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Survey on the Characterization and Classification of Wireless Sensor Networks Applications

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***Abstract*—Nowadays, the users from Wireless Sensor Networks (WSNs) are becoming more and more demanding in terms of choice and diversity of applications. Hence, as the diversity of applications is increasing, it is worthwhile to propose a structure for the set of characterization parameters that allows sketching up a taxonomy for WSN applications. This taxonomy is established via an application-oriented approach, identifying the specific services offered by each application. In this survey we fill this gap in the WSN literature by describing the characterization parameters, organized into six different categories. Our taxonomy for application classification is centred on the different sets of parameters that have high impact on a given future WSN application. Typical attributes and values from related research works are considered as a reference but, in this survey, we propose inter- and intra-connections among the considered application groups. Based on these connections, new application groups have been proposed for applications that share common characterization parameters along with a holistic overview of WSN applications taxonomy and the discussion of the three generations of WSNs towards communication between *things* and the Internet of *Things*, as well as future trends for the development of WSN applications. Moreover, detailed parameters from different projects and authors in the field of WSNs are joint together for comparison purposes.**

***Index Terms*—Wireless Sensor Networks, WSN applications, taxonomy, WSN characterization parameters, survey.**

I. Introduction

Although in the past two decades there has been a strong research effort on legacy mobile communications and unlicensed wireless systems, several researchers consider that in the next five years, an inversion of the main trends will occur, and the focus will be in interdisciplinary research on Wireless Sensor Networks (WSNs). This interdisciplinary research is stimulating the development of new WSN services and applications to be supported by sensor nodes. Since these sensor networks are starting to take part of our life, there are gradually more and more applications where these smart systems are used. These

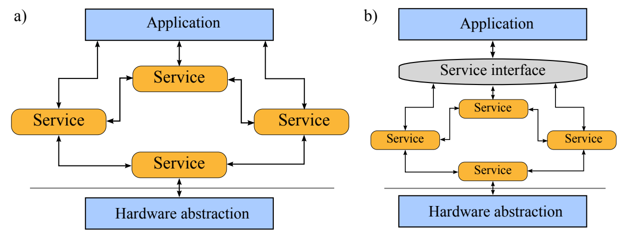

Fig. 1. Application interface with the protocol stack in the a) absence or b) presence of a general service interface. (adapted from [2])

concepts enable a massive-scale deployment of WSNs applied to a wide range of applications and will change the way we interact, live or even work within the surrounding ambient.

WSNs are mission-driven service providers which efficiently deliver services subject to the required Quality of Service (QoS), as well as physical and link layer constraints. As service providers, WSNs can be modelled at different levels of abstraction. For each level, a set of services and a set of metrics are defined. Hence, a service can be defined as a unit of operation upon which the various WSN components are established. A service can be informally defined as an abstraction that encapsulates “an organizational unit” [1]. The presence of a service interface raises the level of abstraction for the interaction between the application and the WSN [2] and expresses sensing tasks as application semantics, as shown in Fig. 1 b). WSNs are typically mission-oriented. It is the mission that guides all the functionality of the sensor network, while sensors collectively deliver services to accomplish the network’s mission, based on their sensing, computing, storage, communication, and energy capabilities as well as on the data they collect and process. A WSN application can be defined as the task designed for the sensor network. WSN devices could either tightly interact with the human user or interact with the surrounding environment where the network is embedded into, since sensor nodes are equipped with sensing and actuation devices, to measure/influence the environment.

One of the objectives from this survey is to contribute for the development of a new classification for WSN applications that extends the traditional and simple approach of just analysing and evaluating some classification and characterization parameters for the applications. Rather, since WSNs aim at a wide range of applications, an important goal is to create a systematic classification of WSN applications. Such WSN applications classification should discriminate between different groups of characterization parameters. To achieve the goal from this complex task this survey organizes the available

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information on WSN applications classification and characterization parameters from different authors and projects. The mere classification of WSN applications does not satisfactorily help designers or researchers to have a complete insight about the possible application requirements or possible outcomes from a specific WSN application area. As the diversity of applications is increasing, there is therefore the need to identify and clarify the set of characterization parameters that allows for sketching up a classification taxonomy.

Hence, another objective is to fill this gap in WSN literature by providing a holistic overview of the relations between different groups of characterization parameters, with the same range of variation for a certain set of parameters. As a result, apart from the detailed classification from WSN applications, the survey also provides a tool to understand which requirements are mandatory for a certain WSN application area.

The identified characterization parameters are divided into six categories, namely service, communication & traffic, service components, network, node, and operation environment(s) [3], [4], where a set of parameters is defined for each group of characteristics. We centre the proposed taxonomy for application classification on different sets of relevant parameters for a given future WSN application. Based on the different applications characteristics and classes, it is possible to build up a taxonomy for WSNs, facilitating to better understand which type of applications belong to a certain group, with specific characteristics.

The WSN applications taxonomy that constitute the outcome from this survey is build-up from tables whose content includes different attributes and values for the characterization parameters that we have identified as the most prominent ones. We propose inter- and intra-connections among the proposed application groups. As the fields of application of WSNs continue to evolve, these connections facilitate to understand how the applications similarities (or differences) may justify the ability to derive new groups of applications.

Besides, another contribution from this survey is the proposal of a new classification from the WSN applications summarized in the tables (for a quick reference to the reader), based on the combination of attributes and identification of some common features between characterization parameters.

Along with the application classification and taxonomy characterization parameters, a chronological comparison between WSN applications is presented and discussed. It allows for understanding the evolution path for WSN applications. Different generations of WSNs are identified and new WSN application areas as well as future trends are discussed.

In the remainder of this paper we thoroughly explore the different parameters that allow for classifying the WSN applications from each field. Section II addresses the state-of-the-art on WSNs along with the motivation. Section III addresses the taxonomy for the characterization parameters, including the service, communication & traffic, service components, network parameters, node parameters and operation environments. A possible taxonomy for characterization parameters is presented in Section IV, where different applications are grouped into sets of applications, depending on the field of application. A holistic overview of the WSN applications taxonomy is also given and new WSN applications categories are proposed. For the sake of simplicity, we only analyze twelve WSN applications with the corresponding attributes and values for the different parameters. As different applications fields present the same attributes or values for the parameters, we identify the links that may exist between different applications in this taxonomy. Section V presents a roadmap for the WSN applications and addresses the associated future trends. Finally, conclusions are drawn in Section VI.

II. State-of-the-Art and Motivation

The WSN literature of today offers two types of approaches to analyse and classify the MAC protocols. On the one hand, the traditional Medium Access Control (MAC) protocols classification is done according to the general medium access technique being used, whilst emphasizing their advantages and disadvantages whenever possible. In [5], the specific requirements and design trade-offs of a typical wireless sensor MAC protocol are discussed. On the other hand, in contrast to traditional surveys, the authors from [6] provide a classification organized according to the problems dealt by the MAC protocols. These authors address the main focus of the considered MAC protocols, design guidelines, as well as their disadvantages and weaknesses. A more recent survey [7] addresses the evolution of WSN MAC protocols, by surveying papers over the period 2002-2011. The protocols are evaluated in terms of energy efficiency, data delivery performance, and required overhead to maintain protocol's mechanisms. More specific works about the asynchronous WSN MAC protocols are discussed in the survey from the authors of [8], which identifies and studies different aspects of MAC protocols for WSNs. These issues comprise the delay efficiency and their latency. In addition, the authors from this work organize these MAC protocols into six categories.

The most recent surveys on routing protocols available in the literature, such as the one from [9], present a classification of the protocols based on an approach similar to the one from traditional MAC protocols surveys. Their study on the state-of-the-art of routing protocols includes a description of the network characteristics, design objectives and routing issues. Other works go beyond the classification of routing protocols based on the network type and protocol operation and address their security aspects [10], a hot topic in WSNs research. A well-documented survey on security protocols in mission-critical WSN applications was written by the authors from [11]. This work starts by identifying the threats and vulnerabilities that may affect WSNs, as well as the defence methods applied within the network layer. Their security protocols classification is based on the division of the security issues into seven categories: cryptography, key management, attack detections and preventions, secure routing, secure location security, secure data fusion, and other security issues. Moreover, the advantages and disadvantages, as well as countermeasures and design considerations for the security protocols issues, are addressed for the current secure schemes in each category.

Security protocols for static sensor networks represent a large extent of existing works in the literature. There are specific security protocols for Mobile Wireless Sensor Networks

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(MWSN). A state-of-the-art survey concerning the security aspects in MWSN is given in [12]. The security requirements taxonomy for MWSN are based on forward secrecy, backward secrecy, data survival, authentication, access control, access privacy, data source location privacy, sink location privacy, key management, intrusion detection and intrusion resilience.

Previous milestone surveys have focused on the importance of the different protocols that coexist in the protocol stack, e.g., MAC or network layers, of a sensor node and the interconnection that exist between the different layer protocols to achieve high energy efficiency. One characteristic that is commonly addressed in all the surveys is the dependence of the different protocols on the type of application they are going to be applied to. The diverse nature of the WSN applications in the WSNs literature brings additional issues to the attempt of classifying or distinguishing WSN applications according to their main characteristics. Some of these works are surveys about the WSN applications, where applications are classified according to the design space, deployment, mobility, resources, cost, energy, heterogeneity, size, lifetime and QoS [13]. Surveys concerning application layer issues [13], [14] are reasonably limited. A comparison of the advantages and disadvantages of the technologies applied in each of the presented applications is addressed in [14]. The technologies are categorized by the communication mechanism, scalability to large WSNs, fault tolerance and the requirements to use the technology.

Some of the research works that characterize the different protocols that are associated to each layer from the WSN protocol stack are limited to a specific layer or present a limited scope. We are not the first authors to undertake a survey on classification of WSNs. However, some surveys classify WSNs based on their application characteristics or their application issues, which limits the classification from the broad spectrum of WSN applications. In our work, instead, based on the lessons learned from this survey, which joins together the contributions from different projects and authors we present a taxonomy that provides a more in-depth analysis through a richer set of classification and characterization parameters.

Other distinctive features from our survey are the proposal of inter- and intra-connections among different applications groups, identification of the sets of characterization parameters that group together sets of applications with common characteristics, the concrete illustration of the mapping of the state-of-the-art by means of a chronological roadmap for the WSN application and the associated future trends.

III. Taxonomy for the Characterization Parameters

Nowadays, many applications are being created. However, in this survey we only cover a set of meaningful WSN applications from the ones that exist in the literature. This survey addresses the difficult task of organizing a huge amount of WSN applications. Due to the broad diversity nature of the WSN applications throughout the different fields of applications from WSN, many WSN projects have not been considered mainly due to the lack of information. Since we intend to propose a taxonomy for WSN applications classification based on the identified characterization parameters, we only have addressed properly documented WSN projects. By identifying different types of characterization parameters, the proposed taxonomy distinguishes between the functional and technical requirements for the classification of WSN services and applications, as shown in Table I.

Depending on the values of the different parameters that identify/characterize WSN applications, these characterization parameters can be organized into six groups: service, communication & traffic, service components, network, node, and operation environment(s) [3], [4].

A. Service Parameters

The WSN characterization parameters from Table I include the delivery requirements from the WSN applications, how communications are established among WSN nodes, how the

TABLE I
Characterization parameters for WSN applications.

Categories	Characterization Parameters
Service	Delivery requirements
	Directionality
	Communication symmetry
	End-to-end behaviour
	Interactivity
	Delay tolerance
	Criticality
Communication & Traffic	QoS
	Bit rate
	Latency/delay
	Synchronization
	Class of service
	Modulation
	Communication direction
Service components	Type of traffic
	Packet delivery failure ratio
	Data acquisition & dissemination
Network	Lifetime
	Scalability
	Density
	Sensing range
	Self-organization
	Security
	Addressing
	Programmability
	Maintainability
	Homogeneity
	Mobility support
Node	Microprocessor
	Radio transceiver
	Overall energy consumption
	Sampling rate
	Type of function
	Communication range
	Power supply
Operation environment	**Sensor network scenarios** -Single hop versus multi-hop -Multiple hop sinks and sources -Mobility scenario
	Framework -Public: Urban, Road, Rural, Commercial -Private: Emergency dedicated
	Deployment scenarios -Offices, Industry, Home, Military, Civil, Metropolitan

application reacts or behaves to different packet priorities, the quantity of packets in the data stream in both directions, and the way the application reacts to simple interaction between nodes.

In terms of delivery requirements, a WSN application is either in Real-Time (RT) or Non-Real-Time (NRT) [2]. On the one hand, RT packets are transmitted as soon as possible, with no waiting in the queue [15], as they are sensitive to the aggregation latency. On the other, NRT packets wait in the queue until the number of accumulated packets is equal to the maximum aggregation limit. So, RT applications may provide a quick result but at higher energy costs, e.g., by forcing nodes to wake-up earlier than they would wake-up anyway, or, alternatively, provide it slowly but at reduced energy cost.

WSNs communications can be unidirectional (Uni) or bi-directional (Bid). Unidirectional communications can only send data from the sensor nodes to the sink node [16], [17]. However, a bi-directional communication is more efficient and allows for the sensor nodes to send data to the sink node, while receiving control data from the sink node (e.g., topology change, schedule information, slot allocation and routing paths). Directionality is intrinsically related with the sensor node hardware, namely if the hardware presents a single or dual radio transceiver. Nowadays, unidirectionality is not common in WSN applications. However, this attribute should be considered in our analysis since first WSN applications used to be very simple and only considered unidirectional communications from the sensor to the sink [16], [17].

Bi-directional communications can be either symmetric (Sym) or asymmetric (Asym). In symmetric links the data rate or volume is the same in both directions, averaged over time. In asymmetric links the data rate or volume averaged over time differs in the two communication directions [18], [19].

WSNs may require to fulfil end-to-end or non-end-to-end performance. The end-to-end parameter characterizes the trust relationship in a network that is established between the sender and receiver [15].

Interactivity characterizes the type of support for WSN need of simple request/response interactions, retrieving a measured value from some sensor node or setting a parameter in some sensor nodes. If the interaction pattern is synchronous, then the result (or possibly the acknowledgement) is expected to be immediate. Otherwise, asynchronous event notifications can be supported, e.g., where a requesting node collects information on the occurrence of a certain event. The interactivity is deeply related to the sensor *stimuli*.

WSN applications may be delay tolerant or not. If they are not delay tolerant they are usually classified as RT applications. Additionally, RT applications may tolerate some amount (i.e., short values) of delay.

The criticality is another relevant parameter which characterizes the entire WSN application. The application may be mission-critical or non-mission-critical. It does not depend on the network itself, but exclusively on how the network is used. For example, an application whose sensor nodes are used for patient heart rate monitoring is more critical than another that monitors regular exercise activities.

B. *Communication & Traffic Parameters*

Communication & traffic characterization parameters determine the WSN network resources (bandwidth and buffer) required to support this application and include QoS performance metrics of the WSN application. Supporting QoS in WSNs is still a largely unexplored research field. However, in the last years several works have addressed different protocols for applications in which QoS constraints are considered in their design [13]. Two perspectives can be identified for QoS in WSNs:

i) **Individual QoS** - Applications impose specific requirements on the deployment of sensors, in the number of active sensors, measurement precision of sensors and so on [20];

ii) **Collective QoS** - From the network QoS perspective, the application that is actually carried out by itself is not so important, as how data is delivered to the sink node and how the corresponding requirements are fulfilled.

