Architectural Classification for the Design of Wireless Sensor Networks

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***Abstract*— In the recent years, the diversification of wireless sensor network (WSN) applications has made the design space of such networks very large. This poses numerous challenges to researchers and increasingly great difficulties for designers to make decisions regarding proper technical solutions. As a result, before any design implementation, it is essential that wireless sensor networks be subject to rigorous analysis. This paper provides an original contribution to this analysis by classifying wireless sensor network applications with respect to their functional properties. Five distinct general classes of wireless sensor networks are thus derived: body area sensor networks, data collection networks, location-sensing networks, multimedia sensor networks and control-oriented sensor networks. For each class, we give illustrative applications, discuss in detail specific features and characteristics, and describe general architectural functionalities and some of their technical implications such as power consumption, network topology, data delivery model and quality of service. This classification would benefit the WSN research and industrial community and lays a groundwork for further study in the WSN area.**

I. Introduction

In many research papers [1], [24], [3], a wireless sensor network (WSN) is defined as a large-scale, ad hoc, multi-hop, unpartitioned network of largely, homogeneous, small, resource-constrained, mostly immobile sensor nodes that would be randomly deployed in an area of interest. While this definition is certainly valid for a large class of applications (in particular from the military domain, which originally promoted WSNs), now, an increasing number of WSN applications cannot be adequately defined in this way. Indeed, WSNs have witnessed a tremendous upsurge in the last decade due to their use in many civilian application areas, including environment and habitat monitoring, healthcare applications, home/industrial automation and control, precision agriculture and inventory tracking as surveyed in [11]. As a result, giving a precise definition of wireless sensor networks is not an easy task, and the literature on the subject does not provide a unified view of the concept.

Faced to this general trend of diversification, large amounts of research being done in the WSN area are trying to provide useful tools and design methods in order to implement efficient wireless sensor networks. As a consequence, different technical solutions are proposed according to two approaches: application-specific approach and generic approach.

On one hand, in application-specific approach, a technical solution is application-driven, that is, it carries only the requirements actually needed by the application. This approach is encouraged by device resource constraints, which impose application-specific optimization. It is acceptable when devices are inexpensive and numerous enough, so that a specific solution could be dedicated to a specific application. However, the wide range of potential applications would lead to proprietary and expensive technical solutions. Additionally, if a little modification impacts the application requirements, then the envisioned solution would be no longer optimized.

On the other hand, the generic approach, which provides a technical solution on a common basis to a large broad of applications, can be motivated by the fact that several sensor applications sometimes share a subset of requirements. Practically, this can be achieved for example by developing a modular hardware architecture with different low layer protocols and basic services. Then a software level could be just built on, and adapted to fit each specialized application requirement. ZigBee consortium [15] has followed this approach by specifying high layer protocols over the IEEE 802.15.4 standard for WPAN. This is also the adopted approach by the e-SENSE project [6], which aims to provide building blocks for generic WSNs. Such an approach might not only prove helpful as a framework for flexible WSN design, but might also reduce costs by constructing new specialized applications from an off-the-shelf spectrum of modular hardware and software architectures. However, this increases the system complexity, which is problematic in resource-constrained sensor networks, and therefore it is not a suitable way for designing tailor-made applications for which a customized solution is recommended in order to optimize specific networking mechanisms such as medium access control or routing.

Whatever the adopted WSN design approach, it is essential that WSNs be subject to rigorous analysis before any design implementation in order to assist designers in making better decisions regarding proper technical solutions. Many earlier recent research efforts have raised this vision. For example, Tilak *et al.* [22] describe WSNs from a networking point of view, classifying WSNs on the basis of communication and network parameters. Akyildiz *et al.* [1] give a survey on WSNs where they cover the architecture, communication protocols, and algorithms for different aspects of WSNs. An attempt to provide a general conceptual framework for characterizing the WSN design space is also suggested in [19], where a sensible set of dimensions of the design space such as cost, size, resource, energy, mobility, and deployment are individually discussed as well as their technical implications.

We realize that most of the work done on classifying WSNs is mainly based on hardware and application requirements. As the field of applications is very rich and evolves rapidly, this leads to various application-specific fine-grained classes, which poses difficulties for designers to make proper technical solutions. Therefore, which criteria have to be considered for an efficient spadework of WSN design? In this paper, we provide a classification of WSNs based on the following two principles. Firstly, the obtained classes should be coarse-grained and enable to find a tradeoff between the application-specific approach and the generic one. Secondly, these classes should be built on fixed criteria that are insensitive as well as possible to the wide range of application requirements, and hence covering all potential applications. Insight of these principles, we classify the large spectrum of WSNs into distinct classes with respect to their functionalities.

In the rest of this paper, we present five general classes of WSNs: wireless body-area sensor networks, wireless data collection networks, wireless location-sensing networks, wireless multimedia sensor networks and wireless control-oriented sensor networks. For each class, we first provide illustrative but not exhaustive scenarios and applications, pinpoint specific features and characteristics and describe general architectural functionalities and some of their technical implications. Finally, we conclude with some comments.

II. Wireless Body-Area Sensor Networks

One substantial class of WSNs consists in integrating multiple devices with sensor functionality inside a small-scale area called body[1] to provide a set of services to a user or machine. Typically, these devices can be placed strategically on a person/animal or embedded on a machine to measure one or more vital signs (*e.g.*, heart rate, oxygen saturation), context information (*e.g.*, position, activity) or physical parameters (*e.g.*, temperature, strain). These wearable/embedded devices setup a network that can monitor various vital/physical signs related to the body, enabling control and diagnostic procedures, optimal maintenance of a chronic condition or simply collection of data that can be utilized for knowledge discovery through data mining for instance. This special class of WSNs is called Wireless Body-Area Sensor Network (WBASN).

