Chapter 2
A Decade of Wireless Sensing Applications: Survey and Taxonomy

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Abstract The popularity of low-power wireless sensors increased significantly in the last decade, triggering a golden era for wireless sensor network research and development. During the early years of the twenty-first century, wireless sensor network applications have evolved from small demonstrations with a lifetime of only a few hours to complete systems made up of hundreds of tiny wireless nodes deployed in a wide variety of settings, ranging from harsh and remote environments to residential buildings and clinical units. This survey gives an overview of the most relevant applications of wireless sensor network applications deployed during the last ten years, and classifies them using a novel taxonomy that aims to help identifying relevant programming constructs and run-time services. With more than 60 applications reviewed, ranging from military and civilian surveillance to tracking systems, from environmental and structural monitoring to home and building automation, from agriculture and industrial settings to health care, this survey will serve as a reference to guide researchers and system designers.

1 Introduction

Evolving from research at the University of California, Berkeley, CA, USA in the early years of the twenty-first century, wireless sensor networks (WSNs) have become an important research area with a high number of dedicated conferences and journals.

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The typical WSN consists of a number of tiny devices equipped with a microcontroller, a low-power radio, and a number of sensors to perceive their surrounding environment. These devices are usually networked in a multi-hop fashion, to enable cooperation among nodes and real-time delivery of sensed data to the user. The original vision of WSNs consisted of randomly dropping large quantities of tiny and low-cost embedded devices over a large area in order to enable ad hoc measurements. The resulting dense distribution of tiny sensor nodes would enable a better area coverage, an improved accuracy, and a greater fault tolerance compared to the use of traditional isolated sensors. However, this vision was beyond the technological capabilities at that time and the first prototypes of WSNs actually consisted of a small number of matchbox-sized devices, often called "motes." Still, their relatively small size allows a careful placement close to the phenomenon of interest, enabling unprecedented spatial and temporal resolution at rather low costs.

These properties, combined with the minimal need of human intervention, led to a great success of the WSN vision, and paved the way to the adoption in a wide range of applications, ranging from environmental monitoring and precision agriculture to industrial automation and personalized health care. Until today, most WSN deployments have a strong scientific background. Their main purpose is the demonstration of new technologies and the exploration of remaining limitations; the requirements of the actual application at hand are often secondary. Consequently, most deployments are carried out by computer scientists and not by the intended end-users.

One of the first application areas in the early years of WSN research was military surveillance, in which sensor nodes are seen as a tool to enable reliable and unobtrusive intrusion detection and tracking of enemy forces [9, 83]. In these scenarios, the sensor nodes are envisioned to be randomly dropped on the battlefield and to automatically self-organize into an operational WSN. A well-known early example is the 29 Palms project conducted in March 2001 by researchers from the University of California, Berkeley, CA, USA [83]. The demonstration employed a network of five sensor nodes that are dropped by an unmanned aerial vehicle (UAV) to monitor a road for passing vehicles. While environmental monitoring applications tend to be comparatively simple by only requiring a straightforward transmission of the sensed data to a single gateway station, early military scenarios like robust tracking of people and vehicles moving in the proximity of a WSN are more complex, as they require in-network processing of the sensed data. This explains why most of the early military deployments are rather small demo applications with a lifetime of only a few hours.

Another typical example of this kind of application is the deployment at Great Duck Island in the year 2002 [62, 72, 102], which is usually regarded as the first significant application deployment of a WSN. In this scenario, a sensor network was used to unobtrusively monitor the environmental conditions around the nests of storm petrels on a small island off the coast of Maine, USA. The goal was to provide a more detailed picture to the biologists examining the nesting behavior of birds. The deployment could not fully meet the expectations due to technical limitations, but it clearly highlighted the utility and usefulness of WSNs. Many deployments in the early years of sensor network research follow the example of Great Duck Island by focusing on environmental research as the primary application area. In these deployments, the WSN is typically used as a large-scale sensing instrument. Despite generating useful data for biological research, the primary aim is usually to demonstrate the usefulness and the advantages of low-power wireless systems compared to traditional approaches. Such advantages include higher spatial and temporal resolution of the measured data, greater flexibility, and lower costs.

Around the year 2004, the number of reported WSN deployments increased significantly. This increase was partly driven by the commercialization of the first WSN platforms, such as Mica2, Mica2Dot, and their later evolutions MICAz and TelosB, which became the de facto standard research platforms for WSNs [84]. Partly, this increase was also due to maturing software infrastructures (e.g., TinyOS, TinyDB), and the increasing robustness of networking protocols. As a consequence, WSNs started to cover a larger set of application areas, including more complex civilian scenarios such as structural monitoring [109], cold chain management [88], precision agriculture [20], emergency response [69], and health care [97, 106]. In the following years, the latter area started to evolve into an independent branch of WSN applications, often referred to as body sensor networks (BSN): networks of miniaturized and low-power noninvasive or invasive wireless biosensors used to monitor the vital signs of patients [114].

Simultaneously, the advent of wireless sensor and actor networks (WSANs) further broadened the application space of WSNs [4]. A traditional WSN is a pure measurement tool that only allows to observe the environment, and decision making processes typically happen outside of the network. WSANs, instead, also feature actuators and hence can exercise some control on the surrounding environment. In a WSAN, the control loop is usually closed within the network, and there is often support for the execution of decision processes. Consequently, the employed software tends to be more complex than in pure data collection applications. Despite their interesting features, the number of actual WSAN deployments is still rather low compared to the amount of WSN deployments. Only three out of over sixty deployments surveyed in this chapter feature actuators.

In the recent years, the number of WSN deployments largely increased and, driven by the overlap of neighboring research areas such as home automation and the Internet of Things, covers an even larger set of application areas. Furthermore, the increasing popularity of WSNs lead to an increase of unconventional application scenarios that combine sensor networks and other technologies, such as mobile robots [16], RFID [38, 39], cell phones, or smart cameras [79]. Such scenarios require more complex solutions than the ones employed in traditional WSN applications, and push the community away from simple low data-rate monitoring applications, which used to be the classical WSN deployments in the earlier years. Instead, classical WSN deployments experience a shift towards more economy-oriented scenarios and early real-world applications begin to appear. A good example is the SFpark project in San Francisco, CA, USA [92], in which sensor network technology is employed to monitor parking spots in a district of San Francisco. The collected data is used to enable demand-responsive pricing and a live search for empty parking spots while aiming to steer demand and to reduce congestion in the streets. In spite of such promising examples, the number of WSN applications outside the scientific community is still limited. Most deployments remain prototypical in character and are conducted by researchers working on sensor network technologies. Commercial applications tend to be conceptually simple and not to exploit the full potential of scientific innovations. For example, advanced multi-hop routing protocols are rarely used.

The following survey gives an overview of WSN applications deployed during the last ten years. It is based on a taxonomy that aims to help identifying relevant programming constructs and run-time services to support a broad range of existing and future WSN applications. Both the taxonomy and the survey are partially based on earlier work conducted in the context of the makeSense project [36]. The remainder of this chapter is structured as follows. In the next section we present a comprehensive taxonomy to classify WSN applications. In Sect. 3 we apply this taxonomy to a range of existing WSN applications and assign the applications to six basic categories based on the identified properties. For each category, exemplary applications are described in detail, and other representatives of the category with noteworthy distinctive characteristics are briefly highlighted. We conclude this chapter in Sect. 4 with an outlook on future WSN developments.

2 Taxonomy

Several taxonomies have been proposed in the literature to classify WSN applications. In 2002, Tilak, Abu-Ghazaleh and Heinzelman [104] defined an early taxonomy that allows the classification of WSNs according to different communication functions, data delivery models, and network dynamics.

Based on a discussion with European experts from academia and industry in 2004, Römer and Mattern [90] proposed an explicit definition of the WSN design space based on a taxonomy consisting of twelve categories. Their design space allows the characterization of WSN applications based on technical properties of the deployed network. It aims to cover the full spectrum of WSN application properties, but it is limited to sense-only applications without actuators. The design space is accompanied by a survey of WSN applications employing the newly defined taxonomy. Römer and Mattern's design space was later refined and simplified by Rocha and Gonçalves [89]. In addition to the simplification, the authors add categories to highlight application-specific needs independently of the employed technical solution.

Based on a survey of WSN taxonomies and the evaluation of existing WSN applications, Ruairí et al. [91] created a solution-neutral taxonomy to cover applications' primary requirements. In contrast to previous work, their taxonomy focuses on properties of the actual application and does not include technical properties of the deployed sensor network.

Bai et al. [11] proposed a WSN application taxonomy with eight dimensions that is used as a tool to identify typical application classes to fasciculate the creation of application-specific languages.

None of the proposed taxonomies seems to fully capture all aspects relevant to WSN design. We propose a refined taxonomy that aims to capture exactly these aspects while still staying concise enough to be useful. Our taxonomy is partially based on early work conducted by Mottola and Picco as part of a survey on WSN programming abstractions [77]. Their taxonomy is also intended as a tool to identify common application requirements that programming platforms must meet.

We now describe the dimensions of our taxonomy. For some dimensions, the possible values are not exclusive, and several of them may apply for a specific application.