Furthermore, from the QoS perspective, there are four basic data delivery models for the sensor network [21], [22]:

i) **Event-driven** - Most of event-driven WSNs applications are interactive, delay intolerant (real-time), mission-critical and non-end-to-end ones. As a consequence, the event detection sensors are very important to the success of the application. The data that flows from these sensors may be highly correlated, leading to a high level of data redundancy. Besides, the data traffic generated by a single sensor may be of very low intensity, but may support bursty traffic. The actions that occur in response to the detected event may need to be distributed to sensors or actuators as quickly and as reliably as possible;

ii) **Query- or Demand-driven** - Most of query-driven applications are interactive, query-specific delay tolerant, mission-critical, and non-end-to-end ones. In order to save energy, queries can be sent on demand. The query-driven delivery model it is similar to the event-driven model, except that in this one the data is pulled by the sink, while the data is pushed to the sink in the event-driven model (e.g., if the sink wants to upgrade the firmware in the sensor nodes);

iii) **Continuous based** - In the continuous based model, sensors send their data continuously to the sink at a pre-specified rate. In this type of data delivery model, different types of traffic can coexist. However, different types of requirements must be fulfilled. On the one hand, RT voice, image, or video data are non-end-to-end delay-constrained applications, whose packet losses can be tolerated. On the other, for NRT data, the delay and packet losses are both tolerated;

iv) **Time-driven** - In time-driven networks, sensor nodes collect and report data from the physical environment periodically. The period between two consecutive data packets from a particular sensor node is referred to as the "data sampling rate". Time-driven sensor

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TABLE II
APPLICATION REQUIREMENTS IN A WSN NETWORK WITH QOS SUPPORT [23].

Parameters	Class			
	Event-driven	**Query-driven**	**Continuous**	**Time-driven**
End-to-End	×	×	×	×
Interactivity	√	√	×	√
Delay tolerant	×	query-specific	√	√
Criticality	√	√	×	√

networks are represented by a simple model in which nodes mostly report data and perform minimum data processing. In turn, all the data processing takes place in the sink node.

The aforementioned delivery models are deeply related with the service characterization parameters shown in Table II (end-to-end behaviour, interactivity, delay tolerance, and criticality).

The authors from [23] address all the above requirements. Application requirements are summarized in Table II, adapted from [23], which shows that there are some differences between WSNs and traditional networks in terms of application requirements. One of these differences is the end-to-end QoS parameter. The WSN application itself is not end-to-end. Although one peer of the application is the sink, while in the other end there is not always a single sensor node but a group of sensor nodes (within the range of the event). When the WSN communication is between a single node and a sink node, then the application is end-to-end. In this particular case, the end-to-end parameter is mentioned in the Table II to show that, in the majority of WSN applications, there is a set of sensor nodes that are scattered over an area that collectively work to sense such event and report to the sink. In [23], as it is considered that these end-to-end network QoS parameters are insufficient to measure the QoS support in WSNs, some collective QoS parameters have been proposed, such as i) collective latency, ii) collective packet loss, iii) collective bandwidth, and iv) information throughput.

The communication & traffic characterization parameters of a WSN application are also specified by its traffic generation pattern and the average duration. The traffic generation in WSNs is often assumed as CBR, on-off, Poisson, or exponentially distributed [24]. The bit rate (given in bits per second) associated to the generation process is the rate the modulator can support for transmission of the binary data.

The latency or end-to-end delay is also one of the key QoS parameters [23]. For some WSN applications, such as real-time monitoring or emergency response networks, performance guarantees (e.g., delay) are required. Two important aspects related to delay are the following: i) data freshness (how recent is the reported data) and ii) response time (the network capability to respond to environmental events or user queries within a given time interval).

The key communication & traffic parameters of a WSN application are related with some of the previous characterization parameters [25] which include classes of service, synchronization (service traffic), and modulation.

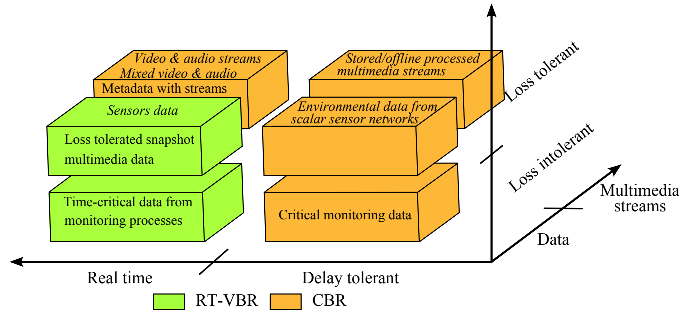

Fig. 2. Definition of the service classes within communication & traffic parameters.

TABLE III
DEFINITION OF THE ACRONYMS FOR THE TRAFFIC CLASSES.

Traffic classes	Acronym	Description
Type of delivery	RT	Real-Time
	DT	Delay tolerant
Type of information	Data	Data
	MS	Multimedia streams
Data loss	LI	Loss intolerant
	LT	Loss tolerant

Since WSNs are gradually becoming similar to legacy communications networks, to support more demanding WSN applications, the classes of service can be viewed from the QoS or ITU-T service traffic perspective. Based on the QoS parameters, two classes of services are identified:

i) **Best-effort delivery (no QoS)** - It is addressed with ABR class of service, where the traffic is processed as quickly as possible [26];
ii) **Real-time delivery of time-based information** - It can be CBR or VBR with time requirements. In the WSN literature, CBR data traffic is commonly employed [27]. There are also a few works that consider VBR (e.g., Poisson distributed [28]) data sources. For VBR [29], based on QoS parameters, some authors consider an application with a VBR class of service as soft QoS one [30].

Data traffic is mapped into four specific classes of service:

i) **CBR** - The monitoring values produced by the CBR WSN application are transmitted at a relatively constant bit rate. Nodes are served with a constant bit rate agreed during the initial setup of the WSN [31];
ii) **RT-VBR** - The bit rate varies between zero and a peak value agreed during the connection setup phase [32];
iii) **ABR** - It is a class in which a minimum data rate is guaranteed by the system for non-real-time applications and ensures the delivery of data [33];
iv) **UBR** - It is a best effort service without performance guarantees. UBR is used for WSN applications that require mobility [34].

Figure 2 graphically presents examples for each type of service. The type of sensor data is presented inside of each

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box. The different axes are associated with the type of delivery (RT or DT), type of information (Data or MS) and data loss (LI or LT). The authors from [35] categorize the mission-critical applications into four different applications classes. The application classes are based on network-driven performance (i.e., the data loss and the type of delivery). Relatively to reference [35], in Fig. 2, the type of information is added as a third dimension to the graph. It shows the different types of data that may appear in WSNs, such as multimedia-related types of traffic. Table III presents possible attributes or values for the type of delivery, type of information and data loss.

According to ITU-T terminology, the service traffic may be classified into two classes of service:

i) **Isochronous traffic (ISO)** - Includes the ability to simultaneously transport different types of traffic (voice, video, and data), across the same system and includes the capability to dynamically allocate bandwidth as the application needs. When there is only sensor data in the network, the traffic of sensed data is typically isochronous (or synchronous) [36];

ii) **Non-isochronous traffic (NISO)** - Is classified by message streams which are generated by their sources on a continuing basis but the delivery to the destination is not based on a continuous delivery (packet delivery fragmentation scheme).

The choice of the modulation scheme is crucial in WSN design and involves the following aspects: the required/desirable bit rate and symbol rate, the implementation complexity, the relationship between the radiated power and target BER, as well as the expected channel characteristics.

Power consumption derives from a modulation scheme which directly depends on the symbol rate rather than on the bit rate [2]. In WSN applications, the most common modulation schemes are the following ones: Binary Phase-Shift-Keying (BPSK) [37], Frequency-Shift Keying (FSK) [37], Gaussian Frequency-Shift Keying (GFSK) [37], Amplitude-Shift Keying (ASK) [38]–[40], Direct Sequence Spread Spectrum Offset Quadrature Phase-Shift Keying (DSSS-O-QPSK) [37].

Finally, in terms of directionality, communications can be either unidirectional or bi-directional. While unidirectional communications are simplex ones, bi-directional communications can be either half-duplex or full-duplex [41]:

- **Simplex (SPX)** - It corresponds to a system, in which the communication occurs only in one direction [42];
- **Half Duplex (HDX)** - A half-duplex system supports communication in both directions. However, only one party or device (i.e., radio transceivers) can communicate at a time (not simultaneously) [43], [44];
- **Full Duplex (FDX)** - This type of systems, composed by two parties or devices to communicate, allows for each one to simultaneously communicate with another one in both directions [45], [46] by means of Frequency-Division Duplexing (FDD) schemes.

New future WSNs may present different types of directionality, such as full duplex. In fact, there are recent deployments that consider full duplex WSNs [46], [47]. Full duplexing directionality can be achieved by emulation of a full duplex communication over a half duplex communication link by considering a Time-Division Duplexing (TDD) scheme [46], or by hardware (with two radio transceivers) [48], [49].

C. Service Components

Basic service components (types of traffic) for WSNs are audio, video and data. The types of traffic and information can be grouped as in Table IV. With the wireless sensor nodes coming of age, a new albeit nascent field of research has sprung up, namely exploration of the possibility of use of video/acoustic sensors to set up multimedia WSNs, to monitor and convey data in the form of only video, audio, or both video and audio streams.

TABLE IV
TYPES OF TRAFFIC VERSUS TYPE OF INFORMATION.

	Types of Traffic					
	Audio		Video	Data		
Types of information	VOI	AMB	STV	LOD	MED	HID
Sensor Data	–	–	–	√	√	√
Sound	√	√	–	–	–	–
Video	–	–	√	–	–	–
Moving pictures and sound	√	√	√	–	–	–
Snapshot images	–	–	√	√	√	√

Moreover, audio can be subdivided into Voice (VOI) and Sound Ambient (AMB), whereas data can be Low-Rate (LOD), Medium-Rate (MED) or High-Rate (HID), as shown in Fig. 3. Additionally, Streaming Video (STV) is the only type of video and can be present or absent from the communication. However, three types of information (i.e., video, moving pictures and sound, as well as sequences of snapshot images) include the STV service component.

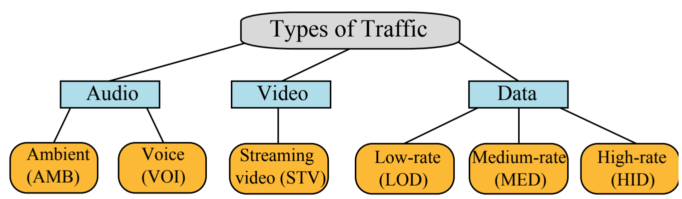

Fig. 3. Basic service components/types of traffic.

Data acquisition and dissemination can be event-based, demand-based, continuous-based or time-based [22], as mentioned in Section III-B. These data dissemination models for sensor networks are not mutually exclusive and can be combined to provide a richer set of data dissemination options.

The packet delivery failure ratio is the average percentage of data packets lost during the data dissemination through node transmissions. This parameter is evaluated in terms of the percentage of lost packets and is very important. Lost packets lead to the degradation of the QoS of the WSN application, energy consumption inefficiency, and overall performance reduction.

D. Network Parameters

The group of network parameters facilitates to characterize the different sensor node protocols (in the protocol stack). These parameters include self-organization, security and mobility support. This group has parameters related to the application of the WSN, such as the lifetime, scalability, density, sensing range, addressing, programmability and maintainability. All these parameters are inherent to the network as a whole.

The lifetime of the network is an essential characteristic in WSNs. The precise definition of lifetime depends on the application at hand. A simple option is to define network lifetime as the time until the first node fails (or runs out of energy), or the time until the network ceases to be fully operational. Usually, this parameter is given in hours.

The ability to support a high amount of sensor node devices is known as the scalability of the network. Scalability is enabled by the employed architectures and protocols [15].

The number of nodes per unit of area gives the density of the network, which is another important characteristic that needs to be defined for WSNs. The density of nodes for an application also depends on the coverage area.

Different applications require different degrees of sensing coverage, which is characterized by the sensing range, the monitoring quality provided by a sensor network in a specific region. Sensor coverage may assume different ranges depending on the type of phenomena being sensed.

Self-organization is defined as the sensor nodes capability to find appropriate paths to establish the best communication among them and with the central node (coordinator node), checking the received power level every time a configuration is built up. It is worthwhile to note that the self-organization of a network can be established either for the entire network or a part of the network.

The security of a WSN is determined by the protection policies associated with the data and WSN application requirements. As the level of security increases the energy consumption also increases, due to strong security policies that are associated to these highest levels. Since security is a vast area, only data encryption is considered in this taxonomy. According to [50], [51], the level of security in WSNs can be classified as:

- **Low** - No security component is enabled and data fusion protocols may be used to reduce energy consumption;
- **Medium** - The security components add security overheads to the data that is transmitted while performing data fusion. In this level, security components do not interfere with the network operation;
- **High** - For the highest security level, cryptography algorithms are employed, preventing in-network processing. In this case, data aggregation protocols replace the data fusion ones.

The addressing scheme is another parameter of the network components group. These identifiers make each sensor node in the network unique, helping to setup routing paths when configuring the WSN. From all the addressing schemes currently being used in WSNs, the ones that are mostly used are the following ones:

- **Data-Centric** - A sensor node may not need an identity, e.g., an address. Rather, applications will focus on the data generated by sensors. In this case, all the data from the sensor nodes are named by attributes. This facilitates a more robust application design [52];
- **Attribute-based** - It is often seen as the most ideal scheme for WSNs. To use this addressing scheme in WSNs, it is worthwhile to guarantee the data-centricity (the sensor network that can be modified to the sensing task at hand [53]) and the application-specificity. A particular node is not likely to be redundant for a specific information, rather a certain region;
- **Geographic addressing** - Frequently, WSNs are deployed randomly in a remote and inaccessible terrain. Geographic addressing will use spatial coordinates. Therefore, localization techniques are essential to work with geographic addresses [2];
- **Address-centric** - In traditional networks like the Internet or ad hoc networks, nodes or stations are named and addressed as well as the data hosted by them. The address-centric scheme assigns to sensor nodes an unique ID (or name/label) based on low-level network topology information [2];
- **Spatial IP** - Each sensor constructs its spatial Internet Protocol (IP) address by taking the (x, y) coordinates of the node location as the two least significant octets in the Internet style IP address. It allows supporting geographic routing as well as routing based on network topology independently of geographic location [54];
- **Address-free** - One of the advantages of address-free WSNs is the possibility to randomly select a unique identifier for each transaction and spatial and temporal locality, rather than using static addresses [55].

The programmability from the wireless sensor nodes is a characteristic that does not only enable to process information but also to facilitate their flexible reaction to the changes in their tasks. The WSN nodes are either programmable or not programmable. The nodes programming must be changeable during operation when new tasks become opportune.

Since the WSN and their environment continuously change (e.g., depleted batteries, failing nodes and new tasks), system adaptation is needed. The maintainability of a WSN represents this adaptive behaviour which a WSN application may have. The network has to maintain itself [56], being able to interact with external maintenance mechanisms whilst ensuring an extended operation at a required service quality.

The homogeneity of the network characterizes how similar to the capabilities of a sensor node are in comparison to the other ones that coexist in the same WSN. The network is homogeneous if all the WSN nodes present the same capabilities in terms of processing, energy and communication resources. A network is heterogeneous if, additionally to these sensor nodes, there are nodes with increased capabilities relatively to the majority of nodes [57].

The last network parameter is the mobility support in a WSN application. Normally, the WSN sensor nodes applications are static. However, in the real-world, nodes may be moving. Therefore, the protocols from different layers of the WSN must be aware of sensor node mobility, in order to establish new paths between nodes, as the nodes move over the

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field. The support of mobility requires additional processing capability from the sensor node.

E. Node Parameters

The sensor node hardware is composed by several modules that jointly form a device with communication capabilities. Since these modules can be chosen from a wide variety of manufacturers, the classification of the sensor node hardware can be categorized based in a set of parameters.