A. Scenarios and Applications

1) Health monitoring and homecare applications: Wearable sensor devices may be used to monitor health status of patients either in pre-hospital or in-hospital environments. They can be used to capture continuous, real-time vital signs like body temperature, blood pressure or heart rate. A number of

[1]Throughout this paper, body denotes alive being as well as machine.

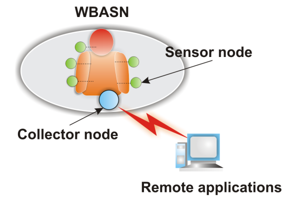

Fig. 1. Wireless body-area sensor network. To communicate with remote applications the collector node can employ WWAN or WLAN connectivity.

recent research efforts and projects focus on building wearable health monitoring wireless systems. The MobiHealth [26] is a promising health project funded by the European Commission to allow patients to be fully mobile while undergoing health monitoring. CodeBlue [14], a Harvard University research project, is also focused on developing wireless sensor networks for medical applications. The CodeBlue system includes wireless pulse oximeter sensors, wireless electrocardiogram (ECG) sensors, and triaxial accelerometer motion sensors. These sensors, when outfitted on patients in hospital or disaster environments, form a network to wirelessly transmit vital signs to healthcare givers, facilitating automatic vital sign collection and real-time triage.

2) Animal care applications: Sensor devices can be widely used to remotely monitor animal health. For example, in [21], bovines can be equipped with a suite of sensors for monitoring body temperature, blood oxygen saturation, respiratory rate, ambient humidity, etc. Data from these sensors are collected by a low-power, embedded unit worn in a cow bell or collar. They are then collated into a data stream that can be periodically uploaded wirelessly to a Bluetooth-compliant monitoring station.

3) Condition-based machine maintenance: Wireless sensor devices can be embedded inside machines to facilitate real-time monitoring and extensive data processing for machine maintenance. Previously, wired systems for machinery condition-based maintenance (CBM) suffer from limitations due the cost of wiring and the lack of flexibility. Using WSNs will allow to reach inaccessible locations, restricted areas and mobile assets. In [23], a wireless sensor network is implemented in order to continuously monitor manufacturing processes and equipments in a factory environment. For this purpose, sensor devices are attached to equipments and machines. They can measure machinery physical parameters or trigger required actions. Then they transmit these measurements to a server for collective data analysis, control, decision-making and storage.

B. Specific Features and Characteristics

From these illustrative applications, we point out specific features and characteristics of WBASNs. These specific characteristics directly affect the network architecture options. First, a WBASN consists of devices with sensor functionality, which are always confined in a small area with range of few centimeters to up few meters. Second, the number of devices can reach about 50. Third, the primary function of these devices is to measure physical/physiological signs related to the body, generating a sporadic/cyclic and application-specific traffic and providing real-time/offline feedbacks. Fourth, devices are always immobile, manually deployed at strategic parts of the body. Redundancy of devices is not often possible because of the small size of the body. Finally, to make useful the measured information, the WBASN can interact with external systems in close proximity.

C. Architecture Description

We propose here a general WBASN architecture. Independently of the end-application, there are two types of network nodes involved in this architecture (see Figure. 1). First, *sensor nodes* must satisfy several requirements such as minimal weight, miniature form-factor, low power communication and data processing, low cost and seamless integration to the WBASN. Sensor nodes have to perform vital signs or physical parameters sampling, analogue to digital conversion and then transmitting this data. Each sensor node can be implemented as a tiny patch or a wearable/embedded node integrated into different parts of the body. Second, the *collector node*, which interfaces WBASN sensor nodes, should have more complex capabilities in terms of processing, communication and storage. It can be wearable/embedded on the body like sensor nodes, handheld or simply in close proximity of the body. The collector node can be implemented on a PDA, a cell phone or a computer.

The collector node configures, manages and controls the WBASN. The network configuration encompasses the following tasks:

- Sensor node registration (type and number of sensor nodes)
- Initialization (specifying sampling frequency and mode of operation)
- Customization (running body-specific calibration or body-specific signal processing procedure upload)
- Setting secure communication if necessary

Once the WBASN is configured, the collector node manages the network, taking care of channel sharing, time synchronization and data retrieval and processing.

The collector node can be integrated into a broader system like a Wireless Local Area Network (WLAN) or Wireless Wide Area Network (WWAN). For example, to communicate with a remote server, the collector node can employ a mobile phone (2G, GPRS, 3G) or a WLAN to reach an Internet access point. In this case, the collector node collects data from sensor nodes and sends real-time reports to the external system (*e.g.*, telemedical system) where data can be integrated into useful applications for analysis, control and storage. However, if a link between the collector node and the external system is not available, the collector node should be able to store the data locally and initiate data uploads when the link becomes available. This scheme allows full mobility of the body (*e.g.*, patient, animal in wild area) and enables logging sensory readings for later use and analysis. This is very useful in hostile field or outdoor environment where data is collected for later analysis.

D. Architectural Implications

- Network topology: Given that WBASNs are always confined in a small bubble, even when the collector node is not attached to the body but remains in close proximity, radio short-range communications are sufficient. Therefore WBASNs may have a single hop topology where each node is able to communicate with other node. In particular, sensor nodes can be organized in star topology where collector node acts like a master and sensor nodes like slaves. This is shown in Figure. 1. This topology can be either static or dynamic due to node variation (*e.g.*, when new sensor nodes are added).
- Data delivery model: In the proposed architecture, the primary traffic is in the upstream direction from the sensor nodes to the collector node, although the latter may occasionally generate certain downstream traffic for the purposes of query and control. Depending on specific applications, the delivery of upstream traffic may be event-driven, continuous, query-driven or hybrid [22].
- Quality of service: Generally WBASN applications require low data rate. For example, consider a modest WBASN consisting of one tri-axis accelerometer operating at a 200 Hz sampling rate (16-bit samples) and an ECG sensor operating at 1 kHz (16-bit samples). The obtained data rates are 3.2 kbps and 16 kbps respectively. Thus the minimum bandwidth the system must support is 18.2 kbps. However, because the information communicated is status information, required data rate changes slightly differently from application to another and in unpredictable way. This depends on the sample rate, the nature of operations (normal or urgent) and the measured signs.
- Power consumption: Sensor nodes have limited energy. As a result, it is important to maintain high energy efficiency in order to maximize system lifetime. However, in case of WBASN where operations can be handled in indoor environment (home, hospital, factory), constraints on system lifetime, *i.e.*, on power consumption, can be partially relaxed.

