Energy Efficiency in Wireless Sensor Networks: a top-down survey

Article *in* Computer Networks · July 2014

DOI: 10.1016/j.comnet.2014.03.027

Yacine Challal
University of Doha for Science and Technology

Energy Efficiency in Wireless Sensor Networks: a top-down survey

Tifenn Rault, Abdelmadjid Bouabdallah, Yacine Challal

Université de Technologie de Compiègne
Heudiasyc UMR CNRS 7253
60205 Compiègne, France

Abstract

The design of sustainable wireless sensor networks (WSNs) is a very challenging issue. On the one hand, energy-constrained sensors are expected to run autonomously for long periods. However, it may be cost-prohibitive to replace exhausted batteries or even impossible in hostile environments. On the other hand, unlike other networks, WSNs are designed for specific applications which range from small-size healthcare surveillance systems to large-scale environmental monitoring. Thus, any WSN deployment has to satisfy a set of requirements that differs from one application to another. In this context, a host of research work has been conducted in order to propose a wide range of solutions to the energy-saving problem. This research covers several areas going from physical layer optimization to network layer solutions. Therefore, it is not easy for the WSN designer to select the efficient solutions that should be considered in the design of application-specific WSN architecture.

We present a top-down survey of the trade-offs between application requirements and lifetime extension that arise when designing wireless sensor networks. We first identify the main categories of applications and their specific requirements. Then we present a new classification of energy-conservation schemes found in the recent literature, followed by a systematic discussion as to how these schemes conflict with the specific requirements. Finally, we survey the techniques applied in WSNs to achieve trade-off between multiple requirements, such as multi-objective optimisation.

Keywords: State-of-the-art, Wireless Sensor Networks, Energy efficiency

1. Introduction

There is abundant literature relating to energy-saving in WSNs as numerous methods have been proposed in the last few years, and there is still much ongoing research on how to optimise power usage in battery-limited sensor networks. However, none of the proposed solutions is universally applicable. For example, if safety applications require fast and timely responsiveness, this is not the case for other applications, such as in agriculture where the delay property is not as important. We believe that WSN energy-saving problems should be tackled by taking into consideration application requirements in a more systematic manner.

In [1], Yick et al. provide a general survey of wireless sensor networks. This study reviews sensor platforms and operating systems, network services issues and communication protocol challenges, but it does not addresses the energy issues. In [2], Anastasi et al. present a valuable taxonomy of energy-conservation schemes. However, the authors mainly focus on duty cycling and data-reduction approaches. There also exist several technique-specific surveys that concentrate on only one energy-efficient mechanism (like energy-efficient routing protocols, data aggregation techniques, energy harvesting approaches [3–5]) since every category of solution often represents a whole research area in itself.

Our aim is to provide WSN designers with a top-down survey that offers a holistic view of energy-saving solutions while taking into consideration the specific requirements of the applications. In this paper, we propose a new classification of energy-efficient mechanisms which integrates the most recent techniques and up-to-date references. Moreover, we give particular attention to the design of energy-efficient sensor networks that satisfy application requirements. Our study is original in that we focus on the trade-offs between meeting specifications and sustainability that necessarily arise when designing a WSN. We thus discuss mechanisms that enable a satisfactory trade-off between multiple requirements to be achieved. To the best of our knowledge, this is the first time that this approach has been taken.

The rest of this paper is organised as follows. In the next section, we present the main categories of applications we have identified and their respective requirements. Then, in Section 3, we discuss existing standards for low-power wireless sensor networks and show that current standards cannot respond to all application needs. In Section 4, we

Email addresses: tifenn.rault@utc.fr (Tifenn Rault), abdelmadjid.bouabdallah@utc.fr (Abdelmadjid Bouabdallah), yacine.challal@utc.fr (Yacine Challal)

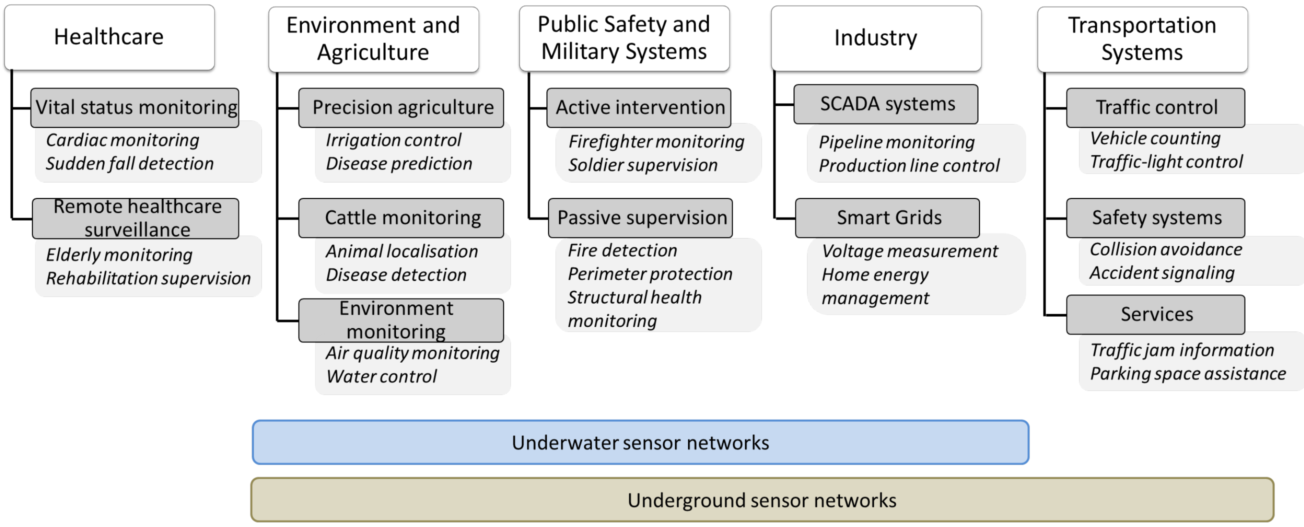


Figure 1: Taxonomy of WSN applications.

give an overview of the major energy-saving mechanisms developed so far and discuss their advantages and shortcomings regarding the set of identified requirements. In Section 5, we review techniques proposed in the literature to achieve a trade-off between multiple requirements, including network lifetime maximisation. Finally, Section 6 concludes this paper.

2. WSN applications and their requirements

In this section, we propose a taxonomy of WSN applications, given in Figure 1, and we summarise in Table 1 the specific requirements of each described application.

2.1. Healthcare

Wireless sensor networks used in healthcare systems have received significant attention from the research community, and the corresponding applications are surveyed in [6–8]. We identify two types of healthcare-oriented systems, namely, *vital status monitoring* and *remote healthcare surveillance.*

In *vital status monitoring* applications, patients wear sensors that supervise their vital parameters in order to identify emergency situations and allow caregivers to respond effectively. Applications include mass-casualty disaster monitoring [9], vital sign monitoring in hospitals [10], and sudden fall or epilepsy seizure detection [11].

Remote healthcare surveillance concerns care services that are not vital and for which the constant presence of a healthcare professional is not necessary. For example, as illustrated in Figure 2, body sensors can be used to gather clinically relevant information for rehabilitation supervision [12], elderly monitoring [13] or to provide support to a physically impaired person [14].

WSNs used in healthcare must meet several requirements. In particular, they have to guarantee **hard real-time data delivery delays**, **confidentiality** and **access control**. They must also support **mobility** and provide **Quality of Service**. Indeed, in the context of early and life-critical detection of emergencies such as heart attacks and sudden falls, the real-time aspect is decisive. In this case, situation identification and decision-making must occur as quickly as possible to save precious minutes and the person's life. Therefore, the data delivery delay between the nodes and the end-user must be short in order to meet hard real-time requirements. It is also necessary that healthcare networks support node mobility to ensure the continuity of service when both patients and caregivers move. Additionally, exchanged healthcare data are sensitive and medical information must be kept private by restricting access to authorized persons. Thus, achieving confidentiality and access control through a communication network requires the establishment of mechanisms for data protection and user authentication. Furthermore, when WSNs are integrated into a global hospital information system, critical data such as alarms share the bandwidth with less sensitive data such as room temperature. Therefore, traffic prioritisation is essential to satisfy strict delay requirements through QoS provisioning.

2.2. Industry: manufacturing and Smart Grids

The automation of monitoring and control systems is an important aim for many utility companies in manufacturing, water treatment, electrical power distribution, and oil and gas refining. We consider the integration of WSNs in *Supervisory Control and Data Acquisition (SCADA) systems* and *Smart Grids.*

SCADA systems refer to computer systems that monitor and control industrial processes. Wireless sensors, together with actuators, can be used for factory automation, inventory management, and detection of liquid/gas

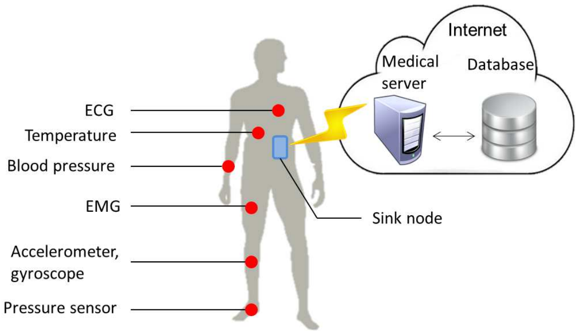


Figure 2: Illustration of a Body Sensor Network

leakages. These applications require accurate supervision of shock, noise and temperature parameters in remote or inaccessible locations such as tanks, turbine engines or pipelines [15, 16].

The aim of *Smart Grids* is to monitor the energy supply and consumption process thanks to an automated and intelligent power-system management. The potential applications of sensor networks in smart grids are: sensing the relevant parameters affecting power output (pressure, humidity, wind orientation, radiation, etc.); remote detection of faulty components; control of turbines, motors and underground cables; and home energy management [17, 18].

The main requirements of industrial applications are **bounded delay**, **robustness** and **security**. Indeed, the products handled in industry can be very dangerous and require special care in storage and handling. For example, in an oil refinery, due to their high volatility and flammability, products with low boiling points evaporate easily, forming flammable vapors. Thus, the pressure in a tank or the temperature of a furnace can quickly become critical. This is why strict delays must be ensured so that the time that elapses between the detection of an anomaly and the intervention of the operator enables the incident to be resolved. Furthermore, in many industries, networks are subject to diverse disturbances such as faulty components, node failure, disconnections and congestion. This is because sensors operate under harsh conditions, as motes placed in pipelines or tanks experience high pressure and temperatures, or continuous vibrations. So, industry implementations must ensure data reliability at all times. Moreover, given the sensitivity of the data, availability, integrity, authenticity and confidentiality are all security problems that must be taken into consideration when designing an industrial communication network.

2.3. Transportation systems

Various studies related to the integration of WSNs and transportation systems have already been conducted: they include *traffic monitoring* and real-time *safety systems* sharing bandwidth with commercial *services*.

In *traffic-monitoring* systems, wireless sensors are embedded on roadways and intersections in order to collect traffic data. For example, they can count vehicles in queues to adjust traffic signals or the number of toll booths and lanes opened [19, 20].

In *safety systems*, wireless sensors are employed to cope with situations such as emergency braking, collision avoidance, lane insertion assistance and hazardous driving conditions warnings (stop-and-go waves, ice on the road, crossing animals) [21, 22].

In addition to passenger-safety applications, commercial on-board applications are being devised by service providers. They include route guidance to avoid rush-hour jams [23], smart high-speed tolling, assistance in finding a parking space [24] and automobile journey statistics collection [25].

Due to the life-critical characteristics of transport applications, the WSNs designed in this domain must guarantee **hard real-time delays**, **security** and **QoS** while supporting **mobility**. For instance, systems related to driving safety must ensure tight bounded end-to-end delays in order to guarantee response times. This constitutes the main challenge of such applications since people's lives are at stake. For traffic monitoring applications, timely information is also required in order to ensure efficient real-time management of vehicle flow. In future Intelligent Transportation Systems (ITSs), safety systems and service applications will share the same wireless channel which requires tools to integrate service differentiation. Indeed, critical information and traffic-control should have higher priority than other service packets. Furthermore, vehicle-to-vehicle and vehicle-to-infrastructure communications are constrained by car speed. So, mobility is inherent to the automotive domain as nodes evolve in an extremely dynamic environment. Finally, the life-critical characteristic of some applications raises security issues in the transport network, which may be the target of a cyber-attack. Thus, the network must be protected against data corruption that could give false information about traffic or conditions on the road. By relaxing the power factor, nodes can support sophisticated encryption algorithms to provide a higher level of security.