Goal. Traditionally, WSN have been seen primarily as a *sense-only* tool to passively collect data. Such scenarios do not require control logic inside the network. For wireless sensor and actor networks (WSANs) this is not necessarily true, anymore [4]. The collected data could still be forwarded to a central location at which the control logic is implemented, but this is highly inefficient. Such applications follow a *sense and react* pattern.

$$goal \in \{\text{sense-only, sense-and-react}\}.$$

Sampling. Depending on the application scenario, WSNs follow different approaches for data collection and processing. In the *periodic* case, the nodes regularly read their sensors, process the resulting data, and possibly react accordingly. *Event-triggered* WSNs stay dormant for most of their lifetime and wait for some rare event. Each node monitors its sensors until a relevant event is detected. Following the successful detection of an event, the WSN becomes active and performs the required distributed processing.

$$sampling \in \{\text{periodic, event-triggered}\}.$$

Sensed phenomenon. Similarly to Ruairí et al. [91], we discriminate the sensed phenomena based on two orthogonal properties. The phenomenon sensed by a WSN can either be *discrete* or *distributed*. We consider a phenomenon to be discrete if it is located at a specific place and can usually be fully detected by a single sensor. Multiple sensors may be required if the phenomenon is mobile, for example to facilitate tracking, or they may allow a higher fidelity of the collected data. Distributed phenomena affect an area or volume and can only be fully captured by a larger number of sensors. WSNs may be used to monitor just a *single* phenomenon or *multiple* independent phenomena.

$$sensed\ phenomenon \in \{\text{single, multiple}\} \times \{\text{discrete, distributed}\}.$$

Data rate. The type of deployed sensors largely influences the capabilities and properties of a WSN. For this survey, we use an abstract classification of sensors based on the amount of generated data. We distinguish between two classes of sensors: *low* data-rate sensors, such as temperature and humidity sensors, that create a stream of simple numerical values and *high* data-rate sensors that produce large amounts of data per reading, like video cameras, or which require a high sampling rate, such as microphones and vibration sensors. The border between these classes is sometimes fuzzy. As a rule of thumb, we consider those sensors as high date-rate sensors that generate amounts of data that exceed the usual data-rate of WSN radio links. Most WSNs employ low data-rate sensors.

$$data\ rate \in \{\text{low, high}\}.$$

Heterogeneity. WSNs were originally envisioned to be largely *homogeneous*. In reality this is frequently not true: modern WSNs often consist of nodes that differ in the set of employed *sensors*. In addition, some WSNs employ multiple node *architectures* that offer different resources, for example in terms of storage space or processing power, and thus are bound to serve different purposes. Similarly, some nodes in the network may have a larger power supply available or they can harvest energy, which allows them to spend more time in an active state than the majority of the other nodes.

$$heterogenity \subset \{\text{sensors, architecture}\}.$$

Mobility. Most WSNs are *static*, but there are applications that require mobility. In the latter case, all the nodes or a subset of the *nodes* in the network are mobile. A typical example is having the sensor nodes directly attached to some animals. Active movement of the nodes is rare and thus not considered in this survey. The *base station* of the WSN is also not necessarily situated at a fixed location. It may move within the WSN or even occasionally leave the communication range of the network.

$$mobility \subset \{\text{mobile nodes, mobile base-station}\}.$$

Connectivity. The connectivity of a WSN depends on the communication range of the deployed radio, its surrounding environment, and the degree of network dynamics. Mobility influences the connectivity of a WSN, but disruption of communication can also be caused by an changing radio environment, even if the nodes stay at fixed locations. If at least one (multi-hop) communication path between each pair of nodes in the network is constantly expected, we consider the network to be *connected*. Note that sporadic unintended packet losses may also occur in the *connected* case. If the network is occasionally partitioned as part of normal operation, the network is considered to have *intermittent* connectivity. In some networks the nodes are isolated most of the time and enter the communication range of other nodes only *sporadically*.

$$connectivity \in \{\text{connected, intermittent, sporadic}\}.$$

Processing. In early WSN applications, the majority of data processing is performed outside of the network. To reduce the amount of data to be transmitted and to leverage the nodes' processing capabilities, it is sometimes beneficial to move parts of the data processing directly into the network. In-network processing can occur in different forms ranging from simple filtering to sophisticated control logic. We discriminate the following types of processing: *filtering*, *compression*, *aggregation*, *tracking*, *event detection*, *classification*, *interpretation*, and *decision making*. *Filtering* and *compression* allow to reduce the amount of data to be transmitted or stored. *Aggregation* further reduces the data by fusing values several sensors while passing it trough the network. If the network has the ability to autonomously scan for the occurrence of predefined events, we specify this as *event detection*. Further data processing can either take the form of *classification* or *decision making*. The result of the later is an immediately useful result suitable to act upon.

Orthogonally, processing can happen at different locations in the network. We distinguish local processing at a single *node*, distributed processing in the *network*, processing at a *gateway*, and processing at some *server* outside of the WSN system.

$$\begin{aligned} processing \subset \{&\text{filtering, compression, aggregation, tracking,}\\ &\text{event detection, classification, decision making}\}\\ &\times \{\text{node, network, gateway, server}\}. \end{aligned}$$

Storage. To allow later analysis of the gathered data, most applications require some form of *persistent* data storage. In addition, if the network is not constantly connected, some form of *caching* is required to permit a delayed transmission. Storage can happen either directly at the *node* that created the data, somewhere in the *network*, at the *gateway*, or at some *server* outside of the WSN system.

$$storage \subset \{\text{caching, persistent}\} \times \{\text{node, network, gateway, server}\}.$$

Services. Besides the processing of the data, further support services may be required for successful WSN operation. For many application scenarios it is necessary to spatially and temporally correlate the measurements of different sensors. This usually requires some form of *time synchronization* among the nodes. If node positions are not precisely know in advance there is also a need for some kind of *localization*.

If the sensed data is of privacy-critical nature, like vital patient data in a hospital, or its integrity is important, then the data needs to be protected against overhearing or tampering. This can be realized by implementing *encryption* and *authentication*.

Long-term deployments with changing environments or requirements raise a need for remote maintenance functions. *Reprogramming* or *reconfiguration* systems allow to meet new requirements by remotely adapting the nodes' software.

$$\begin{aligned} service \subset \{&\text{localization, time synchronization, authentication, encryption,}\\ &\text{reprogramming, reconfiguration}\}. \end{aligned}$$

Communication primitives. Deployed WSN employ a range of diverse communication primitives. Simple sense-only networks usually use only some form of *collection* to relay the gathered data towards the sink. More complex networks may employ a broad range of different processing primitives.

Especially heterogeneous networks may be organized in *clusters*. All nodes in a cluster communicate solely with a designated cluster head. This cluster head serves as a gateway to the outer world by communicating with other cluster heads and the base station of the WSN. In heterogeneous networks the nodes serving as cluster heads usually possess excessive resources in terms of energy supply, storage capacity, and computational power.

$$communication\ primitives \subset \{\text{single-hop unicast, multi-hop unicast, single-hop broadcast, flooding, collection, cluster}\}.$$

3 Survey

In this section, we present a comprehensive survey of well-documented WSN applications based on a systematic review of the leading WSN publication venues. The survey only includes applications whose feasibility has been demonstrated by either a prototype or a real-world deployment. We explicitly exclude pure testbeds and similar applications. A complete list of the applications covered in this survey can be found in Table 1. For each deployment, we report the approximate time frame, network size, and overall lifetime. If the year of the actual deployment is not explicitly stated, we assume the date of the earliest publication. We further map all the surveyed systems to the taxonomy presented in Sect. 2, and we summarize their properties in Tables 2 and 3. We finally categorize the surveyed applications into six classes based on the type of output returned to the user and on the complexity of the employed technical solution. For each class, we examine representative applications in detail and we highlight further deployments with distinguishing properties.

Most applications are using the WSN technology as a pure measurement instrument, and the collected data is typically transferred to a central server for post-processing and analysis. Hence, the network simply delivers the raw data, and its analysis is up to the end-user. This is typically the case for scientific deployments in which all the collected data is relevant. The indiscriminate collection of the complete raw data is also useful in prototypical deployments in order to be able to verify the correct operation of each single node. We divide this class of applications into three sub-classes: *Low-Rate Data Collection*, characterized by a periodic collection using low data-rate sensors; *High-Rate Data Collection*, characterized by periodic collection in which the data-rate generated by the sensors is particularly high; and *On-Demand Data Collection*, in which the user triggers the collection of data on-demand. Please note that in deployments that fall into one of these categories any processing or analysis of the data is left to the user: the WSN itself does not process the data. In another notable set of applications, the sensor network performs on-node processing and event detection or it even classifies the observed data within the network. As a result, the user does not get a raw collection of data anymore, but instead the notification about the occurrence of a given event or an instance of a class. We group these applications in the *Event Detection and Classification* class. Some other WSNs build upon the in-network event detection to localize or even track their position. The

Table 1 Basic properties of the presented WSN applications[1]

