobiles, Robotic nodes	Relocatable, repeatable node mobility, heterogeneous nodes.
DES-Testbed[123]	WSN, Mesh	95 MSB-A2 95 Linux nodes,	Define, schedule, run, monitor and evaluate experiments.
WISEBED[124]	WSN	550 motes (iSense, TelosB, MicaZ, Mica2, TmoteSky)	Federation architecture, co-simulation support, topology virtualization, mobility support (40 mobile robots)

Table 7 Comparison of open access WSN testbeds in terms of desirable features. A ✓denotes that the testbed supports the feature, an X denotes inadequate support, and – denotes that it is not known if the feature is supported or not.

Testbed	Nodes and Scale	Heterogeneity	Mobility	Deployment	Federation	SW-Reuse	Analysis tool	Web-interface
CitySense[99]	30	–	X	Outdoor Distributed	X	✓	✓	✓
TWIST[101]	204	✓	X	Indoor	X	✓	✓	✓
Tutornet[102]	104	✓	X	Indoor	X	–	–	X
MoteLab[103]	190	X	X	Indoor	X	✓	✓	✓
Mobile Emulab[106]	250	X	✓	Indoor	X	✓	✓	✓
Kansei[109]	96	✓	X	Indoor	X	–	✓	✓
KanseiGenie[109]	700	✓	X	Indoor	✓	–	✓	✓
NetEye[111]	130	X	X	Indoor	X	–	✓	✓
w-iLab.t[112]	200	X	✓	Indoor	X	–	✓	–
Sensei-UU[121]		✓	✓	Indoor Outdoor	X	–	✓	–
DES-Testbed[123]	95	X	X	Indoor Outdoor	X	–	✓	–
SensLAB[117]	1024	✓	✓	Indoor	✓	✓	✓	✓
WISEBED[124]	550	✓	✓	Indoor Outdoor Distributed	✓	✓	✓	✓
CONET[120]	40	–	✓	–	✓	–	–	–

cess one or multiple testbeds by connecting to the overlay network.

In addition to the platforms described above, several commercial solutions exist for WSN platforms such as WiEye and Sun Spot. However, most of these testbeds consist of only a few dozens of nodes and are expensive which make it difficult to perform large-scale experiments. Existing open research testbeds differ in terms of scale, node capabilities, programming model, etc. In general, most of the testbeds are not open to the broad community. Usually the networks are small consisting of only a few dozens of nodes and dedicated to internal use. Moreover, the testbeds lack mobility feature and the possibility to study hierarchical protocols in order to interconnect sensor network clouds through the Internet. Furthermore, many platforms use IEEE 802.15.4 MAC layer and impose a specific choice of Operating System like TinyOS [125,104]. This results in two problems; first, fixing the MAC layer to only IEEE 802.15.4 discourages any research that targets the optimization or improvement of MAC layers, and second, imposing a specific choice of OS restricts applications to use an OS that may not be efficient in terms of energy consumption and clock frequency optimization. Nevertheless, the large-scale WSN platforms like

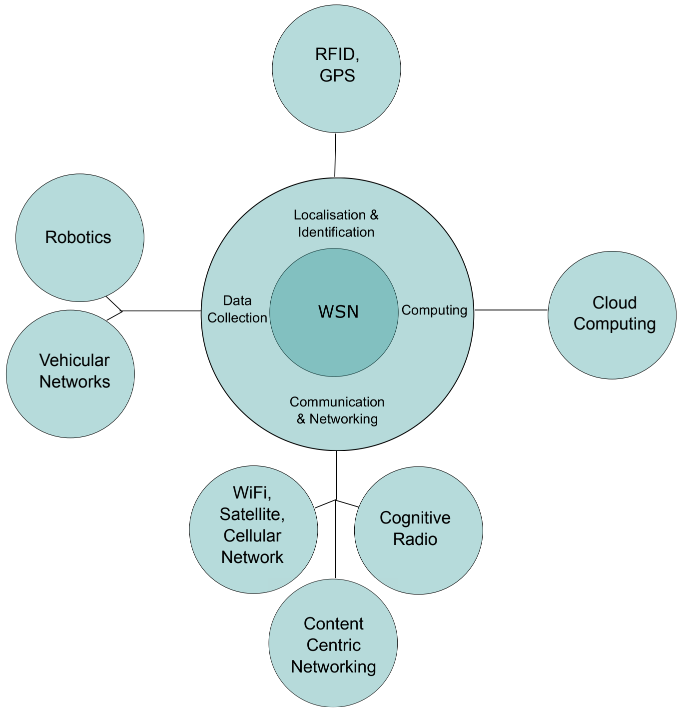

Fig. 17 Potential synergies between WSN and other existing and emerging technologies.