III. Wireless Data Collection Networks

In this section, we consider the Wireless Data Collection Network (WDCN) class, which encompasses systems allowing various end-applications and services to reach out into the physical world of sensors. The substantial functionality of this class of WSNs is to collect data sensed by sensor devices *spread out over an area of interest*. Application domains mostly include environmental and habitat monitoring and precision agriculture for instance.

A. Scenarios and Applications

1) Great Duck island sensor network: This is a WSN deployed on Great Duck island, USA, for monitoring seabird

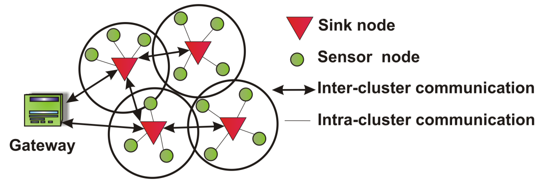

Fig. 2. A clustered distributed architecture for wireless data collection sensor network. Sink nodes act as cluster-heads.

nesting environment and behavior [13]. Many kinds of sensor nodes are installed inside burrows and the surface in order to measure environmental parameters (*e.g.*, humidity, temperature, ambient light) and to detect the presence of birds. Sensor nodes are deployed in clusters that are widely separated. Each cluster contains a special sensor node with long-range directional antenna that connects the cluster to a remote station. The latter is connected to a database back-end system via a satellite link. Thus, sensor readings are accessible to scientific via the Internet.

2) GlacsWeb system: In order to understand climate change and its effect on sea level rise, a WSN is deployed in Briksdalsbreen glacier, Norway [16]. The system is composed of sensor nodes called probes deployed in drill holes at different depths in the glacier ice, a base station on the ice surface. Sensor nodes measure parameters like temperature, strain and pressure and transmit it to a base station. The latter measures supra-glacial displacements using GPS and transmits the data collected to a database in the university of Southampton, United Kingdom, via a GSM link.

B. Specific Features and Characteristics

Based on the above illustrative examples, a WDCN presents the following specific features and characteristics. First, a WDCN is composed of a large number of (potentially) heterogenous sensor devices ranging from tens, hundreds to thousands of nodes, and scattered with low duty cycle deployment over a physical area of interest (*e.g.*, forest, agriculture field, building) of size ranging from few meters to hundreds of kilometers. Second, the task of each sensor device is to sense environmental data (*e.g.*, light, temperature) primarily about its immediate surroundings, and to deliver these data to an end-application. Finally, an essential aspect of WDCNs is the tight coupling of the sensed data with time and space. This means that WDCNs, compared with other classes of WSNs, enable applications to observe the variation of a particular physical sign over a region of interest and during a period of time. In contrast to WBASN where generally only one sensor node is required to sense one particular physical sign, a WDCN features multiple sensor devices widely distributed to sense the same physical phenomenon.

C. Architecture Description

We describe in the Figure. 2 a general WDCN architecture. There are two types of nodes: *sensor nodes* and *sink nodes*. First, sensors nodes are small devices with limited capabilities in terms of storage, processing and communication. Sensor nodes can be numerous and are deployed in dense or sparse manner. The main functionality of a sensor node is limited to sensing the environment, generating readings, and transmitting the readings to a neighboring sink node. Depending on the size of the network and the covered area, sensor nodes can relay traffic for other sensor nodes. Second, sink nodes are devices with much greater capabilities than sensor nodes. They are deployed with fewer number or, in some cases, one single node per network might be sufficient. The main functionality of a sink node is to collect, process and control data issued from the whole network or from one particular group of sensor nodes.

Collected data may be delivered to a remote system where end-applications and services are implemented. This interaction can be ensured by a gateway between the WDCN and the remote system. This gateway must be equipped with high capabilities, enclosed in environmentally protected housing and provided with the adequate power. It communicates with other sink nodes and gathers sensed data from the whole WDCN. To provide the collected data to remote end-applications, the gateway may feature WLAN or WWAN connectivity and persistent data storage. This allows remote end-users to interact with a database located at the gateway. However, for on-site mobile users, a direct interaction with both sensor and sink nodes may be sufficient. This can especially arise during initial deployment or maintenance tasks. We can imagine a PDA-like device to enable such interactions.

D. Architectural Implications

- Network topology: Several topology options can be possible. It mainly depends on the size of the WDCN, the coverage area and the resource constraints. Clearly, as sensor nodes are assumed to be equipped with very limited energy supply, they can then only transmit data within short range. Conversely, sink nodes have more capabilities, therefore each sink node can act as a cluster-head and thus groups the sensor nodes in its vicinity into a cluster to form a sensing domain (Figure. 2). If sink nodes have to ensure connectivity to the gateway, there are then two possible ways. First, without energy constraints on sink nodes, this can be done by a single hop communications using another interface to limit interference. Second, if sink nodes are energy constrained, then sink nodes may not be capable of transmitting data to the gateway in one hop. Therefore, they should typically form a multihop network (the communication domain) by forwarding each other's messages until the gateway is reached.
- Data delivery model: A specific challenge in the envisioned architecture is the way to deliver data to end-applications. We can list three different data delivery models [22]. First, in the observer-initiated data delivery model, the end-application must formulate an interest and issue it to the WDCN. Each sensor node holding a data matching to this interest must report answers to the interest originator at the appropriate rates and

with the required accuracy. Second, in the event-driven model, sensor nodes report information only if an event of interest occurs. In this case and in contrast with the previous model, the observer is interested only in the occurrence of a specific phenomenon or a set of phenomena. Finally, in the continuous model, sensor nodes communicate their data continuously at a pre-specified rate. As a consequence, sensor nodes require periodically available resources to transmit their data.