The node characteristics form a set of parameters that help to distinguish the type of nodes and the characteristics that the nodes present in a specific WSN application. A set of characterization parameters is defined for each WSN application that covers essentially the node hardware description, as well as the sampling rate of the external sensors that are attached to the node. This set of parameters defines the operation of the sensor jointly with their different communication protocols and the associated control of the sensor nodes hardware. Each of the hardware components has to operate properly, while balancing the trade-offs between low energy consumption and high efficient operation (to fulfil the assigned tasks).

Different applications require different levels of processing capabilities. This processing is handled by the microprocessor/microcontroller. The microprocessor/microcontroller is the main component of the sensor node. It is responsible to process all the relevant data and is capable of executing arbitrary code in the sensor node while coordinating the interaction with neighbouring nodes. In our taxonomy, we distinguish the type of microprocessor/microcontroller in terms of the System on a Chip (SoC) characteristics.

In a WSN, a sensor node is a device with communication capabilities. The radio transceiver enables that each sensor node is identified as a unique entity in a WSN and is of paramount importance. The radio transceiver is the key component that allows for sensor nodes to communicate wirelessly with other sensor nodes over a wireless channel. In our taxonomy we distinguish the radio transceivers by the manufacturer and respective transceiver model. For the sake of energy efficiency its choice must be energy aware.

The overall energy consumption also plays an important role in on the WSN application along with the need for a longer lifetime. In our characterization parameters, we define pre-established intervals for the maximum achievable lifetime, where the WSNs are grouped into each of the following intervals: a) [24, 720] h, b) [721, 25920] h, and c) >25920 h.

The Sampling Rate (SR) corresponds to the number of samples taken from the sensed event signal and reported as data packets to the sink node [58]. Since the sensor nodes have different types of sensors attached to them, the SR can be different for each of them [59]. We classify the sampling rates into three categories:

- **Low SR** - varies between 0.001 Hz and 100 Hz;
- **Medium SR** - varies between 100 Hz and 1 kHz;
- **High SR** - higher than 1 kHz.

The role of the WSN entities depends on the processing capabilities and how sensor nodes themselves take on specific functions and behaviours in the network. If the application supports heterogeneous nodes, these roles are assigned according to various sensor node properties (e.g., location, type of sensors and actuators).

In our taxonomy we define the roles of WSN device as:

- **Sensor node** - It comprises the microprocessor/microcontroller, radio transceiver, and sensors; and facilitates to measure the physical quantities [2].
- **Sink node** - It can be a sensor node but with extended data processing capabilities, since it receives data from all the sensor nodes of the WSN, while it manages the network [2];
- **Sensor and actuator node** - It comprises the same basic sensor node components plus actuators [60];
- **Anchor node** - Node with known localization, which supports the remaining sensor nodes in the localization process [61];
- **Cluster head** - Sensor node to whom all nodes in the cluster (group of nodes, created according to geographical area, type of sensor, type of phenomenon, task, etc) send the collected data; the cluster head is then responsible for sending the received data to the sink node. It also delivers data coming from outside the cluster (commands, queries, etc.) to the cluster members [60], [61];
- **Gateway node** - It is a node responsible for the connection and delivery of data to other communication networks from other technologies (e.g., Wi-Fi, fixed access to Internet or WiMAX) [60], [61].

It is worthwhile to mention that, in the perspective of [61], [62], [63], collaborative WSNs are managed by a software tool whose user (person) interacts with the WSN, querying the network, visualizing data, etc. The user customizes the work of the sensor nodes; the data collected by sensor nodes is used by the user's application.

As the radio transceiver is the key component in a sensor node, the range of each sensor node depends on the choice of the radio transceiver. Besides, trade-offs between the maximum range of the sensor node and the network lifetime maximization is always a critical decision. The range depends on the radio output power and comprises two components: the fixed and variable components. The first one corresponds to the minimum acceptable power from the radio transceiver while the second one depends on the variation of the output power up to the maximum allowable value. For example, IEEE 802.15.4-compliant devices should be capable of transmitting at a minimum of -3 dBm. Their maximum output power needs to comply with the local radio spectrum regulations as well as for other communication standards. The communication range of each sensor node in a WSN application depends on which type of radio transceiver the sensor node uses and on the trade-offs to render network lifetime maximization in battery-powered nodes.

Finally, different types of power supply can be used in WSN nodes. In our characterization, we distinguish between three energy sources: i) battery, the most common way to power up sensor nodes, ii) harvesting device, which collects energy from the surrounding environment (e.g., vibrations, solar, heat or electromagnetic energy), and iii) local supply, by means of

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TABLE V
SYSTEM ON A CHIP CHARACTERISTICS OF MICROCONTROLLERS.

Microcontroller	Architecture	Clock speed	Memory		Peripherals		Power management	Platform
			RAM	Flash	Timers	ADC		
ATMega 128L	8-bit	8 MHz	4 kB	128 kB	4	10-bit	Six sleep modes Software selectable clock frequency	Mica2/Mica2Dot/ MicaZ; Cyclops; CSIRO ICT'S FleckTM-3
ATMega 103L	8-bit	6 MHz	4 kB	0.125 kB	3	10-bit	Four sleep modes	Mica
AT90LS8535	8-bit	8 MHz	0.512 kB	8 kB	3	10-bit	Three sleep modes	Rene
ATMega 163	8-bit	8 MHz	1 kB	16 kB	3	10-bit	Four sleep modes	Rene2 , Dot
ATMega 1281	8-bit	8 MHz	8 kB	128 kB	6	10-bit	Power-on reset Programmable brown-out detection; Six sleep modes;	Firefly
ATMega 8	8-bit	16 MHz	1 kB	8 kB	3	10-bit	Power-on reset Programmable brown-out detection; Six sleep modes;	BTnode
PIC18LF4620	8-bit	4-8 MHz	1 kB	64 kB	4	10-bit	Power saving idle and sleep modes	TUTWSN
MSP430F1611	16-bit	8 MHz	10 kB	48 kB	2	12-bit	Supply voltage supervisor with programmable level detection	TelosB Tmote Sky
MSP430F449	16-bit	8 MHz	2 kB	60 kB	2	12-bit	Supply voltage supervisor with programmable level detection	WSN430
MSP430F149	16-bit	8 MHz	2 kB	60 kB	3	12-bit	Five power-saving modes	BSN
Xetal II	16-bit	84 MHz	10 MB	N.A.	N.A.	N.A.	Controlled by power management chip	WiCa
MSP430F1612	16-bit	1-11 MHz	5 kB	55 kB	2	12-bit	Supply voltage supervisor with programmable level detection	Freie Universitat's ScatterWeb
OKI ML 67Q5002	32-bit	57.6 MHz	32 kB	256 kB	1 (8 ch.)	10-bit	Power tracker, supervisor, Controlled clock divider peripherals switch on/off	Yale's XYZ
INTEL Xscale (PXA255)	32-bit	100 -400 MHz	64 MB	32 MB	4	4x10-bit	No support for network wake-up; battery monitoring utility; power management unit.	UC Berkeleys's Stargate
INTEL Xscale (PXA270)	32-bit	500 MHz	N.A.	N.A.	1	12-bit	Power management chip; Supply voltage reduction; Four low-power modes; Dynamic voltage and frequency management	NIT-Hohai Node
INTEL Xscale (PXA271)	32-bit	13-416 MHz	32 MB	32 MB	1	12-bit	Power management chip; Supply voltage reduction; Four low-power modes; Dynamic voltage and frequency management	Crossbow's Imote2/ Stargate 2
Atmel AT91SAM7S (ARM 7TDMI)	32-bit	55 MHz	64 kB	256 kB	3	10-bit	MCU power management; Software controlled phase locked loop	Standford's MeshWye; WiSN motes; Imote; MeshEye;
Freescale Coldfire MCF5282	32-bit	66-80 MHz	64 kB	512 kB	12	10-bit	Fully-static operation with processor sleep; Wake-up with external interrupts; Clock enable/disable for each peripheral;	Coldfire MCF5282 ZigBee ready Demo kit
AT91RM9200	32-bit	180 MHz	16 kB	128 kB	6	10-bit	Slow clock operating mode software power optimization capabilities	SUN spot
TI-TMS320 VC 5509A	32-bit	108 MHz 144 MHz 200 MHz	192 kB	128 kB	2	10-bit	Programmable low-power control of six device functional domains	-
PHILIPS NXP LPC2106	16/32-bit	1 MHz 30 MHz 60 MHz	64 kB	128 kB	2x32-bit	N.A.	Two low power modes; Processor wake-up from via external interrupt	CMUcam3
ADSP- BF537 Blackfin	16/32-bit	600 MHz	32 MB	4 MB	8x32-bit	12-bit	Dynamic clock up to 600 MHz	CMU's DSPCam

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an uninterrupted power supply.

In addition to the aforementioned node parameters, several surveys have been published concerning the hardware aspects on the different Wireless Multimedia Sensor Networks (WMSNs) sensor nodes [59], [64]–[68]. Other works, such as the ones from [69]–[71], characterize the hardware of the typical WSN sensor nodes (in which the hardware is simpler and does not support multimedia features). Based on all these works we propose SoC characteristics for a specific microcontroller in Table V, jointly with the reference to the sensor node platform that employs the microcontroller. By knowing the characteristics of a specific microcontroller in detail, it is possible to better plan the usability of its functions for a WSN application. This table presents not only the SoC characteristics of the microcontrollers but also other important features that are not present in the referenced papers such as the clock speed, type of power management, number of available timers and ADC resolution.

F. Operation Environments

The operation environment characteristics define the context in which the WSN applications are deployed. This group of parameters is sub-divided into three sub-groups: i) WSN scenarios, ii) WSN framework, and iii) deployment scenarios. The first sub-group distinguishes between the single-hop, multi-hop, and mobility scenarios. From the basics of radio communication and the inherent power constraints, radio communications are limited by the feasible distance between the sender and receiver. Note that the simple direct communication (single-hop) between source and sink is not always possible owing to the resulting coverage difficulties. The second sub-group is the operation framework: i) public, or ii) private. The third one (deployment scenarios) allows for shedding light on the environments for WSN applications deployment.

Before describing the operation environments where the WSN can be deployed in, it is worthwhile to define what source and sink nodes are. A source is any entity in the network that can provide information, i.e., typically a sensor node but it can also be an actuator node that provides feedback about an operation. A sink, on the other hand, is the entity where information is required. Figure 4 presents these three main types of sink nodes in a case with single-hop communication. Figure 4 a) considers the sink as a normal sensor node in the network (with no extended capabilities); Fig. 4 b) assumes the sink node as sensor node with extended capabilities; and Fig. 4 c) considers a sink node, which is a gateway, with extended capabilities and connected to the higher layers networks in the hierarchy [2].

For much of the remaining discussion, the distinction between the various types of sinks is actually irrelevant. It is however important to know whether sources or sinks are able to move. However, what sinks and sources do with the information is not a primary concern of the networking architecture. In the context of the most common sensor network scenarios, the first distinction is between single-hop and multi-hop networks. From the basics of radio communication and the inherent power constraints, radio communications

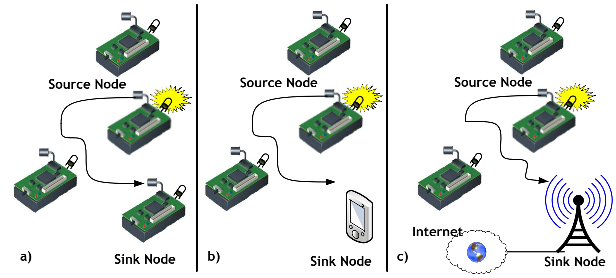

Fig. 4. Main types of sinks within single-hop communication.

have a limitation on the feasible distance between a sender and a receiver. Because of this limited distance, the simple direct communication between source and sink is not always possible, as shown in Fig. 5, specifically in WSNs, as they are intended to cover broad areas (e.g., in environmental or agriculture applications), operating in difficult radio environments with strong attenuation (e.g., in buildings). To overcome such limited distances, an obvious solution is to use relay nodes, with the data packets taking multi-hops from the source to the sink. This concept of multi-hop networks, shown in Fig. 5, is particularly attractive for WSNs, as the sensor nodes themselves can act as such relay nodes, eliminating the need for additional devices.

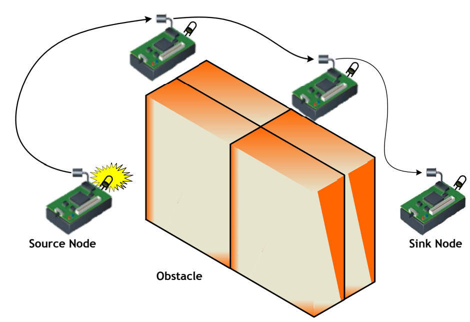

Fig. 5. Example of multi-hop network.

While multi-hopping is an evident and working solution to overcome problems with large distances or obstacles, it has also been claimed to improve the energy efficiency for the communications. In fact, the authors from [72] classify the misconception that multi-hopping saves energy as the number one myth about energy consumption in wireless communication. Great care should be therefore taken when applying multi-hopping aiming to improve the energy efficiency. In such a network, a node has to correctly receive a packet before it can forward it somewhere else. In alternative, innovative approaches attempt to exploit even erroneous reception of packets. For example, they explore the cases when multiple nodes send the same packet and each individual transmission can not be received but, collectively, a node can reconstruct the full packet, e.g., by applying the frame capture effect [73].

Another scenario is the multiple sinks and sources one. Besides networks with only a single source and a single sink, in many scenarios, there are multiple sources and/or multiple sinks. In the most challenging case, shown in Fig. 6, multiple sources that should send information to multiple sinks are

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present. Either all or some of the information has to reach all or some of the sinks.

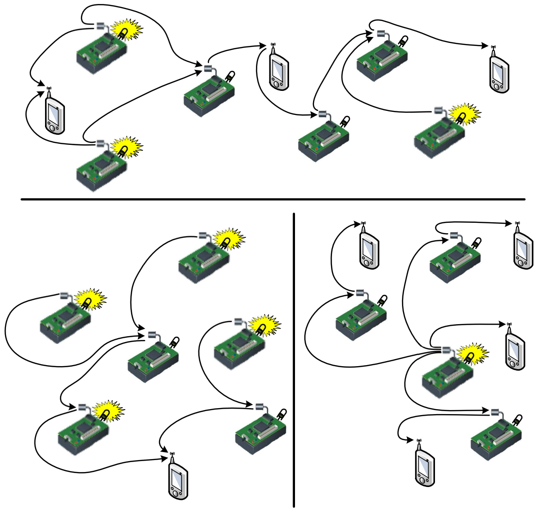

Fig. 6. Deployment scenarios with multiple sources and/or multiple sinks.

A third scenario is the mobility one [74]. Although in the scenarios discussed above all participants were stationary, one of the main virtues of wireless communications is its ability to support mobile participants. In WSNs, mobility can be presented in three main forms:

- **Node mobility** - Wireless sensor nodes themselves can be mobile. This mobility is application dependent. In examples like environmental control, node mobility should not happen; in livestock surveillance (e.g., sensor nodes attached to cattle), mobility is the common rule. Because of node mobility, the network has to reorganize itself frequently enough, to be able to properly operate. It is clear that there are trade-offs between the frequency and speed of node movement, on the one hand, and the energy required to maintain a desired level of functionality in the network, on the other hand.
- **Sink mobility** - In Fig. 7, the information sinks can be mobile. While this can be a special case of node mobility, the important aspect is the mobility of an information sink that is not part of the sensor network, for example, a human user requested information via a PDA while walking in an intelligent building. In a simple case, a requester can interact with the WSN at one point and complete its interactions before moving on. Other case considers a mobile requester which is particularly interesting. However, if the requested data is not locally available the requester would likely communicate only with nodes in its vicinity in order to retrieve the data from some remote part of the network. The network, possibly with the assistance of the mobile requester, must make provisions that the requested data actually follows and reaches the requester despite its movements [74];
- **Event mobility** - In applications like event detection, in particular tracking applications, the cause of the events or the objects (to be tracked) can be mobile. In such scenarios, it is important that a sufficient number of sensors permanently covers the observed event. Consequently, sensors will wake-up around the object, and will be engaged in higher activity to observe the present object. Only then, they will go back to sleep. As the event source moves throughout the network, it is accompanied by an area of activity within the network. The authors from [75] characterized this effect as the "Frisbee" model (which also describes algorithms for handling the "wake-up wavefront"). This notion is described in Fig. 8.