SensLAB, TWIST, Motelab, and Kansei as described in this section facilitate experimentation and deployment of scalable sensor network.

7 Potential synergies

A recent phenomenon in WSN research is to explore synergy between sensor networks and other technologies. In this section, we describe how integration of WSNs with existing wireless and mobile communication technologies as well as emerging technologies such as RFID, robotics, vehicular networks, cloud computing, cognitive radio and content-centric networking, as shown in figure 17, can help sensor networks achieve their full potential. We present some examples in literature that explore potential synergies among WSNs and other technologies to improve their overall performance.

7.1 Synergy between mobile robots and WSNs

Some researchers have focused on synergy between autonomous robots and sensor networks. The work of Kotay et al. [126] focuses on synergy between GPS-enabled robots and networked sensors to provide localization services and better robot navigation. The synergy between robot and sensor networks is utilised in support of search and rescue and first response operations. WSNs enhance the robots' capabilities to sense and enable them to act in response to events outside their perception range. At the same time, mobile robots enhance sensor networks via their ability to bring new sensors to designated locations and move across the sensor field for sensing, data collection, and communication. Gupta et al. [127] propose a mechanism for the transportation of resources by integrating robots with sensor network services. The integration of sensor networks and robotic research results in an interesting problem space of interrelated issues open for exploration.

7.1.1 Using mobile robots to harvest data from sensor fields

WSN technology enables high fidelity data collection over large geographic regions and extended periods of time. However, it is not economical to deploy an end-to-end environmental monitoring WSN over a large geographic area. One reason is that depending on the environment, the range of individual wireless links is between 10 and 50 meters and therefore, a large number of relay points is necessary for multi-hop data collection. Another reason is reliable delivery of data over wireless links consumes high energy. Moreover, since wireless links are lossy, the probability of loss (and re-transmission) increases with increase in the length of the routing path. Lastly, in addition to the energy used to carry sensor measurements, the motes need to exchange control traffic to support the routing paths used for forwarding the data traffic, that further depletes their limited energy [128].

The above issues can be addressed by using mobile robots. In [128], authors show synergy between mobile robots and a static sensor field in environmental monitoring through a system in which robots act as mules (data mules) that collect the measurements gathered by sensing nodes. This system uses autonomous robots as data mules as an alternative to an end-to-end wireless network (that forwards the measurements of the motes to a back-end database). These mules visit locations within the communication distance of each of the static motes, download their measurements and return to a remote base station to offload the gathered data. Figure 18 shows the overall architecture of the system which includes sensing motes, multiple robots acting as data mules, and a gateway to which robots offload gathered data and receive further commands. Each robot communicates with the sensing nodes and the gateway via a locally connected mote and all gathered data are finally stored in a back-end database for further processing and visualization.

This approach offers several advantages. First, data mules can move nearby a mote to make sure that the quality of the wireless link is high. Second, since the robot moves adjacent to the mote, the mote can reduce the transmission power of its radio, further reducing its energy consumption. Thus, with this approach motes can conserve energy that they would otherwise use to forward data, thereby prolonging the network's lifetime. Lastly, it is easier to recharge the robots' batteries than replacing motes' batteries. However, in order to suc-

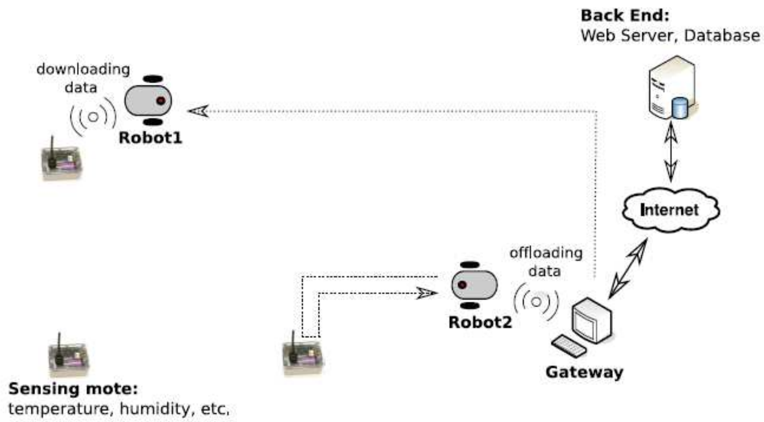

Fig. 18 Overall system architecture: synergy between mobile robots and WSN[128].

cessfully deploy such an integrated robot and sensor network, new challenges such as planning robots' trajectories must be overcome.