Application	Year	Size	Lifetime	Class
① Environment monitoring: PODS [19]	2002	*Tens*	Weeks	Low-rate data collection
② Habitat monitoring: Great Duck Island [62, 72, 102]	2002	Tens (100)	Months	Low-rate data collection
③ Glacier monitoring: GlacsWeb [74]	2004	Tens (9)	Months	Low-rate data collection
④ Power monitoring [53]	2004	*Tens*	Years	Low-rate data collection
⑤ Soil and Moisture monitoring [23, 24]	2004	Tens (9)	Weeks	Low-rate data collection
⑥ Vineyard monitoring: Unwired wine [17, 20]	2004	Tens (65)	Months	Low-rate data collection
⑦ Wildfire monitoring [35]	2004	Tens	Hours	Low-rate data collection
⑧ Environment monitoring: Redwood Eco-Physiology [32, 105]	2005	*Tens*	Days	Low-rate data collection
⑨ Forest fire detection: FireWxNet [37]	2005	*Tens*	Days	Low-rate data collection
⑩ Irrigation [57]	2005	Tens (5)	*Days*	Low-rate data collection
⑪ Landslide detection: SenSlide [94]	2005	*Tens*	Months	Low-rate data collection
⑫ Tunnel monitoring [27]	2005	Tens (18)	Weeks	Low-rate data collection
⑬ Water monitoring [81]	2005	Tens (5)	*Months*	Low-rate data collection
⑭ LOFAR-agro [63]	2006	*Tens*	Months	Low-rate data collection
⑮ Environment monitoring: SensorScope [15]	2007	Tens (16)	Months	Low-rate data collection
⑯ Irrigation: FLOW-AID [13]	2007	Tens (10)	Months	Low-rate data collection
⑰ Tunnel control and monitoring [31, 26, 78]	2007	*Tens*	Months	Low-rate data collection
⑱ Fire detection and tracking [8]	2008	Tens (12)	Hours	Low-rate data collection
⑲ Greenhouse Monitoring [3]	2008	Tens (4)	Days	Low-rate data collection
⑳ AC metering [49, 50]	2009	Tens (49)	Weeks	Low-rate data collection
㉑ Environment monitoring: GreenOrbs [75]	2009	Tens (120)	Weeks	Low-rate data collection
㉒ Environment monitoring: PermaSense [18]	2009	Tens (25)	Years	Low-rate data collection
㉓ Reliable Clinical Monitoring [29]	2009	Tens	Days	Low-rate data collection
㉔ Soil monitoring: Suelo [86]	2009	Tens (13)	Months	Low-rate data collection
㉕ Vineyard monitoring [7]	2009	Tens (27)	*Months*	Low-rate data collection
㉖ Wildlife and environmental monitoring [38, 39]	2009	Tens (36)	Months	Low-rate data collection
㉗ Duty cycling building: HVAC [2]	2010	Tens	*Days*	Low-rate data collection
㉘ MEDiSN [59]	2010	Tens (55)	Days	Low-rate data collection

(continued)

Table 1 (continued)

Application	Year	Size	Lifetime	Class
㉙ Electronic Shepherd [103]	2004	*Tens*	Months	Low-rate data collection
㊻ Pipe monitoring: PIPENET [101]	2004	*Tens*	Months	Low-rate data collection
㉛ Relic protection in the forbidden city [65, 66]	2007	Tens (34)	*Weeks*	Low-rate data collection
㉜ Substation monitoring [80]	2008	Tens (45)	Weeks	Low-rate data collection
㉝ Structure monitoring: Four Seasons [109]	2004	*Tens*	Days	High-rate data collection
㉞ Industrial plant monitoring: Oil tanker [61]	2005	*Tens*	Months	High-rate data collection
㉟ Volcano monitoring [108]	2006	*Tens*	Days	High-rate data collection
㊱ Structure monitoring: Golden Gate Bridge [56]	2007	Tens (64)	Months	High-rate data collection
㊲ Structural monitoring [110]	2009	Tens (21)	*Days*	High-rate data collection
㊳ Structure monitoring: Torre Aquila [25]	2009	Tens (16)	Months	High-rate data collection
㊴ Underground animal tracking [73]	2010	Tens (14)	Months	High-rate data collection
㊵ Zebra monitoring: ZebraNet [51, 115]	2002	*Tens*	Months	On-demand data collection
㊶ Antelope monitoring: wildCENSE [87]	2006	*Tens*	Months	On-demand data collection
㊷ Environment Monitoring: LUSTER [93]	2007	Tens (20)	Weeks	On-demand data collection
㊸ High-fidelity Motion Analysis [70]	2009	Tens (9)	Days	On-demand data collection
㊹ Cane-toad monitoring [46, 47, 98]	2004	*Tens*	*Weeks*	Event detection and classification
㊺ Fence monitoring [111]	2007	Tens (10)	*Days*	Event detection and classification
㊻ Acoustic monitoring: VoxNet [6]	2008	Tens (8)	Days	Event detection and classification
㊼ Human monitoring: BehaviorScope [71, 14]	2008	*Tens*	*Days*	Event detection and classification
㊽ Coal mine monitoring [67]	2009	Tens (27)	*Days*	Event detection and classification
㊾ Fall detection: WeCare [5]	2010	*Tens*	Days	Event detection and classification
㊿ Activity recognition: PBN [54]	2011	Tens (5)	Hours	Event detection and classification
51 Intrusion detection: 29 Palms [83]	2001	Tens (5)	Weeks	Localization and tracking
52 Cold chain management [88]	2004	Tens (55)	Years	Localization and tracking

(continued)

Table 1 (continued)

Application	Year	Size	Lifetime	Class
㊳ Intrusion detection: A Line in the Sand [9]	2004	Tens (90)	Days	Localization and tracking
㊴ Robot navigation [16]	2004	Tens (9)	Hours	Localization and tracking
㊵ Sniper localization: PinPtr [99]	2004	Tens (60)	Months	Localization and tracking
㊶ Tracking: EnviroTrack [1, 44]	2004	Tens (70)	Days	Localization and tracking
㊷ Intrusion detection: ExScal [37]	2005	Thousands (1200)	Days	Localization and tracking
㊸ Parking lot surveillance [79]	2009	*Tens*	Days	Localization and tracking
㊹ Radio-based localization [113]	2012	Tens (16)	Days	Localization and tracking
㊺ Animal control: Networked Cows [22]	2004	Tens (10)	Weeks	Actuation
㊻ HVAC [34]	2005	*Tens*	*Weeks*	Actuation
㊼ Animal control [107]	2007	Tens (13)	Days	Actuation

[1]Values written in italics could not be determined with absolute certainty based on the literature available: these values have been estimated to the best of our knowledge

latter can be as simple as detecting a moving sensor or may require complex signal processing as in [99]. We group these applications in the *Localization and Tracking* class. Finally, applications that involve not only sensing but also actuation and actively manipulate the monitored environment are grouped in the *Actuation* class.

3.1 Low-Rate Data Collection

It is probably not surprising that low-rate data collection was the first application scenario for WSNs, and that it still represents the majority of existing deployments. These applications are typically characterized by periodic monitoring with low-data-rate sensors, such as simple temperature or infrared sensors that usually produce a single scalar value per measurement. Furthermore, they usually support an extensive lifetime of the network up to several years [21]. As it can be observed in Table 3, these applications rarely employ sophisticated in-network processing. The low data-rate makes it feasible to communicate the collected raw data without filtering, compression, or aggregation.

3.1.1 Environmental Monitoring

The most prominent example of this application class is probably a series of deployments between 2002 and 2004 at Great Duck Island in Maine,USA [72, 102] ②. The goal of these deployments was the long-term observation of the breeding behavior and nesting conditions of Leach's Storm Petrels. The involved biologists were especially interested in the usage patterns of the nesting burrows and how these are affected

Table 2 Mapping of WSN applications to the taxonomy presented in Sect. 2 (1/2)[2]

Application	Goal	Sampling	Phenomenon	Data rate	Heterogeneity	Mobility	Connectivity
① Environment monitoring: PODS [19]	SO	Periodic	Single distributed	Low	Homogeneous	Static	Connected
② Habitat monitoring: Great Duck Island [62, 72, 102]	SO	Periodic	Multiple discrete	Low	Sensors	Static	Connected
③ Glacier monitoring: GlacsWeb [74]	SO	Periodic	Single distributed	Low	Homogeneous	Nodes	Intermittent
④ Power monitoring [53]	SO	Periodic	Multiple discrete	Low	Architecture	Static	Connected
⑤ Soil and Moisture monitoring [23, 24]	SO	Periodic	Multiple distributed	Low	Sensors, architecture	Static	Connected
⑥ Vineyard monitoring: Unwired wine [17, 20]	SO	Periodic	Single distributed	Low	Homogeneous	Static	Connected
⑦ Wildfire monitoring [35]	SO	Periodic	Multiple distributed	Low	Homogeneous	Static	Connected
⑧ Environment monitoring: Redwood Eco-Physiology [32, 105]	SO	Periodic	Single distributed	Low	Homogeneous	Static	Connected
⑨ Forest fire detection: FireWxNet [37]	SO	Periodic	Single distributed	Low	Sensors	Static	Connected
⑩ Irrigation [57]	SO	Periodic	Multiple distributed	Low	Homogeneous	Static	Connected
⑪ Landslide detection: SenSlide [94]	SO	Periodic	Single distributed	Low	Architecture	Static	Connected
⑫ Tunnel monitoring [27]	SO	Periodic	Single distributed	Low	Homogeneous	Static	Connected
⑬ Water monitoring [81]	SO	Periodic	Multiple distributed	Low	Sensors, architecture	Static	Connected
⑭ LOFAR-agro [63]	SO	Periodic	Single distributed	Low	Homogeneous	Static	Connected
⑮ Environment monitoring: SensorScope [15]	SO	Periodic	Multiple distributed	Low	*Homogeneous*	Static	Connected
⑯ Irrigation: FLOW-AID [13]	SO	Periodic	Multiple distributed	Low	Sensors	Static	Connected
⑰ Tunnel control and monitoring [26, 31, 78]	SO	Periodic	Single distributed	Low	Homogeneous	Static	*Connected*

