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A survey of architectures and scenarios in satellite-based wireless sensor networks: system design aspects

N. Celandroni[1], E. Ferro[1,*,†], A. Gotta[1], G. Oligeri[1], C. Roseti[2], M. Luglio[2], I. Bisio[3], M. Cello[3], F. Davoli[3], A. D. Panagopoulos[4], M. Poulakis[4], S. Vassaki[4], T. De Cola[5], M. A. Marchitti[5], Y. F. Hu[6], P. Pillai[6], S. Verma[6], K. Xu[6] and G. Acar[7]

[1]*CNR-ISTI, Pisa, Italy*
[2]*University of Roma2, Rome, Italy*
[3]*CNIT, Genoa, Italy*
[4]*ICCS-NTUA, Athens, Greece*
[5]*DLR, Wessling, Germany*
[6]*University of Bradford, Bradford, UK*
[7]*ESA-ESTEC, Noordwijk, The Netherlands*

ABSTRACT

This paper is not a survey related to generic wireless sensor networks (WSNs), which have been largely treated in a number of survey papers addressing more focused issues; rather, it specifically addresses architectural aspects related to WSNs in some way connected with a satellite link, a topic that presents challenging interworking aspects. The main objective is to provide an overview of the potential role of a satellite segment in future WSNs. In this perspective, requirements of the most meaningful WSN applications have been drawn and matched to characteristics of various satellite/space systems in order to identify suitable integrated configurations. Copyright © 2012 John Wiley & Sons, Ltd.

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1. INTRODUCTION

Satellite technology is a key element to enhance future wireless sensor network (WSN)-based applications that have large areas of interest and various bandwidth requirements. The selection of the most suitable satellite technology involves the evaluation of a vast gamut of standards and air interfaces, access schemes, security methods and operational systems. The drivers for the selection of an optimized WSN–satellite architecture come, on one hand, from the applications' requirements and, on the other hand, from the characteristics of the available WSN technology. Figure 1 sketches the conceptual scheme of the study highlighting key elements addressed in this paper. In particular, five WSN application scenarios are identified as significant: monitoring and surveillance of remote areas, emergency communications, support for supervisory control and data acquisition (SCADA) systems, critical infrastructures (CIs) and environmental monitoring.

Figure 2 shows a generic architecture for a distributed WSN where satellite systems provide access to the Internet. A local WSN usually relies on a *sink* or *base station*, which communicates with a number of wireless sensors via a radio link while providing connection to a remote control system. Each wireless sensor node has the capability to collect data and to route them to the task manager node through the sink. Sensor nodes can perform many tasks, such as remote monitoring, event detection and identification,

*Correspondence to: Erina Ferro, Wireless Networks Laboratory (WNLAB), CNR-ISTI (Istituto di Scienza e Tecnologie dell'Informazione "A. Faedo"), An Institute of National Research Council (CNR), Via G. Moruzzi, 1, San Cataldo, 56124 Pisa, Italy.
†E-mail: Erina.Ferro@isti.cnr.it

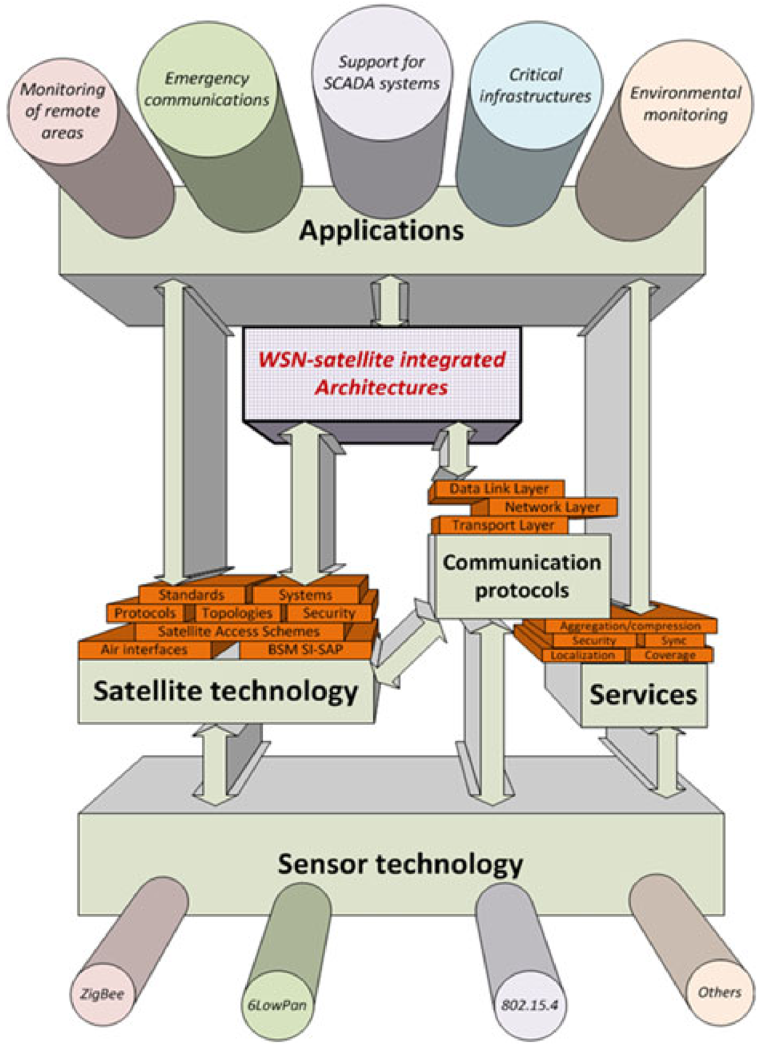

Figure 1. A taxonomy for the definition of wireless sensor network (WSN)–satellite architectures. SCADA, supervisory control and data acquisition; BSM SI-SAP, Broadband Satellite Multimedia Satellite Independent–Service Access Point.

location sensing and local control of actuators. The combination of these different types of sensing with wireless connections can be efficiently adopted in many application areas. Definitely, the overall architecture of an integrated system has to be tailored on the requirements of each application scenario considered.

This paper is not a survey related to generic WSNs, which have been extensively treated in the classical survey [1] and later expanded in [2] and [3], among others; rather, it specifically addresses architectural aspects related to WSNs in some way connected with a satellite link. This paper concentrates on the architectural aspects only, and it is organized as follows. Section 2 presents the application scenarios and provides considerations on traffic models applicable for the different kinds of WSN applications. Section 3 presents meaningful state-of-the-art technology for both WSNs and satellite, as stand-alone segments. Section 4 contains an analysis of the main characteristics of WSNs. Section 5 provides a trade-off analysis of satellite–WSN integrated systems, taking into considerations results from previous sections. Section 6 presents the mapping between the selected scenarios, the WSN traffic types and the satellite technology adoptable. Section 7 concludes this survey paper.

2. APPLICATION SCENARIOS AND TRAFFIC MODELS

Wireless sensor network scenarios in their interaction with satellite systems can be classified on the basis of the characteristics of the target application and the corresponding traffic requirements.

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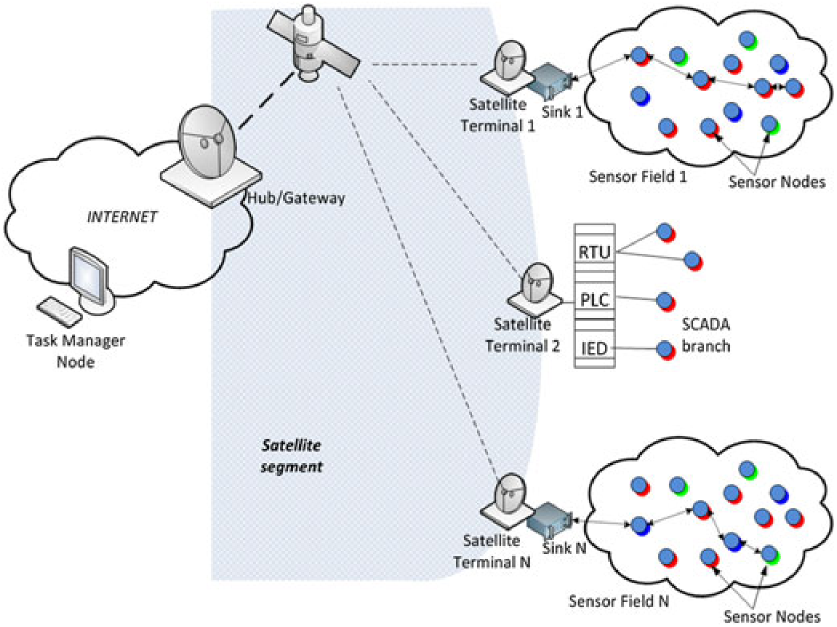

Figure 2. A generic satellite-based wireless sensor network architecture. RTU, remote terminal unit; PLC, programmable logic controller; IED, intelligent electronic device; SCADA, supervisory control and data acquisition.

Accordingly, we have identified five application scenarios, each one presenting specific traffic patterns and issues.

2.1. Application scenario definition

2.1.1. Monitoring and surveillance of remote areas. Wireless sensor networks enable on-demand and adaptive sensing (including imaging) of a broad set of physical and ecological phenomena across different spatial and temporal scales from a heterogeneous suite of sensors, both *in situ* and *in orbit*. *In situ* sensors efficiently complement space-based sensors, although they present some challenges to be addressed. First, many applications require the installation of sensors over areas where a connectivity to the rest of the terrestrial infrastructure is not easy to achieve. Second, the system must flexibly support different sensing capabilities, as required by the specific applications. Third, the system must be robust enough to allow communications in harsh environments. This monitoring scenario includes surveillance applications. Data generation is usually triggered by events (i.e. observed parameters over a threshold), whereas some applications require a periodic report on target area conditions (e.g. pictures, temperature and salinity).

Satellite communications can address major challenges acting as the backhaul to relay *in situ* data to a central database. Satellite systems should be further enhanced with capabilities (i.e. localization information and access point for remote communications) that integrate data coming from heterogeneous sensors and a monitoring system aimed to both monitor the system status and recover from potential failures. In the case of unattended sensors, direct sensor–satellite links can be envisaged with the support of innovative techniques, such as distributed collaborative beamforming. In addition, extensive data caching could prevent data loss when failures occur.

2.1.2. Emergency communications. In emergency situations, a large number of sensors could be randomly deployed in inaccessible areas for disaster relief operations. Thus, sensor networks must be enhanced with self-organizing capabilities. A further enhancement concerns a cooperative effort of sensor nodes. Because sensors are equipped with an on-board processor, they can perform some basic processing on the raw data before transmitting them to the gateway. As far as long-range connectivity is concerned, satellite segments play a fundamental role, and in some cases, they represent the only viable solution.

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2.1.3. Support for supervisory control and data acquisition systems. Supervisory control and data acquisition systems are computers, controllers, instruments, actuators, networks and interfaces that manage the control of automated processes and allow the analysis of the overall system through data collection. They usually operate over wide geographical areas, preferably as stand-alone and properly 'isolated' systems in order to minimize vulnerability to overload, interference, interruption of service, security attacks, fraud and so on. In general, SCADA systems do not require frequent transmissions of long messages, so that they might use low-rate communications, of course, as long as the selected media and data protocols provide reliable data transactions. Data rates in the range of few kilobits per second can be considered adequate for target performance. Obviously, SCADA traffic patterns tightly depend on the nature of the scan process. In general, three different alternatives can be identified:

- periodic scans with all data returned with each scan response (the system can be modelled as a continuous bit rate source);
- periodic scans with only changed data returned (report by exception); and
- no scanning, with remote terminals reporting changed data on detection (closest to a Poisson distribution).

The communication architecture may involve a single medium or a wide area system backbone (i.e. satellite) with a shorter-range (last-mile) wireless network. The access to the air interfaces must follow some 'smart' criteria: data not triggering decisions to the SCADA master control centre might not be transmitted at all, whereas critical data must be immediately available to be transferred as urgent messages through the network. At the same time, data protocols must be extremely robust, implementing efficient error handling mechanisms and allowing peer-to-peer and store-and-forward communications.

2.1.4. Critical infrastructures. The protection of CIs and counterterrorism are interesting applications for WSNs. As a matter of fact, critical buildings and facilities, such as power plants, airports and military bases, have to be protected against potential intrusion. The large-scale nature of CIs requires scalable and low-cost technology for improving monitoring and surveillance. WSNs can be relatively easily deployed at large scale without requiring additional infrastructures; satellite systems can help meet such a requirement. The distributed nature of a WSN, enhanced with satellite-based connections, increases the survivability of the network in critical situations, where either failures or attacks may compromise part of the system, still providing sufficient information about the CI to help the system manager prevent further damage and start the recovery process. On the other hand, WSN effectiveness for CI protection strongly depends on the reliability of the WSN itself. A WSN that fails in reporting a faulty condition prevents the CI manager from carrying out the most appropriate maintenance needed to fix the problem in progress. Therefore, system aspects, such as redundancy, integrity, real-time behaviour, and security and availability, are essential requirements to make WSN services dependable. Definitely, this scenario should require networks of video, acoustic and other sensors.

2.1.5. Environmental monitoring. Environmental monitoring can be used for animal tracking, forest surveillance, contamination/flood/fire detection, weather forecasting and so on. It is a natural candidate for applying WSNs, because the variables to be monitored, such as temperature and humidity, are usually distributed over a large region. Integration of a satellite-to-WSN communication segment can surely guarantee the coverage over a very large area.