7.1.2 Data muling over underwater WSNs using an Autonomous Underwater Vehicle

Small autonomous underwater robots allow to explore and monitor underwater environments, permitting applications such as long-term monitoring of underwater habitats, monitoring and surveillance of ports, and ground activities (e.g., manufacturing and agriculture) on the water quality. These applications require long term underwater presence over a large area and quick response to triggers within the environment. The response might include visit by a sensor-rich robot, data upload, or physical repositioning of the network nodes. However, in order to perform such tasks, there should be a synergy between mobility and communication. A sensor network provides robots the ability to access data beyond their perception range while robots support the sensor network by deploying, moving and retrieving nodes, making repairs when required, and acting as data mules to forward information between disconnected sensor clusters. The main features of such interactions include: locating and docking with modules; placing, retrieving, and organizing modules; cooperative navigation with docked AUVs (Autonomous Underwater Vehicles); communications, and data muling over a deployed sensor node [129].

In [129] authors present a system for collecting data from an underwater sensor network using an AUV as a data mule which is an example of useful synergy between mobile robot and sensor network. The system consists of an AUV called Starbug and many static Underwater Sensor Nodes (USN) networked together optically and acoustically. The AUV can interact with static sensor nodes to upload, download, or transport data to a different physical location. The AUV can locate the static sensor nodes using vision and hover above them for data upload. As mentioned previously, such underwater networks can perform many useful tasks such as long-term environmental monitoring or surveillance.

7.1.3 Data Spider: Efficient data collection in WSNs

Conventional deployments of WSNs rely on static base-stations (SB) to gather data. However, for applications with dynamic data generation (e.g., tracking and detection), SB suffer from long routes and communication bottlenecks, which significantly reduce reliability and lifetime.

A solution to address this issue is to use synergy between WSN and mobile base-station (MB) for an efficient data collection in sensor networks as described in [130]. The MB-based data collection system, *data spider* as proposed in [130] consists of two subsystems; a WSN component and a MB component. The WSN component is a lightweight dynamic routing tree maintenance protocol (DTR) which tracks the location of the base-station (MB) to provide an always connected network. Whereas the MB component (base-station algorithm) of data spider relies on the data delivered to it by DTR and complements DTR by trailing towards the data generation. This decreases the number of hops data requires to be delivered to the MB and increases the reliability and lifetime of DTR. Thus, an integrated usage of WSN and MB improves the efficiency of data collection in sensor networks significantly.

7.2 Micro-Blog: Map-casting from Mobile Phones to Virtual Sensor Maps

The next generation sensor networks are envisioned to be interactive and large-scale. It will be possible to organize millions of global data points on a visual platform, and queried and answered through human participation.

In this context, Micro-Blog [131] is a new paradigm that utilizes synergy between sensors, wireless and mobile communication and may transform the way we learn, interact, and make decisions. Micro-Blog combines four different components which are as follows; powerful phone sensors, mobile wireless networks, information processing, and spatial visualization. The basic concept in Micro-Blog is that users can record multimedia blogs on the fly by using microphones and cameras in mobile phones. First, the application running on the mobile phone creates the *microblog* and associates the blog with the time and GPS location of the device. Then, the application transports the microblog over a peer-to-peer, WiFi, or cellular wireless network, to reach a server that places the blog on a map (e.g., Google Maps). This process is called map-casting. Afterwards, various web services can be used to mine, group and correlate these blogs depending on user interests, social networks, etc. Moreover, in regions where microblogs are not available on a map, Internet users can geo-cast queries to mobile phones located around that region. Human responses to these queries can be map-cast back that will enable knowledge-sharing between strangers [131]. Figure 19 shows the architecture for Micro-

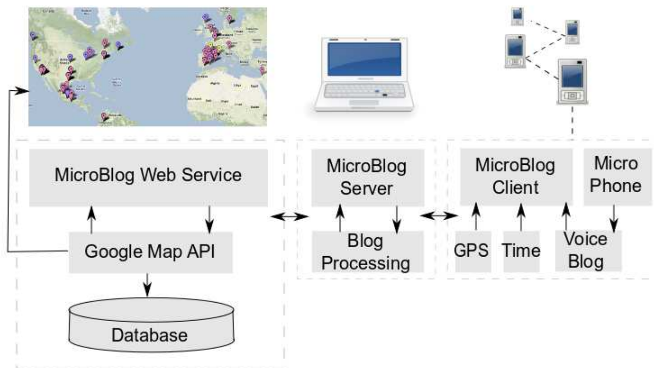

Fig. 19 The architecture for Micro-Blog.