- In-network processing: Unlike traditional networks where data are stored in a centralized location, in WDCN interesting data are distributed over a large area. Because of the node redundancy, data generated from different locations can be highly correlated. So, not all sensor node readings are of interest to the end-applications. As a result, data are processed in the network itself in various forms, which can consist in data aggregation, data filtering or data compression [11].
- Quality of service: In addition to traditional QoS metrics such as bandwidth, latency and packet-loss, WDCN supports specific QoS metrics. Indeed, what is relevant in data collection is the amount and the quality of information that can be extracted at a given sensing region about the observed objects or events. Thus, in general, end-applications require successful event detection, but not successful transmission of all messages.
- Power consumption: When deployed, a WDCN needs often to run for a long period ranging from few months up to several years. Thus, one technical challenge is how to minimize energy consumption in order to maximize system lifetime. Due to the low duty cycle deployment of WDCN, turning off some sensors node should not disturb operations. This observation can be exploited to reduce energy consumption by enabling sensor nodes to support multiple states of operations. Typical states are “active”, “idle” and “sleep” [8].

IV. Wireless Location-Sensing Networks

Despite their variety, all WSNs have unique basic features in common. Perhaps, the most essential feature is that they are embedded to the real world to sense a physical phenomenon such as temperature, pressure, light, strain and radiation. The measurements taken by the sensor devices are usually transmitted through wireless communications to other sensor devices to feed an end-application. Nevertheless, there are various WSN end-applications where the extracted information from the physical phenomenon are not the goal but rather a tool to infer another information of interest. This is typically the scope of one distinct class of WSNs called Wireless Location-Sensing Networks (WLSN), where the location of people, equipment and other tangibles seems to be the most relevant information required by the end-application.

A. Scenarios and Applications

1) The Cricket location-support system: This system [17] allows applications running on mobile and static nodes to learn their physical locations by using listeners that hear and analyze information from beacons spread throughout a building. It uses ultrasound emitters to create those beacons and RF signal for synchronization of the time measurement. The Cricket system helps devices to learn where they are by performing all their own triangulation computing. The system has decentralized management, control and computing. Consequently, it is the responsibility of the receiver to perform all the processing operations leading to a power burden. The Cricket system can accurately delineate 4×4 square foot[2] regions.

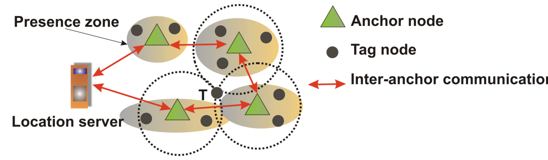

Fig. 3. Wireless location-sensing network. Tag node T is located with triangulation operations and simultaneously identified by 3 anchor nodes, whereas the other nodes are simply associated to presence zones.

2) Tag-ID based location systems: Some prototype systems use Radio Frequency IDentification (RFID) technology for location [5]. To be located, people or objects carry RFID tags that can be detected by one or several sensors called readers. Then, these sensors relay related measurements to a controller, which performs location computing. One very important feature of RFID systems is the power supply to the RFID tag. Passive RFID tags do not have their own power supply, and therefore all the required power must be drawn from the electromagnetic field of the sensor device. Conversely, active RFID tags incorporate a battery, which supplies all or part of the power for the operation of the RFID tag. The main advantages of RFID-based location systems are the low cost of tags (less than a 1 dollar for passive tags), small volume and very-low energy consumption. The main disadvantages are the short range ($\preceq$ 10 m) and the relatively high cost of the sensor devices.

B. Specific Features and Characteristics

WLSNs share the following specific features and characteristics. First, to be located, people or objects have to carry a device that provides their representation and a way to identify them. This device produces a physical phenomenon, which is sensed by sensor devices. The sensed physical phenomenon can be an emitted infrared (IR) signal, an ultrasonic wave, a visible light (video frames) or a radio-frequency (RF) signal. According to the used physical phenomenon, there are different advantages and limitations. For example, the line-of-sight requirement is one limitation of the use of IR in contrast to RF signal that copes with this limitation.

Second, WLSNs employ several techniques to infer the location information by exploiting the sensed phenomenon. Triangulation, scene analysis, and proximity are the three principal location techniques. Triangulation uses the geometric properties of triangles to compute locations [7]. It can

[2] 1 foot (ft)=30, 48 cm

be divided into two subcategories: lateration using distance measurement, and angulation using primarily angle or bearing measurement. Scene analysis uses the features of a scene observed from particular vantage point to draw conclusions about the location of the observer or objects in the scene. Proximity location technique consists in determining when an object is near a known location. These location techniques may be employed individually or in combination.

Third, WLSNs can generally provide two kinds of location information: physical and symbolic. Physical location requires more fine-grained information to determine the point P of the space where a device exists with a certain accuracy and precision. This is also called the position. When the WLSN computes positions of devices in relation to the same-shared reference, the position is called absolute whereas when each device has its own frame reference the position is called relative. Symbolic location encompasses areas such as corridors, rooms, shelves, and thus requires coarse-grained information.

C. Architecture Description

We illustrate in Figure. 3 a general architecture for WLSNs whose main goal is to locate different kind of entities. Although this architecture is independent on the sensed physical phenomenon, we consider only RF-based technologies that can be used for both communication and sensing. Three types of nodes are involved in this architecture: *tag nodes*, *anchor nodes* and the *location server*.

Tag nodes, which need to be located or to learn their own locations, should satisfy several requirements such as minimal weight, miniature form-factor, ultra-low power communication, data processing and storage. They induces an RF physical interaction to be used for both sensing and communications with anchor nodes. Tag nodes can be deployed in high quantities and in a redundant fashion over a large area of interest. They can be attached to or incorporated into a product, animal, or person to which they provide representation (*e.g.*, age, gender, expiry date) and a way to identify them. The RF physical interaction can occur periodically or only triggered in the vicinity of an anchor node.