2.4. Public safety and Military systems

Wireless sensor networks can help to anticipate and manage unpredictable events, such as natural disasters or man-made threats. We categorise public safety and military applications into *active intervention* and *passive supervision.*

Active intervention refers to systems with nodes attached to agents for temporary deployment and is dedicated to the safety of team-oriented activities. While working, each member carries a sensor so that a remote leader will be able to monitor both the holder's status and the environmental parameters. This applies to emergency rescue teams [26], miners [27] and soldiers [28].

With *passive supervision*, static sensors are deployed in a large area such as a civil infrastructure or nuclear site for long-term monitoring. Relevant examples of passive supervision applications are surveillance and target tracking [29], emergency navigation [30], fire detection in a building, structural health monitoring [31, 32] and natural disaster prevention such as in the case of tsunamis, eruptions or flooding [33].

Due to their critical nature, public safety and military applications are characterised by the need for **short delays**, **service differentiation** and **data integrity** provisioning. In addition, active intervention applications must support **mobility** and passive supervision should ensure **coverage**. First, a decisive parameter to take into account when designing a public safety system is the delivery delay, as in emergency applications, timely alarm reporting is necessary for the system to be reactive. Furthermore, public safety and military systems deal with both everyday monitoring data and warning data. Thus, anomaly detection alarms should be sent in packets having high priority over regular reports through an efficient service differentiation mechanism. Finally, both kinds of public safety applications should guarantee data integrity: in active intervention, corrupt data could endanger agents by giving false information to headquarters; in passive supervision, an ill-intentioned person could circumvent a surveillance system by sending false data.

In the case of active intervention, mobility is inherent to the architecture as wearable sensors are carried by working people. Moreover, from drilling tunnels to the fire field, active intervention applications are often characterised by their use in harsh environmental conditions. In these conditions, the network should be resistant to node failure and poor link quality by means of a fault-tolerant routing scheme. Long-term infrastructure monitoring requires the deployment of untethered static sensors in order to supervise the region of interest. Therefore, passive supervision applications may run into coverage problems when required to entirely supervise a building or a tunnel.

2.5. Environment and agriculture

WSNs are particularly well suited to agricultural and open-space monitoring applications since wired deployment would be expensive and inefficient. A variety of applications have been developed in *precision agriculture*, *cattle monitoring* and *environmental monitoring*.

In *precision agriculture*, sensor nodes are scattered throughout a field to monitor relevant parameters, such as atmospheric temperature, soil moisture, hours of sunshine and the humidity of the leaves, creating a decision support system. Another purpose of precision agriculture is resource (water, fertiliser, pesticides) optimisation [34], frost protection, disease development prediction [35].

In *cattle monitoring* applications, general surveillance of livestock is convenient to keep watch on cattle health status, to detect disease breakouts, to localise them and to control end-product quality (meat, milk) [36, 37].

The use of WSNs for diverse *environmental monitoring* applications has been studied for coastline erosion [38], air quality monitoring [39], safe drinking water and contamination control [40].

The main requirements of environmental and agricultural applications are **scalability**, **coverage** and **lifetime prolongation**. Agricultural fields, grazing land and monitored sites can reach several tens of hectares, so the number of motes deployed varies from dozens to thousands. This is why scalability is an important issue when developing protocols to support a high quantity of nodes and ensure full coverage of the controlled area. Corke et al. [41] have conducted several real experiments in natural environments and have shown that outdoor conditions could be very harsh and impact the feasibility of communication. Typically, foliage, rain or humidity can lead to the breakdown of inter-node links, resulting in highly variable and unpredictable communications. Fault tolerant routing schemes must therefore be set up to ensure area coverage and cope with failure or temporary disconnection. In most environmental monitoring applications, nodes are static as they are deployed on the ground in fields, in forests or along the banks of rivers. Nevertheless, mobility must be taken into account, whether this is desired or not. Unwished-for mote displacement can be caused by heavy rains, wind, animals or engines. When mobility is intentional, nodes and sinks are embedded in vehicles [42] or a natural moving bearer such as animals.

2.6. Underground and underwater sensor networks

Underground and underwater sensor networks are emerging types of WSNs, which are used in different categories of applications including environmental monitoring, public safety and industry. They differ from traditional terrestrial networks in that the sensors are deployed in special environments that make communications difficult and impact their ease of deployment. *Underground sensor networks* consist of sensors that are buried in and communicate through dense materials like soil or concrete. Such networks can be used for soil moisture reporting in agriculture [43], infrastructure supervision, intrusion detection [44] and transport systems [45]. *Underwater sensor networks* rely on immersed sensors and are used in a variety of applications such as ocean supervision [46], water quality monitoring [47], disaster prevention, surveillance [48] and pipeline monitoring.

Underground and underwater sensor networks share common requirements such as **robustness** and **coverage**. The main characteristic of these networks is their lossy channel due to extreme environmental conditions. Indeed, acoustic communications for underwater sensors and electromagnetic waves for underground sensors suffer from lower propagation speed, noise and path loss, which lead to the degradation of the signal [45, 48]. Therefore,

		Scalability	Coverage	RT Delay	QoS	Security	Mobility	Robustness
Healthcare	Vital status monitoring	- -	- -	+ +	+	+ +	+ +	+
	Remote surveillance	- -	- -	+	+	+ +	+ +	-
Agriculture and Environment	Precision agriculture	+ +	+ +	- -	- -	- -	- -	+
	Cattle monitoring	+ +	-	-	- -	- -	+	-
	Environment monitoring	- -	- -	+	+	+ +	+ +	-
Public Safety & Military systems	Active intervention	- -	- -	+ +	+	+ +	+ +	+ +
	Passive supervision	- -	+	+ +	+	+ +	- -	-
Transportation systems	Traffic control	- -	-	+ +	+ +	+ +	+ +	-
	Safety system	- -	-	+ +	+ +	+ +	+	+
	Services	- -	- -	-	+	+	+	-
Industry	SCADA systems	- -	-	+ +	+	+ +	- -	+ +
	Smart grids	+	-	+ +	+	+ +	- -	+ +

Requirement importance	
- -	very low
-	low
+	high
++	very high

Table 1: WSN applications requirements.

they require the development of specific communication protocols to ensure the application's reliability. Coverage is also an issue since it may not be possible to optimally deploy the nodes due to the ground profile, the costs and the efforts required for excavation. Moreover, these networks are inherently three-dimensional (which raises additional issues) since the devices can be deployed at varying depths depending on the phenomenon to supervise. Besides these requirements, energy is of great importance due to the difficulty of unearthing a device to replace it or recharge its battery.

2.7. Discussion

The main WSN requirements that we identified in the different applications are *scalability*, *coverage*, *latency*, *QoS*, *security*, *mobility* and *robustness*. In Table 1, we summarise the importance of these requirements for every class of application considered in this section. In these applications, sensors are expected to operate autonomously for a long period of time, ranging from weeks to months. However, every application is constrained in terms of energy due to the scarce battery resources of the sensors, which limits the network lifetime. Indeed, it may not always be possible to manually replenish the motes because of their number, the maintenance cost or the inaccessibility of monitored regions. This is the case of structural health monitoring applications, precision agriculture and environment monitoring, transportation systems. Furthermore, some applications such as healthcare applications can tolerate battery replacement, but we believe that the rapid depletion of the battery prevent their wide adoption. Indeed, efforts are still made to propose energy-efficient solutions for body area networks to foster the acceptance of these technologies by the patients. This is why the design of WSNs requires, in both cases, the development of energy-efficient solutions that meet a specific set of requirements.

In order to achieve energy efficiency, we first present in the next section existing standards developed for low-power wireless sensor networks.

3. Low-power WSN standards

Wireless sensor network standards have been specifically designed to take into account the scarce resources of nodes. In what follows we give a brief description of low-power standards including IEEE 802.15.4, ZigBee, WirelessHART, ISA100.11a, Bluetooth low energy, IEEE 802.15.6, 6LoWPAN, RPL and MQTT.

IEEE 802.15.4 [49] specifies the physical and MAC layers for low data rate wireless personal area networks (LR-WPANs). In the beacon-enabled mode, the standard allows energy to be saved by implementing duty cycling, so that all nodes can periodically go to sleep. In practice, a coordinator sends beacon packets to synchronise the nodes, and the superframe structure presented in Figure 3 is subdivided into three parts: 1) a contention access period during which nodes use a slotted CSMA/CA 2) a contention-free period containing a number of guaranteed time slots (GTS) that can be allocated by the coordinator to specific nodes and 3) an inactive period during which the end-devices and coordinator can go to sleep.

ZigBee [50] is a wireless technology developed as an open standard to address the requirements of low-cost, low-power devices. ZigBee defines the upper layer communication protocols based on the IEEE 802.15.4 standard. It supports several network topologies connecting hundreds to thousands of devices.

WirelessHART [51] operates on the IEEE 802.15.4 specification and targets field devices such as sensors and actuators that are used to monitor plant equipment or processes. The standard characteristics are integrated security, high reliability and power efficiency. WirelessHART relies on a fixed length TDMA scheme so nodes can go to sleep when it is not their slot time. Moreover, it specifies a central mesh network where routing is exclusively determined by the network manager that collects information about every neighbouring node. It uses this information to create an overall graph of the network and defines the graph routing protocol. In practice, the standard does not specify how to implement such a graph routing so some research work already proposes multipath routing protocols

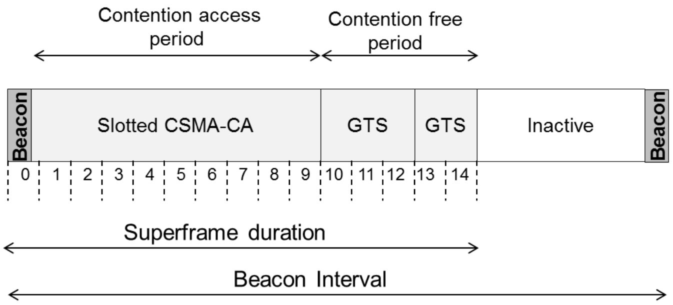


Figure 3: The superframe structure of the IEEE 802.15.4 beacon-enabled mode.

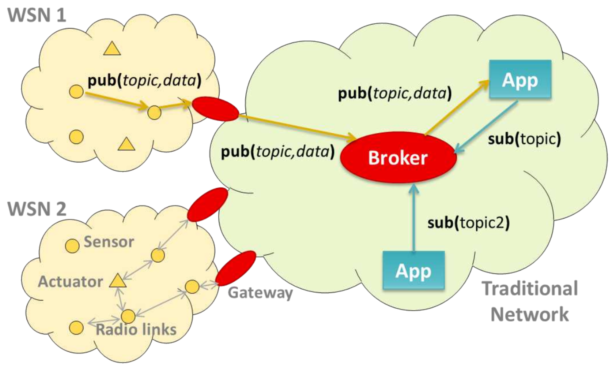


Figure 4: MQTT-S architecture for WSN with Pub/Sub communications.

for industrial processes [52, 53]. While these studies take link quality into consideration for the routing decisions, it may be possible to use the node battery-level information in order to further improve energy savings.

The *ISA100.11a* [54] standard relies on the IEEE 802.15.4 specification and is dedicated to reliable wireless communications for monitoring and control applications in the industry. ISA100.11a uses deterministic MAC scheduling with variable slot length, allowing nodes to go into sleep mode when it is not their time slot. Moreover, the standard defines non-router nodes that do not act as forwarders and experience very low energy depletion. Finally, the standard requires each device to report its estimated battery life and associated energy capacity to the System Manager which allocates communication links based on the reported energy capabilities. In addition to low power consumption, ISA100.11a also focuses on scalable security; robustness in the presence of interference; and interoperability with other wireless devices such as cell phones or devices based on other standards.

Bluetooth Low Energy (BLE) [55] addresses low-cost devices with very low battery capacity and short-range requirements. It is an extension of the Bluetooth technology that allows communication between small battery-powered devices (watches, wireless keyboards, sport sensors) and Bluetooth devices (laptops, cellular phones). In terms of energy efficiency, Bluetooth low energy is designed so that devices can operate for over a year thanks to an ultra low-power idle mode. BLE is suitable for a variety of applications in the fields of healthcare, sports and security.