Blog. It includes implementing a light weight Java client on the Mobile phone, a bluetooth/WiFi/cellular based wireless routing protocol, a Micro-Blog web service, and a visualization front end. The system enables a phone to transport a microblog to the server. The web service and visualization front end receive the microblog, processes them, and places them on Google maps.

7.3 SensorCloud: Wireless sensing and cloud computing

WSN applications use real-time sensor data supplied by sensor nodes responsible for sensing and local preprocessing. This huge amount of data usually needs to be processed in some fashion. Since WSNs are limited in their processing power, battery life and communication speed, cloud computing offers a real option to satisfy the computing needs that arise from processing and analyzing the data gathered by sensors. Cloud computing [132, 133] is a new emerging paradigm for the Internet-based software systems. The cloud provides scalable processing power and several kinds of connectable services. Combining the concept of wireless sensing with cloud computing makes WSNs attractive for long term observations, analysis and use in different kinds of environments. For example, WSNs with cloud computing can be used to monitor civil infrastructure or public health, by building a new computing, communication, and management system architecture for sensing, processing, and storing physical data [134].

The Shelburne Vineyard project [135] uses synergy between WSN and cloud computing to monitor its vines. A wireless environmental sensing system has been deployed to monitor key conditions during the growing season of grapes. A distributed network of low-power wireless nodes and a new cloud-based data service called SensorCloud are used to remotely monitor temperatures in real-time to ensure crop health. The SensorCloud platform is used to access unlimited continuous environmental data, to analyze trends and to create alerts, which notify key personnel when environmental thresholds are exceeded. The scalable network monitors all the plant varieties of the vineyard and supports cost-effective condition based cultivation and harvesting.

7.4 Integration of WSN and RFID

There are a number of applications where just an object's identity or location is not sufficient and additional information through sensing environment conditions is required. A WSN uses a variety of sensors to provide information about the condition of the objects as well as the environment, but it cannot identify objects individually. On the other hand, Radio Frequency Identification (RFID), a popular technology developed for short-range (2mm-2m) identification purposes, allows the detection and identification of objects, but it does not provide information about the condition of the objects it detects. Thus, integrating WSN-RFID technology is an attractive solution for such applications as it will be more efficient in terms of capabilities as well as cost [136]. Such an integration benefits from synergy between the two technologies by converging sensing capability of WSN with RFID's identification capabilities. This enables a number of heterogeneous applications which require a high synergy between detection and tagging.

One possible application of integrated WSN-RFID technology is in robotics (e.g., robots based rescue missions). Robots equipped with RFID readers and sensors will be able to sense the environment using sensors and better understand their environment after reading IDs from the tagged objects around them. The information about the environment can be used for navigation of the robots [137]. Another application of integrated WSN-RFID technology is in food logistics and supply chain management processes for better monitoring. In food logistics and supply chain management, RFID is widely used as it is capable of identifying, categorizing, and managing the flow of goods [138]. In addition, RFID tags can monitor temperature, identify problem areas and raise alarms. Though RFID loggers (RFID tools) required for such applications are low-cost and available in high quantities, due to their low reading range, they require manual handling. This issue can be addressed by integrating RFID with WSN as WSN provides longer reading range as well as other benefits like different network topologies and flexibility, variety of sensors that are already implemented and low power consumption [31]. Thus, integration of WSN and RFID provides a significant improvement on monitoring.

Though wireless sensor nodes are expected to be quite cheap with mass production, still the RFID tags will remain extremely cheaper in comparison to them. This makes using RFID tags instead of wireless sensor nodes an economical solution in WSN applications where only the presence and location information of objects are required. Thus, the development of wireless sensor devices based on RFID is beneficial and extends the range of possible applications. Moreover, integration with RFID equips sensor nodes with tag IDs and using tag IDs instead of MAC addresses (of sensor nodes) could be an efficient solution for wireless sensor nodes. Furthermore, RFID can enrich a sensor network by providing sensing capabilities to the objects, for example, RFID could be an alternative solution in harsh environments where sensor nodes may fail to work. However, some open issues need to be addressed to achieve an efficient integration of the two technologies such as how to reduce possible interference in large integrated RFID networks and WSNs.