The number of environmental applications for sensor networks is quite large and includes the following:

- pollution study;
- chemical/biological detection;
- precision agriculture;
- biological and environment monitoring in marine, soil and atmospheric contexts;
- fire detection;
- meteorological and geophysical research;
- flood detection; and
- bio-complexity mapping of the environment.

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As a matter of fact, this application scenario can be considered as a subcategory of the monitoring of remote areas, which is focused to the collection of geo-physical parameters worldwide. In terms of traffic characteristics, short messages are most likely exchanged upon event detection.

2.2. Wireless sensor network traffic models

There are still a few obstacles to overcome before WSNs finally become a mature technology. One of the key obstacles is the energy constraint in most inexpensive sensor nodes, where batteries are the main source of power supply. The communication aspects dominate the energy consumption; energy expenditure is lower for sensing and computation, whereas the cost of transmitting a single bit is approximately three orders of magnitude larger than the cost of performing a single processing operation in a typical sensor node [4]. Thus, minimizing the energy consumption due to communication is the key factor for the relaxation of the energy constraint in WSNs. The knowledge about communications in WSNs is still partial and vague, especially in terms of traffic characteristics and communication patterns; obviously, this knowledge can aid in understanding the energy consumption and its distribution in WSNs. However, this obstacle is not so easy to be removed in the near future; thus, optimizing the design of WSNs is very important in order to consume the minimum energy. Such an aspect greatly impacts on the traffic pattern of the WSN. On the other hand, potential application areas of WSNs show contrasting properties, which prevent the development of universal algorithms/protocols serving all purposes. Military applications may require very fast response time, whereas in agriculture, delay sensitivity may be traded with energy conservation. Likewise, a communication protocol may perform in a very energy-efficient manner when used for one application, and it may perform quite poorly in another.

One application-dependent characteristic is the type of data messages generated by the WSN nodes. The model that represents the aggregate offered packet traffic in the network, or the traffic generated by a cluster of sensor nodes, can be used to determine the maximum stable throughput, the expected delay and the packet loss characteristics. Furthermore, the effects of parameters such as node density and target velocity can be investigated in depth, once an appropriate data traffic model is available.

Data generated by WSN applications can be categorized as *event driven* or *periodic data*, as suggested in [5]. In the latter case, constant bit rate can be used to model the data traffic arrival process when the bit rate is constant, whereas when the bit rate is variable, a Poisson process could be used to model the data traffic arrival. For event-driven scenarios, such as target detection and target tracking, bursty traffic can arise from any corner of the sensing area if the local sensors detect an event. A Poisson process has also been used in [6] to model the traffic arrival process for a cluster-based WSN; however, the traffic at each sensor node was assumed to be a Poisson arrival process without any discussion as to whether this was appropriate. Actually, the widely used Poisson processes are quite limited in characterizing bursty traffic [7, 8].

Instead of Poisson processes, an ON/OFF model (Figure 3) is proposed in [9] to capture the burst phenomenon in the source data traffic at each sensor node in the target tracking event-driven WSN scenario. A typical WSN for target tracking consists of spatially distributed sensor nodes monitoring a mobile target collaboratively. When a target enters the surveillance area, any sensor node with sensing ability will discover this target if the target is within its sensing range. As long as the target remains in the sensing range, the alarmed sensor node will keep reporting its observation about the target to a base station through a multi-hop path. Thus, this kind of event-driven working manner generates bursty source traffic at the sensor node. For the source traffic generated by each single sensor

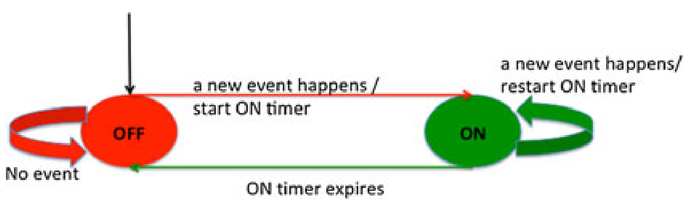

Figure 3. ON/OFF state transition diagram.

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node, the traffic bursts are designated by ON periods, and the silence intervals between traffic bursts are designated by OFF periods. Thus, the sequence of traffic is viewed as the interchanging of ON and OFF periods. It is found that the frequencies of observed ON/OFF periods can vary when the location of the considered source node varies. With the target mobility model used in their simulation, the source nodes located in the centre of the surveillance area experience more ON/OFF periods than those located close to the edge of the surveillance area. Moreover, the choice of ON timer could also affect the ON/OFF periods (both the count and the lengths of periods) observed. However, both ON and OFF period distributions are found to follow the generalized Pareto distribution very well, and this match exists independently of the location of the considered source sensor node and also independently of the choice of the ON timer.

Recently, there has been a great deal of research on using mobility in WSNs (mobile sensor networks) to facilitate surveillance and reconnaissance in a wide deployment area. Besides providing an extended sensing coverage, node mobility along with the spatial correlation of the monitored phenomenon introduces new dynamics in the network traffic. This dynamics could lead to long-range dependent (LRD) traffic, which necessitates network protocols fundamentally different from those employed in the traditional (Markovian) traffic.

The mobile sensor network not only inherits the characteristics from conventional WSNs but also possesses the gene from mobile ad hoc networks (MANETs). The joint effects of these attributes could introduce new dynamics to the network traffic, which are barely observed in conventional static WSNs. As an example, the mobility variability of humans (in this case, sensor nodes are attached to humans) and the spatial correlation of the collected information lead to the pseudo-LRD (i.e. LRD) traffic, whose autocorrelation function follows a power law form with Hurst parameter up to a certain cutoff time lag [10].

Surveillance WSNs represent the WSN applications in which the deployed sensor nodes monitor an area for potential intruder entrance; when an intrusion is detected, the detecting sensors send data packets to the sink so that the necessary actions can be taken. Such a network can be employed for security applications, habitat monitoring or disaster management applications. Because of the distinctive properties of these applications, the generated data are bursty and require a specific packet traffic model. The underlying packet traffic model, if not accurate, can result in dissimilar performance outcomes for the same average packet traffic loads. This observation is significant because improper packet traffic models may result in underestimated or overestimated performance and lead to inefficient protocol design and implementation. In [11], the authors defined a new packet traffic model framework for intrusion detection applications, using the Elfes sensor detection model [12] for modelling the probability that a sensor detects an event at distance d. An alternative detection model that incorporates false alarm rate and additive white Gaussian noise is the Neyman–Pearson detector [13]. However, the Elfes model can accommodate the Neyman–Pearson detector through a proper parameter matching, as indicated in [14].

3. STATE-OF-THE-ART REVIEW

The aim of this section is to survey the most prominent standards being used in both WSN and satellite environments, respectively, and some popular satellite systems.

3.1. Wireless sensor network technology

The ZigBee standardization framework is essentially the only one available in terms of protocol and architecture specifications. Other working groups part of Internet Engineering Task Force (IETF) are mostly interested in some aspects of routing and encapsulation over WSN; as such, they can be also considered as applicable to the ZigBee protocol architecture. In short, the overall protocol architecture is composed of three main building blocks:

- application and networking layer: ZigBee recommendation;
- lower layer: IEEE 802.15.4 recommendation; and
- interface between upper and lower layers for IPv6 transport: (IPv6 Low power Wireless Personal Area Network) framework.

These three elements are expanded in the next sections. The interested reader can refer to the references reported therein for a more detailed description of each considered standardization framework.

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3.1.1. ZigBee. The ZigBee Alliance has developed a very low-cost, very low-power consumption, two-way wireless communications standard. Solutions adopting the ZigBee standard are embedded in consumer electronics, home and building automation, industrial controls, PC peripherals, medical sensor applications, toys and games.

This standard recommendation [15] contains specifications, interface descriptions, object descriptions, protocols and algorithms pertaining to the ZigBee protocol, including the application support sublayer, the ZigBee device objects, the ZigBee device profile, the application framework, the network layer and the ZigBee security services. The ZigBee Alliance has built this foundation on the IEEE 802.15.4 standard (described later on) by providing the network layer and the framework for the application layer. The application layer framework consists of the application support sublayer and the ZigBee device objects. The overall ZigBee protocol architecture is depicted in Figure 4.

3.1.2. 6LoWPAN. 6LoWPAN is a set of standards defined by the IETF, which creates and maintains all core Internet standards and architecture work. The IETF 6LoWPAN working group [16] was created to enable IPv6 to be used with wireless embedded devices and networks. Features of the IPv6 design such as a simple header structure, and its hierarchical addressing model, made it ideal for use in wireless embedded networks with 6LoWPAN. Additionally, it is by creating a dedicated group of standards for these networks that the minimum requirements for implementing a lightweight IPv6 stack with 6LoWPAN could be aligned with the most minimal devices. Finally, it is by designing a version of Neighbour Discovery specifically for 6LoWPAN that the particular characteristics of low-power wireless mesh networks could be taken into account. The result of 6LoWPAN is the efficient extension of IPv6 into the wireless embedded domain, thus enabling end-to-end IP networking and features for a wide range of embedded applications. Reference can be made to [17] for the detailed assumptions, problem statement and goals of early 6LoWPAN standardization. Although 6LoWPAN was targeted originally at IEEE 802.15.4 radio standards and assumed layer 2 mesh forwarding [18], it was later generalized for all similar link technologies, with additional support for IP routing in [19, 20].

The first 6LoWPAN specifications were released in 2007, first with an informational RFC [17] specifying the underlying requirements and goals of the initial standardization and then with a standard

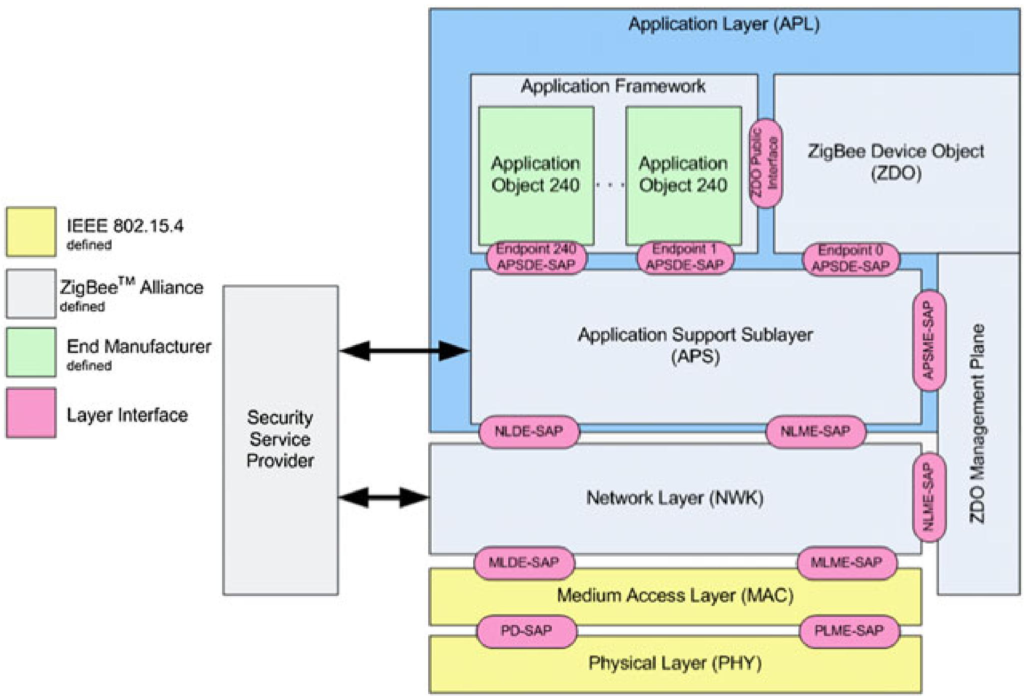

Figure 4. Outline of the ZigBee stack architecture. APS, sub-layer data entity (APSDE); APS Management Entity (APSME); Network Layer Data Entity (NLDE); Network Layer Management Entity (NLME); Mac Layer Data Entity (MLDE); Physical Data (PD); Physical Layer Management Entity (PLME).

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track RFC [18] specifying the 6LoWPAN format and functionality. Through experience with implementations and deployments, the 6LoWPAN working group continued with improvements to header compression [19], 6LoWPAN Neighbour Discovery [20], use cases [21] and routing requirements [22]. In 2008, a new IETF working group was formed, routing over low-power and lossy networks (ROLL) [22]. This working group specifies routing requirements and solutions for low-power, wireless and unreliable networks. Although not restricted to use with 6LoWPAN, that is one main target.

3.1.3. IEEE 802.15.4. The IEEE 802.15.4 [23] standard defines the physical layer and medium access control (MAC) sublayer specifications for low data rate wireless connectivity with fixed, portable and moving devices with no battery or very limited battery consumption requirements typically operating in the personal operating space of 10 m. It is foreseen in the standard that, depending on the application, a longer range at a lower data rate may be an acceptable trade-off.

An IEEE 802.15.4 network is part of the wireless personal area network (WPAN) family of standards although the coverage of the network may extend beyond the personal operating space, which typically defines the WPAN.

A well-defined coverage area does not exist for wireless media because propagation characteristics are dynamic and uncertain. Small changes in position or direction may result in drastic differences in the signal strength or quality of the communication link. These effects occur whether a device is stationary or mobile, as moving objects may impact station-to-station propagation.