Anchor nodes have higher capabilities than tag nodes in terms of communication, data processing and storage. They can be fixed and positioned at strategic sites (*e.g.*, facility entrance, store shelves, dock door, assembly line), plugged into electrical outlets or randomly deployed. When an anchor node is positioned at a strategic site, a presence zone should be defined around it. This presence zone represents the sensing domain of the anchor node within which a tag node can be detected and considered in proximity of the associated site. However, if anchor nodes are randomly deployed, *i.e.*, not necessary attached to strategic sites, then to locate tag nodes, it is necessary to compute anchor node positions in advance. This operation can be performed thanks to external positioning systems such as GPS [2] or GALILEO [4], which are not appropriate solutions in indoor environment. Otherwise when necessary, anchor node positions can be computed relying on an infrastructure-free method. This consists in determining positions step by step and propagating positions information from node to node provided that reference positions are known in advance. This requires more powerful anchor nodes with the ability to communicate with each other leading to a great impact on the design.

There are various ways to locate tag nodes spread over the area of interest. This depends on the nature of location information required by the end-application. First, if only a coarse-grained and symbolic location information is required, then the used location technique is based on proximity. Thus, a tag node detected at a presence zone will be recognized, identified and associated with this presence zone. Second, if a fine-grained and physical location information is required, *i.e.*, the position is needed, then the location technique is based on triangulation. In this case, each tag node being detected is simultaneously identified at least at 3 anchor nodes. Finally when necessary, it is possible that a tag node be able to learn its own location (position or symbolic location) by locally performing location operations. This poses an increasingly great design challenge.

The location server has higher capabilities than the other nodes. In case of a centralized architecture, it can monitor, manage and control all the anchor nodes. Thus, all location operations can be performed at the location server. These operations encompass the following essential tasks:

- Specification of the required location techniques
- Definition of presence zone characteristics
- Computation of anchor nodes positions
- Identification, tracking of tag nodes and location computing (positions or association with presence zone)

The location server may feature connectivity to broader systems like a datawarehouse for manufacturing control and materials management, a PABX for telephony call routing or a telemedical system for patients tracking. A promising use of this architecture can be in context-aware applications where devices react and adapt according to what is happening in their context, in particular to their location information [12].

D. Architectural Implications

- Network topology: When symbolic location information are required, an anchor node can act as a cluster-head, grouping all the tag nodes associated with its presence zone into a cluster. The network domain formed by all anchor nodes ensures that all the sensed information can be forwarded to the location server (Figure. 3). This can be done wirely or wirelessly in either a multihop or single hop fashion depending on the size of the network and the coverage area. However, when tag nodes positions are required, which means that a tag node is sensed at least at 3 anchor nodes, then no subnet partitioning is needed and a flat topology can be setup.
- Quality of service: Fidelity parameters like accuracy and precision characterize more significantly the quality of service in WLSNs. Accuracy measures how close to a true or accepted value the computed location lies while

precision is the degree to which further computed locations will show the same or similar results. QoS metrics can also encompass the number of tag nodes detected per anchor node and per time unit, the delay to propagate location information from node to node for location computing, and the induced overheads. Depending on the end-application, these metrics or their variants could be used. For example, anchor nodes may be used to regularly transmit update measurements to the location server for real-time tag node tracking. This kind of applications requires lower delay and higher bandwidth.
- Power consumption: By placing location computing operations on the location server, energy burden on anchor nodes decreases. It is possible to reduce more again energy consumption by enabling anchor nodes to support multiple states of operations. For example, if location sensing operations are only requested on demand, then the location server can make some anchor nodes in sleep mode and "wakes up" another when necessary [8].

V. Wireless Multimedia Sensor Networks

WSNs were initially devised as a collection of inexpensive, small, resource-constrained devices with the ability to communicate with each other wirelessly over a limited range. These stringent capabilities make physical scalar data (*e.g.*, temperature, pressure) the typical transmitted data in the network. This is fundamentally because handling higher amount of data would have required higher capabilities and more power consumptions.

Nowadays, with the availability of powerful codecs, inexpensive, tiny and very low power audio and video devices such as CMOS cameras and microphones [18], it is expected that in the near future, "traditional" WSNs be able to support multimedia data such as video and audio streams generated from the environment. This is the scope of Wireless Multimedia Sensor Networks (WMSNs). This class of WSNs will not only enhance existing applications such as tracking, security and environmental monitoring, but it will also enable several applications such as multimedia surveillance and emergency.

A. Scenarios and Applications

1) Multimedia surveillance and emergency applications: WMSNs can be used to enhance existing surveillance and emergency systems. A large number of camera-enabled sensor nodes can be deployed to extend the ability of authorities to monitor public areas and private properties. A WMSN can be also rapidly deployed by emergency groups exposed to hazardous situations in case of mass causality event (*e.g.*, earthquake, flood, chemical spill). Multimedia information such as voice or images can be then conveyed by the deployed WMSN from the disaster region to the emergency center.

2) Telepresence applications: WMSNs can be used to support telepresence applications. A telepresence system is a system in which the human uses of displays and body-operated remote actuators and sensors to control distant devices. It provides a virtual environment for humans to control devices (*e.g.* robots) in a hostile or remote real environment. One example, the JASON project [10], consists in deploying multimedia sensor nodes in inaccessible locations where the passage of too many people is harming the immediate environment or artefacts (*e.g.*, undersea exploration of coral reefs, ancient Egyptian tombs). This enables users to remotely explore these locations.