IEEE 802.15.6 [56] is a recent standard that defines the PHY and MAC layers for low-power devices operating in the vicinity of, or inside a human body for medical and non-medical applications. A BAN (Body Area Network) is composed of one hub and up to 64 nodes, organised into one-hop or two-hops star topologies. At the MAC level, the channel is divided into super-frame structures, which are further divided into different access phases to support different traffic and channel access modes (contention based and contention free). There are eight user priorities, ranging from best-effort to emergency event reports. These are differentiated based on the minimum and maximum contention windows. The standard also supports 3 levels of security: level 0 - unsecured communications, level 1 - authentication only, level 2 - authentication and encryption.

6LoWPAN [57] stands for IPv6 over Low power Wireless Personal Area Networks. 6LoWPAN is designed for low-power devices that require Internet communication. It enables IEEE 802.15.4-based networks to send and receive IPv6 packets so that small devices are able to communicate directly with other IP devices, locally or via IP networks (e.g. Ethernet).

RPL [59] is a distance vector Routing Protocol for Low Power and lossy networks compliant with IPv6, specifically designed to meet the requirements of resource-constrained nodes. RPL is optimised for many-to-one communications for data collection, but it also supports one-to-many and one-to-one communications. RPL creates a Directed Acyclic Graph (DAG) anchored at a border router of a WSN. A node maintains several parents to construct different routes towards the sink and selects its preferred parent based on an Objective Function that uses routing metrics. For example, a draft [60] proposes to select the path that minimises the sum of Expected Number of Transmissions (ETX) over traversed links but the design of the Objective Function is still an open research issue. Thus, it is possible to create a DAG focusing on energy efficiency, as in Kamgueu et al. [61] who use the node's remaining energy as an RPL routing metric. RPL offers other features like fault-tolerance, self-repair mechanisms, and security [62].

MQTT [63] (Message Queuing Telemetry Transport) is a lightweight publish/subscribe protocol for one-to-many message distribution. Currently undergoing standardisation, MQTT is envisioned to be the future protocol for the Internet-of-Things to connect devices with low bandwidth and power budget over TCP/IP infrastructures. MQTT-S [64] extends MQTT for Wireless Sensors and Actuators Networks on non-TCP/IP networks. As illustrated in Figure 4, *publishers* produce information and send their data to the *broker* via a *pub* message. *Subscribers* interested in receiving certain data send a *sub* message to the broker. If there is a match between a subscriber's and a publisher's topics, the broker transfers the message to the subscriber.

Name	Wi-Fi	WiMAX	WiMedia	Bluetooth	ZigBee	Bluetooth low energy
Standard	IEEE 802.11b	IEEE 802.16	IEEE 802.15.3	IEEE 802.15.1	IEEE 802.15.4	
Applications	internet access web, email, video	broadband connections	real-time multimedia streaming	cable replacement	low-power devices communication	Bluetooth ↔ low-power device communication
Devices	laptop, tablet console	PC peripheral	wireless speaker, printer television	mobile phone, mouse keyboard, console	embedded systems, sensors	watch, sport sensor, wireless keyboard
Target lifetime [58]	hours	-	-	days - months	6 months - 2 years	1-2 years
Data rates	11 Mbps	30-40 Mbps	11-55 Mbps	1-3 Mbps	20-250 Kbps	1 Mbps
Transmission range	100 m	50 km	10 m	10-50 m	100 m	10 m
Network size	32	-	245	7	65000	-
Success metric	Flexibility Speed	Long range	High data rates	Cost Convenience	Reliability, Cost, Low-power	Low-power

Table 2: Wireless standards characteristics.

MQTT-S saves energy by supporting multiple gateways to balance the load in the network. It also supports sleeping clients (subscribers/publishers) and size-limited packets to be compliant with ZigBee. Moreover, most of the protocol logic is handled in the broker and the gateway, which makes the device's implementation lightweight [65]. Although MQTT is already implemented in various projects [66], there is a lack of evaluation regarding the energy-efficiency of the protocol.

3.1. Discussion

Bluetooth low energy and IEEE 802.15.4-based standards have been specifically developed for battery-operated devices. They enable energy-saving through duty cycling and include optional modes that can be disabled for further network lifetime optimisation. In Table 2 we compare these two WSN-specific standards with other well-known wireless standards (Wi-Fi, WiMax, WiMedia, Bluetooth) regarding data rate, transmission range, scalability and applications.

In terms of applications, existing healthcare platforms often interface with Bluetooth due to the suitability of this technology for body area networks that demand short communication ranges and high data rates. However, Bluetooth technology may quickly deplete a nodes' energy. In this case, BLE or IEEE 802.15.6 may be considered as alternatives. ZigBee technology is suitable for a large number of applications thanks to its scalability and energy-efficiency. For example, in smart home automation, ZigBee data rate and radio range are sufficient for room supervision. Nevertheless, in a more complex monitoring system, both ambient sensor networks and body sensor networks may be integrated together and further connected to the Internet via 6LowPan. In large-scale outdoor deployment, the Zigbee 100-meter achievable radio range may quickly become limiting. In this case, we envision that WiMax-enabled gateways will be able to mesh the topology to connect the network to the Internet. Thus, the integration of different technologies and standards is necessary to respond to the needs of emerging and challenging applications such as Smart grids, Intelligent Transportation Systems and Healthcare Information Systems.

Standardisation is a key issue for the success of WSN markets. Although application-specific standards are emerging, such as WirelessHART and ISA100.11a for industry, and IEEE 802.15.6 for body sensor networks, they can still be improved in regard to application requirements. For instance, some research studies propose to optimise standard parameters such as packet size, slot length, contention window length or even introduce alternative protocols. Moreover, the performance of recent standards (e.g., MQTT, IEEE 802.15.6) need further investigation, because there is a lack of evaluation concerning these solutions and a lack of comparisons with well-established protocols. It also appears that current standards cannot respond to all application needs, notably regarding hard real-time requirements and security issues. In parallel to ongoing standardisation efforts, many solutions have been developed which strongly consider energy-saving.

4. Energy-saving mechanisms

In this section, we review the major existing approaches proposed to tackle the energy consumption problem of battery-powered motes. The proposed taxonomy of energy-efficient mechanisms is summarised in Figure 5.

4.1. Radio optimisation

The radio module is the main component that causes battery depletion of sensor nodes. To reduce energy dissipation due to wireless communications, researchers have tried to optimise radio parameters such as coding and modulation schemes, power transmission and antenna direction.

Modulation optimisation aims to find the optimal modulation parameters that result in the minimum energy consumption of the radio. For instance, energy depletion is caused by the circuit power consumption and the power consumption of the transmitted signal. For short distances, circuit consumption is greater than the transmission power while for longer ranges the signal power becomes dominant. Existing research tries to find a good trade-off between the constellation size (number of symbols used), the information rate (number of information bits per symbol), the transmission time, the distance between the nodes and the noise. Cui et al. [67] showed that the energy consumption required to meet a given Bit Error Rate (BER) and delay requirement can be minimised by optimising the transmission time. Costa and Ochiai [68] studied the energy efficiency of three modulation schemes and derived from this the modulation

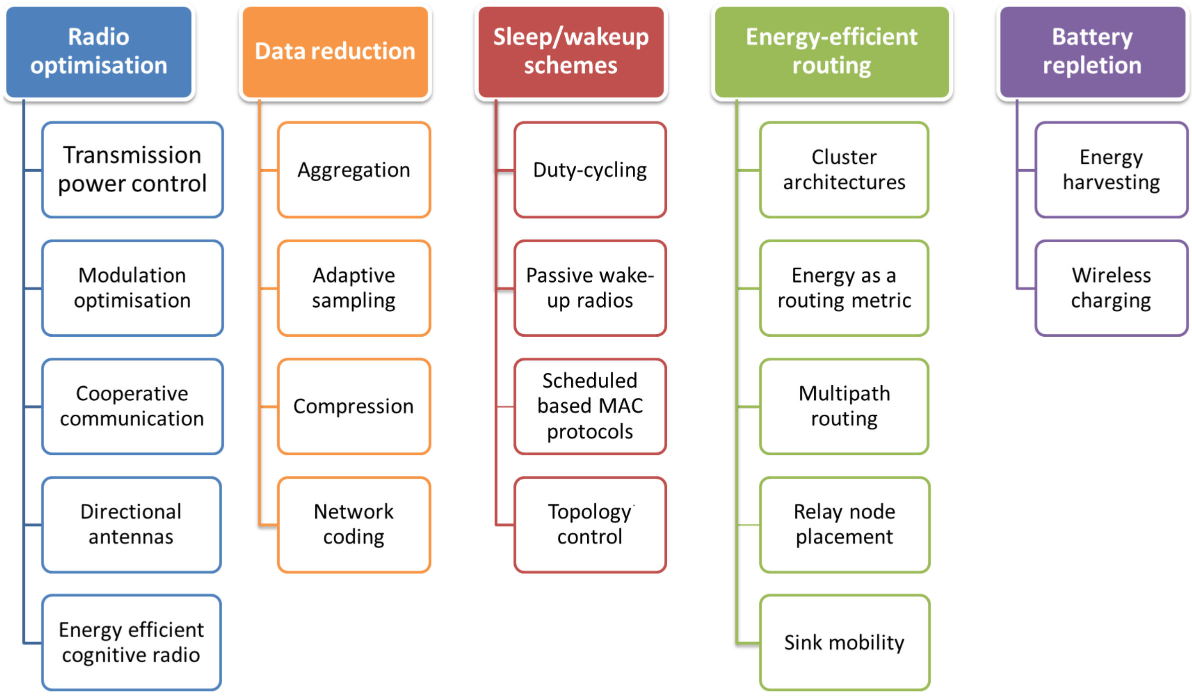


Figure 5: Classification of energy-efficient mechanisms.

type and its optimal parameters that achieve minimum energy consumption for different distances between nodes.

Cooperative communications schemes have been proposed to improve the quality of the received signal by exploiting several single-antenna devices which collaborate to create a virtual multiple-antenna transmitter. The idea is to exploit the fact that data are usually overheard by neighbouring nodes due to the broadcast nature of the channel. Therefore, by involving these nodes in the retransmission of data it is possible to create spatial diversity and combat multi-path fading and shadowing [69]. Jung et al. [70] investigated how cooperative transmission can be used to extend the communication range and thus balance the duty cycling of nodes as normal relay sensors can be replaced by other cooperative nodes. Cui et al. [71] and Jayaweera [72] compared the energy consumption of both SISO (Single Input Single Output) and virtual MIMO (Multiple Input and Multiple Output) systems and show that MIMO systems can provide better energy savings and smaller end-to-end delays over certain transmission range distances, even with the extra overhead energy required for MIMO training.

Transmission Power Control (TPC) has been investigated to enhance energy efficiency at the physical layer by adjusting the radio transmission power [73, 74]. In CTCA (Cooperative Topology Control with Adaptation) [75] the authors propose to regularly adjust the transmission power of every node in order to take into consideration the uneven energy consumption profile of the sensors. Therefore, a node with higher remaining energy may increase its transmission power, which will potentially enable other nodes to decrease their transmission power, thus saving energy. However, TPC strategy has an effect not only on energy but also on delays, link quality, interference and connectivity. Indeed, when transmission power decreases, the risk of interference also decreases. Moreover, fewer nodes in the neighbourhood are subjected to overhearing. On the contrary, delay is potentially increased, because more hops will be needed to forward a packet. Finally, transmission power influences the network topology because the potential connectivity between sensors will vary, and it also favours the spatial reuse of bandwidth if two communications can occur without interference.

Directional antennas allow signals to be sent and received in one direction at a time, which improves transmission range and throughput. Directional antennas may require localisation techniques to be oriented, but multiple communications can occur in close proximity, resulting in the spatial reuse of bandwidth. In contrast to omnidirectional motes which transmit in unwanted directions, directional antennas limit overhearing and, for a given range, require less power. Thus, they can improve network capacity and lifetime while influencing delay and connectivity [76, 77]. To take advantage of the properties of directional antennas, new MAC protocols have been designed [78, 79]. However, some problems that are specific to directional antennas have to be considered: signal interference, antenna adjustments and deafness problems [80].