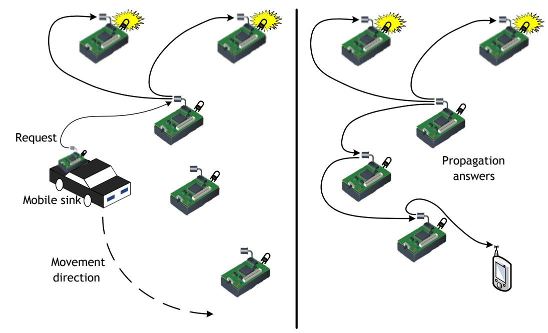

Fig. 7. Deployment scenario with the presence of a mobile sink.

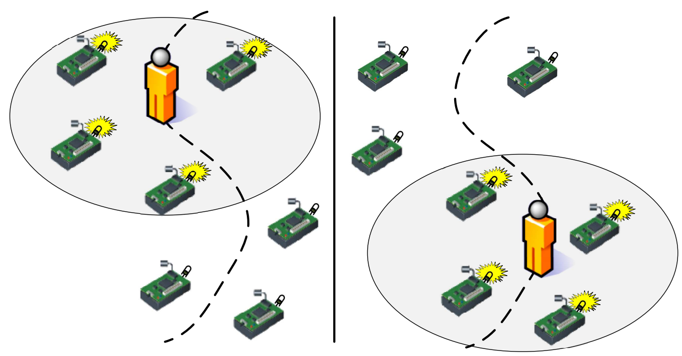

Fig. 8. Event mobility in wireless sensor and actuator networks.

Besides sensor network scenarios themselves, to perform a complete definition of the operation environment it is worthwhile to define the framework, which is divided into main two subsets [76]:

- **Public** - Urban, roads, rural or commercial zones;
- **Private** - Emergency dedicated.

In terms of mobility, the devices or entities present typical average speed (V_{av}) values that can be taken into account to design new WSN applications with mobility support. The scenarios of mobility can be characterized by a triangular distribution for the velocity of the mobile elements of a mobile WSN. These typical values are summarized in Table VI.

The deployment scenarios are defined by the set of services/applications operating simultaneously in the WSN. The typical geographical areas/zones of operation are the following ones: Offices, Industry, Home, Military, Civil, Metropolitan and Rural.

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TABLE VI
TYPICAL VALUES FOR THE AVERAGE VELOCITY FROM WSN ENTITIES.

	Entity	V_{av}	Article(s)
	Mobile WSN node	0.1 ms^{-1}	[77]
		0.42 ms^{-1}	[78]
	User (fastest human)	10 ms^{-1}	[79]
	Mobile sink	1-10 ms^{-1}	[79]
Telemedicine	User (walking)	2 ms^{-1}	[80]
	Car (normal speed)	10 ms^{-1}	
	Car (high speed)	20 ms^{-1}	

IV. RANGE OF VARIATION FOR THE CHARACTERIZATION PARAMETERS

The wide diversity of WSN applications motivates the need for their classification. Hence, the most suitable solution to organize the different types of applications is to taxonomize sensor networks and systems into two categories, Category 1 WSNs (C1WSNs) and Category 2 WSNs (C2WSNs) as presented in [81]. In the C1WSNs category, WSNs are mainly multi-hop, supporting massive data flows, with dynamic routing and high density network. In turn, in the C2WSNs category, WSNs are mainly single-hop, with static routing, a low/medium density network, supporting source-to-sink applications, present transaction-based data flows and suitable for applications in confined short-range spaces. In massive data flow there is a high amount of data that is exchanged within the network for a given time frame (i.e., high throughput). Usually, these massive data flows comprises with the continuous based data delivery model, in which nodes are continuously sending and receiving data. In transaction-based data flow, the amount of data that is exchanged within the network for a given time frame is low or moderate compared to massive data flow (i.e., low and/or medium throughput). Transaction-based data flow considers the remaining data delivery models such as event-, query/demand- and time-driven with low or moderate throughput. Their characteristics are presented in Table VII. This list of parameters facilitates to compare the differences and similarities between both categories. In Table VII we define a node as Repeater Node (RN) if it supports communications on behalf of other sensor nodes. If a node forwards the packets it is referred as a Forwarder Node (FN).

On the one hand, if a node forwards information from other node it is a cooperative node. On the other, if a node only handles its own information, then it is a non-cooperative node. In Table VII, dynamic routing is a mechanism that has the same function as static routing except it is more robust, since it finds the best route from a wider set of paths.

Besides the division of WSNs into these two categories (C1WSNs and C2WSNs), the applications that belong to these two categories fall into two different user requirement classes: Event Detection (ED) and spatial and time random Process Estimation (PE), [82]. For the sake of convenience, the attributes for each characteristic that allows for comparing both these classes are summarized in Table VIII. One characteristic of the ED class that is not presented in Table VIII is the network coverage, deeply related with the nodes' sensing range and event type.

If the sink nodes utilize a demand-driven data acquisition scheme to periodically query the nodes, the periodicity of queries must be chosen so that the event is detected and the data is delivered to the sink nodes on time.

TABLE VII
COMPARISON OF THE C1WSNS AND C2WSNS CHARACTERISTICS.

Characteristics	C1WSNs	C2WSNs
WSN scenario	$\geq$ 1-hop away from (RN) or (FN)	1-hop away from FN
WSN topology	Multipoint-to-point	Point-to-point Multipoint-to-point
Radio link range	Measured in thousands of meters	Measured in hundreds of meters
Sensor node repeater function	Wireless router	Wireless router
Forwarding node supported mechanisms	Dynamic routing $>$ one physical link to the network Data processing	Static routing one physical link to the terrestrial network
Nodes behaviour	Cooperative & non-cooperative	Non-cooperative
Network density	Large-scale systems	Simple and short-range wireless systems
Data flow characterization	High Throughput	Low and/or medium Throughput
Sensor node capabilities	Repeater Forwarder	Non-repeater Forwarder
Applications examples	Environmental monitoring National security systems	Residential systems Confined short-range spaces, e.g., home, factory, building

TABLE VIII
COMPARISON OF THE ED AND PE CLASSES.

Characteristics	ED	PE
Data acquisition	Event-driven Demand-driven Not time-driven	Periodic estimation of physical phenomenon Demand-driven
Signal processing capabilities	Simple compare with threshold & send to sink	Data gathering & forwarding to sink(s) sink collects & handles packets from nodes
Node density	Enough to guarantee a given event detection probability	Enough to ensure the process is accurately estimated
Efficient mechanisms support	Distributed localization algorithms	Sampling frequency allow event tracking
Connectivity issues	Alarm packets arrive with high probability & in a short time	Process estimation error $<$ threshold
Main issues	Coverage Connectivity Distributed localization Ensure low packet losses and delays	Signal processing Connectivity Time synchronization Ensure low process estimation error
Application requirements	Min. probability of coverage Max. localization error Min. probability of connectivity Max. packet loss probability Max. packet delivery delay	Max. estimation error Max. localization error Min. probability of connectivity Max. packet loss probability

TABLE IX
CHARACTERIZATION OF CATEGORY C1WSNS APPLICATIONS.

Applications Area	Applications	Class
Metropolitan Operation	-Highway monitoring [83] [84]	PE
Military	-Condition-based-monitoring [85] [86] [87] [88]	PE
	-Surveillance [89]	ED
	-Borders Monitoring [90]	ED
Civil Engineering	-Structural Integrity Monitoring [91]	ED
Environmental Monitoring	-Monitoring Volcanic Eruptions [92], [93]	PE & ED
	-Habitat Monitoring [94]	PE & ED
	-Water Monitoring [95] [96] [97]	PE & ED
	-Weather Monitoring [98] [99]	PE & ED
	-Forest Fire Detection [100] [101]	PE & ED
	-Precision Agriculture [102] [103]	PE & ED
Logistics	-Target Tracking [104] [105]	ED
	-Warehouse Tracking [106]	PE & ED
Position & Animals Tracking	-Immersive Roam [107]	ED
	-Real-Time Relative Positioning System [108]	ED
	-Wild-Life Tracking [109] [110] [111]	ED
Transportation	-Smart Roads [112] [113]	PE
-Automobile [114]		PE
-Sensor & Robots [115] [116]		PE & ED
-Reconfigurable WSN [117]		ED
-Nanoscopic Sensors [118]		ED

TABLE X
CHARACTERIZATION OF CATEGORY C2WSNS APPLICATIONS.

Applications Area	Applications	Class
Industrial Automation	-Commercial Spaces	PE & ED
	-Smart Factory [119]	PE & ED
Health	-Pre-Hospital [120]	PE & ED
	-In-Hospital Emergency Care [121]	PE & ED
	-Telemedicine [122]	PE & ED
	-(Tele)Rehabilitation [123]	PE & ED
Mood-based Services	-Personal Coaching [124]	ED
Entertainment	-Dynamic Spaces [125]	ED
	-Gaming [126]	ED
	-Gesture/body Tracking [127]	ED
-Smart Office [128]		ED
-Sports [129]		ED
-Building Automation [130]		ED
-Home Control [131]		ED

A. Holistic Overview of the WSN Applications Taxonomy

The large amount of work that has been produced over the last 10 years on the different areas of WSNs allows us for identifying the different parameters of our proposed application taxonomy. We have classified key WSN applications for the different areas, as well as analyzed the WSN applications evolution over the years. The time stamps on the publications of different projects also allow us to observe how the different areas have appeared chronologically for the past 10 years, facilitating to foresee the future trends. After gathering all the information from different projects, in this work we have summarized it in tables (whilst considering the different areas). However, since it is difficult to present all the comparison tables for all the groups of parameters, we opt for presenting tables with a subset of parameters. These tables are a representative sample of all the work performed by us on the taxonomy for the characterization and classification of WSNs.

By combining the C1WSNs and C2WSNs categories with the ED and PE classes we were able to organize the main WSN applications areas and the corresponding sub-applications of each area. The applications from the C1WSNs and C2WSNs categories are presented in Tables IX and X, respectively. Since it is not feasible to present all the classification tables the identification of the most common attributes or values for the corresponding parameters is followed by a brief discussion on the achieved results for each group of parameters:

- **Service parameters** - The majority of the analysed applications requires real-time delivery, all have a bidirectional communication, present a symmetric communication, do not need end-to-end connection, are mostly interactive and are mission-critical. Moreover, all the identified applications are delay tolerant except for the water monitoring, automobile, telemedicine and smart office applications. These four applications are not delay tolerant. Besides, the delay parameter depends on the delivery requirement parameter, which, in turn is related with the QoS class. Other parameters, like the class of service and traffic class, are influenced by the characterization parameters from this group. Since, in the majority of the WSN applications, the delivery requirement is real-time, the traffic class (from the communication & traffic parameters group) is frequently real-time.
- **Communication & traffic parameters** - The majority of the applications follow an event-driven data delivery model, related to the attributes chosen in the service parameters described above. Event-driven applications are defined as interactive, non delay tolerant, mission-critical, real-time, and non-end-to-end ones. Most of the applications present a bit rate that varies up to 57.6 kbps. However, nowadays there is a significant number of applications that work at a bit rate higher than 115.2 kbps. For a considerable number of applications, the minimum acceptable delay for data delivery varies between 0 and 250 ms, while the maximum acceptable delay varies around 250-1000 ms. Nonetheless, there are some applications with a maximum delay that varies around 1-10 s, or even 63 s, depending on the deployment scenario (n.b., harsh environment allows for higher delays tolerance).
Nearly all applications need a synchronized platform for nodes to work. Only the structural integrity monitoring, wild-life tracking and gaming do not require a synchronized platform. However, the sports application may require or not a synchronization scheme, depending on the type of sport being monitored. In terms of delivery requirement the majority of the WSN applications are in real-time. Since the class of service and traffic classes are influenced by the parameters from the service parameters group, the most common service traffic is the Real Time & Loss Tolerant & Data (RT&LT&Data), while the most prominent classes of service are the Isochronous & Real Time-Variable Bit Rate (ISO&RT-VBR) and Isochronous & Constant Bit Rate (ISO&CBR). The packet delivery failure ratio (PDFR) for some applications varies between 1 and 10 %, although this aspect is not well

described in some of the studied projects. The types of modulation scheme employed in the applications are the FSK (DSSS) and DSSS-O-QPSK, with half-duplex communication capabilities. The latter modulations correspond to an IEEE 802.15.4 compliant radio transceiver. In terms of service components, the most usual ones are the HID, MED and LOD. These applications areas are more suitable for the event-driven delivery model. However, some applications present a combination of STV+HID or STV+LOD+MED+HID service components. The most prominent model for data acquisition & dissemination is the event-driven one, followed by demand and event-driven combination models. These models are deeply related with the QoS parameter as well as with the delivery requirement and delay tolerance parameters (from the service parameters group). Depending on the delivery requirement and the delay tolerance of the WSN application, the QoS model that is assumed by the application must fulfil the requirements from the service group and from the acquisition & dissemination model (closely related with the QoS model).

- **Network parameters** - This group is the one with the vastest variety of parameters (from all the groups of parameters). First, the lifetime of the analysed applications mainly varies between 29 and 720 h, i.e., most of them are short-term applications. Besides, applications present a deployment of no more than 50 sensor nodes in real-scenario deployments, while covering an area larger than 100 m^2 in the majority of the applications. Only the density of nodes in indoor applications differs from this value (i.e., less than 10 m^2). Building divisions impose special attention to the propagation phenomenon and sensor nodes deployment. This shows that high scalable deployments are still not fully feasible. As sensor hardware does not allow for long sensing range, the sensing area is limited to 10 m^2 for all the applications. Hence, the WSN applications are cooperative and limited in the sensing of the phenomenon. This sensing restriction allows for reducing the redundancy of the sensed data. From the studied applications, almost all have a self-organization procedure. Only border monitoring, precision agriculture and (tele) rehabilitation applications consider mechanisms to organize only a part of the network. Habitat and weather monitoring applications do not consider any type of mechanism to organize the network automatically. Besides, there is a lack of security mechanisms in the majority of the applications. Only in some applications (e.g., military) the security (medium or high) is considered. In practice, in the WSN applications, the addressing is performed mainly in two ways: i) MAC address or ii) node ID. *In situ* node reprogramming without the need for suspending all the network operation is not usual in more than half of the analysed applications. Nonetheless, there are some applications that allow for sensor node reprogramming. The use of mechanisms to ensure the maintainability of the sensor nodes is common in the majority of the applications. The WSNs are composed by different devices that together form the network itself. In the studied applications, it is typical to observe a heterogeneous nature in terms of WSN network composition. Finally, the mobility support feature is employed in nearly half of the applications from the different areas.
- **Node parameters** - Microprocessors/microcontrollers are mostly ATMEL, TI or DustNetworks ones, while the most used radio transceivers are the CC1000 and the CC2420 ones. The studied WSN applications use hardware commercially available that already incorporate these radio transceivers. In addition, the former is IEEE 802.15.4 standard non-compliant and the latter one is compliant. If we wish to change the radio transceiver only experts are capable of changing the radio transceiver. In terms of overall energy consumption, with sensors attached, the majority of the applications present an energy consumption less or equal than 50 mA, and few applications require an energy consumption of around 51 and 100 mA (considering a power supply of 3.3 V). The applications that present a higher consumption are typically the ones that have a higher sampling rate. The most common reporting frequencies in the studied applications are the medium and low sampling rates. Regarding the type of function that is performed by the different devices in WSNs, the majority of the applications are composed by sensor and sink nodes and always a user. Some applications have already started to have a gateway, allowing the WSN to connect to the Internet and disseminate the gathered data. Other applications also possess actuators connected to the sensor nodes, in order to execute the commands given by the central node. The communication range is related with the type of radio transceiver, the transmission power and the signal propagation environment where it is inserted. The majority of the applications achieve a range of at least 50 m. Finally, the power supply used by the WSN devices is mainly formed by batteries. In some cases, however, batteries are combined with an energy harvesting device (e.g., solar panel).