7.5 Cognitive Radio Sensor Networks (CRSN)

Conventional WSNs use fixed spectrum allocation policy and their performance is limited due to limited processing and communication power of resource-constrained sensor nodes. With significant growth in the applications that use the unlicensed spectrum bands over which WSN operates, there is a real challenge for efficient utilization of the spectrum. This challenge can be addressed by exploiting the synergy between WSNs and Cognitive Radio (CR) technology [139]. The CR technology allows opportunistic access to the spectrum through intelligent spectrum sensing and dynamic spectrum utilisation. Incorporating cognitive radio capabilities in WSNs forms a new sensor networking paradigm called cognitive radio sensor networks (CRSN). A CRSN is a distributed network of wireless cognitive radio sensor nodes, which sense an event signal and collaboratively communicate their readings over dynamically available spectrum bands in a multi-hop manner to fulfill the application related requirements. Cognitive radio improves spectrum utilization and increases communication quality with opportunistic spectrum access capability and adaptability to the channel conditions [140]. Thus, using the CR technology in resource-constrained WSNs improves the spectrum utilization, and enables the deployment of multiple overlaid sensor networks in a specific region. In addition, cognitive radio capabilities provide multiple channel availability that can be used to overcome the problems due to the dense deployment and bursty communication nature of WSNs.

One potential application of CRSN for emergency reporting in healthcare WSNs is described in [141] that explores synergy between CR and sensor network. Healthcare WSNs enable efficient monitoring of patients and emergency reporting. However, they are subjected to high concurrency for free-spectrum access, that decreases the quality of service and damages the emergency reporting to a medical central station. A CRSN utilizes the spectrum more efficiently and can improve the performance of healthcare networks. The cognitive radio sensor nodes coupled with the patients' bodies form a cognitive healthcare network that measure vital signs and can identify their emergency degrees. The CR technology provides the capabilities to dynamically allocate resources according to the emergency degree of each patient.

Figure 20 shows the topology of a typical CRSN. Since CRSN is a recent emerging paradigm there are several research issues that need to be studied to overcome the challenges for the realization of CRSN. Cognitive radio approaches need to designed that focus on energy efficient communication to exploit transmission power and spectrum characteristics vs performance and

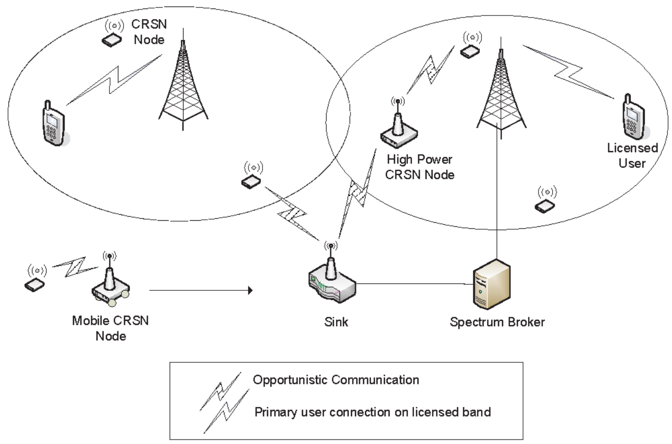

Fig. 20 Topology of a typical cognitive radio sensor network (CRSN).

reliability trade-off. In addition, low cost algorithms need to be designed for spectrum sensing and dynamic spectrum usage.

7.6 Satellite-based WSNs: Integrating satellite technology and WSNs

Global scale sensing can be achieved with nano-and pico-satellites by integrating satellite technology to WSNs [142]. Integrating satellite systems to WSNs brings about a beneficial synergy in support of several significant application scenarios, such as surveillance and monitoring of remote areas, emergency communications, support for supervisory control and data acquisition (SCADA) systems, critical infrastructures (CIs) and environment monitoring [9].

Traditional satellite missions are extremely high cost as they are very expensive to design, build, launch and operate. This has motivated the aerospace industry to focus on space missions consisting of several, distributed, small and inexpensive satellites. Such distributed space missions require hundreds to thousands of satellites for simultaneous multipoint sensing. These missions, hindered by the lack of a low-cost mass-producible sensor node, can benefit by integrating the concepts of distributed satellite systems and terrestrial WSNs. A novel, subkilogram, very-small-satellite design can enable these missions [143]. Distributed systems of small sensor-equipped satellites improve the cost efficiency and performance of missions.