Depending on the application requirements, an IEEE 802.15.4 WPAN may operate in either of two topologies: the star topology or the peer-to-peer topology. In the star topology, the communication is established between devices and a single central controller, called the personal area network coordinator. The peer-to-peer topology also has a personal area network coordinator; however, it differs from the star topology in that any device may communicate with any other device as long as they are in range of one another. Peer-to-peer topology allows more complex network formations to be implemented, such as mesh networking topology.

3.1.4. Others. *Future Internet* is a term used to describe research into what the Internet architecture and protocols could look like in 10–20 years. The US National Science Foundation has a long-term initiative on Future Internet Design, which covers network architecture, principles and mechanism design. Several European projects specialize in Future Internet research, for example, the EU 4WARD project [24], in cooperation with the European Future Internet Assembly. Although most of the research related to Future Internet does not consider embedded devices and networks, this aspect is starting to gain interest. The EU SENSEI project [25], for example, specializes in making wireless sensors and embedded networks a part of the global Internet, both current and future. One of the subjects of the project is how wireless embedded networks and 6LoWPAN-type functionality can be made an integral part of the Future Internet. Several examples throughout this paper are taken from the SENSEI project, as it has been doing leading work in this area. More recently, the importance of standards, marketable applications and the importance of Internet services have encouraged the WSN community to become involved with 6LoWPAN standardization and the Internet Protocol for Smart Objects (IPSO) Alliance. The result is that much the innovation produced through WSN research is starting to be applied to wireless embedded Internet technology, a good example being the IETF ROLL working group [22].

3.2. Satellite technology

3.2.1. Digital Video Broadcasting–Return Channel via Satellite Second Generation. Since the original definition of the Digital Video Broadcasting–Return Channel via Satellite (DVB-RCS) specification in 2001, several versions of the specification describing the requirements for the implementation of a system providing an interaction channel for satellite distribution systems have been issued (current version in [26]). The sum of these specifications allowed adapting the DVB-RCS systems to different market segments, from small to large networks and from fixed to mobile terminals. However, the evolution of the physical layer techniques and the stabilization of IP standards necessitated more fundamental modifications, which could only be implemented in a consistent way via the definition of

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a second-generation system, that is, DVB-RCS Second Generation (DVB-RCS2) [27]. This standard was conceived to provide a standardized broadband interactivity connection as an extension of the Digital Video Broadcasting Satellite (DVB-S) systems. It defines the MAC and physical layer protocols of the air interface used between the satellite operator hub and the interactive user terminal, as well as the network layer and the essential functions of the management and control planes of the terminal. It embraces the Generic Stream Encapsulation (GSE) [28] and the DVB-S Second Generation (DVB-S2) standards implemented in the commercial broadcasting environment, exploiting economy of scale. In order to provide real interoperability, DVB-RCS2 describes higher-layer components adapted to satellite interactive systems, which are parts of control and management planes and mainly rely on DVB and IETF standards or are derived from them.

A typical RCS2 network utilizes a satellite with multi-beam or single-beam coverage. In most networks, the satellite carrying the forward link signal also supports the return link. The forward link carries signalling from the network control centre (NCC) and the user traffic to the RCSTs (interactive satellite system terminals). The signalling from NCC to RCSTs, which is required to operate the return link system, is called 'forward link signalling'. A network management centre (NMC) provides the overall management of the system elements and manages the service-level agreement assigned to each RCST.

DVB-RCS2 is suitable for two network topologies:

- star network system; and
- transparent star network system with contention access.

Future releases of the system are foreseen, and they will cover the following:

- Layer 1 transparent mesh overlay system with dedicated or contention access; and
- regenerative mesh systems switching at different layers.

These network topologies can be summarized in two main reference architectures:

(1) Transparent systems

- Transparent satellite(s). One or more transparent satellites provide the link between terminals and the Hub, or among terminals for the transparent mesh system. Digital transparent processor payloads can also give multi-beam connectivity.
- Hub/NCC. It performs the control (NCC) and management (NMC) functions, and it interfaces user plane (traffic gateway) functions.
- Star or mesh overlay terminals (RCSTs). The star transparent terminal complies with the specifications of the RCS2 standard, providing star connectivity or mesh connectivity with a double satellite hop. The mesh overlay transparent terminal is more complex; it includes two or more demodulators (adapted to DVB-S2 or DVB-RCS2 waveform) and provides both single-hop mesh and star connectivity.

(2) Regenerative system (future release)

- Regenerative satellite. It performs demodulation, demultiplexing, decoding, and possibly decapsulation, functions at the receiver side, on-board switching (at layer 2 or layer 3) for multi-beam systems, and the corresponding transmission functions after signal regeneration.
- Management station. It provides the management (NMC) and control (NCC) plane functions to the satellite network users.
- Regenerative satellite gateway (RSGW). An RSGW provides regenerative RCST users with access to terrestrial networks. There may be one RSGW giving service to a small number of terminals or to hundreds of terminals. Essentially, they comprise one RCST, a service-level agreement enforcer and an access router, but they may also include voice, traffic acceleration servers or a backhauling module.
- Regenerative terminals. These RCSTs are identical in terms of hardware to the star transparent terminals. The software may include Connection Control Protocol functionality to support dynamic mesh connectivity.

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User traffic transmission over random access channels is a recent feature supported by DVB-RCS2. This capability may be particularly useful for large networks with thin and sporadic traffic. Indeed, support for random access is normative in DVB-RCS2 for SCADA terminal profile. According to the standard, *waveform_id* = 3 and *waveform_id* = 13 are defined for Slotted Aloha (SA) and Contention Resolution Diversity Slotted Aloha (CRDSA) [29] random access allocation channels. CRDSA provides a more efficient use of burst repetition: it generates two replicas of the same burst at random time instants within a frame, like Diversity Slotted Aloha (DSA) [30]. In addition, CRDSA can resolve most of the DSA packet collisions, which are *cleared up* through a simple yet effective successive interference cancellation approach, which uses frame composition information from the replica bursts. The main CRDSA advantages lie in the improved packet loss ratio and the reduced packet delivery delay versus the channel load, jointly with a much higher operational throughput, compared with DSA and SA.

It should be noted that in battery-constrained sensor networks, the continuous DVB-S2 reception on the forward link may be undesirable for long unattended periods of operation. It may be preferable that the sensor node turns off the communication unit completely when there is no activity. DVB-RCS2 supports dedicate logon slot allocation, a feature that may be useful to provide contention-free logon opportunities to low-battery sensor nodes that periodically wake up, log on, transmit, log off and sleep.

3.2.2. Geostationary Earth Orbit-Mobile Radio. Geostationary Earth orbit (GEO)-Mobile Radio (GMR-1) [31] is a mobile satellite system standard jointly promoted by European Telecommunications Standards Institute (ETSI) and Telecommunications Industry Association. One of the key features of GMR-1 air interface is its close similarity to terrestrial Global System for Mobile Communication (GSM) at the upper protocol layers. This characteristic allowed the integration of standard GSM services into satellite systems, by using as much as possible off-the-shelf components such as the mobile switching centre, the visitor location register and the short message service centre. In addition, GMR-1 introduces several important features aiming at optimizing performance over the satellite channel, such as integrated position-based services and single-hop terminal-to-terminal calling. Because the protocol architecture of GMR is heavily based on GSM, enhancements to the GSM protocol have been easily incorporated into GMR-1. The most important step forward has been the inclusion of packet switching services via the General Packet Radio Service (GPRS) and Enhanced GPRS protocols. The system design envisaged data rates up to 144 kbps for early service [i.e. Regional-Broadband Global Area Network (R-BGAN)] and 432 kbps with further enhancements. With respect to terrestrial GPRS, several modifications have been implemented for the MAC/logical link control protocol layer to address the GEO system delay. First, a single-phase access is adopted. In addition, GEO mobile packet radio service implements a slow release of the uplink temporary flow identity in combination with periodic unsolicited uplink grants, so that the terminal has an uplink resource if new packets arrive in the terminal's uplink queue. The Thuraya system was designed to complement terrestrial GSM systems, allowing subscribers to switch a dual-mode phone between the terrestrial and satellite networks; it is an example of a GMR-based network.

3.2.3. Broadband Satellite Multimedia Satellite Independent–Service Access Point. The Broadband Satellite Multimedia (BSM) reference architecture [32] consists of three major groupings of BSM elements, as reported in Figure 5.

The mentioned groups of elements are the BSM system, the BSM network (BSMN) and the BSM subnetwork. Together they correspond to a BSM network where the NMC and NCC plus any additional elements are required to provide network services. The BSMN corresponds to a BSM subnetwork together with BSM interworking and adaptation functions. Finally, the BSM subnetwork consists of all the BSMN elements below the so-called Satellite Independent–Service Access Point (SI-SAP). SI-SAP is the common interface between any BSM family of satellite dependent lower layers and the SI upper layers (e.g. IP). The BSM protocol architecture supports families of air interface protocols, where each family defines the physical layer and the data link layer. Each air interface family is expected to use a combination of a satellite link control layer, a satellite MAC and satellite physical layers, which, usually, are jointly optimized for a specific range of satellite architectures and/or for a specific range of traffic types [32]. The SI-SAP interface provides a standard interface to upper layers

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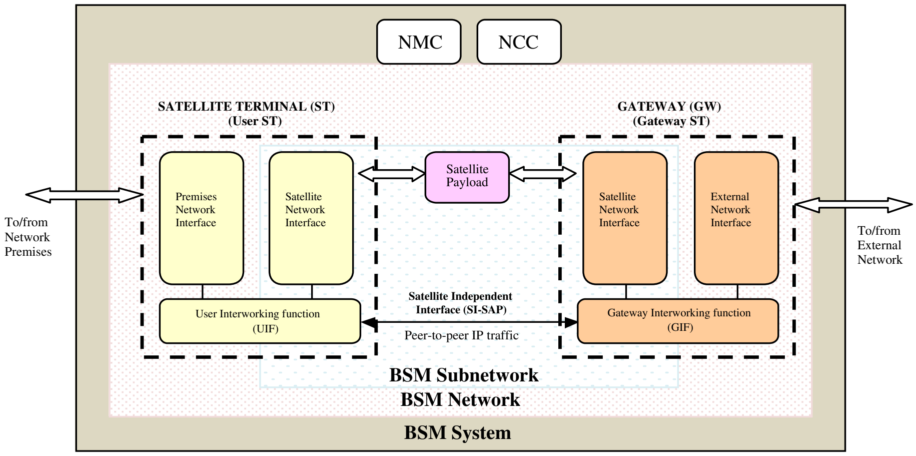

Figure 5. Broadband Satellite Multimedia (BSM) reference model. NMC, network management centre; NCC, network control centre; SI-SAP, Satellite Independent–Service Access Point.

of the protocol stack independently of the satellite dependent lower layers. An integrated WSN–satellite architecture can make use of the SI-SAP interface to provide the convergent layer for WSN integration with heterogeneous satellite technologies.

3.2.4. Global Satellite Phone Service. The Global Satellite Phone Service (GSPS) was introduced by Inmarsat to offer users communication by mobile voice calls, text messages, low-speed data and GPS location data on a global basis. GSPS is a second-generation family of products, which includes three main components: IsatPhone (mobile satellite phone), LandPhone (fixed satellite phone) and FleetPhone (maritime satellite phone). Its precursor is collectively referred by Inmarsat as *satellite phone services* to offer communication services on a regional basis throughout parts of Europe, the Middle East, Africa and Asia [33].

IsatPhone Pro is the first new product in the GSPS family of mobile satellite phones to provide a global handheld service for land-based users. In June 2010, Inmarsat certified that the GSPS handheld mobile Earth Monitoring Station (EMS), identified as IsatPhone Pro, is acceptable for use with the Inmarsat satellite communication system [34]. Stratos Global, the leading global provider of advanced mobile and fixed-site remote communications solutions, is the first Inmarsat distribution partner to reach a milestone of 2000 IsatPhone Pro activations in January 2011. GSPS data services allow a 2.4-kbps voice codec. This data speed is suitable for text-based email.

The GSPS family of satellite phones provides services via an enhanced GMR-2 air interface (GMR-2+) over the three Inmarsat-4 satellites. A single combined, co-located NCC-gateway serves each satellite. Three functionally identical NCC-gateway sites are required and strategically located in Asia, Europe and North America. Inmarsat is responsible for establishing terrestrial interconnection arrangements for call termination from the gateway sites in the three locations [33].

3.2.5. DENISE. The Demonstrator Emergency aNd Interactive S-band Services (DENISE) system [35], which is in the process of being standardized by ETSI under the name of S-Band Mobile Interactive Multimedia (S-MIM), describes an integrated satellite/terrestrial mobile system that provides interactive broadcast/multicast, data acquisition and two-way real-time services to subscribers. The S-band payload of a GEO satellite is assumed to provide communication links to users; however, non-GEO satellites are also compatible with this integrated system provided that Doppler pre-compensation countermeasures are put in place.

On the forward link, a broadcast radio access interface is used according to the requirements specified. On the return link, the radio interface is based on two nonexclusive options depending on the service required:

(1) asynchronous access using Spread Spectrum Aloha random access; and
(2) synchronous access using quasi-synchronous code division multiple access [36].