B. New WSN Applications Categories

Based on the previous holistic overview of the WSN applications taxonomy, we are able to identify some common features between characterization parameters, enabling to propose a new classification of the applications, based on the combination of the parameters' attributes. The first group of the three categories is related with the time related constraints of applications, which relates the lifetime, scalability, maintainability, sampling rate, power supply and acquisition & dissemination classes parameters. This time related application group considers that all the WSN applications that present the same attributes for the respective parameter belong to the corresponding category, as shown in Table XI. The three possible categories are: the Long-Term Applications (LTA), Medium-Term Applications (MTA), and Short-Term Applications (STA).

In Table XI (time related applications categories) the parameters that are considered to group the different WSN

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applications into one of the three categories are sufficient. For these categories, the time is a very important issue and allows for easily identifying the WSN applications that last longer or are supposed to present a longer usable lifetime. Therefore, the lifetime parameter for these categories is essential in order to provide a time basis in which different periods of time (in hours) correspond to long, medium and short term deployment of WSN applications. The sampling rate parameter is related with the lifetime parameter. On the one hand, a WSN application with higher sampling rate generally has a shorter lifetime. On the other, low sampling rates lead to a longer lifetime. Another characterization parameter that is deeply related with the lifetime and sampling rate is the acquisition and dissemination. This parameter represents how the data acquisition is performed during the lifetime of the sensor nodes. By being aware of the type of acquisition the WSN application has, it is possible to infer which type of acquisition and dissemination schemes are common in certain application areas. To complement the grouping of WSN applications into one of the three categories, the maintainability parameter is also related with the lifetime, since it contributes to save energy (when the WSN application is maintainable), and consequently to increase the lifetime. The size of the network (i.e., scalability) is another parameter that influences the lifetime of the WSN application. Larger networks are more robust, and therefore aiming at long-term WSN applications.

Tables XII, XIV and XVI consider the positive match ratio corresponding to the WSN application from a specific category. This assessment parameter is the ratio between the number of parameters that correspond to the attribute or value for such application category and the total number of parameters considered for each category from Tables XI, XIII and XV. The right hand side column shows if the WSN application belongs (or not) to the respective category. If the application presents a positive match ratio equal to 1 then we assign "Yes" to the entry of the column. Apart from "Yes" or "No", this column also may present the attribute "Y/N", meaning that the WSN application nearly fulfils all the necessary attributes to belong to the category (i.e., it only misses one attribute or value for such application category). Otherwise, "No" is assigned to the column.

TABLE XI
CATEGORIES FOR TIME RELATED APPLICATIONS.

Parameters	Category		
	LTA	MTA	STA
Lifetime	> 25920 h	[721; 25920] h	[24; 720] h
Scalability	> 400 nodes	[51; 400] nodes	≤ 50 nodes
Maintainability	Maintainable	Maintainable	Maintainable
Sampling rate	Low/Medium	Medium	High
Acquisition & dissemination	Low event/ demand-driven	Medium event/ time-driven	High event/ time-driven

Table XII presents different WSN applications organized among the LTA, MTA and STA categories, which aggregate the WSN applications with common parameters. It is noticeable that, for the LTA category, both border monitoring (military area) and highway monitoring (metropolitan area) share the same attributes and values. Even though these applications are from different areas, the combination of these parameters envisages a long-term solution application.

For the MTA category, the aggregation of WSN applications has not resulted in full positive match of the parameters. However, dynamic spaces (entertainment area) and habitat monitoring (environmental area) are applications which almost fulfil all the requirements of medium-term applications. Again, different application areas belong to the same time related category but each application envisages different purposes.

In the STA category, wild-life tracking (position and animals tracking area) positively matches all the characterization parameters attributes and values from this category, and is a typical short-term application. This is due to limited lifetime and small scalability of the hardware attached to the animal being tracked, along with the high reporting data rate. Other WSN applications, such as monitoring volcanic eruptions, surveillance and condition-based monitoring do not fully match the attributes and values for the parameters from this category. However, these applications can be assumed as nearly short-term ones.

From Table XII it is possible to summarize that applications from the LTA category present a combination of large lifetime with high scalability while presenting a low or medium event-driven acquisition and dissemination data model. Applications from the STA category are characterized by limited lifetime and small scalability. Finally, applications from the MTA category correspond to medium lifetime and scalability parameters and can be assumed as nearly LTA or STA.

The second group of three categories considers the data stream related constraints of applications. In this group, the service components, and data rate parameters are combined, enabling to form up the three new categories. The applications can be classified as High Data Stream Applications (HDS), Medium Data Stream Applications (MDS), and Low Data Stream Applications (LDS), as shown in Table XIII. The objective of Table XIII is to organize the WSN applications into one of the three categories, which are related to the data stream in WSNs. In this table, it is enough to consider only two parameters. With this categorization, the intention is to help on the quick identification of the set of WSN applications whose primary concern is the bit rate. By identifying the intended WSN application, it is possible to analyse in detail a project that may serve as a basis for further research work. The service components parameter enables to distinguish the types of traffic that are expected to be present in a WSN application (depending on the application area). The most bandwidth demanding WSN applications consider the types of traffic with the widest requirements in terms of bandwidth, such as Data-HID, Video-STV and Audio-VOI (defined in Fig. 3). In turn, the lowest bit rates are associated to the types of traffic with the lowest requirements in terms of bandwidth. The bit rate is related to the service components parameter, which also defines the category in Table XIII. Hence, low, medium and high bit rates correspond to the LDS, MDS and HDS categories from Table XIII, respectively. The addition of more parameters to Table XIII might help the reader but

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TABLE XII
AGGREGATION OF WSN APPLICATIONS FOR TIME RELATED CATEGORIES.

			Parameters						
	Applications	**Project**	**Lifetime (h)**	**Scalability (nodes)**	**Maintainability**	**Sampling rate**	**Acquisition & dissemination**	**Positive match ratio**	**Belongs to the category**
LTA	**Range of variation**		*> 25920*	*> 400*	*Maintainable*	*Low/ Medium*	*Event/demand-driven*		
	Border Monitoring	SBInet [90]	72000	1200	Maintainable	Low	Event-driven	5/5	Yes
	Target Tracking	VigilNet [104] Trio [105]	2640	564				4/5	Y/N
	Highway Monitoring	TrafficDot [83]	70090 - 96360	2340		Medium		5/5	Yes
	Precision Agriculture	Good-Food [102], [103]	5208	16		Low	Demand-driven Time-driven	3/5	No
	Structural Integrity Monitoring	Sustainable Bridges [91]	26280	-		High	Event-driven Time-driven	3/5	No
MTA	**Range of variation**		*[721; 25920]*	*[51; 400]*	*Maintainable*	*Medium*	*Event/time-driven*		
	Water Monitoring	AquaWSN [95], [96]	168	65	Maintainable	Low	Time-driven	3/5	No
	Smart Factory	Anshan [119]	30000	407		Medium	Event-driven Time-driven	3/5	No
	Forest Fire Detection	FireBug [100], [101]	N.A.	11		Low		3/5	No
	Gaming	Trove [126]	12648	11			Event-driven	2/5	No
	Dynamic Spaces	CMUseum [125]	17520	43		Medium		4/5	Y/N
	Habitat Monitoring	Great Duck Island [94]	5208	33		Low-Medium-High	Demand-driven Time-driven	4/5	Y/N
STA	**Range of variation**		*[24; 720]*	*≤ 50*	*Maintainable*	*High*	*Event/time-driven*		
	Personal Coaching	e-Sense [124]	600	N.A.	Maintainable	Low	Demand-driven Event-driven	3/5	No
	Weather Monitoring	Infoclima [98]	1680	9			Demand-driven	3/5	No
	Monitoring Volcanic Eruptions	Reventador volcano [92], [93]	168	11		Medium	Demand-driven Event-driven	4/5	Y/N
	Surveillance	Virtual-Patrol [89]	72	60		High	Event-driven	4/5	Y/N
	Condition-based Monitoring	WiBeaM [85]	1220	5				4/5	Y/N
	Wild-life Tracking	Hogtrob [110], [111]	179	3				5/5	Yes

we consider that these two WSN characterization parameters are the most prominent and essential ones for data stream applications.

Table XIV considers data stream related categories for different WSN applications and the relations among different applications areas. Typically, high data stream applications require larger bandwidth than other applications. Therefore, the real-time relative positioning system, telemedicine, dynamic spaces and highway monitoring applications are associated to the high data stream category. All these applications share the high bit rate and high demanding bandwidth traffic classes.

In the medium data stream category, the most common WSN applications are the ones related with monitoring events or associated to the user. These applications are medium bit rate applications and are associated to regular traffic sensor service components, i.e., MED. Note that the gaming application fulfils all the requirements of the medium data stream category. However, the remaining MDS applications from Table XIV only present one of the attributes. Either they present a MED service component or a medium bit rate.

TABLE XIII
CATEGORIES FOR DATA STREAM RELATED APPLICATIONS.

Parameters	**Category**		
	HDS	**MDS**	**LDS**
Service components	Data-HID/ Video-STV/ Audio-VOI	Data-MED	Data-LOD
Bit rate	High Bit rate $\geq$ 115.2 kbps	Medium Bit rate [57.6; 115.2] kbps	Low Bit rate $\leq$ 57.6 kbps

Low data stream applications present low bit rate jointly with low traffic sensor service components, i.e., LOD. Since the majority of the WSN applications use high reliability short packets of information, the weather monitoring, precision agriculture, warehouse tracking and automobile applications present all the attributes from the low data stream category. Many of the WSN applications that belong to the MDS or LDS category are also part of the LTA and MTA categories

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TABLE XIV
AGGREGATION OF WSN APPLICATIONS FOR DATA STREAM RELATED CATEGORIES.

<table>
<tr><th rowspan="2"></th><th rowspan="2">Applications</th><th rowspan="2">Project</th><th colspan="2">Parameters</th><th rowspan="2">Positive match ratio</th><th rowspan="2">Belongs to the category</th></tr>
<tr><th>Service components</th><th>Bit rate (kbps)</th></tr>
<tr><td rowspan="7">HDS</td><td>Range of variation</td><td></td><td>HID/STV/VOI</td><td>High bit rate (≥ 115.2)</td><td></td><td></td></tr>
<tr><td>Immersive Roam</td><td>LEMe Room [107]</td><td>STV-HID</td><td rowspan="2">Low bit rate</td><td>1/2</td><td>No</td></tr>
<tr><td>Smart Roads</td><td>AstroRoads [112], [113]</td><td rowspan="2">HID</td><td>1/2</td><td>No</td></tr>
<tr><td>Real-Time Relative Positioning System</td><td>ICLS [108]</td><td rowspan="4">High bit rate</td><td>2/2</td><td>Yes</td></tr>
<tr><td>Telemedicine</td><td>EasyMed [122]</td><td rowspan="2">STV-HID</td><td>2/2</td><td>Yes</td></tr>
<tr><td>Dynamic Spaces</td><td>CMUseum [125]</td><td>2/2</td><td>Yes</td></tr>
<tr><td>Highway Monitoring</td><td>Traffic Dot [83]</td><td>STV-LOD
MED-HID</td><td>2/2</td><td>Yes</td></tr>
<tr><td rowspan="7">MDS</td><td>Range of variation</td><td></td><td>MED</td><td>Medium bit rate ([57.6; 115.2])</td><td></td><td></td></tr>
<tr><td>Border Monitoring</td><td>SBInet [90]</td><td rowspan="3">MED</td><td rowspan="3">Low bit rate</td><td>1/2</td><td>No</td></tr>
<tr><td>Habitat Monitoring</td><td>Great Duck Island [94]</td><td>1/2</td><td>No</td></tr>
<tr><td>Sensor & Robots</td><td>Robomote [115]</td><td>1/2</td><td>No</td></tr>
<tr><td>Forest Fire Detection</td><td>FireBug [100], [101]</td><td>LOD</td><td rowspan="2">Medium bit rate</td><td>1/2</td><td>No</td></tr>
<tr><td>Gaming</td><td>Trove [126]</td><td rowspan="2">MED</td><td>2/2</td><td>Yes</td></tr>
<tr><td>Personal Coaching</td><td>e-Sense [124]</td><td>High bit rate</td><td>1/2</td><td>No</td></tr>
<tr><td rowspan="7">LDS</td><td>Range of variation</td><td></td><td>LOD</td><td>Low bit rate (≤ 57.6)</td><td></td><td></td></tr>
<tr><td>Smart Office</td><td>Open secure office [128]</td><td>MED</td><td rowspan="6">Low bit rate</td><td>1/2</td><td>No</td></tr>
<tr><td>Weather Monitoring</td><td>Infoclima [98]</td><td rowspan="4">LOD</td><td>2/2</td><td>Yes</td></tr>
<tr><td>Precision Agriculture</td><td>Good-Food [102], [103]</td><td>2/2</td><td>Yes</td></tr>
<tr><td>Warehouse Tracking</td><td>Sensor-scheme [106]</td><td>2/2</td><td>Yes</td></tr>
<tr><td>Automobile</td><td>Intelligent Tires [114]</td><td>2/2</td><td>Yes</td></tr>
<tr><td>Smart Factory</td><td>Anshan [119]</td><td>HID</td><td>1/2</td><td>No</td></tr>
</table>

from Table XI. This is due to the close relation between the attributes from the characterization parameters. Low event report and short packets lead to long or medium-term applications.

In Table XIV the intention from this categorization is to assist the reader to quickly identify the WSN applications in which the bandwidth is the primary concern. HDS applications require higher bandwidth and higher bit rate than other applications. The most common WSN applications in the MDS category are related to either monitoring events or the user. Applications from the LDS category present low bit rate, jointly with low traffic sensor type of traffic, i.e., LOD. Besides, typically, LDS applications correspond to low reporting frequency events.

The third group is subdivided into two categories and refers to the delivery requirements and delay sensitivity of the applications. These categories include the delivery requirement, end-to-end connection, criticality, delay tolerance, QoS, class of service, and traffic classes parameters. This group is subdivided into the Real-Time & Sensitive Delay Demanding Applications (RT-SDD) and Non-Real-Time & non Sensitive Delay Demanding Applications (NRT-nSDD) categories, as shown in Table XV.

To group WSN applications into one of the two categories from Table XV, the considered parameters are sufficient. These parameters have been chosen because timeliness issues must be addressed in the considered parameters for the delivery and delay sensitivity related categories. For these categories, the delay is an important issue. The provision of delay guarantees in WSNs is challenging due to sensor nodes' limitations in terms of energy supply, as well as computational and communication capabilities.

The delay is the most critical delivery requirement parameter. Depending on the real-time (or non-real-time) nature of the WSN application, the QoS class parameter is also related to the delivery requirement. In real-time event-driven applications, the event needs to be reported to a sink node as soon as possible. In demand and periodic-driven WSN applications, real-time delivery may not be required. The end-to-end connection parameter is needed to identify if the WSN application presents a cooperative (non-end-to-end) or point-to-point (end-to-end) relationship among nodes.

TABLE XV
CATEGORIES FOR DELIVERY AND DELAY SENSITIVITY RELATED APPLICATIONS.