(continued)

Table 2 (continued)

Application	Goal	Sampling	Phenomenon	Data rate	Heterogeneity	Mobility	Connectivity
⑱ Fire detection and tracking [8]	SO	Periodic	Multiple distributed	Low	Homogeneous	Static	Connected
⑲ Greenhouse Monitoring [3]	SO	Periodic	Multiple distributed	Low	Homogeneous	Static	Connected
⑳ AC metering [49, 50]	SO	Periodic	Multiple discrete	Low	Sensors	Static	Connected
㉑ Environment monitoring: GreenOrbs [75]	SO	Periodic	Single distributed	Low	Homogeneous	Static	Connected
㉒ Environment monitoring: PermaSense [18]	SO	Periodic	Multiple distributed	Low	Homogeneous	Static	*Intermittent*
㉓ Reliable Clinical Monitoring [29]	SO	Periodic	Multiple discrete	Low	Sensors	Nodes	Intermittent
㉔ Soil monitoring: Suelo [86]	SO	Periodic	Multiple distributed	Low	Homogeneous	Static	Connected
㉕ Vineyard monitoring [7]	SO	Periodic	Multiple discrete	Low	Sensors, architecture	Static	Connected
㉖ Wildlife and environmental monitoring [38, 39]	SO	Event	Single discrete, Multiple distributed	Low	Sensors	Base station	Intermittent
㉗ Duty cycling building: HVAC [2]	SO	*Periodic*	Single distributed	Low	Sensors	Static	Connected
㉘ MEDiSN [59]	SO	Periodic	Multiple discrete	Low	Sensors	Nodes	Connected
㉙ Electronic Shepherd [103]	SO	Periodic	Multiple discrete	Low	Architecture	Nodes	*Sporadic*
㊿ Pipe monitoring: PIPENET [101]	SO	Periodic	Multiple discrete	Low	Sensors	Static	*Connected*
㉛ Relic protection in the forbidden city [65, 66]	SO	Event	Multiple discrete	*Low*	Architecture	Static	Connected
㉜ Substation monitoring [80]	SO	Periodic	Multiple discrete	Low	Sensors	Static	Connected
㉝ Structure monitoring: Four Seasons [109]	SO	Periodic	Single distributed	High	Homogeneous	Static	Connected

(continued)

Table 2 (continued)

Application	Goal	Sampling	Phenomenon	Data rate	Heterogeneity	Mobility	Connectivity
㉞ Industrial plant monitoring: Oil tanker [61]	SO	Periodic	Multiple discrete	Low, high	Sensors	Static	Intermittent
㉟ Volcano monitoring [108]	SO	Periodic	Single distributed	High	Homogeneous	Static	Connected
㊱ Structure monitoring: Golden Gate Bridge [56]	SO	Periodic	Single distributed	High	Homogeneous	Static	Connected
㊲ Structural monitoring [110]	SO	Periodic	Single distributed	High, low	Homogeneous	Static	*Connected*
㊳ Structure monitoring: Torre Aquila [25]	SO	Periodic	Multiple distributed	Low, high	Sensors	Static	Connected
㊴ Underground animal tracking [73]	SO	Periodic	*Single discrete*	*Low*	Sensors, architecture	Nodes	Sporadic, connected
㊵ Zebra monitoring: ZebraNet [51, 115]	SO	Periodic	Multiple discrete	Low	Homogeneous	Nodes, base station	Sporadic
㊶ Antelope monitoring: wildCENSE [87]	SO	Periodic	Multiple discrete	Low	Homogeneous	Nodes, base station	*Sporadic*
㊷ Environment Monitoring: LUSTER [93]	SO	Periodic	Single distributed	Low	Sensors, architecture	Static	*Intermittent*
㊸ High-fidelity Motion Analysis [70]	SO	Periodic	Multiple distributed	*Low*	Homogeneous	Nodes	Intermittent
㊹ Cane-toad monitoring [46, 47, 98]	SO	Event	Multiple discrete	*High*	Architecture	Static	Connected
㊺ Fence monitoring [111]	SO	Event	Multiple discrete	High	Homogeneous	Static	Connected
㊻ Acoustic monitoring: VoxNet [6]	SO	Event	Multiple discrete	High	Homogeneous	Static	Connected
㊼ Human monitoring: BehaviorScope [14, 71]	SO	Periodic	Multiple discrete	High	Sensors	Static	Connected
㊽ Coal mine monitoring [67]	SO	Event	Multiple distributed	Low	Homogeneous	Nodes	Connected

(continued)

Table 2 (continued)

Application	Goal	Sampling	Phenomenon	Data rate	Heterogeneity	Mobility	Connectivity
㊾ Fall detection: WeCare [5]	SO	Event	Multiple discrete	Low, high	Sensors, architecture	Nodes	Connected
㊿ Activity recognition: PBN [54]	SO	Periodic	Single discrete, multiple distributed	High, low	Homogeneous	Nodes, base station	Connected
51 Intrusion detection: 29 Palms [83]	SO	Event	Multiple discrete	*Low*	Homogeneous	Base station	Intermittent
52 Cold chain management [88]	SO	*Periodic*	Multiple discrete	Low	Sensors, architecture	Nodes	Intermittent
53 Intrusion detection: A Line in the Sand [9]	SO	Event	Multiple discrete	*Low*	Homogeneous	Static	Connected
54 Robot navigation [16]	SO	Event	Single discrete	Low	Homogeneous	Base station	Connected
55 Sniper localization: PinPtr [99]	SO	Event	Single discrete	*Low*	Homogeneous	Static	Connected
56 Tracking: EnviroTrack [1, 44]	SO	Event	Multiple discrete	Low	Homogeneous	Static	Connected
57 Intrusion detection: ExScal [37]	SO	Event	Multiple discrete	Low	Homogeneous	Static	Connected
58 Parking lot surveillance [79]	SR	Event	Multiple discrete	*High*	Sensors, architecture	Static	Connected
59 Radio-based localization [113]	SO	Peridic	*Single discrete*	*Low*	Sensors	Static	Connected
60 Animal control: Networked Cows [22]	SR	Event	Multiple discrete	Low	Homogeneous	Nodes	Intermittent
61 HVAC [34]	SR	Periodic	Multiple distributed	Low	*Homogeneous*	Static	*Connected*
62 Animal control [107]	SR	Event	Multiple discrete	*Low*	Homogeneous	Nodes	Connected

[2]Values written in italics could not be determined with absolute certainty based on the literature available: these values have been estimated to the best of our knowledge

Table 3 Mapping of WSN applications to the taxonomy presented in Sect. 2 (2/2)[3]

Application	Processing	Storage	Services	Communication
① Environment monitoring: PODS [19]		Persistent[server]	Time synchronization	Collection, multi-hop unicast
② Habitat monitoring: Great Duck Island [102, 62, 72]		Persistent[server]		*Collection (cluster)*
③ Glacier monitoring: GlacsWeb [74]		Caching[node], persistent[gateway]	*Time synchronization*	*Multi-hop unicast*
④ Power monitoring [53]		Persistent[server]		*Collection*
⑤ Soil and Moisture monitoring [23, 24]		Persistent[node, server]		*Single-hop unicast*
⑥ Vineyard monitoring: Unwired wine [17, 20]		*Persistent[server]*	Synchronization	*Collection*
⑦ Wildfire monitoring [35]		Persistent[server]	Localization (GPS)	*Collection*
⑧ Environment monitoring: Redwood Eco-Physiology [105, 32]		Caching[node], persistent[gateway]		*Collection*
⑨ Forest fire detection: FireWxNet [37]		Persistent[server]	Time synchronization	Collection, multi-hop broadcast (cluster)
⑩ Irrigation [57]	Decision making [gateway]			*Collection*, Single-hop unicast
⑪ Landslide detection: SenSlide [94]	Filtering [node], aggregation [network], classification [server]	*Persistent[server]*		Collection, multi-hop unicast (cluster)
⑫ Tunnel monitoring [27]		Persistent [gateway]		*Collection*
⑬ Water monitoring [81]		Persistent[server], *Persistent[gateway]*		*Multi-hop unicast*
⑭ LOFAR-agro [63]	Compression[note]	Persistent [node]	Reprogramming	Collection
⑮ Environment monitoring: SensorScope [15]		*Persistent[server]*	Time synchronization	Multi-hop unicast
⑯ Irrigation: FLOW-AID [13]	Decision making [gateway]	Persistent[server]		*Multi-hop unicast*
⑰ Tunnel control and monitoring [26, 31, 78]				Collection, flooding

(continued)

Table 3 (continued)