Energy-efficient cognitive radio: A cognitive radio (CR) is an intelligent radio that can dynamically select a communication channel in the wireless spectrum and can adapt its transmission and reception parameters accordingly. The underlying Software-Defined Radio (SDR) technology is expected to create fully reconfigurable wireless transceivers which automatically adapt their communication parameters to network demands, which improves context-awareness. However, CR requires significant energy consumption compared with conventional devices due to the increased complexity involved for new and sophisticated functionalities [81]. In this context, designing energy-efficient cognitive radio sensor networks is a key challenge in the intelligent use of battery energy. Recent cognitive radio studies are interested in the power control of transmitters [82], residual energy-based channel assignment, and combining network coding and CR. Open research issues include the development of cross-layer approaches for MAC, routing or clustering protocols that take advantage of cognitive radio opportunities.

4.2. Data reduction

Another category of solutions aims to reduce the amount of data to be delivered to the sink. Two methods can be adopted jointly: the limitation of unneeded samples and the limitation of sensing tasks because both data transmission and acquisition are costly in terms of energy.

Aggregation: In data aggregation schemes, nodes along a path towards the sink perform data fusion to reduce the amount of data forwarded towards it. For example, a node can retransmit only the average or the minimum of the received data. Moreover, data aggregation may reduce the latency since it reduces traffic, thus improving delays. However, data aggregation techniques may reduce the accuracy of the collected data. Indeed, depending on the aggregation function, original data may not be recovered by the sink, thus information precision can be lost. Data aggregation techniques dedicated to wireless sensor networks are surveyed in detail by Rajagopalan and Varshney in [3] and by Fasolo et al. in [83].

Adaptive sampling: The sensing task can be energy-consuming and may generate unneeded samples which affects communication resources and processing costs. Adaptive sampling techniques adjust the sampling rate at each sensor while ensuring that application needs are met in terms of coverage or information precision. For example, in a supervision application, low-power acoustic detectors can be used to detect an intrusion. Then, when an event is reported, power-hungry cameras can be switched on to obtain finer grained information [2]. Spatial correlation can be used to decrease the sampling rate in regions where the variations in the data sensed is low. In human activity recognition applications, Yan et al. [84] propose to adjust the acquisition frequency to the user activity because it may not be necessary to sample at the same rate when the user is sitting or running.

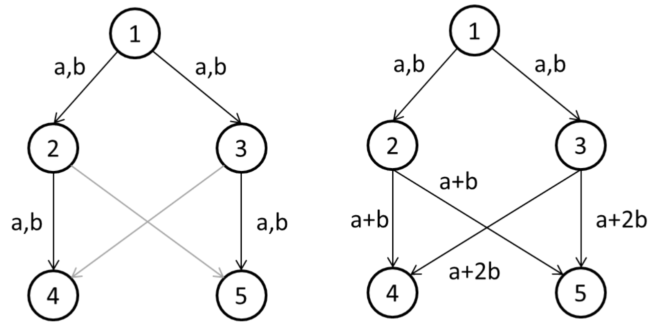


Figure 6: An example of network coding.

Network coding (NC) is used to reduce the traffic in broadcast scenarios by sending a linear combination of several packets instead of a copy of each packet. To illustrate network coding, Figure 6 shows a five-node topology in which node 1 must broadcast two items of data, a and b. If nodes simply store and forward the packets they receive, this will generate six packet transmissions (2 for each node 1, 2 and 3 respectively). With the NC approach, nodes 2 and 3 can transmit a linear combination of data items a and b, so they will have to send only one packet. Nodes 4 and 5 can decode the packet by solving linear equations. Therefore, two packets are saved in total in the example. Network coding exploits the trade-off between computation and communication since communications are slow compared to computations and more power-hungry. Wang et al. [85] combine network coding and Connected Dominating Sets to further reduce energy consumption in broadcast scenarios. AdapCode [86] is a data dissemination protocol where a node sends one message for every N messages received, saving a fraction of the bandwidth up to (N-1)/N compared to naive flooding. The receiver node can recover the original packets by Gaussian elimination after receiving N coded packets successfully. Moreover, AdapCode improves reliability by adapting N to the node density, because when N increases and the density decreases, it becomes harder to recover enough packets to decode the data. Reliability is further enhanced by allowing nodes receiving less than N packets to send a negative acknowledgement to retrieve missing data.

Data compression encodes information in such a way that the number of bits needed to represent the initial message is reduced. It is energy-efficient because it reduces transmission times as the packet size is smaller. However, existing compression algorithms are not applicable to sensor nodes because of their resource limitations. Therefore, specific techniques have been developed to adapt to the computational and power capabilities of wireless motes. Kimura et al. [87] have surveyed compression algorithms specifically designed for WSNs.

4.3. Sleep/wakeup schemes

Idle states are major sources of energy consumption at the radio component. Sleep/wakeup schemes aim to adapt node activity to save energy by putting the radio in sleep mode.

Duty cycling schemes schedule the node radio state depending on network activity in order to minimise idle listening and favour the sleep mode. These schemes are usually divided into three categories: *on-demand*, *asynchronous* and *scheduled rendezvous* [2]. A summary of the properties of each category is given in Table 3. Duty cycle based protocols are certainly the most energy-efficient but they suffer from sleep latency because a node must wait for the receiver to be awake. Moreover, in some cases it is not possible for a node to broadcast information to all of its neighbours because they are not active simultaneously. Finally, fixing parameters like listen and sleep periods, preamble length and slot time is a tricky issue because it influences network performance. For example, a low duty cycle saves a large amount of energy but can drastically increase communication delays. Thus, protocol parameters can be specified prior to deployment for simplicity, although this leads to a lack of flexibility, or they can be set up dynamically for improved adaptation to traffic conditions. Concerning duty cycling, some work has been done to adapt the active period of nodes online in order to optimise power consumption in function of the traffic load, buffer overflows, delay requirements or harvested energy [88, 89]. For more details about duty cycling, information can be found in [2] and [90].

Passive wake-up radios: While duty cycling wastes energy due to unnecessary wake-ups, low-power radios are used to awake a node only when it needs to receive or transmit packets while a power-hungry radio is used for data transmission. Ba et al. [91] consider a network composed of passive RFID wake-up radios called WISP-Motes and RFID readers. A passive RFID wake-up radio uses the energy spread by the reader transmitter to trigger an interruption that wakes up the node. In practice all sensors cannot be equipped with RFID readers since they have a high power consumption. This is a major shortcoming because, coupled with the short operational range of RFID passive devices, it restricts their use to single-hop scenarios. Simulations have shown that WISP-Motes can save a significant amount of energy at the expense of extra hardware and increased latency in data delivery. The authors demonstrated their benefits in the case of a sparse delay-tolerant network with mobile elements equipped with RFID readers.

Topology control: When sensors are redundantly deployed in order to ensure good space coverage, it is possible to deactivate some nodes while maintaining network operations and connectivity. Topology control protocols exploit redundancy to dynamically adapt the network topology based on the application's needs in order to minimise the number of active nodes. Indeed, nodes that are not necessary for ensuring connectivity or coverage can be turned off in order to prolong the network lifetime, as in Figure 7. Misra et al. [92] propose a solution capable of maintaining network coverage while minimising the energy consumption of the network by activating only a subset of nodes, with the minimum overlap area. In a recent work, Karasabun et al. [93] consider the problem of selecting a subset of active connected sensors for correlated data gathering. This is very useful in some applications like environmental monitoring, when the sensed data are location-dependent, since the data of inactive nodes can be inferred from those of active nodes due to the spatial correlation.

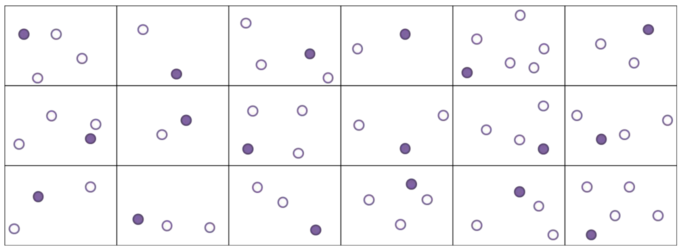


Figure 7: Example of a topology control method applied to a network. To ensure the field coverage, a sensor must remain activated in each square area. The other nodes are deactivated.

4.4. Energy-efficient routing

Routing is an additional burden that can seriously drain energy reserves. In particular, in multi-hop schemes, nodes closer to the sink are stressed because they have to route more packets. Therefore, their battery depletes faster. In what follows, we discuss the general energy-saving mechanisms of different routing paradigms. For an extensive review of energy-aware routing protocols, survey articles can be found in [4, 94, 95].

Cluster architectures organise the network into clusters, where each cluster is managed by a selected node known as the cluster head (CH). The cluster head is responsible for coordinating the members' activities and communicating with other CHs or the base station. Cluster techniques have been proposed to enhance energy efficiency because they help to limit energy consumption via different means: i) they reduce the communication range inside the cluster which requires less transmission power, ii) they limit the number of transmissions thanks to fusion performed by the CH, iii) they reduce energy-intensive operations such as coordination and aggregation to the cluster head, iv) they enable to power-off some

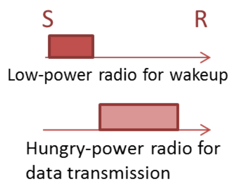
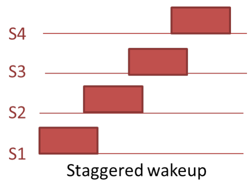
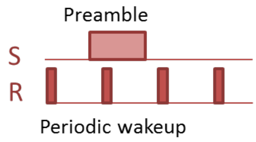
Type	**On-demand**	**Schedule rendez-vous**	**Asynchronous**
Principle	Wake up a node only when another wants to communicate with it.	Nodes wakeup at the same time as its neighbours according to a wakeup schedule. Then they go to sleep until their next rendez-vous.	Each node wakes up independently but its active period must overlap with its neighbours.
Broadcast	No	Yes	No
Synchronisation	No	Yes	No
Energy-efficiency	Nodes remain active only for the minimum time required.	More collisions because nodes wakeup at the same time after an inactive period.	Nodes need to wake up more frequently. Either the sender sends long preamble or the receiver remains awake longer.
Examples of applications	Even-driven application with low duty cycle.	Data-gathering application with possibility of aggregation.	Mobile applications when the neighbourhood is unpredictable.
Illustration			

Table 3: Duty cycle properties.

nodes inside the cluster while the CH takes forwarding responsibilities and v) they balance energy consumption among nodes via CH rotation. In addition to energy-efficiency, cluster architectures also improve network scalability by maintaining a hierarchy in the network [96, 97].

Energy as a routing metric: Another solution to extend the lifetime of sensor networks is to consider energy as a metric in the setup path phase. By doing so, routing algorithms do not only focus on the shortest paths but can select the next hop based on its residual energy. Recently, Liu et al. [98] introduced two new energy-aware cost functions. The Exponential and Sine Cost Function based Route (ESCFR) function can map a small change in remaining nodal energy to a large change in the cost function value. By giving preference to sensors with higher remaining energy during route selection, the function enforces energy balance. The Double Cost Function based Route (DCFR) protocol considers the energy consumption rate of nodes in addition to their remaining energy. The rationale behind this is that nodes in hotspots have high energy consumption rates. Thus, the use of this function further improves the energy-balancing performance of the routing protocol, even in networks with obstacles.

Multipath routing: While single-path routing protocols are generally simpler than multipath routing protocols, they can rapidly drain the energy of nodes on the selected path. In contrast, multipath routing enables energy to be balanced among nodes by alternating forwarding nodes. As an example, the EEMRP (Energy-Efficient Multipath Routing Protocol) [99] discovers multiple node-disjoint paths using a cost function depending on the energy levels and hop distances of the nodes and allocates the traffic rate to each selected path. The EECA (Energy-Efficient and Collision Aware) protocol [100] constructs two node-disjoint and collision-free routes between a source and a sink. Multipath routing protocols also enhance network reliability by providing multiple routes, which enables the network to recover faster from a failure, whereas in single path schemes, when a node runs out of power, a new route must be recomputed. The interested reader can consult [101] for a recent survey of multipath routing protocols for WSNs.

Relay node placement: The premature depletion of nodes in a given region can partition the network or create energy holes. Sometimes, this situation can be avoided thanks to the optimal placement of nodes through even distribution or by adding a few relay nodes with enhanced capabilities. This helps to improve energy balance between nodes, avoid sensor hot-spots and ensure coverage and k-connectivity [102]. Several works have focused on finding the minimum number of relay nodes or placing them optimally to prolong the network lifetime [103, 104]. For example, Dandekar and Deshmukh [105] optimise the placement of static sinks to shorten the average hop distance of every node to its nearest sink.