Parameters	Category	
	RT-SDD	**NRT-nSDD**
Delivery requirement	Real-time	Non-real-time
End-to-End connection	End-to-end	Non-end-to-end
Delay tolerance	Non delay tolerant	Delay tolerant
Criticality	Mission-critical	Non-mission-critical
QoS	Event/Continuous/Demand driven	Query driven
Class of service	ISO&RT-VBR	ISO&CBR NISO&ABR NISO&UBR
Traffic classes	RT&LT&Data RT&LI&Data	DT&LI&Data DT&LT&Data

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TABLE XVI
AGGREGATION OF WSN APPLICATIONS FOR DELIVERY AND DELAY SENSITIVITY RELATED CATEGORIES.

			Parameters								
	Applications	**Project**	**Delivery requir.**	**End-to-end connection**	**Delay tolerance**	**Criticality**	**QoS**	**Class of service**	**Traffic classes**	**Positive match ratio**	**Belongs to the category**
RT-SDD	**Range of variation**		*RT*	*End-to-end*	*Non delay tolerant*	*Mission critical*	*Event/ continuous/ demand -driven*	*ISO& RT-VBR*	*RT&Data &(LT or LI)*		
	Border Monitoring	SBInet [90]	RT	End-to-End	Non delay tolerant	Mission Critical	Event -driven	ISO& RT-VBR	RT& LT& Data	7/7	Yes
	(Tele)Reha-bilitation	HipGuard [123]					Query -driven			6/7	Y/N
	Pre-Hospital	CodeBlue [120]		Both					RT& LI& Data	6/7	Y/N
	Personal Coaching	e-Sense [124]		End-to-end			Query & event -driven			7/7	Yes
	Gaming	Trove [126]					Event-driven		RT&LT &Data	7/7	Yes
	Immersive Roam	LEMe Room [107]		Non End-to-End					RT&LI &Data	6/7	Y/N
NRT-nSDD	**Range of variation**		*NRT*	*Non End-to-end*	*Delay tolerant*	*Non mission critical*	*Query -driven*	*ISO&CBR NISO&ABR NISO&UBR*	*DT&Data &(LT or LI)*		
	Weather Monitoring	Infoclima [98]	NRT	Non End-to-end	Delay tolerant	Mission critical	Query -driven	ISO& CBR	DT&LT &Data	6/7	Y/N
	Condition-based Monitoring	WiBeaM [85]		End-to-end		Non mission critical	Event -driven	ISO& CBR	DT& LT& Data	5/7	No
	Water Monitoring	AquaWSN [95], [96]		Both		Mission critical	QoS -driven			4/7	No
	Precision Agriculture	Good-Food [102], [103]	RT	Non End-to-end			Query & event -driven		DT& LI& Data	6/7	No
	Forest Fire Detection	FireBug [100], [101]								5/7	No
	Wild-life Tracking	Hogtrob [110], [111]	Both	End-to-end		Non mission critical	Event -driven	NISO& ABR	-	4/7	No

To assess if the WSN application is mission-critical, the following two essential network performance metrics arise from the criticality parameter: delay and reliability. These metrics are discussed within the traffic class parameter from subsection III-B. In addition, the class of service parameter is necessary to verify if the WSN applications adapts its bandwidth or not (ISO or NISO, respectively) and what type of data traffic is exchanged among nodes. This parameter is closely related with the QoS and traffic class parameters. The parameters considered in Table XV are therefore enough to group WSN applications into one of these new categories.

Table XVI aggregates WSN applications according to timeliness aspects, which, in turn, are described by assigning attributes or values to different parameters within the RT-SDD and NRT-nSDD categories. For the real-time and sensitive delay demanding category, the essential requirement is real-time delivery modelling. Additionally, WSN applications must be mission-critical and non delay tolerant. From the considered WSN applications, the border monitoring, personal coaching and gaming fulfil all the requirements from the RT-SDD category. However, other applications, such as (tele) rehabilitation, pre-hospital and immersive roam applications do not fully fulfil the requirements of this category, as they are nearly RT-SDD. Although the applications do not fully belong to the RT-SDD category, conclusions can be extracted regarding the similarities between applications from different areas that do and do not comply to all the characterization parameters in a specific category.

The non-real-time and non-sensitive delay demanding category aggregates WSN applications that are not characterized by a real-time delivery model. Instead, these applications are based on a delivery model that relies on queries. This allows the WSN applications to be assumed as delay tolerant and tolerant to packets losses. In Table XVI, there is no application that fulfils all the requirements for this category. However, weather monitoring positively presents all the requirements, except criticality, as it assumes the application is mission-critical instead of non-mission-critical. The remaining applications in the NRT-nSDD category do not fulfil all the requirements for this category. However, being non real-time is one of the main characteristics for this category.

On the one hand, the majority of WSN applications from the NRT-nSDD category are associated to the LDS category from Table XIV. On the other, the WSN applications from the RT-SDD category are associated to the MDS and HDS categories from Table XIV. This is due to the real-time nature

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from the RT-SDD category, which is usually related to wider bandwidth requirements.

For the RT-SDD and NRT-nSDD categories from Table XVI, the delay is an important aspect, since the provision of delay guarantees in WSNs is challenging, due to the limitations in energy supply, as well as computational and communication capabilities of the sensor nodes. In the RT-SDD category, the essential requirement is real-time delivery, jointly with the support of mission-critical communications. These applications are non delay tolerant. The NRT-nSDD category aggregates WSN applications that are characterized by a delivery model that relies on queries, whilst assuming that the application is delay and packets loss tolerant.

From a more careful analysis, it is possible to state that some of these new application categories are deeply related with each other. Many of the WSN applications that belong to the MDS or LDS category also belong to the LTA and MTA categories. Consequently, low event report and short packets lead to long or medium term applications. It is observable that the majority of WSN applications from the NRT-nSDD category are associated to the LDS category, whereas the WSN applications from the RT-SDD category are associated to the MDS and HDS categories. It is also worthwhile to mention that the real-time nature from the RT-SDD category is usually related to high bandwidth requirements.

C. Example for the WSN Applications Taxonomy

In order to better understand how the WSN applications taxonomy can be applied, in this section, we describe twelve applications from different areas and categories. The chosen areas are the metropolitan, military, environment monitoring, position & animal tracking, industrial automation, health, civil engineering, environmental monitoring, logistics, transportation, automobile and sports. Real-world WSN implementations of the presented applications are the highway monitoring, condition based monitoring, monitoring of volcanic eruptions, immersive roam, smart factory, telemedicine, structural integrity monitoring, forest fire detection, target tracking, smart roads, automobile and sports, respectively.

Tables XVII and XVIII present the values for the attributes for the studied applications, whilst considering the service classification parameters, from our proposed taxonomy. In terms of service parameters the applications are organized as follows:

- **Delivery requirements** - All presented applications need a real-time delivery demand, except for the condition based monitoring, since it is not critical to have the data from the sensors available in a continuous mode. Highway monitoring also presents non-real-time delivery in some types of data (e.g., counting cars).
- **Directionality** - All the applications presented in Tables XVII and XVIII are bidirectional.
- **Communication symmetry** - In terms of communication symmetry parameters, both categories C1WSNs and C2WSNs have applications that share the same attribute for this parameter. Highway monitoring, condition based monitoring, monitoring of volcanic eruptions, smart factory, structural integrity monitoring, forest fire detection, target tracking, smart roads and automobile applications are symmetric, whereas, immersive roam, telemedicine and sports are asymmetric applications. This asymmetry is caused by fluctuations in the data quantities that may occur during the execution of the application.
- **End-to-end connection** - The military and industrial automation areas from different categories (C1WSNs and C2WSNs, respectively) share the need for an end-to-end guarantee. Also, in telemedicine and sports an end-to-end connection may also be needed or not, depending on the type of data being sent by the nodes. In turn, the highway monitoring, monitoring of volcanic eruptions, immersive roam, structural integrity monitoring, forest fire detection, target tracking, smart roads and automobile applications do not require an end-to-end connection, in order to fulfil the requirements of the application.
- **Interactivity** - All the presented applications are interactive, except for the automobile application. In this application the data is reported almost continuously.
- **Delay tolerance and criticality** - The delay tolerance and criticality parameters are deeply related with each other. By observing Tables XVII and XVIII, the majority of the presented applications that are non delay tolerant are also mission-critical. Only a few applications, like smart factory, monitoring of volcanic eruptions, structural integrity monitoring and forest fire detection are simultaneously delay tolerant and mission-critical ones. Usually, the demand for non delay tolerance is a characteristic of real-time applications, while the mission criticality relies on the importance of the data being sent aiming at reaching a certain application requirement.

Table XIX presents the communication & traffic parameters for the considered WSN applications. Details about the most prominent ones are as follows:

- **Synchronization** - All the presented applications require synchronized communications, except for the structural integrity monitoring applications which do not require synchronized communications. The sports application considers both synchronized and asynchronized communications, since it depends on the type of sport being monitored.
- **Class of service** - The class of service and traffic classes are related with the delay tolerance. Figure 2 sheds light on how the different service classes are assigned to the corresponding application. Since the immersive roam, telemedicine and sports applications present fluctuations in the data packet transmission and have a real-time delivery requirement, the class of service is ISO&RT-VBR. Although the structural integrity monitoring application does not presents an asymmetric characteristic it assumes the class of service ISO&RT-VBR. For the remaining applications, the class of service is ISO&CBR, as shown in Table XIX.
- **Traffic class** - All the WSN applications transmit the data traffic class. The differences among the applications rely on the delay and loss tolerance. The highway monitoring, immersive roam, telemedicine and target tracking

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TABLE XVII
SERVICE CHARACTERISTICS FOR WSN APPLICATIONS (I).

Application Area	**Metropolitan**	**Military**	**Environmental monitoring**	**Position & animals tracking**	**Industrial automation**	**Health**
Project	Traffic Dot [83]	WiBeaM [85]	Reventador volcano [92], [93]	LEMe Room [107]	Anshan [119]	MEDiSN [121]
Application	Highway monitoring	Condition based monitoring	Monitoring volcanic eruptions	Immersive roam	Smart factory	Telemedicine
Delivery requirements	RT & NRT	NRT	RT	RT	RT	RT
Directionality	Bid	Bid	Bid	Bid	Bid	Bid
Communication symmetry	Sym	Sym	Sym	Asym	Sym	Asym
End-to-end connection	Non-end-to-end	End-to-end	Non-end-to-end	Non-end-to-end	End-to-end	End-to-end & Non-end-to-end
Interactivity	Interactive	Interactive	Interactive	Interactive	Interactive	Interactive
Delay tolerance	Non delay tolerant	Delay tolerant	Delay tolerant	Non delay tolerant	Delay tolerant	Non delay tolerant
Criticality	Mission-critical	Non-mission-critical	Mission-critical	Mission-critical	Mission-critical	Mission-critical

TABLE XVIII
SERVICE CHARACTERISTICS FOR WSN APPLICATIONS (II).

Application Area	**Civil engineering**	**Environmental monitoring**	**Logistics**	**Transportation**	**Automobile**	**Sports**
Project	Sustainable Bridges [91]	FireBug [100], [101]	VigilNet [104] Trio [105]	AstroRoads [112], [113]	Intelligent Tires [114]	DexterNet [129]
Application	Structural integrity monitoring	Forest fire detection	Target tracking	Smart roads	Automobile	Sports
Delivery requirements	RT	RT	RT & NRT	RT & NRT	RT	RT
Directionality	Bid	Bid	Bid	Bid	Bid	Bid
Communication symmetry	Sym	Sym	Sym	Sym	Sym	Asym
End-to-end connection	Non-end-to-end	Non-end-to-end	Non-end-to-end	Non-end-to-end	Non-end-to-end	End-to-end & Non-end-to-end
Interactivity	Interactive	Interactive	Interactive	Interactive	Non interactive	Interactive
Delay tolerance	Delay tolerant	Delay tolerant	Non delay tolerant	Non delay tolerant	Delay tolerant	Non delay tolerant
Criticality	Mission-critical	Mission-critical	Mission-critical	Mission-critical	Non-mission-critical	Mission-critical

applications are real-time applications. However, only the telemedicine and target tracking applications are packet loss intolerant. This is because of the importance of the data being transmitted. The remaining real-time applications are loss tolerant except in the forest fire detection and automobile applications, since either data can be retransmitted or the reporting frequency is high enough to guarantee a reliable data delivery. The forest fire detection and automobile applications are delay tolerant and loss intolerant. The condition based monitoring, monitoring volcanic eruptions, smart factory, forest fire detection and automobile applications are tolerant to delay. Despite this fact, only the first two aforementioned applications are packet loss tolerant.

- **Modulation** - The most common modulation in the applications addressed in this work is FSK(DSSS), because it is easily supported by simple radio transceivers. However, in the condition based monitoring and target tracking applications, the applied modulation scheme is DSSS-O-QPSK, which is IEEE 802.15.4 compliant.
- **Communication direction** - The communication direction depends on the number of radio transceivers used. If the sensor nodes of the application utilize more than one radio transceiver (if they support full duplex). All the addressed applications are half-duplex, since only one radio transceiver is used in each sensor node.

Tables XIX and XX present the service components for the considered WSN applications. Details are as follows:

- **Type of traffic** - The applications addressed in this work exchange HID traffic, except for the condition based monitoring, forest fire detection, target tracking and automobile applications which only exchange LOD traffic as shown in the rows for the service components from Tables XIX and XX. Besides, the highway monitoring application includes the three types of traffic (LOD, MED, HID) and STV in which highway surveillance is supported by video streaming. The telemedicine application also includes STV traffic, since video streaming can also be transmitted.
- **Packet delivery failure ratio** - The packet delivery failure ratio QoS parameter is of paramount importance. All the applications present values lower than 10% for the PDFR parameter.
- **Data acquisition and dissemination** - All the stud-

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TABLE XIX
COMMUNICATION & TRAFFIC, SERVICE COMPONENTS, NETWORK AND NODE PARAMETERS FOR WSN APPLICATIONS (I).