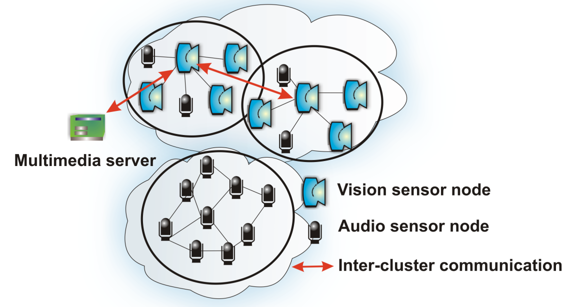

Fig. 4. Wireless multimedia sensor network. The top cloud depicts a multi-tier clustered network of heterogenous multimedia sensor nodes whereas the second one represents a mesh P2P network of homogeneous audio sensor nodes.

B. Specific Features and Characteristics

Several distinctive features make WMSNs different from other classes of WSNs. First, nodes in WMSNs are equipped with multimedia sensor devices that are able to ubiquitously retrieve multimedia content such as video and audio streams or still images from the environment. The amount of multimedia streams gathered in WMSNs can be higher. In addition, multimedia streams like images taken by camera-enabled sensor nodes usually contain a high degree of correlation. Second, "traditional" sensor nodes collect information from the environment within a predefined area determined by the sensing range of the node. In contrast, multimedia sensor nodes may be sensitive to the direction of data acquisition. For example, camera-enabled sensor nodes can capture images of objects or parts of regions that are not necessarily in the node vicinity. The images taken by such sensor nodes are unique for each of them. This is a result of the relative positions and orientations of the cameras toward the observed objects. Finally, the substantial demand of real-time operations in WMSNs can be considered as the most specific characteristic of this class of WSNs.

C. Architecture Description

We introduce here a general architecture for WMSNs (Figure. 4). This architecture aims to convey real-time multimedia contents such as voice generated by users and/or captured images and video of observed areas. There are two types of nodes: *multimedia sensor nodes* and *multimedia servers*. Multimedia sensor nodes can be *audio sensor nodes* or *vision sensor nodes* for instance. They are expected to be tiny, low cost and with reduced complexity and power. Vision sensor nodes are generally fixed at strategic points and are programmed to perform specific operations on the image. These operations include detecting objects in the scene, detecting edges, or getting only particular region of interest, whereas audio sensor nodes can be devices carried by users (e.g., head-mounted) and permits to gather speech sound[3].

Visual contents gathered by vision sensor nodes are wirelessly relayed to a multimedia server. The latter has enough capabilities to perform intensive multimedia data real-time processing (*e.g.*, filtering, correlating and fusing visual content), and also to eventually provide a wireless connectivity to a remote system. Thus, it acts as a gateway and should implement the software front-end for network querying and tasking. To deliver visual contents to remote end-applications (*e.g.*, telemedical center), the multimedia server may feature WLAN or WWAN connectivity.

As regards to audio sensor nodes, they can be considered as radiocommunication terminals that enable a group of users operating together over the same area to communicate with each other in an ad hoc manner. Depending on the end-applications, audio streams can be uploaded from an individual audio sensor node to a remote system via the closest multimedia server. For example, this can be the case of virtual museum visit where a web-application juxtaposes live images gathered from vision sensor nodes deployed in the museum with audio comments given by a professional guide [20].

D. Architectural Implications

- Network topology: Depending on the specific features of WMSNs and the multiple operation modes, there are different potential network topologies (Figure. 4). The best one is usually the one mapping closely the topology of the end-applications. For homogeneous WMSNs solely formed by audio sensor nodes, a P2P mesh topology seems most tempting. This allows audio sensor nodes to communicate with each other in a single hop/multihop manner depending on the coverage area. Conversely, with only vision sensor nodes forming the WMSN, two topologies are possible depending on the number of nodes. In case of few nodes (tens), a star topology may be suited with each vision sensor node connected directly to a multimedia sensor node. However, this topology is not scalable. For a large number, vision sensor nodes can be grouped within clusters to form a single/multi-tiered clustered topology, where particular vision sensor nodes act as cluster-heads. This tiered clustered topology holds even for WMSN consisted of heterogenous multimedia nodes where audio sensor nodes can be incorporated into clusters.
- Quality of service: WMSNs bring QoS requirements at the forefront of performance optimization. Because of the specific nature of real-time multimedia requirements, WMSNs need mechanisms to deliver multimedia content with guarantees for high bandwidth, low delay and low jitter. Packet losses can be tolerated to a certain extent. As a result, there is a need for more capabilities on multimedia sensor nodes compared with "traditional" sensor nodes.
- Power consumption: With stringent multimedia QoS requirements and considering the intrinsically limited capabilities in WSNs, there is an imperious need to tune multimedia content requirements to the properties of WMSNs to ensure that nodes survive longer and provide high quality multimedia contents. Besides stringent QoS requirements, multimedia applications produce high volumes of data, which require high transmission rates and extensive processing, leading to more energy expenditure.

[3]We restrict here the use of audio sensor nodes to gather voice data, other types of audio streams are rather gathered by the so-called acoustic sensor nodes, which belong to the WDCN class.

VI. Wireless Control-Oriented Sensor Networks

Nowadays, advanced technologies enable residential, office or industrial buildings to be equipped by a whole series of electrical and mechanical systems. These systems are used to offer services related to comfort, security, energy saving, communication and control. They include a multitude of appliances such as lamps, radiators, window blinds in home environments, or electrical motors, pneumatic valves, hydraulic pistons in a factory environments. Each appliance is expected to be controlled and adjusted to a specific context, operation mode or personal preferences.

With traditional systems, where the wireless network capabilities have not exhaustively addressed, controlling such appliances requires some degree of user's mobility. For example, to control a lamp for lighting, the user has to be close to the outlet to be able to switch lights. Remote-controls (*e.g.*, Multimedia zapper) have relaxed this constraint and enabled the user to control a particular appliance without any physical contact. However, by getting numerous, remote-controls have a tendency to make life impossible for the user, and hence a need arises to transform those standalone appliances into an intelligent network devices that can be controlled, monitored wirelessly and use each others functionalities. This class of such networks is called Wireless Control-Oriented Sensor Network (WCOSN).

