WSN-SA: Design Foundations for Situational Awareness Systems Based on Sensor Networks

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***Abstract*—WSN-SA is a Wireless Sensor Networks (WSN) framework that is been proposed to support rescue operations in collapsed structures, such as houses and buildings, after natural and human-made disasters. The sensors and actuators are deployed *prior* to the disaster and ideally such sensor network is a required infrastructure of any building. Such SA systems can help to indicate how to distribute the rescue resources and how to identify imminent risks for rescuers and survivors. So far, few situational awareness (SA) systems based on WSNs have been proposed and no long-term realization of such systems has been reported. The goal of this work is to provide the foundations to change this reality so it would be possible to see a SA system accompanying each existing fire system. To this end, a strong emphasis is given to a) the achievement of low total cost of ownership (TCO), b) reliability, c) and expandability for the adopted SA solution.**

I. Introduction

Based on multiple public reports mainly related to earthquake disasters, bodies are found without severe visible injuries in regions where the employed *surface-based* resources (dogs, humans, and post-disaster deployed sensors) potentially could not detect survivors. Also, the real-time conditions (temperature, vibrations, pressure, water, gases, etc.) of some regions below the debris can hardly be measured or captured by surface tools which poses serious risk for rescue team and survivors. If we assume that sensor nodes are deployed with sufficient mechanical robustness there is a high probability of having functional nodes providing information from regions of the disaster area that are inaccessible by any other form. This form of Situational Awareness (SA) system deployed *prior* to the disaster event (e.g., collapsing of a building, food, fire) is the focus of this work.

Ideally, such SA system must accompany any existing fire system in buildings. That is, it would be a mandatory component of the design of any new building. However, in order to realistically accomplish this goal, the solution must be cost-effective, reliable, and easy to expand in terms of porting new sensing technologies that eventually become available. To this end, the proposed framework, called WSN-SA (Wireless Sensor Networks for SA systems), is divided into six technological areas: sensing technology, advanced ad-hoc communication, through-the-debris communication, radio frequency band for SA systems, Dual Operational modes, and ultra-low power Wake-Up on Radio technology. Our contribution in this work is the formulation of the required aspects that must be provided by each one of these areas that are called WSN-SA *foundations*. Moreover, one these areas, Dual Operational Mode, is part of our an-going project and it is being proposed for the first time in relation to WSN-based SA systems.

II. Background & Overall Framework's Vision

The Disaster Management Cycle is composed of these phases: (a) Prevention and Mitigation, (b) Preparedness, (c) Alert, (d) Response, (e) Recovery, and (f) Post Disaster [1]. The situational awareness (SA) solutions, to be used in disaster relief operations (item d), are typically distinct from disaster prevention efforts (items a and c) used to monitor civil structures (buildings, bridges), landslide, pipe leakage, etc. To date, WSN-related solutions have been proposed for the tasks in phases (a)/(c) and (d)/(e), as shown in Table I, under the labels MD and SA, respectively. Part of existing work gives exclusive emphasis on post-disaster scenarios, such as the selection of a specific set of sensors to be used in this case, and deployment guidelines for a WSN at the debris area. Sometimes, the existence of additional telecommunication resources, such as a cellular network, is assumed. Another part of the related work in Table I proposes networks installed *before* the disaster event. In addition to these WSN-related work in Table I, significant research effort has been done involving ad-hoc networks and dynamic routing protocols. In Section III-B, we will see that such work is also fundamental for SA solutions.

The focus of this work, a framework called WSN-SA (Wireless Sensor Networks for Situational Awareness systems), is related specifically to SA solutions deployed at buildings (and similar structures, such as mines) *prior* to the disaster event (e.g., collapsed building, food, fire). As shown at the survey in Table I, few works follow the same approach [2], [3], [4], [5], [6]. The two main goals of a SA system are a) to provide fast and detailed reconnaissance of the affected area in order to allow the proper management related to the usage of the rescue resources and b) to provide indication of imminent risk related to the life and health of rescuers and trapped/injured people. As expected, additional components deployed *after* the disaster event, such as robots, surface sensor networks, and aerial surveillance devices, will also be important for the rescue efforts, although not in the scope of this work.

The potential use of WSNs for Disaster Management Systems (DMS) is initially highlighted in [26]. From that moment on, the application of WSNs for the prevention,

TABLE I. SURVEY OF WSN-RELATED WORK APPLIED TO DISASTER MANAGEMENT SCENARIOS.