Satellite-based WSNs have high potential in space and Earth monitoring applications. Satellite sensor networks in Low Earth Orbit (LEO) can be the preferred technology for different types of Earth Observation (EO) missions such as environment and agriculture studying (e.g., pollution, land, ocean surface and crop condition monitoring), hazard and disaster monitoring (e.g., flood, earthquake, and urban disaster prediction), and observation for security and crisis management (e.g., border, vehicle and activity watching) [142]. Though integration of satellite technology and WSNs is beneficial, it also introduces new challenges in terms of inter-satellite communication and routing that need to be addressed.

7.7 Content Centric Networking (CCN) in WSNs

With WSN applications gaining huge popularity, the focus is now on improving the performance, autonomy and communication efficiency of WSNs. Since WSNs focus on the content of gathered data irrespective of the addresses of sensor nodes, they can benefit from Content Centric Networking (CCN) to improve the existing communication models of WSNs. CCN [144] is a new communication architecture for the Internet of the future aimed at bridging the gap between today's content-centric communications and the old point-to-point communications. Since today's communications are more content retrieval oriented, CCN is based on named data unlike current named hosts (TCP/IP protocols) based Internet architecture. In CCN, information/content is exchanged only in response to a request specifying the name of the data to retrieve. CCN is apt for WSNs as the communication mainly consists of sensor data rather than requests to specific nodes. In a data-driven network, a query instructs each node to sense its environment at a certain rate, for a period of time, and deliver matching data back to the sink [145]. CCN allows focusing on data instead of data location which is important for data-growing networks such as WSNs. Overall, CCN allows networks to self-organize and push relevant content where needed.

In sensor networks, CCN can play a significant role as it enables autonomous sensor networks. A potential application that exploits synergy between sensor network and CCN is CarSpeak [146], a communication system for autonomous driving. CarSpeak enables a car to request and access sensory information captured by other cars in a way akin to how it accesses information from its local sensors. CarSpeak achieves this objective by adopting a content-centric approach where information objects i.e., regions along the road are first class citizens. It names and accesses road regions using a multi-resolution system, which allows it to scale the amount of transmitted data with the available bandwidth.

In-network configuration of WSNs using a content-centric approach can be helpful in efficiently applying in-network configuration operations on sensor nodes using adapted naming schema and introducing a low communication overhead. In WSNs, data or content centric approaches such as in-network processing and data aggregation are important. Though CCN approach is apt for WSNs, the CCN protocol suite (CCNx) [147] designed for PCs is not suitable for resource-constrained WSNs. This problem can be addressed by using a lightweight CCN protocol specifically designed for WSNs [148] to meet the memory and computational constraints of sensor nodes as well as communication patterns in WSNs.

7.8 M2M technology and WSNs in Oil and Gas industry

The complexities and inherent safety requirements in the Oil and Gas industry have led to the adoption of the WSN technology. The oil companies, such as British Petroleum (BP) use WSNs to monitor the industrial plants, pipelines and equipment maintenance. It is crucial to be able to monitor things in real-time for the operations in areas like offshore platform or oil fields as this allows to take decisions and execute corrective actions in real-time as things evolve. Sensors enable collection of data that can be translated into actionable items on a real-time basis. Real-time data is fed into predictive models, which helps in dealing with a critical situation, such as equipment or process failure before it happens.

In addition, the oil companies are now using WSNs to meet business needs including increased worldwide demand for energy and achieve operational goals. More recently, they have started exploring synergy between WSN and Machine-to-machine communication (M2M), that has transformed their business by enabling them to automate and control production sites in widely dispersed geographic areas. M2M is a key enabling technology for the emerging Internet of Things. It enables smart objects, such as smart sensors and actuators, to communicate and interact with each other across different networks and domains. In the oil and gas industry, harsh conditions, such as hostile terrain, harsh weather in remote locations are common barriers to properly monitoring and managing field equipment. Thus, integrating WSN with M2M provides effective solutions for the oil companies enabling them to reduce implementation and maintenance costs, reduce downtime, improve equipment performance, and centralize discrete controls and enhance personal safety by enabling new topologies for remote monitoring and administration in hazardous locations. WSN and M2M solutions are being used in refineries, offshore platforms, pipelines, and ocean-going tankers. For example, in ocean-going tankers, WSN and M2M technologies constantly provide information on the health of the tankers and thus, help to avoid any downtime.