	Application Area	**Metropolitan**	**Military**	**Environmental monitoring**	**Position & animals tracking**	**Industrial automation**	**Health**
	Project	Traffic Dot [83]	WiBeaM [85]	Reventador volcano [92], [93]	LEMe Room [107]	Anshan [119]	MEDiSN [121]
	Application	Highway monitoring	Condition-based monitoring	Monitoring volcanic eruptions	Immersive roam	Smart factory	Telemedicine
Communication & Traffic	**QoS**	Collective QoS (Event-Driven)	Collective QoS (Event-Driven)	Collective QoS (Event-Driven)	Collective QoS (Event-Driven)	Collective QoS (Event-Driven & Query-driven)	Collective QoS (Event-Driven)
	Bit rate (kbps)	$\leq$ 57.6	$\leq$ 57.6	$\leq$ 57.6	$\leq$ 57.6	$\leq$ 57.6	$\geq$ 115.2
	Latency	T_{min}= 1 s T_{max}= 2 s	T_{max}= 0.00867 s (per packet)	T_{max}= 63 s (per hop)	T_{max}= 3 ms	T_{min}= 80 ms T_{max}= 250 ms	T_{max}= 7-8 ms
	Synchronization	Sync	Sync	Sync	Sync	Sync	Sync
	Class of service	ISO&CBR	ISO&CBR	ISO&CBR	ISO&RT-VBR	ISO&CBR	ISO&RT-VBR
	Traffic classes	RT&LT&Data	DT&LT&Data	DT&LT&Data	RT&LI&Data	DT&LI&Data	RT&LI&Data
	Modulation	FSK(DSSS)	DSSS-O-QPSK	FSK	FSK(DSSS)	GFSK or MSK/OOK	FSK
	Communication direction	Half-duplex	Half-duplex	Half-duplex	Half-duplex	Half-duplex	Half-duplex
Serv. components	**Type of Traffic**	STV; LOD MED; HID	LOD	HID	HID	HID	STV; HID
	Packet delivery failure ratio	1% (max.)	9%	4.96%	N.A.	$\leq$10%	6.3%
	Acquisition & dissemination classes	Event-driven	Event-driven	Demand-driven & event-driven	Demand-driven & event-driven	Event-driven & time-driven	Demand-driven & time-driven
Network	**Lifetime (h)**	$\geq$ 25920	[721; 25920]	[24; 720]	[24; 720]	$\geq$ 25920	N.A.
	Scalability	[51; 400] nodes	$\leq$50 nodes	$\leq$50 nodes	$\leq$50 nodes	$>$ 400 nodes	$\leq$50 nodes
	Density	N.A.	N.A.	3 km^2	450 m^2	3000 m^2	N.A.
	Sensing range	N.A.	Local	Local	2 m^2	$<$ 1 m^2	local
	Self-organization	Entire network	Entire network	Entire network	Entire network	Entire network	Entire network
	Security	Low	Low or none	Low	Medium	None	None
	Addressing	Address-centric: MAC address	Address-centric: MAC address	Address-centric: MAC address	Address-centric: node ID	Address-centric: node ID, group ID, cluster ID	Address-centric: address number
	Programmability	Not programmable	Not programmable	Not programmable	Programmable	Not programmable	Not programmable
	Maintainability	Maintainable	Maintainable	Maintainable	Not maintainable	Maintainable	Not maintainable
	Homogeneity	Heterogeneous	Heterogeneous	Heterogeneous	Heterogeneous	Heterogeneous	Heterogeneous
	Mobility support	No support	No support	No support	Support	No support	Support
Node	**Microprocessor**	ATMEL (ATMega 128L)	TI (MSP430F1611)	ATMEL (ATMega 128L)	ATMEL & Microchip (ATMega 128L) & (PIC16F872)	ATMEL (ATMega 128L)	TI (MSP430F1611)
	Transceiver	CC1100	CC2420	CC1000 (433 MHz)	CC1000 (900 MHz)	CC1100 (433 MHz)	CC2420
	Overall energy consumption	0.01044 A	0.0612 A	0.038 A	0.0520 A	0.072503 A	0.040955 A
	Sampling rate	[100; 1000] Hz	>1 kHz	[100; 1000] Hz	>1 kHz	[100; 1000] Hz	[0.001; 100] Hz
	Type of function	Sensor & sink	Sensor & sink	Sensor & sink	Sensor & sink	Sensor & sink + gateway	Sensor & sink
	Communication range	5.5 m	10 m	10.7 m	305 m	$<$ 100 m	$>$ 5 m
	Power supply	Battery	Battery	Battery	Battery & local supply	Battery	Battery

ied applications from the acquisition and dissemination classes are event-driven or a combination of event-driven with another class. Only the telemedicine application corresponds to a demand-driven and time-driven class. Telemedicine only transmits data on demand (or by following a defined reporting frequency).

The network parameters presented in Tables XIX and XX facilitate to understand the impact of the choice of certain attributes or values for the parameters from Tables XVII and XVIII, respectively. Details are as follows:

- **Lifetime** - Highway monitoring, smart factory and structural integrity monitoring present the longest lifetime, even though presenting a real-time delivery, which can be misleading to assume the ones with the highest energy consumption. These applications present a long lifetime because of the low reporting frequency (i.e., ultra low

TABLE XX
COMMUNICATION & TRAFFIC, SERVICE COMPONENTS, NETWORK AND NODE PARAMETERS FOR WSN APPLICATIONS (II).

	Application Area	Civil engineering	Environmental monitoring	Logistics	Transportation	Automobile	Sports
	Project	Sustainable Bridges [91]	FireBug [100], [101]	VigilNet [104] Trio [105]	AstroRoads [112], [113]	Intelligent Tires [114]	DexterNet [129]
	Application	Structural integrity monitoring	Forest fire detection	Target tracking	Smart roads	Automobile	Sports
Communication & Traffic	**QoS**	Collective QoS (Event-Driven)	Collective QoS (Event-Driven & Query-driven)	Collective QoS (Event-Driven)	Collective QoS (continuous) individual specific	Hybrid model	Collective QoS (Event-Driven)
	Bit rate (kbps)	$\leq$ 57.6	[57.6; 115.2]	$\geq$ 115.2	$\leq$ 57.6	$\leq$ 57.6	$\geq$ 115.2
	Latency	T_{min}= 400 ms T_{max}= 1500 ms	T_{min}= - T_{max}= 2 s	T_{min}= - T_{max}= -	T_{min}= - T_{max}= 130 s	T_{min}= - T_{max}= 2.9 s	T_{min}= - T_{max}= -
	Synchronization	Async	Sync	Sync	Sync	Sync	Sync and Async
	Class of service	ISO&RT-VBR	ISO&CBR	ISO&RT-VBR	ISO&RT-VBR	ISO&CBR	ISO&RT-VBR
	Traffic classes	RT&LT&Data	DT&LI&Data	RT&LI&Data	RT&LT&Data	DT&LI&Data	RT&LT&Data
	Modulation	FSK(DSSS)	FSK	DSSS-O-QPSK	FSK(DSSS)	FSK(DSSS)	DSSS-O-QPSK
	Communication direction	Half-duplex	Half-duplex	Half-duplex	Half-duplex	Half-duplex	Half-duplex
Serv. components	**Type of Traffic**	HID	LOD	LOD	HID	LOD	HID
	Packet delivery failure ratio	-	-	1%	0.1%	4%	-
	Acquisition & dissemination classes	Event-driven & Time-driven	Event-driven & Time-driven	Event-driven	Event-driven & event-driven	Event-driven & & time-driven	Event-driven
Network	**Lifetime (h)**	$\geq$ 25920	[24; 720]	[721; 25920]	N.A.	[24; 720]	N.A.
	Scalability	N.A.	$\leq$ 50 nodes	$>$ 400 nodes	$\leq$ 50 nodes	$\leq$ 50 nodes	$\leq$ 50 nodes
	Density	-	3 km^2	50 km^2	N.A.	0.17 m^2	16 m^2
	Sensing range	10-52 m^2	Local	200 m^2	N.A.	$<$ 1 m^2	$<$ 1 m^2
	Self-organization	Entire network	Entire network	Entire network	Entire network	Entire network	Entire network
	Security	Low	Low	None	None	None	None
	Addressing	Address-centric: MAC address	Address-centric: MAC address	Address-centric: MAC address	Address-centric: node ID	Geographic addressing scheme	Address-centric: node ID
	Programmability	Programmable	Not programmable	Programmable	Programmable	Not programmable	Programmable
	Maintainability	Maintainable	Maintainable	Maintainable	Maintainable	Maintainable	Maintainable
	Homogeneity	Heterogeneous	Heterogeneous	Heterogeneous	Heterogeneous	Heterogeneous	Heterogeneous
	Mobility support	No support	No support	No support	No support	Support	Support
Node	**Microprocessor**	TI (DSP 8-bit)	ATMEL (ATMega 128L)	TI (MSP430)	ATMEL & Microchip (ATMega 128L)	ATMEL (ATMega 128L)	ATMEL (ATMega 8)
	Transceiver	CC2420	CC1000	CC2420	CC1000	CC1000	CC2420
	Overall energy consumption	0.053 A	0.036 A	0.0351 A	0.045 A	0.0346 A	0.0289 A
	Sampling rate	$>$ 1 kHz	[100; 1000] Hz	[0.001; 100] Hz	N.A.	N.A.	[0.001; 100] Hz
	Type of function	Sensor & sink	Sensor & sink	Sensor & sink + gateway	Sensor & sink + actuator	Sensor & sink	Sensor & sink + gateway
	Communication range	10-30 m	10.7 m	125 m	305 m	140 m	10 m
	Power supply	Battery	Battery	Battery Solar panel	Battery	Battery	Battery

duty cycles). The remaining applications present short or medium lifetime, due to the high or medium reporting frequency. These higher reporting frequency correspond to more energy drain.

- **Scalability** - Outdoor applications (e.g., highway monitoring and target tracking) present the highest level of scalability, while the ones related with indoor environments present the lowest scalability. Despite this fact, some indoor deployments applications present high scalability, in order to better cover the indoor environment.
- **Self-organization and homogeneity** - The self-organization and homogeneity parameters are equal in all the presented applications.
- **Security** - The applications shown in Tables XIX and XX

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present minimum security level or even no security. This is justified by the increased complexity that is added to the WSN when a security mechanism is considered (along with the increase of the energy consumption). Only the immersive roam application presents medium security level, since it is a recent application.

- **Addressing** - All the applications consider an addressing scheme based on ID's, except the automobile application, which relies on geographic addressing.
- **Mobility support** - There are applications that require an adaptive mechanism (mobility support) to handle changes in the network due to the sensor or coordinator nodes movement. From the analyzed applications, immersive roam, telemedicine, automobile and sports applications include mobility support, since the devices can move around within the environment.

Finally, Tables XIX and XX also mention important values and attributes for the node parameters, such as the type of microprocessor, type of power supply and radio transceiver, and give an appropriate range of possible attributes or values that are expected for each application. The overall values presented for the energy consumption for the corresponding hardware and parameter configuration of an application are only indicative. Details are as follows:

- **Microprocessor** - In off-the-shelf sensor node solutions, the microprocessors more commonly used are the ones from the ATMEL brand but Texas Instruments (TI) microprocessor are also considered. Details are given in Table V from subsection III-E.
- **Transceiver** - As aforementioned, the chosen modulation depends on the type of radio transceiver used in the envisaged application. Applications that use the CC2420 radio transceiver are compliant with IEEE 802.15.4, while the remaining ones are non-compliant. It is worthwhile to mention that CC2420 is able to support real-time video [132], [133], e.g., in the telemedicine application from the MEDiSN project [121].
- **Sampling rate** - Since the sampling rate is deeply related with the application lifetime, higher sampling rates generally correspond to applications with shorter lifetime. On the other hand, the ones with low sampling rate may lead to longer lifetime (note however that the sampling rate is not the only parameter that influences the lifetime of a sensor node).
- **Type of function** - In these projects, the sensor nodes perform mainly simple sensor and sink tasks. In some cases, there is a sink with extended capabilities that allows for connecting the network to the Internet. In the smart roads application the sensor node can also actuate a device, beyond the normal tasks of sensing and reporting data to the sink node.
- **Communication range** - The communication range considerably depends on the type of radio transceiver, the transmission power and frequency band. The applications that utilize a radio transceiver with a low frequency band have a wider communication range.
- **Power supply** - All applications use batteries as the power supply for the sensor nodes, except for the sink node with extended processing capabilities (e.g., immersive roam). In target tracking, energy harvesting devices are used (i.e., solar panels jointly with batteries).

V. WSN Applications Roadmap and trends

This section discusses the chronological evolution for all the highlighted WSN areas for the past 10 years. Key approaches from relevant projects are addressed. The intention is to provide a significant evidence of the usefulness of WSNs in various areas. In fact, it is difficult to identify one application area that cannot benefit from the WSN technology. In addition, the evolution path towards new WSN application areas is discussed together with future trends. Figure 9 organizes the considered WSN applications from Tables IX and X in a chronological manner. The WSN projects considered in this taxonomy are ordered by their duration (*xx* axis) and category, either CW1WSNs or CW2WSNs (*yy* axis). It is worthwhile to note that the majority of the surveyed WSN projects occurred between 2004 and 2008. New WSN projects and future trends on WSN applications are also presented in Fig. 9.

By analysing Fig. 9 and the different parameters in Tables XVII, XVIII, XIX and XX, it is possible to organize WSN applications into three generations.

The first generation (1G) of WSNs is characterized by applications that are considered as isolated and self-contained systems with a WSN gateway (i.e., sink node) as the only node that interacts with the user. In other words, the network centralizes all the data to a central node which delivers the information to the user. The main requirements for the 1G of WSN applications are the following ones:

- Non-real-time delivery is required;
- Non-end-to-end connection;
- Mission criticality is absent;
- No QoS support;
- Simple interaction;
- Low data rate;
- No security;
- Reduced scalability;
- Reduced lifetime;
- No mobility support;
- Mainly employ the event or time-driven data acquisition model;
- Simple hardware.

The habitat monitoring application (from the environment monitoring area) is a representative example.

As the market needs and technology continue to evolve, new challenges have been posed to the field of WSNs, and the second generation (2G) of WSNs emerged. 2G is characterized by heterogeneous WSNs, whose sensor networks are seen as service providers. Additionally, the interaction over Internet is enabled, in order to offer a richer and more complex set of services and information to the end users [134], [135], [136]. The main requirements for the 2G of WSN applications are the following ones:

- Support of real-time applications;
- Need for more robust system operation;

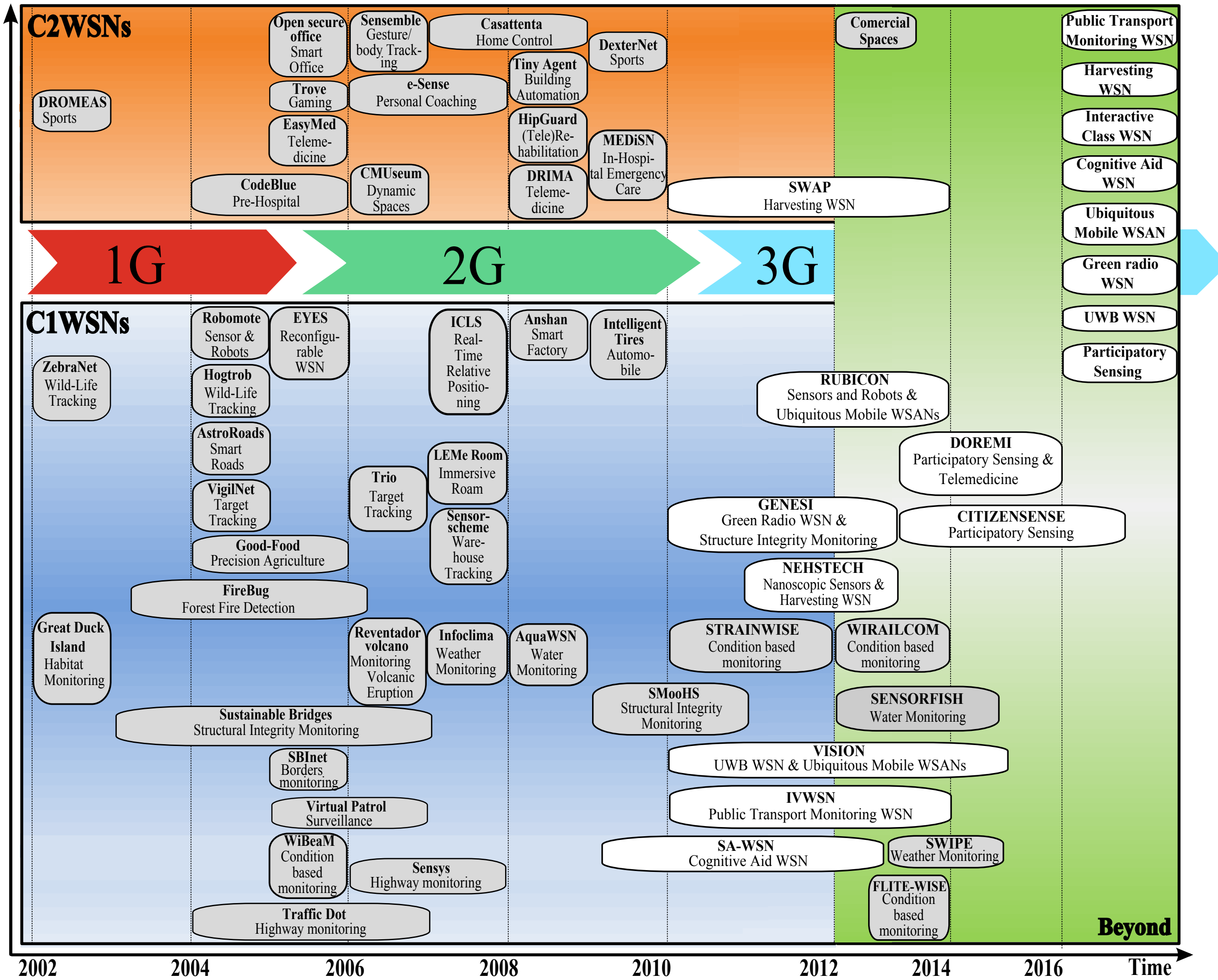

Fig. 9. WSN applications roadmap and future trends (white background boxes are the examples of 3G beyond projects).