Ref year	Pre	Pos	MD	SA	Loc	Sim	Exp	Highlights and Main Focus
[7] 2002		x		x				Overview of the challenges in a post-disaster scenario
[8] 2004		x		x	x	x	x	WSN solution used in the triage process involving rescued people
[9] 2004	x		x					Architecture for detection and alert of flash-flood events
[10] 2012		x		x			x	Robot-assisted medical support involving sensors and actuators
[2] 2004	x			x	x	x		Hybrid network model (cellular) and routing protocol
[11] 2004		x		x		x		Ad hoc networking and routing protocol involving cellular network
[3] 2005	x		x	x	x	x		Power-aware routing strategy for ad hoc sensor network
[4] 2007	x			x	x	x		Protocols for task and data dissemination and location estimation
[12] 2007		x		x	x			Hybrid architecture and protocols assuming collapsed base stations
[13] 2007		x		x		x	x	Middleware for disaster managements scenarios
[5] 2009	x		x	x	x	x	x	Self-reconfigured WSN used to detect disasters in mines
[14] 2009		x		x	x	x		Automatic sensing function alternation
[15] 2010		x	x	x		x		Detection of danger at the disaster area
[16] 2010		x		x	x	x	x	Architecture based on multichannel MAC and collaborative sensing
[17] 2010		x		x				Wireless infrastructure for heterogeneous network
[18] 2010		x		x		x		Lightweight clustering scheme
[19] 2010	x		x				x	Landslide detection
[20] 2010	x		x			x		Machine Learning techniques for distributed event detection
[6] 2011	x			x		x		Data Evacuation strategy for immediate post-scenario data collection
[21] 2011		x		x	x			Hybrid solution to detect *alive* cell phones at the disaster area
[22] 2011		x		x			x	SMS-data relaying solution
[23] 2011		x		x				Survey and protocols of Telemedicine integration with DMSs
[24] 2012	x		x					Survey and taxonomy of some DMSs
[25] 2012		x					x	Survey on human rescue robots

Legend: **Pre/Pos** (Network installed before/after disaster) **MD** (Monitor/Detect event), **SA** (Situational Awareness), **Loc** (Localization), **Sim** (Simulations), **Exp** (Experiments)

alerting, and rescue operations in disaster scenarios are systematically reported in the WSN literature. However, after more than 13 years later, WSNs are still not considered at the emergency preparedness documentation of governmental and telecommunication organizations around the world. As many other projects involving technology, the DMS design, including a SA system, must be economically feasible while attending expected levels of functionality and reliability. In relation to the project budget, the number of nodes (communication aspect) can be relatively small in order to minimize the deployment costs, in particular for small buildings. Similarly, the sophistication and capabilities of the sensor probes (sensing aspect) can also be potentially limited. Finally, the *support* of such SA solution must be also economically-feasible. The bottom line: to be massively deployed around the world, SA systems must have a balanced design is terms of a potential tight budget and also the possibility of progressive technological enhancements with time. Such improvements are expected as soon as standards and procedures are defined, the costs of the devices drastically drop as a function of industrial scale, and governmental laws are eventually applied for this scenario. From the design perspective, the main implications in relation to what was discussed so far can be summarized as follows:

High data-throughput: the typical real-time surveillance needs of a SA system impose a high volume of data traffic in a post-disaster, in particular if audio and video are involved. However, according to the network constraints, the data quality can adjusted.

Wireless communication in confined areas: in case of collapsed buildings, wireless communication without obstacles is hardly achieved and random node topology is expected. Therefore, the communication system must be designed considering very restrictive scenarios. As a result, high transmit power levels, different communication technologies, adaptive routing, and error correction schemes are expected. Also, besides the need of physically protecting the nodes against physical damage, their antennas must be protected and *exposed* for communication at the same time.

Radio frequency (RF) regulation: in order to opportunistically allow the reception of data from other electronic devices potentially functional in the disaster area, such as computers and cell phones, the nodes of a SA system must have the capability to survey the RF spectrum in order to relay information from such data sources. However, the operational RF band(s) of the SA devices is(are) expected to be free in order to not compromise the functionality of the system. Therefore, non-ISM RF bands must be allocated for this goal.

Regular functionality tests: similar to fire systems in buildings, it is expected that SA systems will be regularly tested and evaluated regarding their capabilities. Such extensive tests impose a certain level of energy consumption that must considered in order to avoid a high support cost of the solution due to the need of exchanging batteries very often.

Energy consumption in non-disaster case: this is one of the strongest constraints of a SA system. In order to maintain a network solution with high data-throughput and very small *reaction time* in relation to the detection of a disaster event, the networking protocols are typically very energy-hungry and this fact can impact the feasibility of the solution for long-term. Therefore, a SA node must be adaptive in order to save energy in non-disaster operation and strategically use all the remaining energy in case of disaster. To be a reliable solution, such remaining energy must accommodate the full operation of the SA system for multiple days.