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A number of terminals with different capabilities are foreseen to enable user access to different sets of services. Access to services may be complemented by terrestrial complementary ground components (CGCs). Ku-band feeder links are shown as examples of feeder links to the satellite S-band payload and the CGCs. In general, the feeder links to the S-band satellite payload and the CGCs are independent, that is, not only the same feeder link but also different feeder links can be used, even in different frequency bands. Furthermore, terrestrial networks can also implement the CGC feeder link.

Interconnection with 2G/3G and IP networks is also foreseen to extend the access of user devices to services. The DENISE system provides three sets of user services: service segments 1, 2 and 3, which can be provided concurrently and in different combinations. Each service segment is defined by the inclusion of a number of services and service components, each with similarities in their use of forward (FWD) and return (RTN) links and in their QoS. Table I shows the list of services that can be provided through DENISE and their classification in terms of service segments.

3.2.6. Inmarsat Broadband Global Area Network. The BGAN refers to the Inmarsat global satellite Internet network, which offers telephony and high-speed data transmission.

User equipment contains a terminal (e.g. a PC or a telephone) connected through standard interfaces (e.g. Bluetooth/WiFi or USB) to a BGAN terminal. The BGAN terminal communicates with the BGAN fixed network, which consists of a BGAN gateway, through an Inmarsat-4 satellite (I4). BGAN satellites are bent pipe: the feeder link operates at the C band (6424–6575 MHz in the forward direction and 3550–3700 MHz in the return direction) and has a global coverage beam, whereas the user link is in the L band (1626.5–1660.5 MHz in the forward link and 1525–1559 MHz in the return link) and employs a deployable antenna where up to 256 beams can be used. The service area is subdivided into three types of zones representing the Inmarsat-4 antenna beam patterns: narrow, regional and global. In a typical configuration, there are 19 regional beams (large coverage), 228 narrow beams (focused coverage) and 1 global beam. BGAN services primarily operate in narrow beam, but they are supportable in regional beams.

The BGAN fixed infrastructure consists of three BGAN gateways [37] located in Italy, the Netherlands and Hawaii. The radio frequency system feeds the information received from the user equipment to a radio network controller, which interfaces with the core network in order to route

Table I. DENISE service segments.

	Service	Service components
Service segment 1—broadcast and interactive services	One-way broadcast/multicast services	Streaming Data distribution
	Interactive broadcast/multicast services	Interactive streaming PayPerView Televoting Home shopping Interactive data distribution PayPerUse Content repair
Service segment 2—data acquisition services	Messaging services	Vehicle telemetry Environmental monitoring
	Messaging services in combination with GNSS applications	Anti-theft services Traffic monitoring Automatic toll payment Distress beacon Interactive distress beacon
	SMS	—
Service segment 3—real-time (emergency) services	Public safety and emergency services	eCall Two-way IP connection Broadcast of common interest messages
	Broadband for professional use	DSL-like connectivity

GNSS, Global Navigation Satellite System; SMS, short message service; DSL, digital subscriber line.

calls to the public or private network. The core network is integrated with a terrestrial 3G component (3rd Generation Partnership Project (3GPP), Release 4 Architecture). A mobile switching centre server node supports circuit-switched communication (i.e. public-switched telephone network and integrated services digital network). A media gateway performs the necessary translation, such as transcoding. The serving GPRS and gateway GPRS support nodes allow IP packet-switched communications.

The BGAN system is compatible with terrestrial UMTS services, enabling users equipped with BGAN terminals to access these services over the near-global terrestrial coverage provided by this system. Thus, the BGAN core network architecture is kept the same as that of the UMTS, while its air interface is optimized for the best match between terminal characteristics and satellite propagation channel. The specific system allows information bit-rate from 4.5 to about 492 kbps to three classes of portable user terminals [39]. Specifically, class 1 terminals can transmit at the maximum throughput of 492 kbps (downstream/upstream), class 2 terminals can reach 464 kbps (downstream) and 448 kbps (upstream), and class 3 terminals can achieve 384 kbps (downstream) and 240 kbps (upstream).

3.2.7. Global Mobile Personal Communication Services. Third-generation mobile satellites, comprising constellations of low Earth orbit (LEO), GEO, medium Earth orbit (MEO) and highly elliptical orbit (HEO) satellites (the last two types are not treated in this paper), provide voice and multimedia services to mobile and handheld terminals. Moreover, these third-generation mobile satellite services have entered the realm of personal communications and are also referred to as Global Mobile Personal Communication Services (GMPCSs).

The GMPCS is a personal communication system providing transnational, regional or global two-way voice, fax, messaging, data and broadband multimedia services from a constellation of satellites accessible with small and easily transportable terminals. There are several different types of GMPCS systems: GEO systems, small LEO systems, big LEO systems, MEO systems, HEO systems and broadband GMPCS systems. Except for small LEO satellite systems, which offer messaging services only, all other systems provide mobile satellite telephony services. Moreover, all these systems operate in the L and S bands allocated for mobile services, except for the broadband GMPCS systems, which operate in the Ku band, where mobile satellite systems have been allocated a secondary status. Table II enumerates the features of various GMPCS systems.

Table II. Features of the various GMPCS systems [38]

Types of GMPCS	Services offered	Frequency range	Terrestrial counterpart	Examples
Small LEO (data only GMPCS)	Data services such as messaging in store-and-forward mode	Below 1 GHz	Messaging services such as paging and mobile data services	Orbcomm
Big LEO including LEO, HEO and MEO satellites (narrowband GMPCS)	Real-time voice and data services	1–3 GHz	Cellular telephone	Iridium, Globalstar (LEO), ICO constellation (MEO) and Ellipso constellation (HEO)
GEO (narrowband/ broadband MSS)	Both store-and forward and real-time voice, data and video services	1.5–1.6 GHz and around 2 GHz	Cellular ISDN	Inmarsat, ACeS, APMT, ASC and Thuraya satellite systems
Broadband GMPCS (broadband FSS)	Real-time multimedia including voice and data	Above 10 GHz	Fibre optics	Sky Bridge Teledesic constellation

GMPCS, Global Mobile Personal Communication Services; LEO, low Earth orbit; HEO, highly elliptical orbit; MEO, medium Earth orbit; GEO, geostationary Earth orbit; MSS, mobile satellite system; FSS, fixed service satellite; ISDN, integrated services digital network; ICO, intermediate circular orbit; ACeS, Asia cellular satellite; APMT, Asia-Pacific Mobile Telecommunications; ASC, Afro-Asian Satellite Communications.

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3.2.8. Operational satellite systems. In this section, we report some of the current satellite systems and their main services.

3.2.8.1. GEO satellites operating at L/S band

Satellite	Services
Inmarsat	BGAN family of services; aeronautical services; Inmarsat B/C/M services; mini-M services; global area network services; fleet, Swift 64, Inmarsat D/D+/IsatM2M, mobile data packet services
SkyTerra	phone calls; data transmissions
Thuraya	voice communications with handheld (13 750 simultaneous voice calls);short message service; 9.6 kbps of data and fax service; 60 kbps downlink and 15 kbps uplink 'GMPRS' mobile data service on XT, SO and SG handsets; 144 kbps high-speed data transfer via a notebook-sized terminal (ThurayaDSL); GPS
Solaris Mobile	broadcasting video, radio and data to in-vehicle receivers and to mobile devices; video, radio, multimedia data, interactive services and voice communications

3.2.8.2. GEO European satellite series operating at Ku/Ka band

Satellite	Services
Astra	Broadband satellite communication services such as TV, radio, broadband data and Internet services
Hot Bird	Analogue and digital television, radio and multimedia services to Europe, North Africa and large areas of the Middle East
Intelsat	Hundreds of thousands of telephone circuits
KA-SAT	TV and radio broadcasting services, corporate network solutions and a portfolio of IP applications including distribution of multimedia content, broadband Internet access and Internet backbone connections; broadband Internet access services across Europe and also a small area of the Middle East

4. ANALYSIS OF WIRELESS SENSOR NETWORK CHARACTERISTICS

This section provides an overview of the main systems and the related technological aspects to take into account in the integration of WSNs and satellite.

4.1. Supervisory control and data acquisition

Supervisory control and data acquisition systems aim at acquiring telemetry and generic data from various sensors deployed in the target area/premises and forwarding them to a remote control centre in charge of control and management functions. SCADA objectives include any necessary analysis and control of the target process while displaying gathered information on the operator screen. Furthermore, control actions could be passed back to the process to counter possible system malfunctioning. Figure 6 shows the main components and a general configuration of a SCADA system [40].

The SCADA control centre relies on the interconnection of the following components: a master terminal unit, communication routers, the human-to-machine interface, engineering workstations and the data historian. Main operations include the collection and logging of information gathered by several remote field sites, display of information to the human-to-machine interface, and scheduling of actions based upon detected events. The control centre is also responsible for centralized alarming, trend analysis and reporting. The field site performs local control of actuators and sensors, whereas a deployed remote access device allows operators to perform remote diagnostics and repairs, usually over a separate dial-up or WAN connection. Either standard or proprietary communication protocols, running over serial communications, are used to transport information between the control centre and the field sites, using telemetry techniques (such as telephone line, cable and fibre) and radio frequency techniques (such as satellite).

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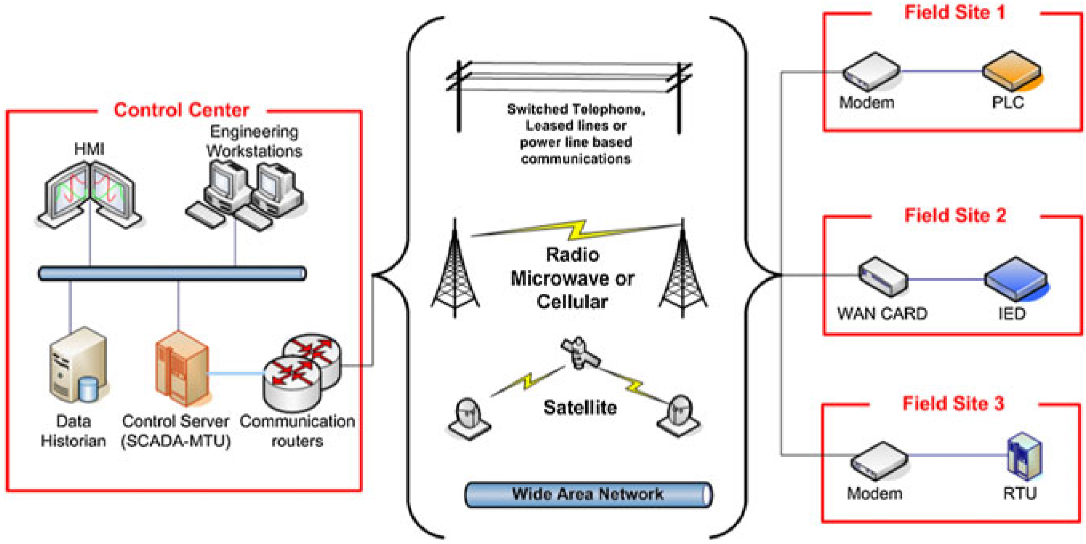

Figure 6. A general supervisory control and data acquisition (SCADA) architecture. HMI, human-to-machine interface; MTU, master terminal unit; PLC, programmable logic controller; IED, intelligent electronic device; RTU, remote terminal unit; WAN, wireless area network.

4.2. Mobility management in the wireless sensor network

The mobility problem in MANETs is caused by mobile nodes, whose movement changes multi-hop routes in the network that have to be handled. In a WSN, this problem can also exist if the sensor nodes are mobile in the given application. There are two additional aspects of mobility to be considered in WSNs. First, the sensor network can be used to detect and observe a physical phenomenon (e.g. in the intrusion detection applications). This phenomenon is the cause of events that happen in the network (such as raising of alarms) and can also cause some local processing aimed at determining whether there is really an intruder. In the case in which the observed phenomenon moves about, the data that have been gathered at one place should be available at the next one. Similarly also in tracking applications, such a task is explicit to ensure that some forms of activity happen in nodes that surround the phenomenon under observation. The second aspect concerns the sink(s) mobility. The sinks of information in WSNs (nodes where information should be delivered to) can be mobile as well. In general terms, this is not different from node mobility in a MANET, but it can cause some difficulties for protocols that efficiently operate in fully static scenarios. In this case, it is necessary to apply opportune trade-offs. Furthermore, in both MANETs and WSNs, mobility can be correlated—a group of nodes that are moving in a similar fashion. For example, this correlation can be caused, in a MANET, by a group of people travelling together. In a WSN, the similar movement of nodes can be correlated because a storm, a river or some other fluids carry nodes together.

The sink node can be either fixed or mobile. The fixed or static sink approach may limit the network lifetime, as the one-hop neighbours of the sink are the bottleneck of the network. The mobile sink approach is a common solution of exploiting sink nodes' mobility in order to become closer in the vicinity of the reporting sensors [41]. It also achieves higher degree of load balancing among sensor nodes and can offer extensive improvements of the network lifetime. On the contrary, the mobile sink approach has several disadvantages. All nodes must know the position of the sink in order to route information to it. Also, most applicative scenarios have the sink acting as a gateway to a backbone network, and it is difficult to engineer a system whereby a mobile sink is always connected to the backbone network.