Application	Processing	Storage	Services	Communication
⑱ Fire detection and tracking [8]	*Tracking[server]*	Persistent[server]		Collection
⑲ Greenhouse Monitoring [3]		Persistent[server]		*Collection*
⑳ AC metering [49, 50]		*Persistent[server]*		Single-hop broadcast
㉑ Environment monitoring: GreenOrbs [75]	*Filtering[node]*			Flooding
㉒ Environment monitoring: PermaSense [18]		*Caching[network]*		*Collection*
㉓ Reliable Clinical Monitoring [29]	Aggregation[network]	Persistent[server]		Collection
㉔ Soil monitoring: Suelo [86]	*Classification*			
㉕ Vineyard monitoring [7]		Persistent[server]		*Collection*
㉖ Wildlife and environmental monitoring [38, 39]	Compression[node]	Caching[network], Persistent[server]		Collection, multi-hop unicast
㉗ Duty cycling building: HVAC [2]	Decision making[server]	*Caching[server]*		Collection
㉘ MEDiSN [59]		Persistent[server]	Reconfiguration	Collection
㉙ Electronic Shepherd [103]		Persistent[server]	Localization (GPS)	Single-hop unicast (cluster)
㊻ Pipe monitoring: PIPENET [101]	Aggregation[node], Event detection[node]	Caching[gateway]	Time synchronization	*Collection*
㉛ Relic protection in the forbidden city [65, 66]	*Event detection[server]*	*Caching[node], Persistend[server]*		*Collection*
㉜ Substation monitoring [80]				*Collection*
㉝ Structure monitoring: Four Seasons [109]	Compression[node]	Persistent[server]	Time synchronization	*Collection*
㉞ Industrial plant monitoring: Oil tanker [61]	Classification[server]	Persistent[server], caching[node]		Collection (cluster)
㉟ Volcano monitoring [108]	Event detection[node]	Caching[node], persistent[gateway]	Time synchronization, reprogramming	Collection, multi-hop unicast
㊱ Structure monitoring: Golden Gate Bridge [56]	*Filtering[node]*	Caching[node]	Time synchronization	*Collection*
㊲ Structural monitoring [110]		*Persistent[server]*	Time synchronization	*Collection*

(continued)

Table 3 (continued)

Application	Processing	Storage	Services	Communication
㊳ Structure monitoring: Torre Aquila [25]	Compression[node], classification[server]	Persistent[server]	Time synchronization, reconfiguration	Collection, flooding
㊴ Underground animal tracking [73]	Compression[node]	Caching[node], persistent[server]	Localization	Single-hop unicast, collection
㊵ Zebra monitoring: ZebraNet [51, 115]	Filtering[network]	Caching[network], persistent[server]	Localization (GPS)	Single-hop broadcast
㊶ Antelope monitoring: wildCENSE [87]	Compression[node]	Caching[node]	Localization (GPS), reconfiguration	*Flooding*
㊷ Environment Monitoring: LUSTER [93]	Aggregation[node]	*Persistent[network]*	Time synchronization	*Collection, single-hop unicast (cluster)*
㊸ High-fidelity Motion Analysis [70]	Filtering[node]	Persistent[node, server]	Reconfiguration, time synchronization	*Single-hop unicast*
㊹ Cane-toad monitoring [46, 47, 98]	Compression[node], filtering[node], classification[network], localization[network]	Caching[node], persistent[server]	Localization (GPS)	Single-hop unicast, collection (cluster)
㊺ Fence monitoring [111]	Filtering[node], event detection[node], event detection[network]		*Time synchronization*	Collection, neighborhood
㊻ Acoustic monitoring: VoxNet [6]	Event detection[network]	Caching[node], persistent[server]	Localization	*Multi-hop unicast*
㊼ Human monitoring: BehaviorScope [71, 14]	Classification[server]	Persistent[server]		
㊽ Coal mine monitoring [67]	Event detection[network], aggregation[network]		Reconfiguration	Collection, flooding
㊾ Fall detection: WeCare [5]	*Event detection[network]*			
㊿ Activity recognition: PBN [54]	Aggregation[node], *filtering[node]*, classification[gateway]	*Persistent[gateway]*		Collection

(continued)

Table 3 (continued)

Application	Processing	Storage	Services	Communication
㉛ Intrusion detection: 29 Palms [83]	Filtering[node], event detection[node]	*Persistent[network]*	Time synchronization, localization	*Collection*
㉜ Cold chain management [88]		*Persistent[server]*		*Collection*
㉝ Intrusion detection: A Line in the Sand [9]	Event detection[node], classification[server], tracking[server]		Time synchronization	Single-hop broadcast, collection
㉞ Robot navigation [16]	*Decision making[network]*			Flooding, single-hop broadcast
㉟ Sniper localization: PinPtr [99]	Aggregation[network], classification[gateway], event detection[node]		Time synchronization, localization	Collection, single-hop unicast
㊱ Tracking: EnviroTrack [1, 44]	Event detection[network], tracking[network], filtering[server]		Time synchronization, localization, reconfiguration	Single-hop broadcast, collection, flooding
㊲ Intrusion detection: ExScal [37]	Classification[node], event detection[node]		Reprogramming	
㊳ Parking lot surveillance [79]	Event detection[node], localization[network]			Collection, flooding
㊴ Radio-based localization [113]	Decision making[gateway]			*Single-hop unicast*
㊵ Animal control: Networked Cows [22]	*Decision making[node]*		Localization (GPS), reprogramming	Multi-hop unicast, single-hop broadcast, flooding
㊶ HVAC [34]	*Decision making[network]*			*Multi-hop unicast*
㊷ Animal control [107]	*Decision making[node]*		Localization (GPS)	Single-hop broadcast

[3]Values written in italics could not be determined with absolute certainty based on the literature available: these values have been estimated to the best of our knowledge

by environmental conditions. In detail, the Great Duck Island deployment consisted of several patches of sensing nodes, connected to a transit network via dedicated more powerful gateway nodes. A single base station provided Internet connectivity and database services for the whole deployment. The sensor patches consisted of two types of nodes: small sensor nodes monitor temperature and humidity in the nesting burrows, while infrared radiation sensors were used to detect the presence of a bird. A second type of nodes was used to monitor the weather conditions outside of the burrows. All nodes were carefully placed by hand and manually configured in advance, and no kind of self-organization or location detection was used [102]. The low data-rate of the employed sensors allowed to transfer all collected data to the base station without in-network aggregation or further processing. Another notable work very close in spirit to the Great Duck Island deployment is the long-term study of rare and endangered plant species by Biagioni et al. in the context of the PODS project [19] ①. Deployed in the Hawaii Volcanoes National Park (Hawaii, USA), the sensor network monitored several species of plants and their environment using temperature, humidity, rainfall, wind, and solar radiation sensors.

These two deployments were the first examples of long-term real-world deployment of WSNs and they became forerunners for a large number of similar deployments in the area of habitat and environmental monitoring. In the Redwood Eco-Physiology project [32, 105] ⑧, several redwood trees in a study area in Sonoma, CA, USA, were equipped with sensor nodes in order to allow a more fine-grained monitoring of the climate changes during the day than previously possible with conventional equipment. The involved quantities measured were air temperature, relative humidity, and photo-synthetically active solar radiation. In the context of the GreenOrbs project [75] ㉑, a WSN was used to observe the effect of different sunlight conditions in shrub thicket and to estimate canopy closure in a forest by collecting temperature, humidity, illumination, and carbon dioxide measurements. This application is especially notable for the high number of sensor nodes involved, with up to 330 nodes deployed in the forest.

In the GlacsWeb project [74] ③, a WSN was employed to generate insights on the conditions inside glaciers. The specific environment poses unusual challenges for the successful deployment of a WSN, as the glacier environment is especially hostile to sensor nodes and as radio communication through ice and water is known to be difficult and highly unreliable. In addition, due to its remote deployment location, the network had to reliably operate over long time intervals without direct interaction. A first prototype was deployed in the year 2003 at Briksdalsbreen in Norway, and an updated version was placed in the same area during 2005. Both networks were composed of a base station and eight sensor nodes. Each node was equipped with sensors to measure temperature, pressure, and the orientation in the ice. In order to survive in the harsh environment, the sensor nodes were encapsulated in robust and waterproof PVC capsules. The nodes were placed in previously drilled holes at predefined locations in the glacier, and data was sampled every four hours. Over time, however, the nodes slowly move with the ice, creating an additional challenge for radio communication. Once a day the collected sensor readings were transmitted to the more powerful base station situated on top of the glacier. The base station in turn relayed the collected data to a reference station with Internet access located at a nearby café via a long-range radio channel. Both prototype systems proved to be capable of gathering useful data and, in spite of the hostile environment, remained operational throughout the intended lifetime. Nevertheless, a high number of sensor nodes failed either because of hardware failure or because they lost radio connectivity with the base station.

GlacsWeb is not the only WSN successfully deployed in a harsh environment. In the context of the PermaSense project [18] ㉒, a WSN was deployed in a highly inaccessible terrain area in the Alps to support the creation of new temperature models. Another application similar in scope and execution is the SensorScope deployment at Le Génépi, Switzerland [15] ⑮. An embedded networked sensing system named Suelo was designed by Ramanathan et al. [86] ㉔ to collect high-resolution data on soil state. A distinctive feature of Suelo is to overcome problems with sensor calibration. If required, the system can automatically call for human verification and assistance. Another example of environmental monitoring application is the prediction of landslides through constant monitoring of ground stress [94, 95] ⑪. This deployment was part of the SenSlide project and showed how to use a WSN to protect human domiciles and infrastructures.