Sink mobility: In WSN architectures that use a static base station, sensors located close to the base station deplete their battery faster than other sensor nodes, leading to premature disconnection of the network. This is due to the fact that all traffic is forwarded towards the sink which increases the workload of the nodes closer to the sink. To increase network lifetime, it is possible to balance the load between nodes using a mobile base station which moves around the network to collect node information. Sink mobility also improves connectivity in sparse architectures and enhances reliability because communication occurs in a single-hop fashion. Thus, it reduces contention, collisions and message loss [2, 106]. When controllable, this mobile displacement can be studied to prevent high latency, buffer overflow and energy depletion [107, 108].

4.5. Charging

Several recent research studies address energy harvesting and wireless charging techniques. Both are promising solutions which aim to recharge sensor batteries without human intervention.

Energy harvesting: New technologies have been developed to enable sensors to harvest energy from their surrounding environment such as solar, wind and kinetic energy [5]. Compared to traditional sensors, rechargeable motes can operate continuously and, theoretically, for an unlimited length of time. They convert ambient energy to electrical energy and then either consume it directly or store it for later use. Energy harvesting architectures often require energy prediction schemes in order to efficiently manage the available power. Indeed, sensors require an estimation of energy evolution to adjust their behaviour dynamically and last until the next recharge cycle. Hence, they can optimise decisive parameters such as sampling rate, transmit power and duty cycling to adapt their power consumption according to the periodicity and magnitude of the harvestable source. It is important to note that nodes remain energy-limited between two harvesting opportunities, so they still need to implement energy-saving mechanisms. For example, motes using solar panels to replenish their batteries can operate intensively during daytime. At night, nodes may enter a conservative mode to use the stored energy. Furthermore, nodes may have an uneven residual energy distribution due to the difference in the quantity of energy collected, and this has to be taken into account when designing protocols [109]. For example, nodes with low residual energy may be assigned higher sleep periods and lower transmission ranges, while those with high residual energy may be preferred when selecting a routing path. Another open perspective is the development of protocols that consider the degradation of the battery over time (leakage, storage loss) [110] which will influence network performance.

Wireless charging: Recent breakthroughs in wireless power transfer are expected to increase the sustainability of WSNs and make them perpetually operational, since these techniques can be used to transmit power between devices without the need of any contact between the transmitter and the receiver. Wireless charging in WSNs can be achieved in two ways: electromagnetic (EM) radiation and magnetic resonant coupling. Xie et al. [111] show that omni-directional EM radiation technology is applicable to a WSN with ultra-low power requirement and low sensing activities (like temperature, light, moisture). This is because EM waves suffer from rapid drop of power efficiency over distance, and active radiation technology may pose safety concerns to humans. In contrast, magnetic resonant coupling appears to be the most promising technique to address energy needs of WSNs thanks to an higher efficiency within several-meter range.

The applications of wireless energy transfer in WSNs are numerous. It has already been applied to power medical sensors and implantable devices [112], to replenish sensors embedded in concrete in a wireless manner [113] and to power a ground sensor from a UAV [114]. The emergence of wireless power charging technology should allow the energy constraint to be overcome, as it is now possible to replenish the network elements in a more controllable manner. In this way, some researchers have already investigated the use of mobile chargers that directly deliver power to deployed nodes [115–118]. A new challenge raised by wireless charging technologies is *energy cooperation*, since nodes may now be able to share energy between neighbors. So, in future wireless networks, nodes are envisioned to be capable of harvesting energy from the environment and transferring energy to other nodes, rendering the network self-sustaining [119]. In order to do this, recent studies demonstrate the feasibility of multi-hop energy transfer [120, 121], which open new perspectives for the design of wireless charging protocols and energy cooperative systems.

4.6. Discussion

It is clear that many efforts have been made to enhance the lifetime of WSNs through a variety of energy-efficient mechanisms. It also appears that energy efficiency and other applications requirements are strongly dependent, so that various performance metrics have to be optimized jointly. Indeed, energy-efficient routing protocols and sleep/wakeup schemes directly influence network latency. Similarly, radio optimisation trades off signal quality for battery conservation, and data reduction approaches can affect the accuracy of the collected information. Additionally, if sensor recharging techniques are promising, energy-saving mechanisms remain essential. In Table 4, we summarise the different energy-saving mechanisms and the WSN requirements they directly influence. For example, we can see that energy-efficient routing solutions can improve the robustness by using multipath routing protocols that provide alternative paths in case of a node failure.

Furthermore, in Table 5, we link Tables 1 (which represents the applications requirements) and Table 4 (which represents the interdependence between energy-efficient mechanisms and other requirements) in order to show how some energy-efficient techniques can be used in specific applications to jointly optimize multiple criteria. Here is an example to explain how to read Table 5: in agricultural applications, sleep/wakeup schemes can influence the coverage by using topology control mechanisms. The justification of these statements can be found in Table 4, and more generally in the discussions in Section 4.

Energy-efficient mechanisms		Impacted requirements	Justification
Data reduction	aggregation, compression adaptive sampling	delay, Qos, scalability	• Data reduction approaches can improve the latency by reducing the amount of packets to be transmitted, decreasing the waiting time in queues. • These methods can improve the QoS by assigning higher priority to certain class of data when performing the aggregation function or when sampling the parameters. • The techniques exhibit good scalability properties by reducing the traffic load.
Sleep/wakeup schemes	adaptive duty-cycling	robustness	• Adaptive duty-cycling schemes can adapt the sleep period to the network conditions to improve context-awareness. • Topology control can be used to enhance the network coverage by characterising how the sensing field is monitored. • TDMA based MAC protocols can achieve good delay under high traffic. • TDMA/CSMA MAC protocols can enhance the QoS by providing guaranteed time slots for high rate periodic data and contention based periods for aperiodic low rate traffic.
	topology control	coverage	
	TDMA based MAC protocol	delay	
	hybrid TDMA/CSMA MAC protocol	QoS	
Radio optimisation	transmission power control	coverage	• Transmission power control and directional antennas techniques affect the coverage by adjusting the communication range (and direction), and thus the node connectivity. • Cognitive radio and cooperative communications impact the quality of the signal through smart channel selection and collaborative re-transmission.
	directional antenna	coverage, robustness	
	cooperative communications energy-efficient cognitive radio	robustness	
Energy-efficient routing	cluster architecture	scalability	• Cluster architectures improve scalability by maintaining a hierarchy in the network. • Multipath routing protocols enhance robustness by providing alternative routing paths in case of node failure. • Relay node placement strategies can control the connectivity between nodes and the network coverage. • Sink mobility can improve the scalability by connecting sparse networks.
	multipath routing	robustness	
	relay node placement	coverage	
	sink mobility	mobility, scalability	

Table 4: Interdependence between energy-efficient mechanisms and applications requirements.

	Healthcare	Agriculture and Environment	Industry	Public Safety Military systems	Transportation systems
Data reduction	**QoS** with compression, adaptive sampling	**scalability** with aggregation	**Qos, scalability** with aggregation, compression, adaptive sampling		
Sleep/wakeup schemes	**delay** with TDMA	**coverage** with topology control	**QoS, delay** with hybrid TDMA/CSMA	**robustness** with adaptive duty-cycling	**delay** with TDMA
Energy-efficient routing	**QoS** with star topology 1-hop communications	**coverage** with relay node placement **scalability** with sink mobility	**robustness** with multipath routing **scalability** with cluster architecture		**coverage** with relay node placement **scalability** with cluster architecture
Radio optimisation	**robustness** with cognitive radio	**coverage** with transmission power control	**robustness** with cognitive radio, cooperative communications	**coverage, robustness** with directionnal antennas	
Sources of energy harvesting	body motion body heat	seismic vibration solar energy	mechanical vibration acoustic noise		solar energy acoustic noise

Table 5: Applications and energy-efficient mechanisms.

Given the interdependence between the different design goals, it is thus necessary to develop solutions that can achieve a satisfactory trade-off between multiple requirements. For this reason, in the next section we will review how research attempts to satisfy multiple objectives including network lifetime maximisation.

5. Energy efficiency and requirements trade-offs

In this section, we present the different techniques explored in the literature to achieve trade-offs between multiple objectives in wireless sensor networks, including energy saving. We have classified these solutions into three categories: *Multi-metric protocols*, *Cross-layer approaches* and *Multi-objective optimisation*.

5.1. Multimetric protocols

As discussed in Section 2, several applications require the optimisation of multiple parameters, like delay and security, while reducing energy consumption. Multi-metric protocols use various network measurements to satisfy multiple application needs. For example, recent application-specific routing protocols have proposed to combine energy efficiency with QoS requirements [122–124] or security concerns [125]. These research works consider the energy reserves of nodes along with video distortion, packet error rate or node reputation. However, this kind of multi-metric protocols raises new challenges. The protocols usually rely on a weight function of various metrics and the weight adjustments are often made following a trial-and-error methodology. Moreover, multimetric protocols require the definition of comprehensive metrics and their maintenance in each node which induces supplementary control message exchange. For instance, the quality of a link can only be estimated statically through RSSI (Received Signal Strength Indication), LQI (Link Quality Indicator) or Packet Rate Reception indicators and varies over time. Thus, these techniques suffer from extra overheads, but on the other hand they enable adaptability to network condition changes to be improved because node decisions are based on metrics whose evolution reflects the network status. Below we present some multi-metric protocols with energy-efficient considerations.

In ATSR (Ambient Trust Sensor Routing) [126] the routing decisions are made locally based on a weight function which takes into account the residual energy of neighbouring nodes, location and trust. The trust evaluation of a neighbour uses seven security metrics such as node reputation, authentication and message integrity in order to detect malicious nodes. The protocol requires additional control messages to evaluate the energy of the neighbouring nodes, and trust levels and weights have to be adjusted to trade off security and energy. The enhanced real-time routing protocol with load distribution (ERTLD) [127] is a real-time routing protocol for mobile wireless sensor networks which makes optimal forwarding decisions based on RSSI, remaining power, and packet delay over one hop. ERTLD can deliver packets within their end-to-end deadlines while improving the flexibility as it can avoid the problem of routing holes. Moreover, it has a higher delivery ratio and consumes less energy than state-of-the-art solutions. Kandris et al. [122] have proposed a hierarchical routing protocol called PEMuR (Power Efficient Multimedia Routing) which is devoted to video routing over a stationary WMSN while satisfying both energy efficiency and QoS requirements. In this solution, the CH selects the path to the base station (BS) whose remaining energy after transmission will be the highest among all of the possible paths. If there is not enough available bandwidth, a CH can choose to drop less significant packets according to their impact on the overall video distortion. PEMuR is well-suited to surveillance applications, traffic control and battlefield monitoring. However, cluster formation is a centralised procedure thus it creates additional overheads: each node sends information about its remaining energy and location to the BS. InRout [124] addresses route selection for industrial wireless sensor networks to provide high reliability while considering the limited resources of sensor nodes. The solution uses Q-learning to select the best possible route online, based on current network conditions and application settings. A node will choose the route that maximises its reward with regard to Packet Error Rate (PER) and energy.

5.2. Cross Layer approaches

Much research has been conducted to tackle energy consumption at all layers, especially at the network, MAC and physical layers. It is expected that an integrated cross-layer design can significantly improve energy efficiency as well as adaptability to dynamic environments. Indeed, cross-layer solutions exploit interactions between different layers to optimise network performances, as surveyed in [128] and [129]. Sensor requirements (QoS, routing, lifetime, security, etc.) are closely linked and require a comprehensive study of existing trade-offs. Cross-layer solutions enable the problem's interdependence to be tackled. As a concrete example, it is possible to monitor the battery level at the physical layer and use this information at the MAC layer to fairly assign communication slots to the nodes. Similarly, it is possible to consider the graph of interference when routing data to optimise the transmission delay. Topology changes are likely to occur in WSNs and may benefit from a cross-layer approach. For instance, after node addition or removal, the neighbourhood is modified which influences network density and interference at the physical layer. Thus, it may be necessary to reallocate the slots or to change the contention window accordingly at the MAC layer while creating different opportunities for path selection at the routing layer.

Regarding energy efficiency, practices that are generally adopted at each layer to save energy such as cluster formation, sleep/active scheduling and power control, are jointly exploited in cross-layer solutions. For example, Gao et al.