Because WSNs are data-centric networks, data management functions are very important. These functions can be categorized as data dissemination [42, 43], data compression and data storage [44]. Three broad classes of sensor network applications emerge, depending on the factors that drive data acquisition and dissemination: *time-driven applications* (nodes in time-driven sensor networks periodically send their data to the sink node), *event-driven applications* (nodes in event-driven sensor

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networks do not send their data periodically) and *demand-driven applications* (it enables network entities to query the nodes for sensor data) [45]. As already said in Section 2.2, communication components consume most of the energy in WSNs, whereas computation uses less. Therefore, it becomes attractive to deploy data aggregation and compression techniques [46], which might increase the energy consumption for the computational task but decrease the number of transmitted packets.

4.3. Unattended wireless sensor networks: properties, issues and trade-offs

Unlike more traditional WSN settings, which assume constant supervision by a sink/control centre and real-time communication, unattended WSNs [47] are only periodically visited by a sink. In such a scenario, the WSN is deployed in a difficult environment and left alone till the next visit for downloading the WSN readings. In this scenario, a WSN must be engineered with the maximum 'self-*' constraints, that is, *self-organized*—the deployment is supposed to be random and therefore the WSN must be able to organize itself in order to guarantee global communication; *self-repairing*—nobody can easily reach the WSN in order to substitute a broken sensor, therefore the WSN is supposed to take a quick action to repair a damage/failure event; and *self-healing*—from a security perspective the WSN must be able to withstand nonauthorized third parties that want to compromise it in order to steal information.

Recent advances in technology have made possible the production of smart, autonomous and energy-efficient sensors; in the following, we divide sensors in two categories, depending on their architectural complexity:

1. Micro-embedded devices or resource-constrained devices

   They are characterized by really simple hardware. They are supposed to be massively deployed in terms of large numbers, such as thousands or even hundreds of thousands. We can presume the micro-embedded device paradigm as 'the cheaper the better'. Nevertheless, they are characterized by severe hardware constraints, and they are provided by a CPU, a memory, a radio and a sensor board with several built-in measuring transducers. The packaging is not tamper proof but provides sufficient robustness in order to guarantee the deployment in the target hostile environment. They can collect and store environmental data, have minimal processing capabilities and can finally transmit the processed data to one or more neighbours [48]. The strength of such devices does not rely on the single sensor entity but rather on the ability to be pervasively deployed and, by communicating together, to constitute a reliable instrument to monitor a wide area.

2. Advanced robots

   Robots can be considered as the last evolution of sensors [49]. They are neither simple nor cheap, but they can move and actively interact with the environment. Clearly, they have sensing capabilities, but they are also provided with high computational power; therefore, they can even perform a preliminary analysis of the sampled data. They can move in order not only to explore new areas but also to substitute another faulty robot, and they can interact with the environment by using several on-board tools. Robots cannot be massively deployed, but their ability to move and their data processing capability can definitely reduce their deployment number. Yet, they cannot have energy constraints: they are provided with large batteries or solar power supply.

4.4. Beamforming

As already said in Section 2.2, energy consumption is one of the major aspects that WSNs have to face. One way to alleviate the problem is by using beamforming techniques so as to increase the radio coverage of each single antenna and decrease the total energy consumption of the sensor networks.

Generally, sensor nodes are very small and inexpensive, and they are almost always equipped with a single antenna. Nevertheless, if the nearby sensor nodes share their information a priori and collaboratively transmit in a synchronous manner, it is possible to form a beam in the intended direction. This approach is well known as collaborative beamforming [50] (rather than cooperative beamforming), as all the nodes in the cluster collaboratively send their shared messages to the same destination (Figure 7).

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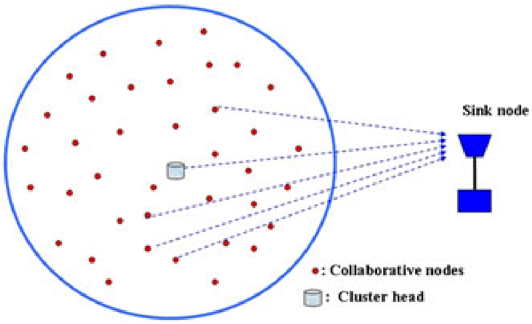

Figure 7. Collaborative beamforming configuration.

Collaborative beamforming exploits the basic principles of phased arrays antennas, and many interesting and useful applications have appeared in modern wireless communication networks. There are two approaches: a centralized beamforming system where the oscillator is the same for all the terminals and the distance among them is known, and the distributed nature of the beamforming system where different oscillators are assumed and phases or coordinates' estimation is required.

For the basic calculations of the array factor gain, some fundamental assumptions are usually taken: (i) each sensor node is equipped with an ideal isotropic antenna element; (ii) all nodes transmit with identical energies, and the path losses of all nodes are also identical; (iii) no reflection or scattering of the signal is considered; (iv) the sensor nodes are sufficiently separated such that mutual coupling effects are negligible; and finally, (v) all nodes are perfectly synchronized (or connected) such that no phase offset or jitter occurs. Collaborative beamforming is achieved if the transmitters of all the sensor terminals coordinate their phases. Several approaches have been proposed to control the phases of the transmitters [51]. One approach requires the accurate knowledge of the transmitters' clocks. This technique does not need feedback from the receiver. Another approach needs the receiver's feedback. In this technique, the sensor terminals randomly adjust their phases, and the receiver informs the transmitters of the signal strength.

Collaborative beamforming may be adopted in modern WSN for the following reasons [52]:

(1) The black-out spots in the sensor networks are minimized, which means that with the employment of the collaborative beamforming techniques, the transmission energy of the individual sensors is balanced and saved over the multiple sensor terminals. Each sensor terminal is able to use a lower power level, and the formed directive electromagnetic waves can reach the receiver at the desired signal strength. The collaborative techniques prevent some of the nodes from running out of energy much faster than the others.
(2) The whole coverage area is increased; this means that receivers that are too far for an individual transmitter are reached with the employment of collaborative beamforming. Collaborative beamforming allows the signals to travel further.
(3) Data security is substantially improved. Beamforming reduces or completely eliminates signals to unwanted directions.

In realizing beamforming, synchronization is a problem to face; one methodology is to use hardware to synchronize the carrier frequency [51]. This requirement can be relaxed by using a lower carrier frequency. For example, if the carrier frequency is 28 MHz, the required synchronization accuracy is 3 ns, and the localization accuracy is 89 cm. At this frequency, the wavelength is 11 m. An efficient antenna's length has to be comparable with the wavelength so that further reducing the carrier's frequency may be impractical.

Data sharing is necessary because each node is detecting only its local information, and the information detected by two nodes at distant locations may be different. Therefore, data need to be shared before performing beamforming transmissions. The literature presents some solutions to this problem: an energy-efficient clustering and routing scheme is proposed in [53], where nodes are deployed along the path from the sensing area to the base station and are divided into clusters. Transmissions are performed using hop-by-hop routing between clusters; the amount of communication is relatively small because of

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the small size of the cluster. If sensor nodes are deployed far away from the base station, and collaborative beamforming is used, in each beamforming transmission, more transmitters are used to increase the transmission distance [54]. The amount of communication among the sensor nodes increases when more transmitters are used. In [55], a generalized data sharing procedure is proposed for a given deployment, and the energy consumed on data sharing is examined.

5. TRADE-OFF ANALYSIS OF SATELLITE–WIRELESS SENSOR NETWORK INTEGRATED SYSTEMS

This section aims at matching WSN applications' requirements to the characteristics of the addressed satellite/space systems in order to identify the most suitable integrated configurations. The organization of the study envisages a top-down approach starting from a characterization of WSN traffic in the various application scenarios defined in Section 2. Specifically, WSN traffic is evaluated through two specific metrics:

- **traffic volume**, which is the amount of traffic expected from sensors; and
- **disruption tolerance**, which is high for unattended sensors and low/null for real-time attended sensors.

As far as the traffic volume is concerned, thresholds have been defined, taking into account likely values of typical narrowband (few dozens of kilobits per second) and broadband (some hundreds of kilobits per second) services. Specifically, the following ranges are defined:

- low $<$ 50 kbps;
- 50 kbps $<$ medium $<$ 500 kbps; and
- high $>$ 500 kbps.

The disruption tolerance index is, instead, strictly related to the type of service classification indicated in Table III. The following correspondences are considered:

- interactive and responsive services (low);
- timely services (medium); and
- noncritical services (high).

5.1. Wireless sensor network traffic analysis

Different standardization groups, such as ITU, ETSI or 3GPP, have covered categorization of multimedia traffic [56–58], where traffic has been categorized as follows:

- audio (conversational voice, voice messaging and streaming audio);
- video (videophone and one-way video);

Table III. End-user multimedia traffic categorized in types of service.

	Services (time constraints)			
Error tolerance	Interactive (delay $<<$ 1 s)	Responsive (delay ~ 2 s)	Timely (delay ~ 10 s)	Noncritical (delay $>>$ 10 s)
Error tolerant	Conversational voice and video $<$ 3% FER	AV messaging $<$ 3% FER	AV streaming $<$ 1% FER	AV on demand $<$ 1% FER
Error sensitive	Command/control messaging	Transaction messaging (e.g. queries and client–server applications)	Push messaging[a]	Data messaging

[a]Push messaging means that the sender initiates the data transfer rather than the recipient; synchronous conferencing and instant messaging are typical examples of push services.
AV, audio–video; FER, frame erasure rate.

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- data (Web browsing, bulk data, high-priority transaction services, command/control, still image, interactive games, telnet, email and instant messaging); and
- background applications (fax, low-priority transaction services, server-to-server email and usenet).

In line with the standardization indications, we suggest eight categories for WSN traffic, as shown in Table III.

Table IV summarizes information relevant to the various WSN traffic models. In particular, for each scenario defined in Section 2, the traffic model most suited to the application characteristics is identified.

In case of event-driven applications, the mobility variability and the spatial correlation of the collected information lead to the pseudo-LRD (i.e. LRD) traffic, which exhibits characteristics significantly different from those of Poisson traffic [10].

By 'approximating' the traffic requirements (Table IV) in order to achieve a unique representative index pair for each application scenario, one can possibly identify a set of associations (application scenario—traffic volume—disruption tolerance), shown in Table V, which can drive the selection of suitable satellite systems.

Considering similarities among several scenarios, it is possible to merge together

- surveillance of remote areas and environmental monitoring; and
- emergency communications and CIs;

thus reducing the analysed scenarios from five to three:

- Scenario 1—*emergency communications* (which includes *CIs*);
- Scenario 2—*support for SCADA systems*; and
- Scenario 3—*monitoring and surveillance of remote areas* (which includes *environmental monitoring*).

5.2. Wireless sensor network–satellite internetworking issues

The integration of satellite and sensor technologies is the key challenge to design the whole network architecture. In particular, the description of WSNs and satellite standards provided in the previous sections showed few degrees of freedom in terms of interconnection with other technologies. In more words, sensor networks and their design from an architecture point of view are mostly considered for native sensor applications and data retrieval from processing centres through terrestrial networks. On the other hand, the satellite technology is essentially devised around the target of delivering streaming or message-oriented applications to the destination, serving as a typical access network. Loosely speaking, this divergence is bridged by the network layer and, in general, by all networking functionalities provided by the higher layer of the protocol stack. In this regard, guidelines or observations about network design guidelines can be drawn from a twofold perspective: technology oriented and research oriented. As far as the former is concerned, it is immediate to see that there are technologies already enabled to be interconnected in heterogeneous systems. This is the case of S-MIM interfaces (for WSNs) and ETSI BSM architecture (for satellite), which inherently support the capability of processing and routing data through satellite air interface (the first) or receive data from other subnetworks and send them to a gateway through the satellite link (the second). The other considered technologies are inherently capable of transporting sensor network traffic, as for DVB-RCS and BGAN (just to mention a few), by means of the usual routing and forwarding functions implemented at the IP layer. More complicated in this setting is the network management that, instead, suffers from functionality fragmentation due to different management schemes applied on the sensor and satellite segments, respectively. Despite these internetworking enablers, there are still some open issues related to network discovery and forwarding efficiency to reduce the power consumption. In fact, these two items are closely correlated, because an efficient forwarding action depends very much on the availability of updated forwarding information basis tables, which in turn can be populated by network discovery algorithms. Furthermore, it is well known from the literature that a sensor node always consumes power in the states where it can while active: standby, transmission and reception. Although the last

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Table IV. WSN traffic models and requirements.

Application scenario	Category of application	Data type	Data traffic model	Types of service	Disruption tolerance	Traffic rate
Surveillance and monitoring of remote areas	Event driven	Push message	ON/OFF (Pareto or Poisson)	Timely	Medium	Low
	Periodic data generation	Image transfers	CBR (deterministic) VBR (Poisson)	Timely	Medium	Medium
Emergency communications	Multimedia communications	Video, audio and data (file transfers)	Elastic traffic	Interactive/responsive	Low	High
	Periodic data generation	Data message	CBR (deterministic) VBR (Poisson)	Responsive	Low	Medium
Support for SCADA systems	Periodic data generation	Command and control messages	CBR (deterministic) VBR (Poisson)	Interactive	Low	Medium
	Event driven	Push message	ON/OFF (Pareto or Poisson)	Responsive	Low	Low
Critical infrastructure	Periodic data generation	Video, audio and data message	CBR (deterministic) VBR (Poisson)	Interactive/responsive	Low	High
Environmental monitoring (sensor–Web)	Event driven	Data message	ON/OFF (Pareto or Poisson)	Noncritical	High	Low

WSN, wireless sensor network; SCADA, supervisory control and data acquisition; CBR, constant bit rate; VBR, variable bit rate.