3.1.2 Wildfire Monitoring

A common application scenario with many similarities to environmental monitoring motivated by biological research is wildfire monitoring. Doolin et al. employed a WSN to monitor wildfire at the Pinole Point Regional Park (Contra Costa County, CA, USA) [35] ⑦. A similar low-rate data collection wildfire monitoring applications has also been developed by Antoine-Santoni et al. [8] ⑱. In a wildfire monitoring application by Hartung et al. [43] ⑨, a portable WSN called FireWxNet was used to monitor weather conditions in the proximity of wild-land fires. The collected data provides the firefighters with a more accurate picture of the local weather conditions and thus increases their efficiency and safety during fire suppression. In contrast to the previous examples, in the FireWxNet project the WSN is not permanently installed, but is intended to be deployed by the firefighters on demand.

3.1.3 Agricultural Settings

In addition to environmental and wildfire monitoring, low-rate data collection WSNs are also frequently used in agriculture. One example is the use of a WSN for monitoring a potato field in the LOFAR-agro project [63] ⑭. The main goal of the deployment was to generate new insights on climate conditions favoring Phytophthora, a fungal disease affecting potatoes and to enable more precise counteractive measures. The WSN was deployed at a remote field in Borger-Odoorn (Drentheand, The Netherlands) and should have supported a lifetime of one year in order to monitor the full growing cycle of the potatoes. It consisted of approximately one hundred nodes and a dedicated base station that was equipped with a Wi-Fi card to connect it to a backbone network. Each sensor node was attached to a combined temperature and humidity sensor. The collected data was relayed to a back-end system via the base station and it was stored for further processing. A second goal of the project was the evaluation of the suitability and reliability of sensor network technology under realistic environmental conditions. In this respect, the project is especially noteworthy for its overall failure. The deployed WSN never operated as intended and was hampered by a very high packet loss rate. According to the authors, only 2 % of the measurements made it to the back-end system. This deployment highlights many of the challenges faced in real-world WSN deployment that are still a major barrier to a more widespread use of sensor networks.

One specific agricultural application area is surprisingly popular among WSN researchers: vineyard monitoring. Several independent WSN deployments in vineyards exist [7, 17, 20, 78] ⑥ ㉕. In all these deployments, the sensor nodes were deployed at a vineyard in order to get a more fine-grained picture of the microclimate in the proximity of the plants. Anastasi et al. [7] further employed the WSN to monitor also humidity and temperature in the cellar used for wine storage and ripening. Other application areas in the agricultural field include greenhouse monitoring [3] ⑲, tracking of sheep [103] ㉙, irrigation control [13, 57, 81] ⑩ ⑬ ⑯ and soil moisture monitoring [23, 24] ⑤.

3.1.4 Industrial Settings

With an increase of reliability and the creation of more robust communication protocols, the use of WSNs has also been explored in industrial settings. Notable applications include monitoring of underground pipes in the PIPENET project [101] ㊽, monitoring of road tunnels [26, 27, 31, 78] ⑫ ⑰, and substation monitoring [80] ㉜. The increasing need to save energy in buildings opens a further area of application for low data-rate WSNs. Kappler et al. [53] ④ and Jiang et al. [49, 50] ⑳ have shown how WSNs allow a fine-grained monitoring of energy consumption of individual devices. Agarwal et al. [2] employed a WSN to provide information on room occupancy in order to operate a Heating, Ventilation and Air Conditioning (HVAC) system based on the actual demand ㉗. This allows to reduce the workload of the HVAC system and enables significant energy savings.

WSNs have also been used in museums or exhibitions to detect unsuitable climate conditions in the vicinity of exhibits. A prototype for relic protection has been deployed in the forbidden city in Beijing, China [65, 66] ㉛ .

3.1.5 Health Care

Low-Rate Data CollectionWSN applications have also been deployed in hospital environments to collect the vital signs of patients. Chipara et al. [29] have built a patient monitoring system and deployed it at the Barnes-Jewish Hospital (Saint

Louis, MO, USA) ㉓. The goal of the deployment was to monitor patients that do not require intensive care, but are at high risk. The patients wore TelosB-based wireless sensor nodes that measure pulse and blood oxygen saturation every 30 and 60 s, respectively. The data was forwarded to a base station through a number of static relay nodes carefully placed in the step-down hospital unit. This configuration also supported the mobility of patients that could hence be monitored even when they left the unit for diagnostic testing. A distinctive feature of this study is the thorough analysis of the system's reliability. On the one hand, the network performed pretty well and delivered more than 99 % of the data to the base station. On the other hand, the quality of the sensed data was affected by several factors, such as the mobility of the patient, the disconnection of the sensors, and the non-optimal placement of the pulse oximeters. Sensor disconnections typically cause long-term failures, and can hardly be noticed by the patients. In this specific deployment, sensor outages longer than 30 min were observed in more than 40 % of the patients, and lasted up to 14 h. Patient movements such as tapping or fidgeting, instead, only lead to short-term invalid sensor readings. In a first attempt to improve sensor reliability, the authors have discussed the impact of oversampling on sensing reliability and have developed an approach for early detection of sensor disconnection. Two other WSN pilot deployments in a clinical setting were carried out by Ko et al. [58, 59] at the Shock Trauma Center of the University of Maryland Medical Center, and in the Johns Hopkins Hospital Emergency Room (Baltimore, MD, USA) ㉘. Similarly to the work of Chipara et al. [29], the sensors employed measured blood oxygen levels and pulse rate, and a set of relay nodes forwarded the collected data to a central unit.

It is important to highlight that these two works are some of the few WSN applications designed for clinical monitoring in which the system was actually thoroughly tested on patients. The literature contains plenty of WSN architectures and prototypes specifically designed for medical applications and health care [12, 42, 96, 112], but they are rarely deployed in the real-world. Examples include the Health and Disaster Aid project [42], in which Gao et al. have proposed an architecture for medical WSN that collects real-time data in a mass casualty event. Similarly, in the context of the CodeBlue project [69], Lorincz et al. have proposed a WSN architecture for emergency response, which allows monitoring of the vital functions of a large number of patients during an emergency and tries to optimize the use of rescuers. Furthermore, in the ALARM-NET project [112], a heterogeneous WSN architecture for assisted-living and residential monitoring was developed using MICAz sensor nodes. We do not include such works in our survey due to the lack of real-world deployments.

3.1.6 Hybrid Systems

Finally, hybrid systems combining WSN and RFID technologies have also been implemented. An example is the wildlife monitoring deployment in Wytham Woods, Oxfordshire, UK by Dyo et al. [38, 39] ㉖. The system was supposed to provide the zoologists with a more detailed picture of the movement patterns of European badgers. The zoologists were especially interested in the social behavior of the animals, which is difficult to observe with traditional technology. Existing approaches, like VHF telemetry are labor-intensive and cannot be used on a large scale and for a prolonged time frame. The system consisted of three components; a number of RFID tags worn by a number of badgers; 26 detection nodes distributed at key locations, such as sets and latrines throughout the wood; and ten additional sensor nodes for micro-climate monitoring. RFID readers consume a significant amount of power when active. Hence, in order to extend the lifetime of the RFID detection, a two level adaptation process was employed. Short-term adaptation adjusts the detection interval of the reader based on recent detection events. This enables more accurate tracking if animals are present. Long-term adaptation adjusts the duty cycle of the detection nodes based on the observed activity pattern of the badgers. For example, if during the day activity is rarely detected, the intervals of time in which the system can be put into sleep mode can be increased. The system successfully operated for a one year period and is believed to be of great use to the involved zoologists [39].

3.2 *High-Rate Data Collection*

While it is usually feasible for low-rate data collection applications to transmit the collected raw data to a central server for processing, this is often not possible in high-rate data collection applications. In such scenarios, the data-rate generated by the sensors usually exceeds the available communication bandwidth or would quickly drain the limited energy budget if the raw sensor data is sent directly to a central unit. Hence, for such applications there is a need to either implement some form of data compression, filtering, or data processing into the network.

3.2.1 Structural Monitoring

A typical application area for high-rate data collection WSNs is structural monitoring, as demonstrated in the Four Seasons project, in which a WSN was deployed at an abandoned four-story building in Sherman Oaks, CA, USA, to monitor the health of the structure during earthquakes [28, 109] ㉝. The building was severely damaged during an earthquake in 1994 and consequently scheduled for demolition. Simultaneously to the sensor network experiment, a series of forced-vibration tests with conventional equipment were conducted. The nodes of the network were equipped with vibration sensors and accelerometers, which allowed to collect seismic structure response data in order to generate new insights on the cause of the damage in the building. The high amount of data generated by these sensors poses a major challenge as it is not possible to simultaneously transfer the data from all sensors. To limit the data to a maintainable rate, the system employed silence suppression and data compression. In addition, vibration analysis requires precise synchronization of the sensor readings. As a global time synchronization scheme would also require a significant amount of bandwidth, the system did not rely on a global synchronization of the nodes, but instead tracked the time it took a packet to travel through the network. This allowed to retrospectively correlate the measurements.

Similar WSN deployments for structural monitoring of bridges have been conducted at the Golden Gate Bridge in San Francisco, CA, USA [56] ㊱, and at a single-span bridge in St. Lawrence County, NY, USA [110] ㊲. The former deployment employed 64 nodes to measure ambient vibrations at a sampling rate of 1 kHz; the latter employed 20 sensor nodes with accelerometers and strain transducers.