[130] took advantage of cooperative communication, hierarchical architectures and data aggregation to enhance energy balance among nodes. Chang et al. [131] combined node placement, topology control and MAC scheduling to better balance energy consumption. Transmission power control and sleep/wakeup scheduling are exploited jointly by Liu et al. [132].

Regarding the optimisation of competing metrics, [133] address joint routing, MAC and physical layer protocols for power allocation in cooperative communication sensor networks under a specified packet-error-rate (PER). Cuomo et al. [134] propose an energy efficient algorithm for PAN coordinator election in IEEE 802.15.4-based sensor networks. They combine the network formation procedure defined at the MAC layer by the standard with a topology reconfiguration algorithm operating at the network layer. By minimising the height of the cluster-tree, their algorithm can reduce the delay and extend the network lifetime. Almalkawi et al. [135] propose a cross-layer design between the routing and MAC layers. Their cluster-based routing protocol balances the load between nodes by constructing several paths based on signal strength and hop counts. In the TDMA-based MAC protocol, the cluster head adaptively assigns slots to active nodes based on the traffic type. Their solution reduces energy consumption and delay, and achieves high throughput and packet delivery ratios by selecting paths with better link quality and by avoiding collisions and interference.

5.3. Multi-objective optimisation

Multi-objective optimisation aims at optimising multiple objective functions simultaneously. Nevertheless, for non-trivial multi-objective optimisation problems (MOPs), no single solution exists that simultaneously optimises each objective function. In this case, the objective functions are said to be conflicting, and there are a (possibly infinite) number of Pareto-optimal solutions. In MOPs it is preferable to obtain a diverse set of candidate solutions that correspond to different trade-off points between the extreme solutions. To achieve multi-objective optimisation in wireless sensor networks, several solutions exploit evolutionary algorithm (EA) principles or game theoretic approaches.

The *Evolutionary algorithm* approach uses mechanisms inspired by biological evolution, such as survival of the fittest, reproduction, mutation, selection, competition and symbiosis. Candidate solutions represent individuals in a population. Each individual possesses a set of distinct characteristics and the fitness function determines the fitness of each individual. Generation after generation, the best-fit individuals are selected for reproduction to give new ones (called offspring). Offspring can be mutated and are then evaluated. The fittest individuals are selected to go into the next generation, and the rest are eliminated. Xue et al. [136] propose a multi-objective differential evolution (MODE) algorithm that produces multiple candidate routes that represent different possible trade-offs between energy consumption and communication latency. In [137], Konstandinidis et al. develop a multi-objective decomposition-based algorithm called DPAP that gives the location and transmit power of each node so that the coverage and the lifetime are simultaneously optimised. In [138], the author applies an evolutionary Multi-Objective Crowding Algorithm (EMOCA) to solve the sensor placement problem in a WSN target detection application. The aim is to maximise the probability of target detection, while minimising the total energy dissipated in the network and minimising the total number of sensors deployed.

Game theoretic approaches have been successfully applied for a variety of applications in WSNs, as surveyed in [139] and [140]. Game theory provides the designer with a useful tool to model the competitive and distributed nature of sensor networks. The solutions exploit rational interactions between nodes or entities, where incentives (such as token or reputation) are used to motivate the players to cooperate instead of acting selfishly (e.g. not relaying data to conserve energy). Felegyhazi et al. [141] foster packet forwarding cooperation between sensors that belong to different authorities. The authority gains a payoff that corresponds to the difference between the benefit of data successfully received by the sink and the energy costs experimented by its sensors for relaying both its own and opponents' packets. Their results show that cooperation through mutual service provisioning is beneficial, particularly for sparse networks or hostile environments where the sinks are shared between authorities. In [142], Zeydan et al. introduce the CAR (Correlation-aware routing) solution to construct data gathering routes aimed at minimising the energy per symbol by exploiting aggregation in correlated data. Every route is associated with a cost that reflects its energy consumption, interference, and aggregation rate. At each iteration, every node investigates the utility associated with all possible paths and then selects the best response that maximises the utility.

There are many studies that deal with multi-objective optimisation, but their practical implementation could consume a lot of resources, which may not be suitable for sensor networks. Indeed, solutions that require heavy computational or storage capabilities are suitable for centralised computations carried out by a base station. On the other hand, solutions that require less computations and storage are convenient for distributed computations carried out at each node [143]. Thus, when considering MOO solutions, it should be investigated whether or not they are applicable to real WSNs since these approaches may be hard to compute on sensor nodes. Typically, the major weakness of the evolutionary approach is that the optimisation process is performed in a central server and requires global knowledge of the network at each node or at the base station. It can lead to scalability issues as the network size increases.

5.4. Discussion

In this section, a classification is provided of solutions proposed in the literature to satisfy multiple objectives. We can distinguish the aforementioned techniques based on the flexibility of the obtained trade-off over time. By flexibility we mean that the trade-off may change over the time depending on the network conditions. For instance, multi-metric protocols usually specify a desired trade-off between the requirements at the conception phase when setting the parameters. Preference is given to a requirement by the designer. For this reason, even if the requirements are highly dependent, the trade-off is decided once and for all. In contrast, MOO solutions explore a variety of candidate solutions at run-time that represent different trade-off points of the design space. Generation after generation, behaviour policy evolves and is adjusted to the network dynamics. In-between, cross-layer approaches are expected to improve network performances by exploiting the interactions between layers. The downside is the complexity of the method that necessitates a good understanding of the interplay of various variables.

6. Conclusion

In the last decade, we have witnessed a proliferation of potential application domains of wireless sensor networks. These applications include, but are not limited to, life-critical healthcare surveillance, large-scale precision agriculture, security-oriented industrial process monitoring and nation-wide smart grid systems. In this paper, we surveyed the recent advances in the development of energy-efficient solutions for WSNs while taking into consideration the other application requirements. We first categorized the different WSN applications and we identified their specific requirements. Then we introduced a new taxonomy of energy conservation schemes and we provided the reader with a comprehensive analysis of how these techniques can affect performance of applications. We finally reviewed some existing methods that allow trade-offs between multiple requirements to be achieved for efficient and sustainable sensor networks.

Acknowledgments

The authors would like to thank the anonymous reviewers and the area editor Stavros Toumpis for their valuable comments that helped to improve the quality of this paper. This work was carried out and funded in the framework of the Labex MS2T. It was supported by the French Government, through the program “Investments for the future” managed by the National Agency for Research (Reference ANR-11-IDEX-0004-02).

References

[1] J. Yick, B. Mukherjee, D. Ghosal, Wireless sensor network survey, Computer Networks 52 (2008) 2292–2330.

[2] G. Anastasi, M. Conti, M. Di Francesco, A. Passarella, Energy conservation in wireless sensor networks: A survey, Ad Hoc Networks 7 (2009) 537–568.

[3] R. Rajagopalan, P. K. Varshney, Data-aggregation techniques in sensor networks: a survey, IEEE Communications Surveys & Tutorials 8 (2006) 48–63.

[4] K. Akkaya, M. Younis, A survey on routing protocols for wireless sensor networks, Ad Hoc Networks 3 (2005) 325–349.

[5] S. Sudevalayam, P. Kulkarni, Energy Harvesting Sensor Nodes: Survey and Implications, IEEE Communications Surveys & Tutorials 13 (2011) 443–461.

[6] H. Alemdar, C. Ersoy, Wireless sensor networks for healthcare: A survey, Computer Networks 54 (2010) 2688–2710.

[7] J. Ko, C. Lu, M. B. Srivastava, J. A. Stankovic, A. Terzis, M. Welsh, Wireless Sensor Networks for Healthcare, Proceedings of the IEEE 98 (2010) 1947–1960.

[8] A. Hadjidj, M. Souil, A. Bouabdallah, Y. Challal, H. Owen, Wireless Sensor Networks for Rehabilitation Application: Challenges and Opportunities, J. of Network and Computer Applications 36 (2013) 1–15.

[9] T. Gao, C. Pesto, L. Selavo, Y. Chen, J. Ko, J. Lim, A. Terzis, A. Watt, J. Jeng, B.-r. Chen, K. Lorincz, M. Welsh, Wireless Medical Sensor Networks in Emergency Response: Implementation and Pilot Results, in: IEEE Conference on Technologies for Homeland Security, Waltham, 2008, pp. 187–192.

[10] R. Fensli, E. Gunnarson, T. Gundersen, A Wearable ECG-Recording System for Continuous Arrhythmia Monitoring in a Wireless Tele-Home-Care Situation, in: 18th IEEE Symp. on Computer-Based Medical Systems, 2005, pp. 407–412.

[11] J. Chen, K. Kwong, D. Chang, J. Luk, R. Bajcsy, Wearable sensors for reliable fall detection, in: 27th IEEE Conference of the Engineering in Medicine and Biology Society, Shanghai, 2005, pp. 3551–3554.

[12] A. Hadjidj, A. Bouabdallah, Y. Challal, Rehabilitation supervision using wireless sensor networks, in: IEEE Int. Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM), Lucca, Italy, 2011, pp. 1–3.

[13] W.-W. Chang, T.-J. Sung, H.-W. Huang, W.-C. Hsu, C.-W. Kuo, J.-J. Chang, Y.-T. Hou, Y.-C. Lan, W.-C. Kuo, Y.-Y. Lin, Y.-J. Yang, A smart medication system using wireless sensor network technologies, Sensors and Actuators A: Physical 172 (2011) 315–321.

[14] H. Ren, M. Meng, X. Chen, Wireless Assistive Sensor Networks for the Deaf, in: IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, Beijing, 2006, pp. 4804–4808.

[15] I. Stoianov, L. Nachman, S. Madden, PIPENET: A Wireless Sensor Network for Pipeline Monitoring, in: 6th Int. Conf. on Information processing in sensor networks (IPSN), Cambridge, MA, 2007, pp. 264–273.

[16] G. Owojaiye, Y. Sun, Focal design issues affecting the deployment of wireless sensor networks for pipeline monitoring, Ad Hoc Networks 11 (2013).

[17] M. Erol-Kantarci, H. T. Mouftah, Wireless multimedia sensor and actor networks for the next generation power grid, Ad Hoc Networks 9 (2011) 542–551.

[18] W. Wang, Y. Xu, M. Khanna, A survey on the communication architectures in smart grid, Computer Networks 55 (2011) 3604–3629.

[19] M. Tubaishat, P. Zhuang, Q. Qi, Y. Shang, Wireless sensor networks in intelligent transportation systems, Wireless Communications & Mobile Computing 9 (2009) 287–302.

[20] C. Wenjie, C. Lifeng, C. Zhanglong, T. Shiliang, A Realtime Dynamic Traffic Control System Based on Wireless Sensor Network, in: Int. Conf. Workshops on Parallel Processing, Oslo, Norway, 2005, pp. 258–264.

[21] H. Qin, Z. Li, Y. Wang, X. Lu, W. Zhang, An Integrated Network of Roadside Sensors and Vehicles for Driving Safety : Concept , Design and Experiments, in: IEEE Int. Conf. on Pervasive Computing and Communications (PerCom), Mannheim, 2010, pp. 79–87.

[22] A. Pascale, M. Nicoli, F. Deflorio, B. Dalla Chiara, U. Spagno-

lini, Wireless sensor networks for traffic management and road safety, IET Intelligent Transport Systems 6 (2012) 67–77.

[23] K. Faez, M. Khanjary, UTOSPF: A distributed dynamic route guidance system based on Wireless Sensor Networks and Open Shortest Path First protocol, in: IEEE Int. Symp. on Wireless Communication Systems, Reykjavik, 2008, pp. 558–562.

[24] D. Tacconi, D. Miorandi, I. Carreras, F. Chiti, R. Fantacci, Using wireless sensor networks to support intelligent transportation systems, Ad Hoc Networks 8 (2010) 462–473.

[25] J. Tavares, F. J. Velez, J. a. M. Ferro, Application of Wireless Sensor Networks to Automobiles, Measurement Science Review 8 (2008) 65–70.

[26] K. Sha, W. Shi, O. Watkins, Using Wireless Sensor Networks for Fire Rescue Applications: Requirements and Challenges, in: IEEE Int. Conf. on Electro/information Technology, East Lansing, MI, 2006, pp. 239–244.

[27] X. Niu, X. Huang, Z. Zhao, Y. Zhang, C. Huang, L. Cui, The Design and Evaluation of a Wireless Sensor Network for Mine Safety Monitoring, in: IEEE Global Telecommunications Conference, Washington, DC, 2007, pp. 1291–1295.