Table V. Rating of scenarios' requirements.

Application scenario	Traffic rate	Disruption tolerance
Surveillance of remote areas	Low	Medium
Emergency communications	High	Low
Support for SCADA systems	Low/medium	Low
Critical infrastructure	High	Low
Environmental monitoring	Low	High

SCADA, supervisory control and data acquisition.

two consume most of the power, a sensor node in standby mode still consumes some power, which cannot be completely neglected. In this regard, it would be ideally more efficient to 'wake' a sensor up only when strictly needed, although this requires some additional signalling at the cost of newer power consumption. From this point of view, the activity being performed within the ROLL working group of IETF provides appropriate solutions, exactly for routing and discovery over lossy and lower-power networks, as those considered in this paper. From this standpoint, it is also worth considering their application extended to the satellite segment, in order to have a homogeneous routing and forwarding framework. This extension can be performed at the IP layer of the satellite terminal and, necessarily, enabled on the gateway to allow complete interoperability between all networked nodes. Concerning the specific protocol implementation, it is necessary to make some distinctions about the routing requirements that each network may exhibit. In general, sensor networks are configured statically and allowed to transport only one specific data service (e.g. monitoring). Hence, in this view, no specific dynamic routing and network discovery would be needed. However, in the case of sensor mules (moving over a given area) or sensors not available because of power outage or functioning problems, the knowledge of neighbours and the related transmission capability is fundamental for efficient routing and forwarding operations.

Apart from the protocol specifications that are needed from an implementation and deployment point of view, an important help to the internetworking challenge can be also offered by a research-oriented framework, which has had its momentum in the last 5 years: cooperative networking. Cooperation can be generally achieved in two ways: information theory and game theory. The first one considers the cooperation between nodes as a special case of MIMO (or SIMO) paradigms [59]. It can be profitably used here in order to improve the delivery efficiency subject to power consumption constraints. As such, this framework can be interestingly used over heterogeneous networks including the satellite segment, thus also shedding some light on the opportunity to forward data through the satellite or directly via traditional terrestrial network, depending on the instantaneous traffic load, the network resource availability and the transmission channel condition. On the other hand, the adoption of game theory considers the cooperation from a more economy-oriented point of view, where agreements between the players (nodes) can be (or cannot be) stipulated [60]. This is obviously the case of cooperative games, which can further reduce to coalitional game in case a grand coalition cannot be formed. In general, the approach here is to form different groups of nodes, depending on the specific topology (graph games) or on the channel conditions, so that the forwarding of data is convenient (payoff) for all coalition components. In turn, routing and forwarding between coalitions can be performed by traditional algorithms or by setting a new game where the border routers of each coalition are again part of a new game, whereby formation [61] of new coalition could be required to maximize the revenue that each node may demand. Alternatively to cooperation, the case of noncooperative games can be considered as well. This can be considered especially suitable in scenarios where different senor applications are transported over the integrated networks, whereby no possible agreement can be stipulated among the involved nodes. In this kind of game, the solution is to find the more appropriate routing decision that allows each node to have the data delivery in a way that is still satisfactory for that node (QoS requirements still matched) and does not penalize traffic performance observed by the other nodes. This essentially leads to the concept of Nash equilibrium, which, although not existing for all possible games, gives a clue about the most appropriate routing decisions to be made when different technologies (with different service availability and requirement figures) are considered.

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5.3. Transport layer configuration for wireless sensor network–satellite interconnection

TCP can be selected as a transport protocol to carry sensor data on satellite link. This choice is aimed to guarantee reliability to data transfers, assuming sensor measurements as sensitive messages.

Data transmission scheduling of sensor applications is different from that coming from common Internet applications (e.g. mail, Web and ftp). Consequently, traditional protocols, designed to efficiently handle Internet traffic, can present poor performance.

A possible solution to address this issue relies on avoiding the management of the transmission of sporadic messages over a single TCP connection. Thus, traffic coming from a WSN can be multiplexed into a single application flow in order to feed a TCP connection at a higher rate. Specifically, the following architecture is proposed as a generic setup:

- A local central sink collects all the sensor traffic.
- Sensor-to-sink transfers are assumed with specific application protocols (non-TCP/IP stacks), and sensor data is transferred at once to the sink; such transfers present a negligible delay.
- Sensor sink is interfaced to the satellite terminal.
- Satellite terminal implements an application proxy, which opens a single TCP-based connection to send data towards the satellite.

A number of advantages can be achieved by using such an approach:

- TCP connection signalling is minimized; considering the potential high number of sensors, the establishment (and termination) of a connection per sensor or even per sensor message transfer would imply continuous three-way handshaking transactions resulting in overhead and delay costs.
- In case of a large sensor population, the aggregation of sensor data makes applications ‘greedy’, allowing a transmission rate constrained only by TCP congestion control.

5.4. Matching satellite systems with traffic volumes

Table VI synthesizes the main characteristics useful to assess a possible integration of the most popular satellite systems with WSNs. Specifically, six parameters are envisaged, each one addresses one or more of the characteristics described as follows.

Communication architecture:

- mesh or star; and
- fixed or mobile satellite terminals.

Bandwidth:

- broadband or narrowband;
- frequency bands; and
- max and min bandwidth values.

Forward link access scheme:

- multiplexing mechanism; and
- bandwidth allotment strategy.

Return link access scheme:

- fixed-sized connections (i.e. GlobalStar channels); and
- variable bandwidth:

- constant–continuous assignment (session-based pre-assignment); and
- dynamic assignment (demand assigned multiple access—i.e. superframe-based assignment).

QoS features:

- QoS management techniques at lower layers; and
- error correction capabilities.

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Table VI. Main characteristics of the addressed satellite systems and standards.

Satellite system	Communication architecture	Bandwidth frequency	Forward link access schemes	Return link access schemes	QoS features	Traffic volume
DVB-RCS2/S2	Star and mesh	Broadband Ku band: 36 MHz Ka band: 125–500 MHz	TDM	TDMA: DAMA (DA) Slotted Aloha (RA) CRDSA (RA)	ACM	High
DENISE	S-band satellite complementary ground components	S-band 1980–2010 MHz 2170–2200 MHz	DVB-SH	SSA QS-CDMA	CAC/DAMA	Medium
GSPS	Three NCC-GW (physical management of three Inmarsat-4 satellites)	2.4 kbps L-band: (Rx) 1525–1559 MHz; (Tx) 1626–1660 MHz	TDM	TDMA/FDM	Adaptive modulation and coding Dynamic assignment	Low
GMR-1	Mesh	Narrowband	GSM like	GSM like	Fixed-size channels	Low
GMR-2/Thuraya	Mesh	Up to 432 kbps shared 16–384 kbps dedicated IP streaming	EDGE based	EDGE based	EDGE based	Medium
Inmarsat/BGAN	Constellation of four prime GEO satellites	L-band:	FDMA/TDMA scheme	FDMA/TDMA scheme	ACM	Medium
	Fixed and mobile users	1626.5–1660.5 MHz (forward link), 1525–1559 MHz (return link)	Not standardized yet	Dynamic assignment Not standardized yet		
HAP	Backhauls Links/point-to-point links/mesh network	Narrowband:	3G based (IMT 2000)	FDMA/TDMA scheme	ACM	Medium/high
		L/S- bands:2 GHz	FDMA/TDMA scheme	Dynamic assignment		
			DVB-S2 type	DVB standards (MF-TDMA)		
	Fixed and mobile users	Broadband: Ka/V-bands: 31/28 GHz, 48/47 GHz (300 MHz)	Not standardized yet	Not standardized yet		
UAV	Beyond LoS/LoS	Narrowband: L/S band Broadband: C/X/Ku/Ka-Bands and above Not Standardized yet	FDMA/TDMA Not standardized yet	Not standardized yet	Not standardized yet	Medium/high

(*Continues*)

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Table VI. (Continued)

Satellite system	Communication architecture	Bandwidth frequency	Forward link access schemes	Return link access schemes	QoS features	Traffic volume
LEO (low frequencies)	Constellation Fixed and mobile users	Narrowband: Below 1 GHz/ L/S band (satellite-user)	FDMA/TDMA/CDMA Not standardized yet	`Fixed-sized connections	ACM Not standardized yet	Medium
Astra series	Star, fixed satellite terminals	Broadband	DVB-S2	MF-TDMA (Astra2Connect)	QoS for VoIP packets (Astra2Connect)	High
Hot Bird series	Star, fixed satellite terminals	Broadband	DVB-S2	NA	NA	High
Intelsat series	Star, fixed satellite terminals	Broadband	DVB-S2	NA	NA	High
KA-SAT satellite	Star, fixed satellite terminals	Broadband	DVB-S2	MF-TDMA (Tooway)	NA	High

DVB-RCS2/S2, Digital Video Broadcasting–Return Channel via Satellite Second Generation/Satellite Second Generation; GSPS, Global Satellite Phone Service; GEO, geostationary Earth orbit; GMR, GEO-Mobile Radio; BGAN, Broadband Global Area Network; HAP, high-altitude platform; UAV, unmanned aerial vehicle; LEO, low Earth orbit; NCC-GW, Network Control Centre-Gateway; LoS, line of sight; TDM, time division multiplexing; DVB-SH, DVB-S services to Handhelds; GSM, Global System for Mobile Communication; FDMA, frequency division multiple access; TDMA, time division multiple access; IMT, International Mobile Telecommunication; CDMA, code division multiple access; DAMA, Demand Assigned multiple access; DA, demand access; RA, random access; SSA, Spread Spectrum Aloha; QS-CDMA, quasi-synchronous CDMA; FDM, frequency division multiplexing; MF-TDMA, multi-frequency TDMA; ACM, admission control; CAC, call admission control; VoIP, voice over IP; NA, Not Available; EDGE, Enhanced Data rates for GSM Evolution.

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Connection availability and reliability (not only mainly related to access schemes but also including physical connectivity and reliability):

- resources are always guaranteed over time (TDMA);
- (RA) with possible transfer interruptions;
- disconnection periods (i.e. LEO constellations); and
- quasi-error-free channel.

The last column in Table VIII associates an index (high, medium/high, medium, low/medium and low) for the traffic rate addressable with the target system, which depends on both bandwidth and resource management policies.

6. DEFINITION OF WIRELESS SENSOR NETWORK–SATELLITE HYBRID ARCHITECTURES

In previous sections, we analysed the volumes and the characteristics of the traffic generated by the WSNs and those supported by most popular satellite systems; we also assembled together some of the five environments previously envisaged as we made considerations relevant to their similarities.

In this section, for each of the three remaining environments, we present the characteristics and the most suitable satellite system usable for transmitting the volume of the particular traffic generated in the specified scenario.

6.1. Emergency communications

Emergency scenarios can benefit from the deployment of a WSN in the target area for a twofold task: to gather important information from the field and to support audio, video and data communication when other terrestrial systems are temporarily not available.

Therefore, sensors are complemented by additional multimedia traffic sources (i.e. PCs, cameras, smart phones and cellular phones). The emergency area might envisage different dislocated zones, where independent WSNs and rescue teams operate for the same coordinated mission, and a control centre (headquarters) remotely located and connected to the Internet. For this reason, the satellite segment must, in general, guarantee a worldwide coverage (GEO systems are preferred). In addition, multiple satellite terminals are needed to give Internet access to different WSNs spread over the overall area of interest. Then, resource management over the return link can be considered as a critical issue.

Table VII collects the main scenario characteristics. The network architecture can be either star or mesh, depending on the terminals' requirement to directly communicate with each other. Such a requirement mainly relies on multimedia communications (i.e. audio calls between spread rescue teams). Instead, sensors are expected to provide data to a single control centre located on the Internet.

Table VII. Emergency communications—main scenario characteristics.

Selected scenario	Architecture	Configuration	Disruption tolerance	Traffic rate	Suitable satellite systems
Emergency communications	Star or mesh, global coverage, bidirectional communications	WSN→sink→satellite access toother multimedia sources in the field	Low	High	DVB-RCS2/S2 Astra series (only for star architecture) Hot Bird series (only for star architecture) Intelsat series (only for star architecture) KA-SAT satellites (only for star architecture) UAV, HAPS (optionally)

DVB-RCS2/S2, Digital Video Broadcasting–Return Channel via Satellite Second Generation/Satellite Second Generation; UAV, unmanned aerial vehicle; HAPS, high-altitude platform.

On this basis, a CI subscenario requires only a long-range link to connect a remote field site with a satellite gateway, interfaced to the Internet. All communications are in general bidirectional:

- Data sensors send data to the control centre, while the control centre could send configuration or management command to sensors.
- Most of the multimedia communications are interactive.

The network configuration is shown in Figure 8. Groups of sensors cooperate to gather and forward data towards a sink, which provides the interface to the satellite system. In parallel, different multimedia sources can also interface to the satellite terminal through a terrestrial wireless link.

The *disruption tolerance* index is 'low' because emergency communications require a high level of availability to provide a reliable support in critical situations. The *traffic rate* index is 'high' because of potential multimedia traffic generation. Taking into account all the aforementioned considerations, suitable satellite systems should support both star and mesh architectures (depending on the specific implemented application), together with broadband capacity and an efficient management of multiple access over the return link. Among the reviewed satellite systems/standards, DVB-RCS2/S2 perfectly matches such requirements. The systems Astra series, Hot Bird series, Intelsat series and KA-SAT satellites may also be applied, but only in case of applications requiring a star-based architecture.