A. Scenarios and Applications

1) Home Automation and Control Applications: A number of recent projects and standards focus on building home automation and controls applications. Z-wave [25] is one example of interoperable wireless communication standard designed for interconnecting home appliances into a WCOSN. This enables such appliances to coordinate their functionalities, to intelligently behave according to users needs and desires. An example would be that, when entering the living room, the drapes go down, the lights dim to a comfortable level, the stereo turns on, and a personalized music is played. Another example consists in turning down the heat in rooms which are not occupied or while windows are open, turning off all the lights when the house is empty, and so on. All these

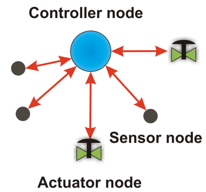

Fig. 5. A star topology for wireless control-oriented sensor Network. All messages issued from sensor/actuator nodes have the controller node as destination.

operations can be triggered by a push on a button or even by a sensor detecting user presence.

2) Industrial Automation and Process Control Applications: WCOSNs can be used to optimize control performance across the entire manufacturing processes. Traditionally, manufacturing processes and industrial machines require a regular intervention of the operator. Such intervention is critical when a disturbance in a process causes plant operations to deviate from its normal operating state. Thus, operators must deal daily with a real-time, highly complex and dynamic environment. However, it is possible to reduce such intervention by coordinating machines and processes with sensor devices. For example, the Honeywell [9] company supplies many proprietary technology solutions for industrial automation and process control applications, by interconnecting appliances into a WCOSN.

B. Specific Features and Characteristics

All WCOSNs have specific features and characteristics in common. Typically, the essential feature consists in a threefold synergy between the user, the environment and the equipments over a local area. The later operate and behave either with respect to user's preferences, according to environmental parameters and context information, or in coordination with other equipments deployed over a local area. Besides the sensing functionality, which is a common feature to all WSNs, WCOSNs especially comprise a mechanism that causes an equipment to be turned on or off, adjusted or moved. The devices carrying out this mechanism are called actuators. Actuators react to environmental parameters and context information detected by sensor devices, then affect the physical world by acting on processes or equipments. Such a close relationship with the physical world is a substantial contrast to other WSN classes specially with WBASNs.

C. Architecture Description

We describe in Figure. 5 a general architecture for WCOSNs consisted of three types of network nodes: *sensor nodes*, *actuator nodes* and the *controller node*. Sensor nodes are battery operated nodes, fixed at strategic points and have to detect environmental parameters and/or context information. Instances of sensor nodes include temperature sensors, presence detectors, gas and smoke detectors in home environment, or chemical sensors, strain/pressure gauges in industrial environment. Actuator nodes, which can be battery or AC powered devices, have to activate appliances (*e.g.*, by power supply) whenever requested. Motor-driven valves, commands for a lamp, hydraulic pistons or piezoelectric motors are some examples of such actuator nodes. The controller node, which can be a static control panel, a handheld command or a remote control, contains extended functionalities to control both sensor and actuator nodes.

All these nodes need to be seamlessly integrated to form a WCOSN. The controller node configures, initiates and manages the WCOSN. Additionally, it implements self-organization management functionalities, which simplify the installation and operation of the network, and may feature connectivity to broader system. The controller node can also supply the user with several information such as the status of a particular equipment/process or a physical parameter (*e.g.*, the actual temperature of the room). Actuator nodes react according to appropriate readings sensed by sensor nodes. For example, an actuator node can act on a thermostat valve and controls the opening and the closing of the radiator valve according to the temperature in the room or the presence/absence of residents.

In this architecture, there are two types of initiated messages: command messages and request messages. The former can be issued either from the controller node or a sensor node towards a particular actuator node in order to trigger some action whereas the latter are initiated from the controller node to sensor nodes whenever interested to a particular environmental/process information. Actuator nodes do not need to initiate any messages, but only need to react to command messages originating from other nodes by acting on equipments or sending status messages. Generally, in this architecture, each node can reach another node though direct communications.

D. Architectural Implications

- Network topology: The envisioned architecture can possibly support two network topologies. First, a mesh topology enabling every node to reach every other node. Thus, each sensor node can send directly a command message to a particular actuator provided that routing information are available. Routing information can be initially assigned by the controller node. Second, a star topology where the controller node acts as a master and the other node as slaves (Figure. 5). Thus, all messages issued from other nodes have the controller node as the destination.
- Quality of service: WCOSNs generally do not require high data rate. A typical communication consists of 4-6 bytes of payload and each node communicate relatively infrequently; every 5-15 minutes. Therefore only few bytes per second are sufficient to transmit command and request messages. As regards to the latency, the required magnitude is about 0.5 s in domestic environment. For example, it would bother users if they expect a light to be switched on for more 0.5 s. In industrial environment, more stringent latency values are required.

- Power consumption: The envisioned architecture needs to handle battery-powered nodes with great power efficiency in order to provide ten or more years of operations. However, if a node is expected to be plugged into electrical outlet, then the power consumption is not of prior interest.

VII. Conclusion and Future Directions

Nowadays, a large number of wireless sensor network applications are expected to be deployed in various domains ranging from environment and habitat monitoring, healthcare applications to industrial automation and control. This diversification of applications raises the question of the design approach to be adopted. The specific-application approach, which consists in providing a specific and new technical solution for each of these applications, will make the deployment of such networks expensive. The generic approach, which provides technical solutions on a common basis to a large broad of applications sharing a large set of requirements, can reduce costs. Practically, this can be achieved by providing off-the-shelf set of modular hardware and software architectures. However, such generic approaches increase the system complexity, which is problematic in resource-constrained sensor networks, and does not offer an optimized technical solution.

In this paper, we have presented an original approach for the design of wireless sensor networks. Such approach relies on the classification of wireless sensor network applications with respect to their functionalities. Then, instead of providing a technical solution for each application or for a large part of applications, we focus on a transversal approach, which gives technical solutions in sight of functional classes of wireless sensor network applications.