A well-known deployment in the field of structural monitoring in heritage buildings is the "Torre Aquila" deployment in Trento, Italy [25] ㊳. The medieval tower Torre Aquila contains a precious and renowned medieval fresco called "Il ciclo dei mesi." The conservation of the tower and of the frescoes is endangered by the planned construction of a road tunnel below the building. Hence, the central goal of the sensor network deployment by Ceriotti et al. [25] was to generate a better insight into the structural behavior of the building and thus allow the assessment of how the construction work might affect the integrity of the tower. The actual deployment consisted of 16 nodes of different type and a dedicated base station. The captured data ranged from low-bandwidth measurements obtained using fiber optic sensors (FOSs) that detected deformations in the tower walls to high-bandwidth vibration measurements captured with a three-axis accelerometer. Additional nodes measure the temperature distribution in the building with the help of analog temperature sensors. The software employed in this deployment is especially noteworthy as it does not build directly on top of a WSN operating system, but it uses instead the TeenyLIME middleware [30], which provides basic network services such as routing and time synchronization.

3.2.2 Wildlife Monitoring

In a second deployment at Wytham Woods, Oxfordshire, UK, Markham et al. [73] employed a WSN for underground tracking of badgers ㊴. Limited radio propagation in the ground did not permit the use of radio-based localization. Instead, a number of magnetics coils was distributed over the set of interest. Each badger to be monitored wore a sensor node equipped with magneto-inductive sensors that periodically record the strength and properties of the magnetic field. All recordings were stored on the node until the badger left the set and moved into vicinity of a base station. In order to minimize the storage requirements, data compression was used. As soon as the badger reached the communication range of the base station, the data was uploaded and stored in an external database through a bulk transfer.

3.2.3 Environmental Monitoring

An example of environmental monitoring with high-rate data collection is an deployment at the active volcano Reventador in Ecuador by Werner-Allen et al. [108] ㉟.The goal of the deployment was the collection of high fidelity data on volcano activity to enable geologists to build a clearer picture of the seismic phenomena.

The deployment consisted of 16 sensor nodes equipped with seismic and acoustic sensors. High resolution seismoacoustic monitoring requires high data rates (up to 1200 bytes/s per node) that exceed the available communication bandwidth. Consequently, it is not possible to transmit the complete raw data. Werner-Allen et al. solved this challenge by only transmitting the data in case an interesting event is detected. Each node temporarily stored the collected data locally. As soon as a pre-defined pattern was detected, the node signaled a detection event to the base station. If a sufficient number of nodes reported an event, the base station triggered data collection and iteratively downloaded the last 60 s of recorded data from each sensor node. A second challenge is the precise synchronization of the logged events. To be useful to the geologists, the data needs to be correlated with a precision in the order of milliseconds. The deployment used global time synchronization based on the time signal of a single GPS receiver at the base station. In addition, a time rectification process was employed to further increase the accuracy of the recorded timestamps.

3.2.4 Industrial Settings

WSNs have also been used to monitor the status of in-field devices in industrial settings using high data-rate sensors. An ongoing deployment as part of the GINSENG project contemplates the replacement of the wired infrastructure at an oil refinery in Sines, Portugal [85]. To monitor the vibrations of industrial machinery and equipment, Krishnamurthy et al. have deployed a WSN in the engine of an oil tanker in the North Sea, and in a central utility support building at a semiconductor fabrication plant [61] ㉞. The system employed approximately 150 off-the-shelf accelerometers, and the data was stored persistently in a server located outside the sensor network.

3.2.5 Health Care

Acceleration measurements, as well as data obtained from cardiac or epilepsy care monitoring employing EKG, EEG also imply high data-rates. High-rate data collections from accelerometer sensors aimed for activity recognition and high-fidelity motor fluctuations monitoring have been carried out by Lombriser et al. [68] and Patel et al. [82]. Nevertheless, we do not include those works in our survey due to the lack of an actual real-world deployment.

3.3 On-Demand Data Collection

In on-demand data collection applications, the user triggers the collection of data on-demand. This class of applications typically involves a persistent data storage on the node or within the network in order to allow later retrieval of data.

3.3.1 Wildlife Monitoring

An example of on-demand data collection is ZebraNet [51, 115] ㊵. The main research goal of this project was to record data on migration patterns of zebras. A second goal was the exploration of the performance of a large-scale mobile WSN. A small amount of zebras were equipped with sensor nodes in the Sweetwaters Game Reserve (Nanyuki, Kenya) during January 2004. Each node was equipped with a Global Positioning System (GPS) receiver for localization in order to accurately log the position of each zebra for several months. The position of the animal was recorded once every hour, and more detailed information about the zebra's movement was recorded for three minutes of each hour. The network covered an area of 100 km^2 and was very sparse, hence the nodes could only sporadically communicate. Consequently, it was necessary to temporarily store the collected data on the nodes. To ensure a higher level of dependability, the data was replicated to other nodes in the vicinity, and the recorded data was collected by a mobile base station on a vehicle regularly driven by the end-user through the observed area. Very notable is the expected lifetime of the system. The application of the collars required the zebras to be tranquilized and put under high stress, hence it should be limited to once a year. Consequently, the network lifetime had to span at least this time frame. To achieve this goal, solar panels were used together with a rechargeable battery. Interesting features described by the authors are the inaccuracy of single GPS readings, and the design of the butyl belting that forms the collar. An application very close in spirit to Zebranet is the wildlife monitoring carried out by Ranjan et al. in the context of the WildCENSE project, in which a WSN was used to observe the movement patterns of antelopes [87] ㊶.

3.3.2 Environmental Monitoring

In the environmental monitoring project LUSTER [93], a WSN was used to monitor the light condition under shrub thickets ㊷. A network composed of 19 sensor nodes was deployed on Hog Island off the Eastern Shore of Virginia. As the remote location of the deployment did not permit a reliable continuous connection to an external data base, the network implemented distributed in-network storage for the collected data. The desired data could be fetched on demand either in situ or via a temporary directional long-range radio link.

3.3.3 Health Care

Another example of on-demand data collection is the deployment of Mercury at the Spaulding Rehabilitation Hospital in Boston, MA, USA [70] ㊸. Mercury is a software architecture running on Shimmer sensor nodes used to continuously sample and store sensor data in a MicroSD flash card for later retrieval. The system has been tested on patients undergoing treatments to measure accelerometer and electromyograph data for several days. Using a reliable transfer protocol based on acknowledgment messages, the end-user can extract selected raw data traces from each node and download them persistently to a server for later analysis. The transfer is triggered remotely by the end-user who needs to specify which specific set of data should be collected. A notable feature of Mercury is the local extraction of features from the collected data. To save considerable bandwidth, storage, and energy, Mercury provides a suite of custom feature-extraction algorithms such as maximum peak-to-peak amplitude, mean, and root mean square of the time series that are computed on the fly as sensor data is being acquired [70]. This implies that in addition to the raw data, the user can request on-demand a filtered dataset. In the next section, we will show a class of sensor network applications in which a filtered dataset is returned to the final user as soon as a given event has occurred.

3.4 Event Detection and Classification

In several WSN applications, the sensor network carries out on-node processing to detect user-defined events or to classify events according to a user-defined set of classes. In such applications, the end-user receives as output of the sensor network a notification of the occurrence of a given event or an instance of a class.

3.4.1 Structural Monitoring

An example of event detection and classification applications is the WSN designed by Li et al. [67] to detect collapses in coal mines ㊽. The goal of their "Structure-Aware Self-Adaptive Sensor System" is to quickly detect and report the collapse area in underground tunnels in order to ensure safer working conditions. The prototype was deployed on a tunnel wall 8 m wide and 4 m high, and 27 Mica2 motes preconfigured with their location coordinates were manually placed at carefully chosen points in the tunnel.

3.4.2 Wildlife Monitoring

The WSN designed by Hu et al. to detect the presence of Cane-toads in a specific area based on acoustic features [46, 47, 98] is a typical example of in-network classification ㊹. The authors deployed a large-scale WSN that incorporates in-network reasoning to autonomously classify toads. The goal of the sensor network was the monitoring of the increasing spread of cane toads in the North-East of Australia, due to its strong impact on Australian native fauna.

In the context of the VoxNet project, Allen et al. [6] employed a WSN to acoustically detect marmots at the Rocky Mountain Biological Laboratory (RMBL) in Gothic, CO, USA ㊻. The network consisted of eight rather powerful ARM-based nodes equipped with acoustic sensors that constantly monitored the environment for marmot alarm calls. The result could be used to notify a biologist on site in order to allow the gathering of further information. Although the network was designed to carry out in-network classification, in the actual deployment the nodes transfered the corresponding raw data to a gateway computer as soon as an interesting event was detected, and an external system employed the data from multiple nodes to deduce a position estimate for the call.

3.4.3 Civilian Surveillance

Wittenburg et al. [111] have demonstrated a rare example of civilian intrusion detection based on fence monitoring ㊺ . In this example, the task of the WSN was to detect and report any incident occurring in the proximity of a fence, such as an intruder just probing the fence or actually climbing over it. In addition to the simple event detection and report, the network carried out also a classification of the activity, and has shown to be reliable even in a multi-hop scenario.