[28] N. Javaid, S. Faisal, Z. A. Khan, D. Nayab, M. Zahid, Measuring Fatigue of Soldiers in Wireless Body Area Sensor Networks, in: Int. Conf. on Broadband and Wireless Computing, Communication and Applications, Compiegne, 2013, pp. 227–231.

[29] E. Cayirci, H. Tezcan, Y. Dogan, V. Coskun, Wireless sensor networks for underwater survelliance systems, Ad Hoc Networks 4 (2006) 431–446.

[30] Y.-C. Tseng, M.-S. Pan, Y.-Y. Tsai, Wireless Sensor Networks for Emergency Navigation, Computer 39 (2006) 55–62.

[31] F. Stajano, N. Hoult, I. Wassell, P. Bennett, C. Middleton, K. Soga, Smart bridges, smart tunnels: Transforming wireless sensor networks from research prototypes into robust engineering infrastructure, Ad Hoc Networks 8 (2010) 872–888.

[32] S. Kim, S. Pakzad, D. Culler, J. Demmel, G. Fenves, S. Glaser, M. Turon, Health Monitoring of Civil Infrastructures Using Wireless Sensor Networks, in: 6th Int. Symp. on Information Processing in Sensor Networks, Cambridge, MA, 2007, pp. 254–263.

[33] J.-u. Lee, J.-e. Kim, D. Kim, J. Kim, P. Jang, RFMS: Realtime Flood Monitoring System with wireless sensor networks, in: 5th IEEE Int. Conf. on Mobile Ad Hoc and Sensor Systems (MASS), Atlanta, GA, 2008, pp. 527–528.

[34] G. Vellidis, M. Tucker, C. Perry, C. Kvien, C. Bednarz, A real-time wireless smart sensor array for scheduling irrigation, Computers and Electronics in Agriculture 61 (2008) 44–50.

[35] J.-A. Jiang, C.-L. Tseng, F.-M. Lu, E.-C. Yang, Z.-S. Wu, C.-P. Chen, S.-H. Lin, K.-C. Lin, C.-S. Liao, A GSM-based remote wireless automatic monitoring system for field information: A case study for ecological monitoring of the oriental fruit fly, Bactrocera dorsalis (Hendel), Computers and Electronics in Agriculture 62 (2008) 243–259.

[36] J. I. Huircán, C. Muñoz, H. Young, L. Von Dossow, J. Bustos, G. Vivallo, M. Toneatti, ZigBee-based wireless sensor network localization for cattle monitoring in grazing fields, Computers and Electronics in Agriculture 74 (2010) 258–264.

[37] K. H. Kwong, T.-T. Wu, H. G. Goh, K. Sasloglou, B. Stephen, I. Glover, C. Shen, W. Du, C. Michie, I. Andonovic, Practical considerations for wireless sensor networks in cattle monitoring applications, Computers and Electronics in Agriculture 81 (2012) 33–44.

[38] A. Nanda, A. K. Rath, S. K. Rout, Wireless Sensor Network for Coastal Erosion : A National Perspective, International Journal of Computer Science & Communication 1 (2010) 1–5.

[39] K. K. Khedo, R. Perseedoss, A. Mungur, A Wireless Sensor Network Air Pollution Monitoring System, International Journal of Wireless & Mobile Networks 2 (2010) 31–45.

[40] P. Jiang, H. Xia, Z. He, Z. Wang, Design of a Water Environment Monitoring System Based on Wireless Sensor Networks, Sensors 9 (2009) 6411–6434.

[41] P. Corke, T. Wark, R. Jurdak, W. Hu, P. Valencia, D. Moore, Environmental Wireless Sensor Networks, Proceedings of the IEEE 98 (2010) 1903–1917.

[42] J. Valente, D. Sanz, A. Barrientos, J. del Cerro, A. Ribeiro, C. Rossi, An Air-Ground Wireless Sensor Network for Crop Monitoring, Sensors 11 (2011) 6088–6108.

[43] V. Parameswaran, H. Zhou, Z. Zhang, Irrigation control using Wireless Underground Sensor Networks, in: 6th Int. Conf. on Sensing Technology, Kolkata, 2012, pp. 653–659.

[44] Z. Sun, P. Wang, M. C. Vuran, M. A. Al-Rodhaan, A. M. Al-Dhelaan, I. F. Akyildiz, BorderSense: Border patrol through advanced wireless sensor networks, Ad Hoc Networks 9 (2011) 468–477.

[45] I. F. Akyildiz, E. P. Stuntebeck, Wireless underground sensor networks: Research challenges, Ad Hoc Networks 4 (2006) 669–686.

[46] O. Bondarenko, S. Kininmonth, M. Kingsford, Underwater Sensor Networks, Oceanography and Plankton Assemblages, in: IEEE Int. Conf. on Intelligent Sensors, Sensor Networks and Information, Melbourne, 2007, pp. 657–662.

[47] D. Pinto, S. Viana, J. Nacif, L. Vieira, M. Vieira, A. Vieira, A. Fernandes, HydroNode: A low cost, energy efficient, multi purpose node for underwater sensor networks, in: IEEE Conf. on Local Computer Networks, Clearwater, 2012, pp. 148–151.

[48] I. F. Akyildiz, D. Pompili, T. Melodia, Underwater acoustic sensor networks: research challenges, Ad Hoc Networks 3 (2005) 257–279.

[49] www.ieee802.org/15/pub/TG4.html, 2014.

[50] www.zigbee.org, ZigBee Alliance, 2014.

[51] www.hartcomm.org, 2014.

[52] Z. Jindong, L. Zhenjun, Z. Yaopei, ELHFR: A graph routing in industrial wireless mesh network, in: IEEE Int. Conf. on Information and Automation, Zhuhai, 2009, pp. 106–110.

[53] G. Gao, H. Zhang, L. Li, A Reliable Multipath Routing Strategy for WirelessHART Mesh Networks Using Subgraph Routing, J. of Computational Information Systems 9 (2013) 2001–2008.

[54] www.isa.org, ISA100, Wireless Systems for Automation, 2014.

[55] www.bluetooth.com/Pages/low-energy.aspx, Bluetooth Low Energy, 2014.

[56] http://www.ieee802.org/15/pub/TG6.html, IEEE 802.15 WPAN Task Group 6 (TG6) Body Area Networks, 2014.

[57] datatracker.ietf.org/wg/6lowpan/charter, 2014.

[58] johnkooker.com/blog/wp-content/uploads/2009/05/jkooker BTZigBeeWibree.pdf, Bluetooth, ZigBee, and Wibree: A Comparison of WPAN technologies, 2013.

[59] http://datatracker.ietf.org/wg/roll/charter/, Routing Over Low power and Lossy networks (roll), 2013.

[60] http://tools.ietf.org/html/draft-gnawali-roll-etxof 00, The ETX Objective Function for RPL, 2010.

[61] P. O. Kamgueu, E. Nataf, T. Djotio, O. Festor, Energy-based routing metric for RPL, Research Report (2013) 1–17.

[62] O. Gaddour, A. Koubâa, RPL in a nutshell: A survey, Computer Networks 14 (2012) 3163–3178.

[63] http://mqtt.org/, MQ Telemetry Transport, 2013.

[64] http://mqtt.org/MQTT-S spec v1.2.pdf, MQTT For Sensor Networks (MQTT-S) Protocol Specification, 2013.

[65] U. Hunkeler, H. L. Truong, A. Stanford-Clark, MQTT-S — A publish/subscribe protocol for Wireless Sensor Networks, in: 3rd Int. Conf. on Communication Systems Software and Middleware and Workshops, Bangalore, 2008, pp. 791–798.

[66] http://mqtt.org/projects, MQTT projects, 2013.

[67] S. Cui, A. Goldsmith, A. Bahai, Energy-constrained modulation optimization, IEEE Transactions on Wireless Communications 4 (2005) 2349–2360.

[68] F. M. Costa, H. Ochiai, A Comparison of Modulations for Energy Optimization in Wireless Sensor Network Links, IEEE Global Telecommunications Conference (2010) 1–5.

[69] A. Nosratinia, T. Hunter, A. Hedayat, Cooperative communication in wireless networks, IEEE Communications Magazine 42 (2004) 74–80.

[70] J. W. Jung, W. Wang, M. A. Ingram, Cooperative transmission range extension for duty cycle-limited wireless sensor net-