Five distinct general classes have been derived. For each class, we have given illustrative applications, discussed in detail specific features and characteristics, and described general architectural functionalities and some of their technical implications. Note that, though WSN applications have very specific requirements, they can lead to quite conventional architectures, which was not obvious at first glance. Moreover, exposing independent classes aims to give a conceptual framework for further design of WSN. Being more complex, a WSN can be built by integrating a set of such classes into a broader system.

Finally, we believe that this classification can hopefully bring a comprehensive and reliable framework for further networking issues such as medium access control, routing, complexity and power consumption tradeoffs.

References

[1] I. F. Akyildiz, S. Weilian, Y. Sankarasubramaniam, and E. E. Cayirci, "A survey on sensor networks," *IEEE Communications Magazine*, vol. 40, pp. 102–114, 2002.

[2] P. H. Dana, "Global positioning system (GPS) time dissemination for real-time applications," *The International Journal of Time Critical Computing Systems*, vol. 12, no. 1, Jan. 1997.

[3] D. Estrin, L. Girod, G. Pottie, and M.Srivastava, "Instrumenting the world with wireless sensor networks," in *Proceedings of the International Conference on Acoustics, Speech and Signal Processing (ICASSP 2001)*, Salt Lake City, Utah, May 2001.

[4] European Space Agency. [Online]. Available: http://www.esa.int

[5] K. Finkenzeller, *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification*, 2nd ed. John Wiley, 2003, pp. 1–7.

[6] A. Gluhak, M. Presser, Z. Shelby, P. Chevillat, P. Scotton, and W.Schott, "e-sense reference model for sensor networks in b3g mobile communication systems," in *15th IST Mobile & Wireless Communications Summit*, Mykonos, Greece, June 2006.

[7] J. Hightower and G. Borriello, "Location systems for ubiquitous computing," vol. 34, pp. 57–66, Aug. 2001.

[8] L. V. Hoesel, T. Nieberg, J. Wu, and P. Havinga, "Prolonging the lifetime of wireless sensor networks by cross-layer interaction," *IEEE Wireless Communications*, pp. 78–86, Dec. 2004.

[9] The Honeywell company. [Online]. Available: http://www.honeywell.com

[10] The JASON Project. [Online]. Available: http://jasonproject.org

[11] H. Karl and A. Willig, *Protocols and Architectures for Wireless Sensor Networks*, 2nd ed. John Wiley, 2003, pp. 1–14, 68–71.

[12] R. Kernchen, D. Bonnefoy, A. Battestini, B. Mrohs, M. Wagner, and M. Klemettinen, "Context-awareness in mobilife," in *15th IST Mobile & Wireless Communications Summit*, Mykonos, Greece, June 2006.

[13] A. Mainwaring, J. Polastre, R. Szewczyk, D. Culler, and J. Anderson, "Wireless sensor networks for habitat monitoring," in *ACM International Workshop on Wireless Sensor Networks and Applications (WSNA'02)*, Atlanta, GA, Sept. 2002.

[14] D. Malan, T. Fulford-Jones, M. Welsh, and S. Moulton, "Codeblue: An ad hoc sensor network infrastructure for emergency medical care," in *International Workshop on Wearable and Implantable Body Sensor Networks*, Imperial College, London, United Kingdom, Apr. 2004.

[15] The MobiHealth Project. [Online]. Available: http://www.mobihealth.org

[16] P. Padhy, K. Martineza, A. Riddoch, H. L. R. Ong, and J. K. Hart, "Glacial environment monitoring using sensor networks," in *Proceedings of Real-World Wireless Sensor Networks*, Stockholm, Sweden, Sept. 2005.

[17] N. B. Priyantha, A. Chakraborty, and H. Balakrishnan, "The cricket location-support system," in *Proceedings of MOBICOM*. Boston, MA: ACM Press, Aug. 2000, pp. 32–43.

[18] M. Rahimi, R. Baer, O. I. Iroezi, J. C. Garcia, J. Warrior, D. Estrin, and M. Srivastava, "Cyclops: In situ image sensing and interpretation in wireless sensor networks," in *Proceedings of the 3rd ACM Conference on Embedded Networked Sensor Systems*, San Diego, CA, Nov. 2005.

[19] K. Römer and F. Mattern, "The design space of wireless sensor networks," *IEEE Wireless Communications Magazine*, vol. 11, no. 6, pp. 54–61, Dec. 2004.

[20] S. Soro and W. Heinzelman, "On the coverage problem in video-based wireless sensor networks," in *Proceedings of the Second Workshop on Broadband Advanced Sensor Networks (BaseNets '05)*, Boston, MA, Oct. 2005.

[21] W. Steve, L. Nagl, T. Hildreth, H. Erickson, D. Poole, M.Spire, and D. Andresen, "Wearable and wireless: Distributed, sensor-based telemonitoring systems for state of health determination in cattle," in *Talbot Symposium on Computers and Veterinary Informatics*, Pennsylvania Convention Center, Philadelphia, PA, July 24–28, 2004.

[22] S. Tilak, N. B. Abu-Ghazaleh, and W. Heinzelman, "A taxonomy of wireless micro-sensor network models," *ACM Mobile Computing and Communications Review*, vol. 6, no. 2, Apr. 2002.

[23] A. Tiwari, F. L. Lewis, and S. S. Ge, "Wireless sensor network for machine condition based maintenance," in *Control, Automation, Robotics and Vision Conference (ICARCV)*, vol. 1, Texas Univ., Arlington, TX, USA, Dec. 6–9, 2004, pp. 461–467.

[24] M. Tubaishat and S. Madria, "Sensor networks: An overview," *IEEE Potentials*, vol. 22, pp. 20–23, Jan. 2003.

[25] The Z-wave alliance. [Online]. Available: http://www.z-wavealliance.com

[26] The ZigBee Alliance. [Online]. Available: http://www.zigbee.org