7.9 Relaying information using vehicular networks and other communication technologies

The paradigm of smart cities is the next step in the evolution of urbanization. Sensors, intelligent vehicles and mobile phones of people networked with each other can provide various services to the users and help in the efficient city management. Many services can be imagined, e.g., sensors can measure pollution and forward the data towards the concerned authority. However, there are many challenges and open issues associated with this paradigm. One of the challenges is to optimally and opportunistically route the information towards the destination with efficient use of energy and resources. For example, sensors would forward the sensed data to some relay nodes such as vehicles. These relay nodes will participate in the forwarding of the information towards the final destination or towards a point with Internet connectivity, that could be through WiFi or cellular network, from where the concerned destination can obtain the data. The routing will have to take care of the unstable environment having intermittent connectivity, resource constraints, multiple paths, mobility of nodes and asymmetric links. Some cross layer algorithms can be designed that can exploit mobility prediction, geo-localisation information, link interference due to other users, resource constraints, etc. Moreover, some vehicular delay tolerant networking approaches can be considered for relaying information.

One interesting example of synergy between vehicular networks and WSN is an integrated VANET-WSN system [149]. The VANET (vehicular ad-hoc network) aims to improve driving safety. However, it may not guarantee timely detection of dangerous road conditions or maintain communication connectivity when the network density is low (e.g., in rural highways). Such limitations of VANET-based system can be addressed by integrating the VANET with WSN. The sensor nodes are deployed along the roadside to sense road conditions, and to buffer and deliver information about unsafe conditions to vehicles regardless of the density or connectivity of the VANET. However, several issues including routing issues should be addressed in order to realize an efficient VANET-WSN system. A recent survey of routing protocols in VANET is given in [150].

8 Additional open research issues

As we saw in this paper, wireless sensor networks present various challenges which are not faced by conventional wireless networks. This necessitates the need to design new protocols and algorithms to meet the challenges and requirements of WSNs. The current research work in WSNs has enabled them to produce high quality results for longer periods of time, however there are several open research issues which need to be addressed. First of all we would like to point out that **Energy efficiency** is still a key concern and attracts WSN researchers. Apart from that, some of the research challenges are already provided in section 7 and here we present some additional future WSN research directions which are as follows. WSN field is evolving dynamically and all that is targeted towards new and new possibilities, such as full body sensors that will include custom attachments and prosthetics in the future. WSNs will be able to predict complex weather patterns and control the actuators that can take appropriate actions for the crops. WSNs in conjunction with Software defined Radio will be able to utilise white TV bands for efficient communication and more cooperative intelligence will allow them to self heal, organise and adaptively reconfigure. In fact, possibilities are numerous and we focus on open research issues related to algorithm and system design.

Addressing Heterogeneity: Most of the existing work in WSNs assume that the network is composed of homogeneous nodes. In this context, a challenging problem is to make best use of the resources in heterogeneous sensor networks. Moreover, the sensor nodes in a WSN may be shared by multiple applications with divergent objectives. Thus, with increase in the use of WSNs there is a need to develop protocols which can efficiently serve multiple applications simultaneously.

Design of Cross-layer solutions: A cross-layer design methodology for resource constrained WSNs is a promising approach. Several cross-layer designs or protocols are proposed in WSNs, but they focus on physical, data-link, network, and transport layers. Future research in cross-layer design should focus on collaboration between all the layers to achieve higher energy saving, network performance, and longer network lifetime. So far the focus has been on cross-layer design and improvement of protocols for WSNs. The development of efficient techniques to correctly model and successfully leverage cross-layer interactions is an open research problem.

Appropriate QoS models: The data-centric nature of WSNs make it difficult to describe QoS. While conventional networks use parameters like delay, packet loss and jitter to specify application QoS requirements, WSNs use parameters like data accuracy, network sensing coverage, fault tolerance and network lifetime. However, it is difficult to translate such data-specific QoS parameters into meaningful protocol parameters. Thus, it is an open research issue to describe and design an appropriate QoS model for WSN. QoS requirements in WSNs are application-specific. QoS is of growing importance in WSN applications such as Cooperating Objects. However, QoS provisioning in WSNs is very challenging due to resource limitation of nodes, harsh conditions of WSN environments, large-scale and random deployment of nodes, and high interdependency between QoS properties. Moreover, future research should address issues of QoS provisioning over heterogeneous networks as well as multi-hop routes in homogeneous networks. An appropriate QoS model for WSN applications should consider various parameters like energy-sustainability, timeliness, reliability, security, scalability, mobility, heterogeneity, etc.