6.2. Support for supervisory control and data acquisition systems

Supervisory control and data acquisition systems combine telemetry and data acquisition, which mainly envisage various sensors deployed in the target area/premises, collecting data and sending it to a central computer in charge of control and management functions. The overall objective includes any necessary analysis and control of target processes while displaying the gathered information of operating equipment.

Supervisory control and data acquisition was originally designed to constitute a private network not connected to the Internet. The rationale is to isolate the confidential information as well as the control

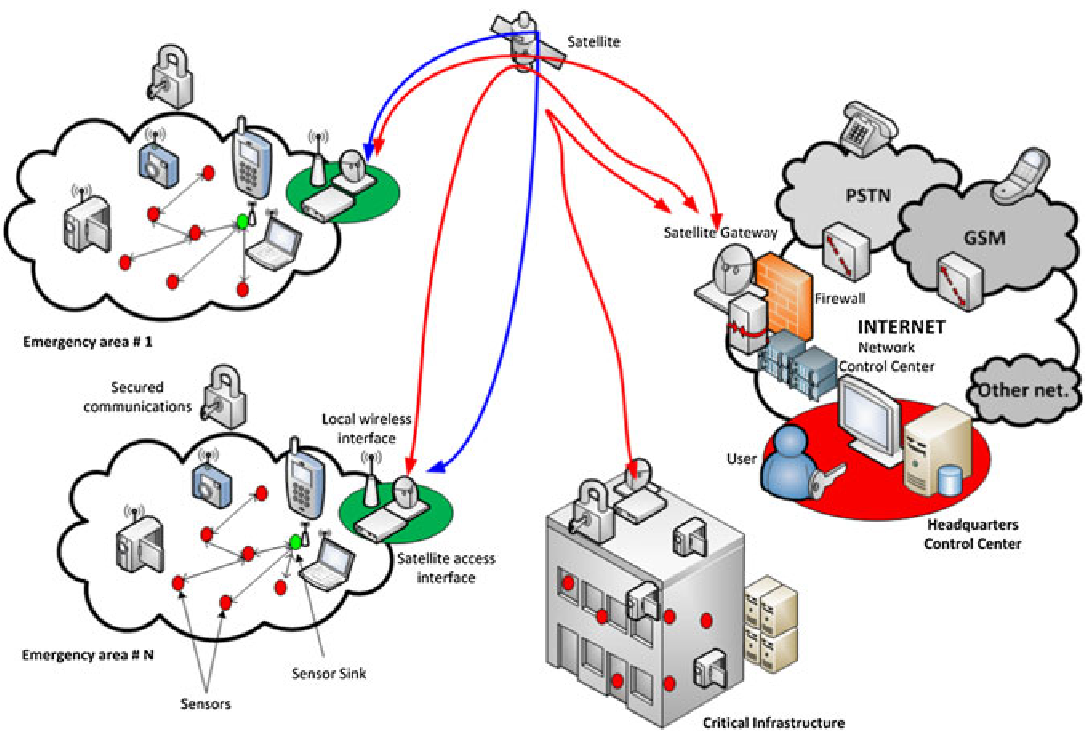

Figure 8. Architecture and network configuration for the emergency scenario. PSTN, public-switched telephone network; GSM, Global System for Mobile Communication.

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of the system itself. The later SCADA integration with wireless communication systems is mainly related to a number of advantages, which are the following:

- wide area and pervasive connectivity;
- enhanced routability;
- parallel polling;
- large addressing range; and
- integration of IT to automation and monitoring networks.

Table VIII reports the selection of the enabling technologies, which can support SCADA applications in the communication field.

Owing to the variety of applications and the relative offered loads that SCADA applications may generate, the *traffic rate* index in Table VIII may vary from 'low' to 'medium'. In any case the *disruption tolerance* index is 'low', because both remote control and supervisory control require low latencies and reliable communications. In fact, these communications are, in general, bidirectional: collected data are sent to the control centre, which could push interactively configurations or management commands to sensors. Taking into account all the aforementioned considerations, suitable satellite systems should support both star and mesh architectures (depending on the specific implemented application). In case of low traffic rates, the following systems are candidates among the reviewed satellite systems/standards: S-MIM, GSPS, GMR-1, GMR-2/Thuraya and Inmarsat/BGAN.

Low Earth orbit constellations can be also considered provided that a continuous real-time coverage is guaranteed. In case of medium traffic rates, DVB-RCS2 foresees a system profile for terminal manufacturers dedicated to SCADA applications. The advantage of broadband capabilities of DVB-RCS2 extends the range of applications and traffic loads that can be included in SCADA scenarios.

6.3. Monitoring and surveillance

Monitoring and surveillance merges 'surveillance and monitoring of remote areas' and 'environmental monitoring' application scenarios. This application is quite different from the previous ones for the following characteristics (Table IX):

- it may operate with temporary disruptions and opportunistic contacts;
- there is low expected traffic; and
- in principle, all satellite systems can fit application-level requirements.

6.3.1. Single-area monitoring and surveillance system. In this scenario (Figure 9), a satellite monitors a single area. There are two possible architectures for the specific scenario. In the first one, there is a cluster of sensors in which the nodes elect the most energy-efficient node (sink node), and they send their information data towards this node by using the ZigBee standard. In this case, various clustering algorithms can be used (traditional clustering techniques, game-theoretic mechanism, etc.)

Table VIII. SCADA—main scenario characteristics.

Selected scenario	Architecture	Configuration	Disruption tolerance	Traffic rate	Suitable satellite systems
SCADA	Star or mesh, global coverage	WSN→sink→satellite access gateway	Low	Low/medium	S-MIM GSPS GMR-1 GMR-2/Thuraya Inmarsat/BGAN DVB-RCS2/S2 LEO constellations

SCADA, supervisory control and data acquisition; WSN, wireless sensor network; S-MIM, S-band Mobile Interactive Multimedia; GSPS, Global Satellite Phone Service; GMR, Geostationary Earth Orbit Mobile Radio; DVB-RCS2/S2, Digital Video Broadcasting–Return Channel via Satellite Second Generation/Satellite Second Generation; LEO, low Earth orbit.

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Table IX. Monitoring and surveillance—main scenario characteristics.

Selected scenario	Architecture	Configuration	Disruption tolerance	Traffic rate	Suitable satellite systems
Single-area monitoring and surveillance system	Mesh	Sensors→sink node→sensor gateway→satellite	Medium/high	Low	BGAN/DVB-RCS
	Star	Sensors→satellite/HAP	Medium/high	Low	BGAN/GEO Satellite/HAP/LEO/UAV
Multi-area monitoring and surveillance system	Mesh	Each cluster of sensors→cluster's sink→base station→satellite	Medium/high	Low	DVB-S2/DVB-RCS2
Environmental monitoring system	Star	Sink node→satellite	Medium/high	Low	GEO Satellite/HAP/LEO/UAV
	Mesh	Sensor nodes→mobile sink→satellite	Medium/high	Low	GEO Satellite/HAP/LEO/UAV

BGAN, Broadband Global Area Network; DVB-RCS, Digital Video Broadcasting–Return Channel via Satellite; GEO, geostationary Earth orbit; HAP, high-altitude platform; LEO, low Earth orbit; UAV, unmanned aerial vehicle.

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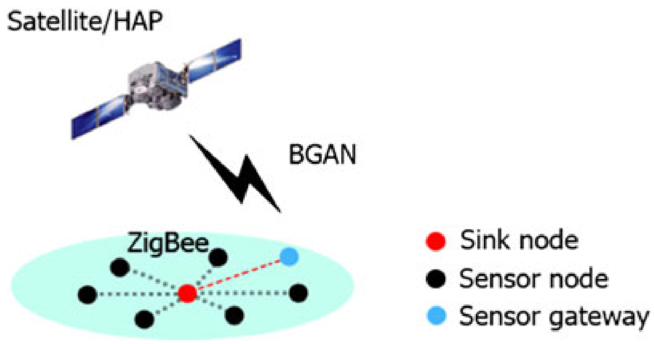

Figure 9. Architecture of single area monitoring network. HAP, high-altitude platform; BGAN, Broadband Global Area Network.

in order to optimize the network lifetime and the energy consumption. Afterwards, the sink node aggregates the data and forwards them to a node with satellite–gateway capabilities (sensor gateway). The sink node and the sensor gateway may be the same nodes. Finally, the sensor gateway sends all the monitored data to a satellite/high-altitude platform by using either BGAN or DVB-RCS standard.

In a different architecture of the same scenario, such as the one depicted in Figure 10, the collaborative beamforming technique may be employed for investigating the direct communication between the sensor nodes and the satellite. Because of the extremely large destination's distance and the current sensors' technology, collaborative beamforming is the only way to succeed in the desired direct communication between typical sensor nodes (with no satellite–gateway capabilities) and a satellite, without a gateway.

Because the WSN-to-satellite collaborative beamforming technique is a modern idea, many issues have to be taken into account for the practical implementation of such a scenario, including hardware constraints, deterministic and stochastic propagation modelling, QoS requirements and power consumption model. Various technologies, such as BGAN, GEO satellite, high-altitude platform, LEO and unmanned aerial vehicle, can be considered. Furthermore, in order to achieve the collaborative beamforming in WSNs, several protocols, which may be often limited by their complexities for achieving the ideal performance, must be executed. A number of interesting design issues that should be considered towards implementing these ideas in practical collaborative sensing networks are the following:

- data sharing protocols in order to compound the data for transmission;
- nodes' time and phase synchronization protocols;
- nodes' positioning and localization protocols;
- radiating sensors clustering protocols; and
- radiating sensors scheduling protocols.

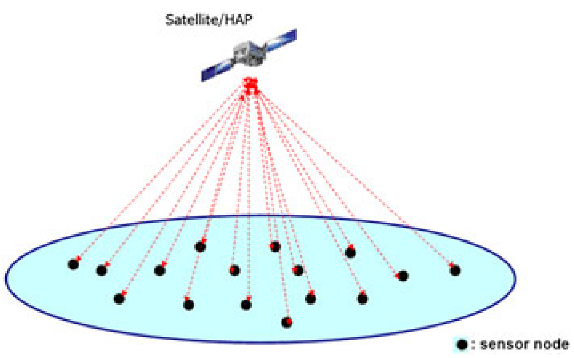

Figure 10. Direct communication of the sensors and the satellite. HAP, high-altitude platform.

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All the aforementioned issues make inevitable the proposal of a unified satellite-based WSN architecture and framework that will bring the idea of WSN-to-satellite cooperative beamforming closer to practice.

6.3.2. Multi-area monitoring and surveillance system. In this scenario, a satellite monitors multiple remote areas (Figure 11). We assume a certain number of sensors' clusters, and in each cluster, the nodes elect the most energy-efficient node (sink node). Moreover, the nodes of each cluster send their data towards the sink node by using the ZigBee standard. Afterwards, each sink node forwards the data to a single base station by using WiMax/3G standards. Finally, the base station sends the monitored data to a satellite by using DVB-S2/RCS2 standards.

In the aforementioned scenarios, the satellite can monitor either one or more sensor networks. The advantage of using a satellite in such a scenario is its versatility to act as a relay node/gateway with the purpose of avoiding either disrupted links and/or congestion, as well as providing a faster communication with respect to a multi-hop terrestrial communication, taking into consideration error probability, bit rate and packet length. The satellite would be communicating with a sensor gateway, placed in a strategic position, or with terrestrial infrastructures.

6.3.3. Environmental monitoring system. In the environmental monitoring scenario, an environmental monitoring system is employed to retrieve the measures of physical quantities, such as temperature, humidity and vibration intensity together with the geographical position where the measures are taken (architecture in Figure 12).

The supporting system is composed of a network of sensors, a group of earth stations (sinks), a satellite backbone and a destination. Each sensor collects physical and position information, encapsulates it into packets and conveys it towards the sinks, which give access to the satellite backbone that connects the sinks to the destination. A single sensor transmits the information to all sinks, but only one sink transmits it over the satellite channel. Even if the redundant transmission of the same data from more than one sink would increase the safety of the system, it would increase also the costs of it. The selection of the sink that forwards the information of a sensor to the destination is important to increase the performance of the system. Specific performance metrics, such as packet loss rate, average packet delay and energy consumption, have to be adopted to evaluate the functionality of the whole system in terms of reliability, reactivity and spent energy.

Direct communication of sensors to the satellite is also possible, as what is happening today with ocean monitoring systems. Here, the sensors (floats and gliders) are substantially well equipped and communicate with a MEO constellation that also serves the purpose of positioning.