3.4.4 Health Care

The need for activity recognition has triggered a wide number of works in the body sensor network community. The PBN system [54] combined a five node BSN with an Android smartphone in order to enable reliable activity recognition ㊿. The system could detect and classify various daily activities, such as cleaning, eating, or watching television. Activity detection was primarily based on two-axis accelerometers attached to the sensor nodes. The necessary data processing was performed autonomously without relying on an external system. The detection and classification quality was improved by employing ensemble learning techniques based on user feedback provided through a smart phone. In BehaviorScope [14, 71], a BSN was used as part of a system to detect different activities of elderly people and to monitor for alarming deviations in their behavior ㊼. In contrast to PBN, this system did not employ sensor nodes worn on the body. Instead, nodes equipped with PIR sensors were distributed in the monitored apartment. WeCare [5] employed a combined BSN and WSN to detect falls ㊾. WeCare is more similar to PBN, but augmented the data from body-worn accelerometers with additional data sources. Fall detection was, for example, verified by video. Actual falls were automatically reported to caretakers or relatives using the cell-phone infrastructure.

3.5 Localization and Tracking

In many applications, not only an event has to be detected, but the location of that event has to be estimated or even tracked over time. Thus localization and tracking algorithms can be seen as a superset of event detection and classification applications.

Note that detecting an event that has to be localized can be as simple as receiving a message [88] or as complex as detecting a certain pattern in an acoustic signal [99].

3.5.1 Military Surveillance

Localization and tracking is frequently employed in military applications and surveillance systems, since the predominant goals are the detection, tracking, and classification of intruders in a given area. Data processing in these scenarios is especially challenging as it requires close co-operation of several nodes. Simon et al. have demonstrated in PinPtr how WSNs can be used to accurately estimate the position of snipers [99] (55). In their deployment, the sensor nodes were equipped with microphones to detect the muzzle blast of firearms, and they performed sound-based localization using distributed data processing. The network further performed a classification of the weapon generating the blast. In the 29 Palms Fixed/Mobile Experiment conducted at Marine Corps Air/Ground Combat Center (MCAGCC) in Twentynine Palms, CA, USA in March 2001, a WSN was dropped from an unmanned aerial vehicle (UAV) to monitor a road for vehicle movements [83] (51). Each of the nodes was equipped with a two-axis magnetometer, which allowed the detection of vehicles in a perimeter of 5–10 m. In addition, the WSN allowed to track vehicles once they were detected. The information on detected vehicles was temporarily stored in the network and later collected by a second flyover of the UAV. As the nodes were randomly dropped by a UAV, they needed to self-organize to allow collective monitoring of the environment. In the EnviroTrack project [1, 44], a similar but larger network was used to track intruders (56). "A Line in the Sand" [9] extended these capabilities by distinguishing between civilian or military vehicles and persons (53). In the ExScal project [37], a location detection of intruders based on proximity was carried out (57). The deployment is especially noteworthy for its unusual size of over 1000 nodes, all carefully placed in a preplanned layout.

3.5.2 Industrial Settings

On the industrial side, mobile networks are envisioned to be deployed for tracking of assets and goods, for instance, to ensure that certain climate conditions are constantly met while some goods travel through the cold chain [88] (52). These application scenarios are also especially challenging from a programming perspective, as they are highly dynamic and a high number of parties are involved.

Na et al. [79] have designed an application for parking lot surveillance that employs also traditional surveillance cameras (58). In this deployment, tracking information from the sensor network was used to control surveillance cameras.

3.5.3 Assisted Navigation

In [16], sensor nodes were employed to assist the navigation of an autonomous robot (54). The sensor nodes acted as signposts for the robot, that makes navigation decisions based on its closest node. In their setting, the robot did not have a pre-decided environment map, as the environment can be dynamically changing.

In their demonstration, Xu et al. [113] employed sensor nodes to track a single person based on received signal strength indication (RSSI) fingerprints (59). The system employed eight sender and eight receiver nodes. The senders periodically send beacon messages to each receiver. Based on previously recorded training data, the position of the person was inferred based on the effect that his or her presence had on the RSSI readings at the eight receivers.

3.6 Actuation

The addition of actuators to a sensor network allows not only to monitor the surrounding environment, but also to actively manipulate it. Such wireless sensor/actor networks (WSANs) raise additional challenges [4]. To allow the execution of control logic, it is necessary to implement control processes inside the network. Centralized decision making is usually not an option, as it would require excessive communication. The need to specify sophisticated control logic makes programming such WSANs especially difficult, which may explain why the number of WSAN applications is still comparatively low nowadays.

3.6.1 Building Automation

Modern buildings feature sophisticated heating, ventilation and air conditioning (HVAC) systems that can benefit from the use of a WSAN [34] (61). By replacing wired sensors and a centralized control system, WSANs promise to reduce costs and at the same time increase the flexibility of the solutions. The control logic of an HVAC system is usually based on the current climate in various parts of the building and a set of preferred temperature levels specified by the building users, and actuators can control heating or cooling devices [34].

3.6.2 Agricultural Settings

In the Animal Control project [107] a WSAN was used to control the behavior of bulls (62). Bull fights during the breeding season sometimes lead to serious injuries that significantly limit the value of the affected animal. As bulls are rather high-value animals, these injuries may lead to high losses for the farmer and are highly undesirable. Wark et al. [107] successfully employed a WSAN to separate bulls on a meadow and prevent them from fighting without a need for additional fences. The bulls were equipped with sensor/actor nodes that allowed to apply unpleasant but harmless stimuli to the animal. In addition, each sensor node was equipped with a GPS sensor that enabled precise localization of the animals. The equipment was worn by the animals in specially manufactured webbing collars. The WSAN constantly monitored the distance between the bulls and their aggressiveness level. If a bull was in the proximity of another bull and started moving in its direction, a small electrical shock was applied by the stimuli actuator. The network was also used to monitor the success of the control action and adjusts the stimuli accordingly. The efficiency of the approach was demonstrated by a 40 min controlled experiment in which all the relevant data was logged for later analysis. In the earlier Networked Cows project, Butler et al. [22] used a similar approach to keep cows within a limited area with the help of virtual fences (60). Both scenarios combine the challenges of mobile WSNs and WSANs, such as the limited connectivity between sensor nodes. Currently, both projects rely on a central control instance and do not implement distributed in-network processing.

4 Summary and Outlook

The early years of the twenty-first century have seen a steep rise in the number and diversity of wireless sensor network applications. This survey examined over 60 applications spanning from scientific demonstrations to real-world deployments, and covered several application areas ranging from military and civilian surveillance to tracking systems, from environmental and structural monitoring to home and building automation, from agriculture and industrial settings to health care.

Triggered by the vision of Smart Dust [52], where thousands of tiny sensor nodes would be dispersed into the environment, researchers began to implement and deploy applications to drive and evaluate their research under realistic conditions. While the first of these systems addressed military applications, the focus quickly shifted towards environmental monitoring, and then agriculture, structural monitoring, home and building automation, health and sports. Due to the lack of real Smart Dust platforms, early systems used matchbox-sized motes assembled from off-the-shelf components [45]. As it turned out, however, these platforms were quite sufficient for many applications, also because the motes were carefully placed instead of dispersed. Yet, there are continuing efforts to build grain-sized motes [64], but so far they did not carry over to application deployments. However, as this technology matures, we may see applications in the future that truly require small size such as intra-body sensor networks, or swarms of tiny flying sensors [33] helping with pollination.

In fact, we can recently observe a general trend to broaden the field and move away from using homogeneous networks of mote-class devices with simple scalar sensors. New types of sensors and actuators such as cameras [10], RFID readers [39], or car controls [40] are being integrated, resulting also in new research challenges due to, for example, high data rates. Hence, high-performance microcontrollers [60] or even mobile phones are becoming interesting platforms that enable new types of applications. Especially smartphone-based participatory sensing applications are recently receiving substantial attention (e.g., [41, 55, 76]), mainly because mobile phones are already ubiquitously deployed and code can be easily distributed using app stores. Thus, very large-scale and redundant "sensor networks" as originally envisions are becoming feasible, but at the same time new challenges arise as placement and use of phones worn by people cannot be easily controlled, and collected data may expose sensitive information about people wearing the phones.

The recent vision of the Internet of Things takes scaling to an extreme in that all objects and places – respectively sensors and actuators embedded into them – shall be connected to the Internet. Thus, the state of the real world becomes accessible online and in real time and converges with the vast amount of information available on the Internet. In order to also connect motes to the Internet, TCP/IP stacks have been squeezed into 8-bit microcontrollers, enabling IP-based sensor networks [48]. Different from traditional sensor networks, there is typically less direct cooperation among sensor nodes in the Internet of Things, as each node monitors and controls the state of an object to which it is attached. One example are large deployments of parking spot occupancy sensors in Barcelona and San Francisco [92] where each node monitors a single parking spot. These deployments are the seeds for even-larger scale smart city projects [100] where many aspects of our urban environment will be monitored, and potentially even controlled and optimized.

This prospect raises serious questions about dependability, trustworthiness, specifically security and privacy aspects, but also ease of use. In fact, only a single application uses encryption to protect sensor data; and the large majority of the surveyed applications were deployed by scientists. While we could largely ignore the above issues in environmental monitoring applications where a system failure was annoying but not harmful and collected data revealed interesting but not privacy-violating insights, this is not the case any more for the applications that appear at the horizon.

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