- Support for heterogeneous networks;
- Inclusion of security support and mechanisms;
- Privacy;
- Control and actuation;
- Support of different types of traffic sources;
- QoS support;
- Mission criticality support;
- End-to-end connection support;
- More complex and more efficient hardware;
- High data rate support;
- Interaction with feedback (when actuation is involved).

As the years pass by, the popularity of WSNs and Machine-to-Machine (M2M) communications has been growing. This evolution has brought up this new class of network traffic [137]. WSNs benefit from the increase in the mobile network penetration over the world as well as the increase in the complexity of the mobile devices. This is achieved by extending the functionalities of each mobile phone, allowing for sensing and gathering information from the environment surrounding the mobile phone user [138], [139], [140]. The M2M communication can be used to connect individual machines and devices over Internet and mobile networks. As such, mobile network operators may offer services that facilitate the use of M2M over mobile networks, while generating additional profit. Until the second generation of WSN applications, the networks did not have suitable openness to the common user. Only experts were able to manipulate and change the WSN behaviour and functionalities. Currently, there is a need for new WSN applications to open up WSNs. This need motivates the creation of macroprogramming frameworks, in order to provide a set of standardized interfaces solutions, services and protocols that allow for an easier interaction between devices in a heterogeneous network, whilst facilitating the role of the applications designer. By opening up WSNs a more reliable and easier integration of WSNs with higher layers networks in the hierarchy will be possible. This integration facilitates the creation of new services whilst enhancing solutions for smart cities, smart homes and smart roads. This new class of network traffic corresponds to the third generation of WSNs (3G), in which the term *things* is introduced, referring to different devices with a unique identification. The communication between *things* drives the need of having traffic characteristics

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different from the traditional human-centric communications.

It is expected, as stated before, that M2M and WSNs services use other wireless or communication technologies as a backhaul. This conceptual scenario is known as the Internet of *Things* (IoT) [141], which has evolved from the convergence of wireless technologies, Micro-ElectroMechanical Systems (MEMS) and the Internet to the level of ubiquitous computing. The IoT delivers one of the most important and envisioned novelties of 3G applications: the inclusion of context information awareness about the surrounding environment, whilst making it available to all users in a traditional manner, like the nowadays Internet services availability. These new WSN applications will be connected with *things* to the Internet, by means of mobile network technologies, which serve as a backbone. Since the new WSN applications will be more Internet-dependent via mobile networks, the operators should reinforce their mobile structures in order to support the new kind of traffic class generated by WSNs, machines and, in general *things*. This is an important aspect since the number of *things* is expected to grow significantly [142], [143], and soon will exceed the number of mobile phone human subscribers.

The 3G of WSN applications (compared with the previous ones) includes all the requirements from 2G plus the new features that have been highlighted before.

Examples of third generation WSN applications also include the heating, ventilation and air-conditioning control (HVAC) applications. HVAC encompasses the monitoring and control of industrial and residential buildings over Internet. These applications are part of smart cities, a 3G scenario in WSN applications. In smart cities, mobile networks work as the backbone that allows for remotely monitoring and controlling buildings with no fixed communication link. The public transport monitoring WSN is also an important part of the smart city concept (e.g., [144]).

The educational application is another 3G WSN area, more specifically the Interactive class room application. This type of application typically sends periodic updates containing a small amount of data [145].

Other types of WSN applications are related with cognitive radios. The authors from [146] present a study to classify the existing literature of this fast emerging Cognitive Radio Wireless Sensor Networks (CRWSN) application area, where they highlight the key research in CRWSN that has already been undertaken, and analyze open problems in the field. A cognitive radio is able to behave, in a certain manner, as a cognitive system, meaning that it has, at least, capabilities of observing, decision making, and adapting. Since, the licensed spectrum allocation approach is regarded as old fashioned, due to the static resource allocation, which leads to spectrum inefficiency, cognitive radios improve spectrum utilization by seeking and opportunistically utilizing radio resources on a real-time basis in the time, frequency, and space domains. The emergence of the cognitive radio technology results in inumerous advantages for WSNs, including economic benefits, as well as solving coexistence, interference management and interoperability issues. Several works have addressed cognitive radio issues in the context of WSNs, including spectrum sensing, coexistence mechanisms, environment awareness, etc. An example of a WSN application with cognitive capabilities is the cognitive aid WSN application [147]. It senses all the traffic from a higher network layer system (e.g., 3G network) and transmits the sensed data to the base station, in order the mobile network is able to tweak its quality parameters. Here, the WSN alleviates the base station in terms of traffic quality assessment, increasing the efficiency of all the mobile network whilst reducing the energy consumption from the base station. Another application area related to the cognitive radio networks is the Ultra-Wideband (UWB) WSN. The project VISION [148] is an example of application for this area. The work from [149] joins together the research undertaken in the COST "TERRA Action [150], with contributions from Working Groups 1 and 2, addressing the use of cognitive radios in the context of medical body area networks applying the UWB radio technology.

Another 3G WSN application area is the ubiquitous mobile WSAN [116], [148]. This application area enables WSNs with sensing and actuation capabilities to interact with ubiquitous computing, leading to a variety of applications with pervasive physical world instrumentation requirements (e.g., environment monitoring, logistics, smart buildings, etc). In order to support the required sustainability, mobility, scalability, and dynamic adaptation of the application, several domains that are common in the first generation WSN are now re-modelled or re-designed.

Green radio communications will facilitate an efficient energy utilization in Information and Communication Technology (ICT) platforms (e.g., Internet or mobile or wireless technologies) that support 3G WSNs. Associated to green radio communications is the harvesting WSN applications that employ harvesting devices in the sensor nodes to scavenge for energy from different types of sources (e.g., solar, thermal, kinetic, etc) [151], [152].

Participatory sensing is also a new type of WSN application which makes use of everyday mobile devices (such as mobile phones), to form an interactive and participatory sensor networks, by enabling public and professional users to collect, analyze and share knowledge from a specific location (e.g., [153], [154]). The objective is to allow people to be more aware of the surrounding environment where they are inserted in, while allowing participation at a personal, social and urban scales. This leads to a higher public concern and a higher conscious awareness [139], [140]. The five main applications areas of participatory sensing are the following ones: urban planning, public health, cultural identity, creative expression, and natural resource management.

Although the different WSN applications are spreading to new areas, the market for short-range, low power RF technologies in the 2.4 GHz ISM band is far from achieving maturity. As a consequence, the new WSN applications are limited to the constraints imposed by the short-range transceivers hardware. The authors from [142] foresee that healthcare and personal fitness are going to be the areas where the low energy chips will be more frequently used. In the context of the Internet of *Things,* tiny Ultra Low Power (ULP) transceivers allow for thousands of devices to communicate while increasing the usefulness of each device. The authors from [155] propose

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four enablers to the Internet of *Things*:

- **Tagging things** - enables real-time wireless/contactless identification and tracking;
- **Sensing things** - enables detection of environmental status and collection of varied data on physical parameters (velocity, presence of foreign objects, temperature, moisture);
- **Shrinking things** - smaller but smarter devices facilitates building intelligence into the edges of the network, and even in materials themselves;
- **Thinking things** - makes possible the networking of smaller and smaller objects.

Embedded intelligence (such as smart cities, and so on), real-time monitoring (medical applications and environmental management), augmented reality and new Internet (Web 3.0) are certainly the major complimentary technologies to look forward to [155]. In a context of convergence among different wireless communication technologies (GSM, 3G, WLAN, WiMAX, LTE), product identification solutions (barcodes, RFID), process control (WSNs, home automation) and network interconnection (Ethernet, Internet) will be a reality.

VI. Conclusions

The available information about the classification and characterization parameters of WSN applications from different areas has been put together enabling to obtain insights about possible applications requirements or possible outcomes from a specific WSN application area. This paper organizes a huge amount of information from different authors and projects for the broad spectrum of WSNs applications classification and characterization parameters. It fills the gap in the WSN literature by providing a holistic overview of the relations between different categories of characterization parameters, with the same value for certain set of parameters. The identified characterization parameters are divided into six categories, namely service, communication & traffic, service components, network, node, and operation environment(s), where a set of parameters is defined for each group of characteristics. We propose inter- and intra-connections among the proposed application groups. As the fields of application from WSNs continue to evolve, these connections facilitate to understand how the applications similarities (or differences) may justify the ability to derive new groups of applications. We are able to identify some common features between characterization parameters, enabling to organize WSN applications of different areas into the proposed categories, based on the combination of the different parameters' attributes.

The first group considers the time related constraints of the application, which sub-divides into Long-Term Applications (LTA), Medium-Term Applications (MTA) and Short-Term Applications (STA). The LTA category considers the applications with large lifetime and high scalability whilst considering low or medium event-driven models. The STA category is defined by limited lifetime and small scalability whereas applications from the MTA category present medium lifetime and scalability.

Applications that consider data stream related constraints are aggregated into the second group and can be classified as High Data Stream (HDS), Medium Data Stream (MDS) or Low Data Stream (LDS). On the one hand, applications from the HDS category are associated to high bandwidth and bit rate. The applications from the MDS category typically monitor events or the user. On the other hand, applications from the LDS category consider low bit rate and exchange LOD traffic. Generally, LDS applications consider low frequency events reporting.

Another group of applications considers the delivery requirements and delay sensitivity of the applications and is sub-divided into Real-Time & Sensitive Delay Demanding Applications (RT-SDD) and Non-Real-Time & non Sensitive Delay Demanding Applications (NRT-nSDD). Requirements from the RT-SDD category comprise the real-time delivery jointly with the support of mission-critical communications which tolerate some amount of delay. The NRT-nSDD category aggregates WSN applications which rely on the queries delivery model and allow packet loss and delays.

From our analysis WSN applications that belong to the MDS or LDS category also belong to the LTA and MTA categories. Applications from LDS category are associated to the majority of WSN applications from the NRT-nSDD category whereas applications from the MDS and HDS categories are shared with the RT-SDD category. Besides, it is worthwhile to mention that the real-time requirement from the RT-SDD category is usually associated to higher bandwidth requirements.

We have also discussed and pointed out the new WSN trends on ongoing research in the different areas of WSN applications, which gives the application designer a holistic and promising guideline. In addition, we provide/propose a detailed table concerning the System on a Chip (SoC) characteristics for a specific microcontroller, jointly with a reference to the sensor node platform that employs the microcontroller. This aids the application designer to better plan the usability of the microcontroller/platform for a WSN evolution application by knowing *a priori* the characteristics from the microcontroller, as well as the sensor node platform.

Newer WSN applications take into account a new paradigm in terms of ubiquitous computing as well as the inclusion of context information awareness. Examples of the new WSN trends involve the so-called smart-cities where all the elements that compose the city are inter-connected and are aware of the function and task from each other. Other new WSN application areas consider the carbon footprint from telecommunication systems, while envisaging to mitigate this environmental impact by associating energy harvesting devices to sensor nodes, aiming at scavenge energy from different types of sources in the environment. Since technologies are increasingly involving the users, other trend in WSNs is participatory sensing, which makes use of everyday mobile devices to form an interactive and participatory sensor network. This involvement increases people awareness on the surrounding ambient, leading to a higher public concern from a specific subject, as well as a higher conscious awareness.

By characterizing WSN projects over the period of 2001-2016, a chronological comparison is presented for existing

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projects in all the highlighted areas, along with the evolution path towards new WSN application areas and future trends. Three generations have been identified based on the vast identification of the fields of WSN applications as well as on the proposed taxonomy. The first generation is characterized by applications within isolated and self-contained systems with a sink node. The second generation is characterized by heterogeneous WSNs, where sensor networks offer a richer and more complex set of services and information to the end users. This new class of network traffic gives the ground to bring to light the third generation of WSN, along with communication between *things*, with traffic patterns different from the traditional human-centric communications. This is known as the Internet of *Things*.

Overall, our aim is to motivate for emerging WSN applications industry opportunities and challenges. This work will certainly help application designers/engineers to find the most suitable hardware and software solutions as well as the *a priori* knowledge of the range of variation for the parameters, facilitating deployment of WSNs and an appropriate development of 3G & beyond WSN applications.

VII. Acronyms

Acronym	Definition
ABR	Available Bit Rate
AMB	Sound Ambient Traffic
ASK	Amplitude-Shift Keying
BER	Bit Error Rate
BPSK	Binary Phase-Shift-Keying
C1WSNs	Category 1 WSNs
C2WSNs	Category 2 WSNs
CBR	Constant Bit Rate
CRWSN	Cognitive Radio Wireless Sensor Network
DSSS-O-QPSK	Direct Sequence Spread Spectrum-Offset-Quadrature Phase-Shift Keying
DT	Delay Tolerant
ED	Event Detection
FDD	Frequency-Division Duplexing
FDX	Full Duplex
FN	Forwarder Node
FSK	Frequency-Shift Keying
GFSK	Gaussian Frequency-Shift Keying
GSM	Global System for Mobile Communications
HDS	High Data Stream Applications
HDX	Half Duplex
HID	High-Rate data
ICT	Information and Communication Technology
ISO	Isochronous Traffic
IP	Internet Protocol
ISM	Industrial, Scientific and Medical
LDS	Low Data Stream Applications
LI	Loss Intolerant
LOD	Low-Rate Data
LT	Loss Tolerant
LTA	Long-Term Applications
LTE	Long-Term Evolution
M2M	Machine-to-Machine
MAC	Medium Access Control
MDS	Medium Data Stream Applications
MED	Medium-Rate Data
MEMS	Micro-ElectroMechanical Systems
MS	Multimedia Streams
MTA	Medium-Term Applications
MWSN	Mobile Wireless Sensor Networks
NISO	Non-Isochronous traffic
NRT	Non-Real-Time
NRT-nSDD	Non-Real-Time & non Sensitive Delay Demanding Applications
OOK	On-Off Keying
OS	Operating System
PDA	Personal Digital Assistant
PE	Process Estimation
PS	Protocol Stack
QoS	Quality of Service
QPSK	Quadrature Phase-Shift Keying
RFID	Radio-Frequency Identification
RT-VBR	Real Time-Variable Bit Rate
RN	Repeater Node
RT	Real-Time
RT-SDD	Real-Time - Sensitive Delay Demanding Applications
SNR	Signal-to-Noise Ratio
SoC	System on a Chip
SPX	Simplex
SR	Sampling Rate
STA	Short-Term Applications
TI	Texas Instruments
TDD	Time-Division Duplexing
UBR	Unspecified Bit Rate
ULP	Ultra Low Power
UWB	Ultra-WideBand
VM	Virtual Machine
VOI	Voice Traffic
WLAN	Wireless Local Area Network
WiMAX	Worldwide Interoperability for Microwave Access
WMSN	Wireless Multimedia Sensor Network
WSN	Wireless Sensor Network
1G	First Generation of WSN
2G	Second Generation of WSN
3G	Third Generation of WSN

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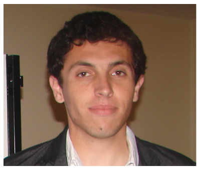

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