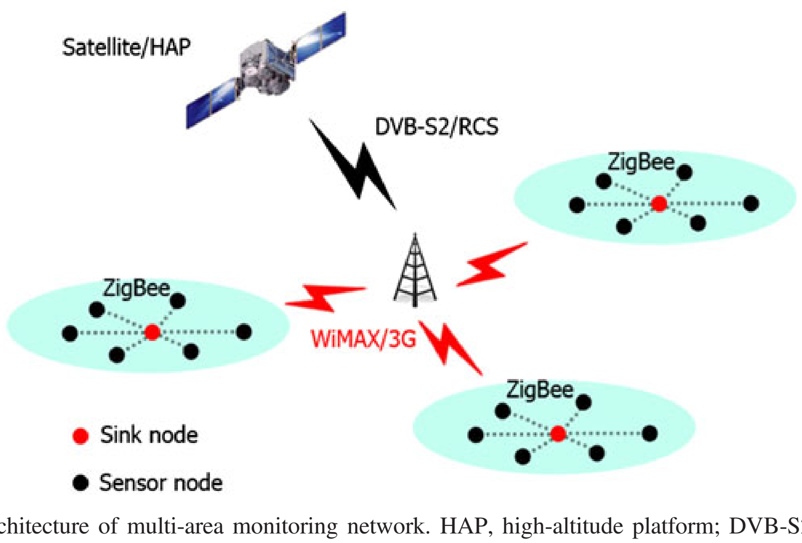

Figure 11. Architecture of multi-area monitoring network. HAP, high-altitude platform; DVB-S2/RCS, Digital Video Broadcasting Satellite Second Generation/Return Channel via Satellite.

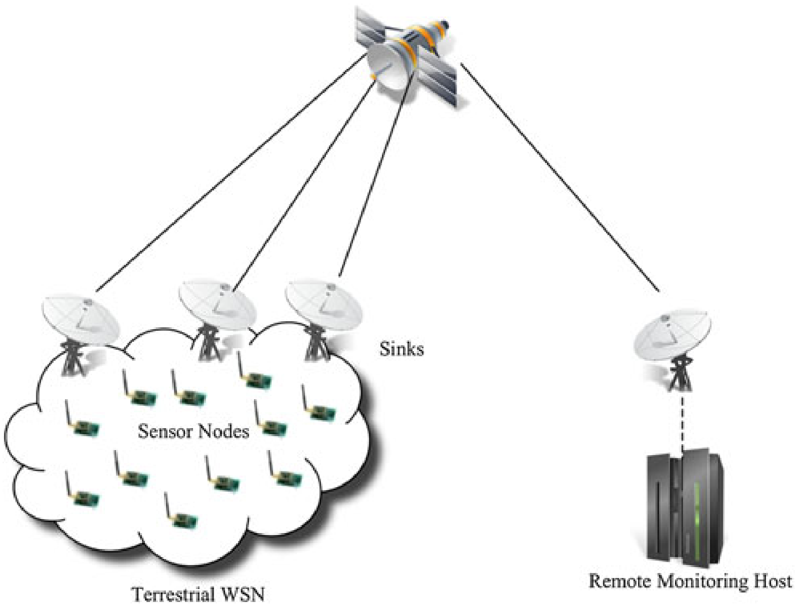

Figure 12. Architecture for environmental monitoring system. WSN, wireless sensor network.

A notable example of this situation is Operational Oceanography, a powerful tool to monitor, analyse and predict the state of marine resources as well as the sustainable development of coastal areas, where near real-time observations at the sea surface and in the water column (e.g. temperature and salinity profiles) need to be collected and sent to remote processing centres [62]. Data are collected by floats (drifting buoys) and gliders (remotely controllable vehicles), which communicate them to remote centres by using satellite systems such as the ARGOS fleet (http://www.argos-system.org/). Each sensor being relatively well equipped and autonomous in this case acts as a sink itself, directly communicating with the satellite when it emerges after a measurement collection period.

In another architecture of the same scenario, we still assume the satellite is controlling more than one WSN, for example, three in Figure 13, but WSNs are too far apart in order to communicate among

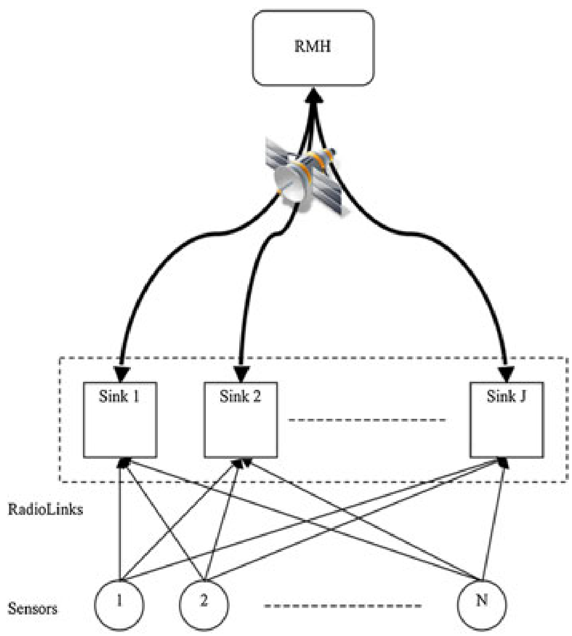

Figure 13. Satellite-based sensor network for environmental monitoring system. RMH, remote monitoring host.

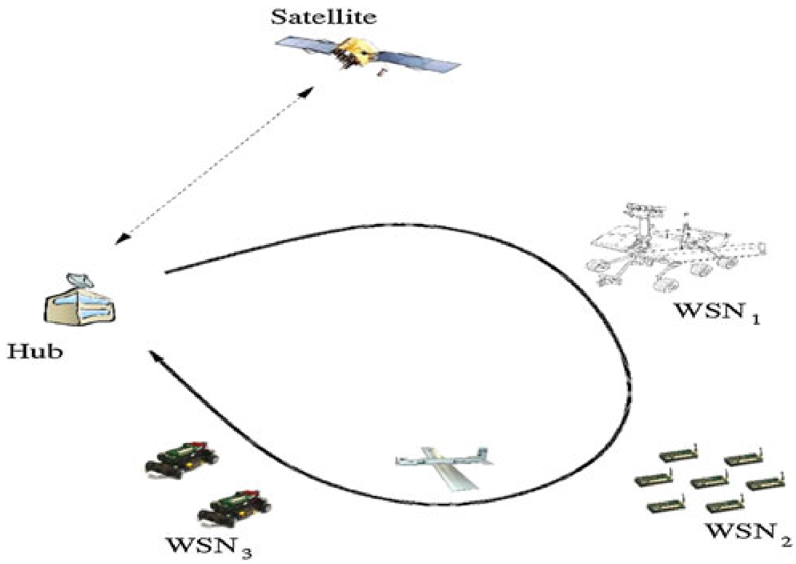

Figure 14. Monitoring system with mobile sink. WSN, wireless sensor network.

them or with the base station); for example, this is the case when the deployment has to cover specific targets in a very large area or obstacles (mountains and/or buildings) that do not allow the communication. In such scenario, a mobile sink (a flying drone or an unmanned aerial vehicle) can periodically visit the WSNs and download the sensed data (Figure 14).

Optimal sink election in a WSN in terms of a given set of metrics can be realized using different techniques such as the following:

- multi-attribute decision-making theory [63] on the following metrics (data queued at a sink): loss rate, average packet delay and energy consumption; and
- game theory, in order to be able to optimize the efficiency of the system in a distributed manner, accounting for the power constraints of the sensor nodes.

7. CONCLUSIONS

Satellite systems can be integrated to WSNs, thus realizing a fruitful synergy in support of a number of application scenarios, such as the following:

- surveillance and monitoring of remote areas;
- emergency communications;
- support for SCADA systems;
- CIs; and
- environmental monitoring.

This paper provided a survey on both sensor and satellite state-of-the-art technologies, with the aim of identifying the best-suited configurations matching requirements associated to each of the aforementioned applications. Standards, including ZigBee, 6LoWPAN and IEEE 802.15.4, have been reviewed. Different EU projects, which are relevant to this field, have also been identified. As far as the satellite technologies are concerned, an overview on DVB-RCS, GMR and GSPS were given. This paper also pointed out that the ETSI BSM SI-SAP can be used as the convergent technology for the integration of WSNs with heterogeneous satellite technologies, and a brief overview on BSM SI-SAP was also given.

An integrated WSN–satellite network scenario has been proposed. The WSN segment can encompass both mobile and fixed WSNs. The challenges and issues for handling mobility in mobile sensor nodes and

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sinks have also been discussed. A comparison of different satellite systems when considering such integration has been carried out.

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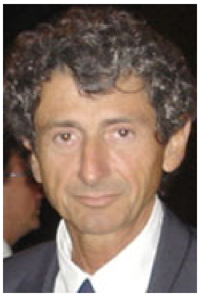
AUTHORS' BIOGRAPHIES

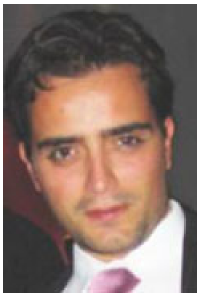


Nedo Celandroni (MS'73) is the director of research at the Wireless Networks Laboratory at CNR-ISTI, the Institute of Information Science and Technologies of the National Research Council (CNR), Italy. His research interests include rain fade countermeasure systems, data quality estimation, VSAT systems, TCP congestion management and TCP over wireless channels.

Erina Ferro (MS'75) is the director of research at the Institute of Information Science and Technologies of the National Research Council (CNR-ISTI), located in Pisa, Italy; she is the head of the Wireless Networks Laboratory (WNLab). She is responsible for ISTI of many national and international projects. Her main scientific interest field is in digital transmissions via satellite.

Alberto Gotta (MS'02-PhD'07) is a researcher at the Wireless Networks Laboratory at CNR-ISTI, the Institute of Information Science and Technologies of the National Research Council (CNR), Italy. His expertise is mainly related to architectures for terrestrial wireless and satellite networks applied in the context of ubiquitous networks for entertainment, multimedia and environmental monitoring.

Gabriele Oligeri (MS'07-PhD'10) was a PhD student at the Wireless Networks Laboratory at CNR-ISTI, Italy, from 2006 to 2011. Currently, he is a postdoctoral researcher at the University of Trento. His research interests include security and privacy for distributed systems.



Cesare Roseti (MS'03-PhD'07) is an assistant professor at the University of Rome 'Tor Vergata', Italy. His research interests include satellite communications and protocol design, cross-layer interactions, security, HAPS/UAV communications, protocol implementation and performance analysis in wired/wireless networks.

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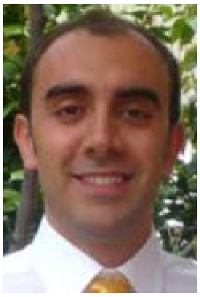
Michele Luglio (MS'90-PhD'94) is an associate professor of Telecommunication at the University of Rome 'Tor Vergata', Italy. His current activities are in designing satellite systems for both mobile and fixed multimedia services.

Igor Bisio (MS'02-PhD'06) is an assistant professor at the Department of Telecommunication, Electrical and Electronic Engineering, and Naval Architecture (DITEN) of the University of Genoa, Italy. His main research activities concern resource allocation and management for satellite communication systems, optimization algorithms and architectures for satellite sensor networks and traffic modelling.



Marco Cello (MS'08-PhD'12) is a research fellow at the Department of Telecommunication, Electrical and Electronic Engineering, and Naval Architecture (DITEN) of the University of Genoa, Italy. His main research activity concerns call admission control in QoS networks and routing and congestion control in intermittently connected networks.

Franco Davoli is a full professor of Telecommunication Networks at the Department of Telecommunication, Electrical and Electronic Engineering, and Naval Architecture (DITEN) of the University of Genoa, Italy. His current research interests are in dynamic resource allocation in multiservice networks, wireless mobile and satellite networks, multimedia communications and services and energy-efficient networking.

Athanasios Panagopoulos (MS'02) is an assistant professor at the School of Pedagogical and Technological Education and is a research assistant in the Wireless and Satellite Communications Group of the National Technical University of Athens. His research interests include radio communication systems design, wireless and satellite communications networks and propagation effects on multiple access systems.

DOI: 10.1002/sat

Marios Poulakis (MS'08) is a PhD student at the National Technical University of Athens. His research interests include wireless and satellite communications with emphasis on radio resource management, optimization theory, cross-layer design and cognitive radios.

Stavroula Vassaki (MS'08) is a PhD student at the National Technical University of Athens. Her research interests include wireless communications, game theory, cognitive radio and resource allocation.

Tomaso de Cola (MS'02 -PhD'10) is a researcher at the Institute of Communications and Navigation at the German Aerospace Center (DLR) (DE). His main research activity concerns TCP/IP protocols, satellite networks, transport protocols for wireless links, interplanetary networks and delay tolerant networks.

Maria Antonietta Marchitti (MS'05-PhD'07) has joined the Institute of Communications and Navigation at the German Aerospace Center (DLR) (DE) in May 2010. Her main research interests are cooperative routing protocols with emphasis on satellite networks.

Y. Fun Hu is a professor of Wireless Communications Engineering in the School of Engineering, Design and Technology of the University of Bradford (UK), where she leads the Future Ubiquitous Networks (FUN) Research Group. Her research interests encompass mobile/wireless/satellite networking, protocol design, security, QoS and mobility management.

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Prashant Pillai (MS'02-PhD'07) is a lecturer in the School of Engineering, Design and Technology at the University of Bradford (UK). His main areas of work are in mobile/wireless networks such as 2G/3G, WLAN/WiMax and bluetooth and satellite-based networks (DVB and BGAN).

Suraj Verma (MS'09) is a researcher at the Bradford University.

K. Xu is a research assistant at the Bradford University.

Guray Acar (MS'97-PhD'01) is with the ESA/ESTEC, the European Space Agency, Noordwijk (NL). His research interests cover radio resource management, MAC protocols, reliable multicast transport protocols, mobility management and system-level and packet-level simulation analyses in mobile and satellite networks.

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