Cooperation in WSNs: Cooperative communications is a promising technique for efficient battery usage in WSNs, due to potential energy savings gained by cooperative diversity. The extent to which different WSNs can cooperate and save their energy should be investigated. In general, cooperative communications can enhance the performance of WSNs by improving network reliability [151]. However, the extent of performance improvement needs to be investigated due to the overhead and energy costs involved with the cooperation. While current studies focus on cooperative communications in the physical layer [152] there is need for higher layer protocols, which can translate the advantages of using cooperative communications to enhance network performance, especially to improve energy efficiency.

WSN deployment, management and self reconfigurability: Sensors are more easy to design than ever. Even if we can produce sensors which are energy self sufficient through energy harvesting for a while, deploying and managing them (e.g., replacing failed nodes) are still complex. The objective will be to add new sensors to replace failed sensor nodes in the deployment field as well as the ability to remove existing nodes from the system without affecting the general objective of the system.

Moreover, combining normal sensors with actuators, that can take actions adds a new dimension to the WSN paradigm. Such that WSNs will not only sense a given environment or state of a system, but will also participate in controlling it through actuators. This will involve automatic control designs and signal processing for state estimation.

Integration with other networks: WSN can function as stand-alone networks or be connected to other networks. For many applications, in order to work efficiently WSNs may be required to interface with other types of networks, such as Internet, WiFi or cellular network. Current work [57, 153, 154] on integrating WSN with the Internet focus on enabling TCP/IP support as TCP/IP is considered as the de-facto standard in network connectivity. Though such integration provides transparent operation of the WSN for end users, it creates new challenges that should be researched such as, the best way to interface different types of networks. Other issues that should be investigated are should the sensor network protocols support (or at least not compete with) the protocols of the other networks? Or should the sensors have dual network interface capabilities? For some WSN applications, these questions will be crucial and research is needed to find good solutions.

Moreover, as discussed in previous section, new communication paradigms such as cognitive radio (CR) technology can help in improving the performance of WSNs. The huge growth of WSN applications operating in unlicensed spectrum bands has led to overcrowding of the existing unlicensed spectrum. Cognitive Radio technology has great potential to improve the spectrum access and enhance the performance of WSNs. Recent advances in CR technology enable applying the Dynamic Spectrum Access (DSA) model in WSNs to get access to less congested spectrum, possibly with better propagation characteristics. However, the requirements imposed by the DSA model make it important to adjust the CR protocols according to the application requirements in order to optimize the performance of a CR-based WSN. Moreover, device capabilities, network topology, and size should also be taken into account in applying CR technology to WSNs. In addition, some open issues that should be further explored are scalability of the incumbent detection and recovery procedures, and coexistence among multiple CR-based WSNs.

Security: Current work on security in WSNs focus on cryptography, key management, secure routing, secure data aggregation, and intrusion detection. Though there are several proposals for secure protocols for data-link layer and network layer, malicious attacks can occur at any layer in the protocol stack. Thus, it is required to explore secure monitoring for different layers of the protocol stack. Ensuring holistic security in WSN in a cost-effective and energy-efficient manner is an open research problem. Other security issues that need to be investigated include security-energy assessment, data assurance, and authentication, level and type of security required, QoS-security evaluation, etc.

9 Concluding Remarks

The research in wireless sensor networks is very dynamic, and there are high expectations regarding applications and business potential of sensor networks. This paper has presented a state of the art on recent developments in wireless sensor network technology and its applications. We have identified the obstacles in the application of sensor networks that should be addressed in order to push the technology further.

Standardization is a key issue for success of WSN markets. We have presented various standards and technologies available for WSNs. For low data rate applications, IEEE 802.15.4 seems to be the most flexible technology currently available, while Bluetooth Low Energy (BLE) can be attractive for applications demanding higher data rates. Moreover, the IEEE 802.15 Task Group 6 (BAN) is developing a new standard specifically oriented to WSNs for Body Area Networks. The choice of technology to be used should be based on the target application as every WSN application has different requirements on the communication system. The development of new technologies like Bluetooth low energy, ZigBee green power, and EnOcean is pushing WSN into new areas of application.

The leading research projects in the domain of WSN are reviewed and some significant WSN platforms are described. Furthermore, we have highlighted how synergy between sensor networks and other technologies can help sensor networks achieve their full potential. The potential synergies are explored among WSNs and other existing and emerging technologies such as RFID, cloud computing, M2M, cognitive radio, vehicular networks and content-centric networking to improve their overall performance and efficiency. Finally, we have identified several open research issues that need to be investigated in future. We believe that, this article with a rich bibliography content, can give valuable insight into recent developments in wireless sensor network research and encourage new research.

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