works, in: Int. Conf. on Wireless Communication, Vehicular Technology, Information Theory and Aerospace and Electronic Systems Technology, Chennai, 2011, pp. 1–5.
[71] S. Cui, A. Goldsmith, A. Bahai, Energy-Efficiency of MIMO and Cooperative MIMO Techniques in Sensor Networks, IEEE J. on Selected Areas in Communications 22 (2004) 1089–1098.
[72] S. Jayaweera, Virtual MIMO-based cooperative communication for energy-constrained wireless sensor networks, IEEE Transactions on Wireless Communications 5 (2006) 984–989.
[73] S. Lin, J. Zhang, G. Zhou, L. Gu, J. A. Stankovic, T. He, ATPC: adaptive transmission power control for wireless sensor networks, 4th Int. Conf. on Embedded networked sensor systems (2006) 223–236.
[74] L. H. Correia, D. F. Macedo, A. L. dos Santos, A. A. Loureiro, J. M. S. Nogueira, Transmission power control techniques for wireless sensor networks, Computer Networks 51 (2007) 4765–4779.
[75] X. Chu, H. Sethu, Cooperative topology control with adaptation for improved lifetime in wireless ad hoc networks, in: IEEE INFOCOM, Orlando, FL, USA, 2012, pp. 262–270.
[76] E. Kranakis, D. Krizanc, E. Williams, Directional versus omnidirectional antennas for energy consumption and k-connectivity of networks of sensors, in: 8th Int. Conf. on Principles of Distributed Systems, Grenoble, France, 2004, pp. 357–368.
[77] H.-N. Dai, Throughput and delay in wireless sensor networks using directional antennas, in: 5th Int. Conf. on Intelligent Sensors, Sensor Networks and Information Processing, Melbourne, 2009, pp. 421–426.
[78] R. Choudhury, R. Ramanathan, N. Vaidya, On designing MAC protocols for wireless networks using directional antennas, IEEE Transactions on Mobile Computing 5 (2006) 477–491.
[79] E. Karapistoli, I. Gragopoulos, I. Tsetsinas, F.-N. Pavlidou, A MAC protocol for low-rate UWB wireless sensor networks using directional antennas, Computer Networks 53 (2009) 961–972.
[80] A. P. Subramanian, S. R. Das, Addressing Deafness and Hidden Terninal Problem in Directional Antenna based Wireless Multi-Hop Networks, Wireless Networks 16 (2010) 1557–1567.
[81] M. Masonta, Y. Haddad, L. D. Nardis, A. Kliks, O. Holland, Energy efficiency in future wireless networks: Cognitive radio standardization requirements, in: IEEE 17th Int. Workshop on Computer Aided Modeling and Design of Communication Links and Networks, Barcelone, 2012, pp. 31–35.
[82] M. Naeem, K. Illanko, A. Karmokar, A. Anpalagan, M. Jaseemuddin, Energy-Efficient Cognitive Radio Sensor Networks: Parametric and Convex Transformations, Sensors 13 (2013) 11032–11050.
[83] E. Fasolo, M. Rossi, J. Widmer, M. Zorzi, In-network aggregation techniques for wireless sensor networks: a survey, IEEE Wireless Communications 14 (2007) 70–87.
[84] Z. Yan, V. Subbaraju, D. Chakraborty, A. Misra, K. Aberer, Energy-Efficient Continuous Activity Recognition on Mobile Phones: An Activity-Adaptive Approach, in: 16th Int. Symp. on Wearable Computers, Newcastle, 2012, pp. 17–24.
[85] S. Wang, A. Vasilakos, H. Jiang, X. Ma, W. Liu, K. Peng, B. Liu, Y. Dong, Energy efficient broadcasting using network coding aware protocol in wireless ad hoc network, in: IEEE Int. Conf. on Communications (ICC), Kyoto, 2011, pp. 1–5.
[86] I.-H. Hou, Y.-E. Tsai, T. Abdelzaher, I. Gupta, AdapCode: Adaptive Network Coding for Code Updates in Wireless Sensor Networks, in: IEEE INFOCOM, Phoenix, AZ, 2008, pp. 1–9.
[87] N. Kimura, S. Latifi, A survey on data compression in wireless sensor networks, in: Int. Conf. on Information Technology: Coding and Computing, Las Vegas, NV, 2005, pp. 8–13.
[88] J. Hsu, S. Zahedi, A. Kansal, M. Srivastava, V. Raghunathan, Adaptive duty cycling for energy harvesting systems, in: Int. Symp. on Low power electronics and design, Tegernsee, 2006, pp. 180–185.
[89] R. de Paz Alberola, D. Pesch, Duty cycle learning algorithm (DCLA) for IEEE 802.15.4 beacon-enabled wireless sensor networks, Ad Hoc Networks 10 (2012) 664–679.
[90] R. Carrano, D. Passos, L. Magalhaes, C. Albuquerque, Survey and Taxonomy of Duty Cycling Mechanisms in Wireless Sensor Networks, IEEE Communications Surveys & Tutorials 16 (2014) 181–194.
[91] H. Ba, I. Demirkol, W. Heinzelman, Passive wake-up radios: From devices to applications, Ad Hoc Networks 11 (2013) 2605–2621.
[92] S. Misra, M. P. Kumar, M. S. Obaidat, Connectivity preserving localized coverage algorithm for area monitoring using wireless sensor networks, Computer Communications 34 (2011) 1484–1496.
[93] E. Karasabun, I. Korpeoglu, C. Aykanat, Active node determination for correlated data gathering in wireless sensor networks, Computer Networks 57 (2013) 1124–1138.
[94] J. Al-Karaki, A. Kamal, Routing techniques in wireless sensor networks: a survey, IEEE Wireless Communications 11 (2004) 1536–1284.
[95] A. A. Abbasi, M. Younis, A survey on clustering algorithms for wireless sensor networks, Computer Communications 30 (2007) 2826–2841.
[96] D. Kumar, T. C. Aseri, R. Patel, EEHC: Energy efficient heterogeneous clustered scheme for wireless sensor networks, Computer Communications 32 (2009) 662–667.
[97] H. Li, Y. Liu, W. Chen, W. Jia, B. Li, J. Xiong, COCA: Constructing optimal clustering architecture to maximize sensor network lifetime, Computer Communications 36 (2013) 256–268.
[98] A. Liu, J. Ren, X. Li, Z. Chen, X. S. Shen, Design principles and improvement of cost function based energy aware routing algorithms for wireless sensor networks, Computer Networks 56 (2012) 1951–1967.
[99] Y. M. Lu, V. W. S. Wong, An energy-efficient multipath routing protocol for wireless sensor networks, International Journal of Communication Systems 20 (2007) 747–766.
[100] Z. Wang, E. Bulut, B. Szymanski, Energy Efficient Collision Aware Multipath Routing for Wireless Sensor Networks, in: IEEE Int. Conf. on Communications, Dresden, 2009, pp. 1–5.
[101] M. Radi, B. Dezfouli, K. A. Bakar, M. Lee, Multipath routing in wireless sensor networks: survey and research challenges, Sensors 12 (2012) 650–685.
[102] M. Younis, K. Akkaya, Strategies and techniques for node placement in wireless sensor networks: A survey, Ad Hoc Networks 6 (2008) 621–655.
[103] S. Ergen, P. Varaiya, Optimal Placement of Relay Nodes for Energy Efficiency in Sensor Networks, in: IEEE Int. Conf. on Communications, Istanbul, 2006, pp. 3473 –479.
[104] S. Misra, N. E. Majd, H. Huang, Constrained Relay Node Placement in Energy Harvesting Wireless Sensor Networks, in: IEEE 8th Int. Conf. on Mobile Adhoc and Sensor Systems, Valencia, 2011, pp. 2155–6806.
[105] D. Dandekar, P. Deshmukh, Energy balancing multiple sink optimal deployment in multi-hop Wireless Sensor Networks, in: IEEE 3rd Int. Advance Computing Conference, Ghaziabad, 2013, pp. 408–412.
[106] M. Di Francesco, S. K. Das, G. Anastasi, Data Collection in Wireless Sensor Networks with Mobile Elements, ACM Transactions on Sensor Networks 8 (2011) 1–34.
[107] R. Sugihara, R. Gupta, Optimizing Energy-Latency Trade-Off in Sensor Networks with Controlled Mobility, in: IEEE INFOCOM, Rio de Janeiro, 2009, pp. 2566–2570.
[108] W. Liang, J. Luo, X. Xu, Prolonging Network Lifetime via a Controlled Mobile Sink in Wireless Sensor Networks, in: IEEE Global Telecommunications Conference, Miami, 2010, pp. 1–6.
[109] P. Nintanavongsa, M. Naderi, K. Chowdhury, Medium access control protocol design for sensors powered by wireless energy transfer, in: IEEE INFOCOM, Turin, 2013, pp. 150–154.
[110] K. Tutuncuoglu, A. Yener, Communicating Using an Energy Harvesting Transmitter: Optimum Policies Under Energy Storage Losses, Submitted to IEEE Transactions on Wireless

Communications (2012) 1–11.
[111] L. Xie, Y. Shi, Y. Hou, A. Lou, Wireless power transfer and applications to sensor networks, IEEE Wireless Communications 20 (2013) 140–145.
[112] F. Zhang, S. A. Hackworth, X. Liu, H. Chen, S. R. J., M. Sun, Wireless energy transfer platform for medical sensors and implantable devices, in: Int. Conf. of the IEEE Engineering in Medicine and Biology Society, Minneapolis, MN, 2012, pp. 1045–1048.
[113] O. Jonah, S. V. Georgakopoulos, Efficient wireless powering of sensors embedded in concrete via magnetic resonance, IEEE Int. Symposium on Antennas and Propagation (2011) 1425–1428.
[114] B. Griffin, C. Detweiler, Resonant wireless power transfer to ground sensors from a UAV, in: IEEE Int. Conf. on Robotics and Automation, Saint Paul, MN, 2012, pp. 2660–2665.
[115] Y. Shi, L. Xie, Y. T. Hou, H. D. Sherali, On renewable sensor networks with wireless energy transfer, in: IEEE INFOCOM, Shanghai, 2011, pp. 1350–1358.
[116] R. Doost, K. R. Chowdhury, M. Di Felice, Routing and link layer protocol design for sensor networks with wireless energy transfer, in: IEEE Global Telecommunications Conference, Miami, 2010, pp. 1–5.
[117] K. Li, H. Luan, C.-C. Shen, Qi-Ferry: energy-constrained wireless charging in wireless sensor networks, in: IEEE Wireless Communications and Networking Conference, Shanghai, 2012, pp. 2515–2520.
[118] M. Erol-Kantarci, H. T. Mouftah, SuReSense: sustainable wireless rechargeable sensor networks for the Smart Grid, IEEE Wireless Communications 19 (2012) 30–36.
[119] B. Gurakan, O. Ozel, J. Yang, S. Ulukus, Energy Cooperation in Energy Harvesting Communications, IEEE Transactions on Communications 61 (2013) 4884–4898.
[120] K. Kaushik, D. Mishra, S. De, S. Basagni, W. Heinzelman, K. Chowdhury, S. Jana, Experimental demonstration of multihop RF energy transfer, in: IEEE 24th Int. Symp. on Personal Indoor and Mobile Radio Communications, London, UK, 2013, pp. 538–542.
[121] M. Watfa, H. Al-Hassanieh, S. Selman, Wireless power transfer and applications to sensor networks, IEEE Communications Letters 15 (2011) 1275–1277.
[122] D. Kandris, M. Tsagkaropoulos, I. Politis, A. Tzes, S. Kotsopoulos, PEMuR: Energy efficient and perceived QoS aware video routing over Wireless Multimedia Sensor Networks, Ad Hoc Networks 9 (2011) 591–607.
[123] S. Ehsan, B. Hamdaoui, A Survey on Energy-Efficient Routing Techniques with QoS Assurances for Wireless Multimedia Sensor Networks, IEEE Communications Surveys & Tutorials 14 (2011) 265–278.
[124] B. Carballido Villaverde, S. Rea, D. Pesch, InRout – A QoS aware route selection algorithm for industrial wireless sensor networks, Ad Hoc Networks 10 (2012) 458–478.
[125] D. Tang, T. Jiang, J. Ren, Secure and Energy Aware Routing (SEAR) in Wireless Sensor Networks, IEEE Global Telecommunications Conference (2010) 1–5.
[126] T. Zahariadis, H. C. Leligou, S. Voliotis, P. Trakadas, P. Karkazis, Energy-aware Secure Routing for Large Wireless Sensor Networks, Wseas Transactions On Communications 8 (2009) 981–991.
[127] A. A. Ahmed, An enhanced real-time routing protocol with load distribution for mobile wireless sensor networks, Computer Networks 57 (2013) 1459–1473.
[128] G. Miao, N. Himayat, Y. G. Li, A. Swami, Cross-layer optimization for energy-efficient wireless communications: a survey, Wireless Communications and Mobile Computing 9 (2009) 529–542.
[129] L. D. Mendes, J. J.P.C. Rodrigues, A survey on cross-layer solutions for wireless sensor networks, Journal of Network and Computer Applications 34 (2011) 523–534.
[130] Q. Gao, J. Zhang, X. S. Shen, B. Larish, A Cross-Layer Optimization Approach for Energy Efficient Wireless Sensor Networks: Coalition-Aided Data Aggregation, Cooperative Communication, and Energy Balancing, Advances in Multimedia (2007) 1–12.
[131] C.-Y. Chang, H.-R. Chang, Energy-aware node placement, topology control and MAC scheduling for wireless sensor networks, Computer Networks 52 (2008) 2189–2204.
[132] S. Liu, Y. Bai, M. Sha, Q. Deng, D. Qian, CLEEP: A Novel Cross-Layer Energy-Efficient Protocol for Wireless Sensor Networks, in: Int. Conf. on Wireless Communications, Networking and Mobile Computing, Dalian, 2008, pp. 1–4.
[133] L. Shi, A. O. Fapojuwo, Cross-layer optimization with cooperative communication for minimum power cost in packet error rate constrained wireless sensor networks, Ad Hoc Networks 10 (2012) 1457–1468.
[134] F. Cuomo, A. Abbagnale, E. Cipollone, Cross-layer network formation for energy-efficient IEEE 802.15.4/ZigBee Wireless Sensor Networks, Ad Hoc Networks 11 (2013) 672–686.
[135] I. T. Almalkawi, M. G. Zapata, J. N. Al-Karaki, A Cross-Layer-Based Clustered Multipath Routing with QoS-Aware Scheduling for Wireless Multimedia Sensor Networks, International Journal of Distributed Sensor Networks (2012) 1–11.
[136] F. Xue, A. Sanderson, R. Graves, Multi-Objective Routing in Wireless Sensor Networks with a Differential Evolution Algorithm, in: IEEE Int. Conf. on Networking, Sensing and Control, Ft. Lauderdale, FL, 2006, pp. 880–885.
[137] A. Konstantinidis, K. Yang, Q. Zhang, D. Zeinalipour-Yazti, A multi-objective evolutionary algorithm for the deployment and power assignment problem in wireless sensor networks, Computer Networks 54 (2010) 960–976.
[138] R. Rajagopalan, Multi-objective optimization algorithms for sensor network design, IEEE Annual Wireless and Microwave Technology Conference (2010) 1–4.
[139] R. Machado, S. Tekinay, A survey of game-theoretic approaches in wireless sensor networks, Computer Networks 52 (2008) 3047–3061.
[140] H.-Y. Shi, W.-L. Wang, N.-M. Kwok, S.-Y. Chen, Game Theory for Wireless Sensor Networks: A Survey, Sensors 12 (2012) 9055–9097.
[141] M. Felegyhazi, J.-P. Hubaux, L. Buttyan, Cooperative packet forwarding in multi-domain sensor networks, in: IEEE Int. Conf. on Pervasive Computing and Communications Workshops, Kauai Island, HI, USA, 2005, pp. 345–349.
[142] E. Zeydan, D. Kivanc, C. Comaniciu, U. Tureli, Energy-efficient routing for correlated data in wireless sensor networks, Ad Hoc Networks 10 (2012) 962–975.
[143] R. V. Kulkarni, A. Förster, G. Venayagamoorthy, Computational Intelligence in Wireless Sensor Networks: A Survey, IEEE Communications Surveys & Tutorials 13 (2011) 68–96.