Power sources: typically, SA nodes are not connected to the mains power for security, reliability, and practical reasons related to the locations where such nodes can be installed. Therefore, a careful analysis is necessary in relation to the energy scavenging options and also the use of hybrid power sources involving rechargeable and non-rechargeable batteries. However, it is important to highlight that both batteries have drawbacks in the SA scenario: the lifetime of a rechargeable battery is typically smaller than 2 years and non-rechargeable batteries have low power-density and cannot directly support very power-hungry loads. This energy study must be done case-by-case according to the class of the SA node. The SA nodes are expected to have different sensing and acting capabilities; therefore, they will eventually belong to different

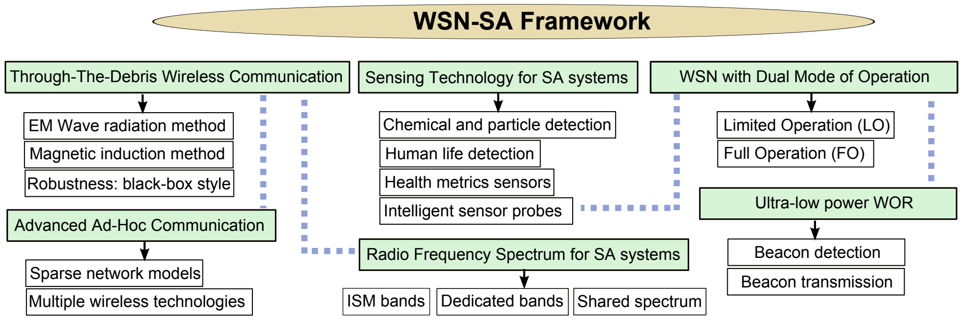

Fig. 1. The WSN-SA framework with its six foundations.

functionality/energy classes.

Based on this preliminary exposition of the main characteristics of SA systems, a recommended way to deal with the design challenges is to use a *framework*. This design strategy is specially appropriate in this context because, for some cases many different solutions are supported, and for other cases, few solutions exist or are still under development. Therefore, rather than a step-by-step guide indicating what sub-solution to use, in a design framework we start by separating the main design goals, understanding the relations (including trade-offs) among these goals, and leaving room to the final WSN designer to select the proper technology considering details of a specific scenario. Accordingly, the WSN-SA framework is presented in the next section.

III. Foundations of the WSN-SA Framework

The WSN-SA framework has six foundations as shown in Fig.1. Each foundation represents a main design challenge that must be critically evaluated. Note that each design aspect is not fully independent of each other. The dashed lines in this figure indicate such relationships. Each of the six framework foundations, the associated technical terms, and the underlying relations among them will be discussed next.

A. *Sensing Technology for SA system*

Many papers listed in Table I have references or detailed discussion on the expected sensing technology required in a post-disaster scenario, such as in [10], [24]. In the context of this framework, it is important to highlight that the employed sensors in SA systems may have different characteristics in relation to regular sensors used in WSNs. Three classes of probes must be carefully investigated: chemical and particle detectors, human life detectors, health metrics probes. The last two classes of probes are still under investigation and different techniques can be used [10]. Besides the typical energy and data-flow characteristics, it is also important to investigate the longevity of these probes and how frequently maintenance is required.

An additional aspect to be highlighted is related to the intelligent sensor probe. The term refers to the next generation of sensors that have the dual capacity of maintaining ultra low-power consumption while being capable of detecting events in fractions of a second [27]. This component is fundamental to switch a SA node from its low-power mode of operation to its regular mode when it has full capabilities in terms of network performance, as will be discussed later in this section.

B. *Advanced Ad-Hoc Communication*

A significant amount of work has been done in ad-hoc communication and part of this work is related to disaster scenarios, such as in [4], [11], [12], [28]. However, typically these works consider the assumptions of a high-density network or the use of mobile nodes. This line of research is still important for SA systems if we consider the potential use of *surface networks* (WSNs deployed on top of the disaster area after the event [1]). Nonetheless, for the context of SAs deployed prior to the disaster, the main goal is, besides the communication with the nodes at the boundaries of the affected area, also to establish successful communication with the nodes in difficult access areas. In this context, the network is considered *sparse* for at least three reasons. First, many SA systems will potentially have an initial deployment with a relative small number of nodes due to economical reasons. Second, although the nodes are expected to be protected against physical damage, a significant number of nodes can still be damaged. Moreover, some nodes can be completely isolated from the network, no matter the available communication technology they use (e.g., a node in a completely submerged room in a flooding event).

An additional scenario where a post-disaster network is considered a very sparse one is related to the use of under-the-debris communication technology (to be explained in the next section). To the best of our knowledge, this aspect is not mentioned in the literature, but consider the relevance of this analysis. According to the existing chaotic post-disaster scenario, the regular form of communication which is typically based on a relative high frequency (due to the need of a higher data rate for the SA application) cannot be realized, as illustrated in Fig.2. In this case, a certain SA node can try a low-frequency technology as a way to achieve communication at the harsh environment, despites the possible cost of a strong data throughput reduction. Depending on the selected technology, the average inter-node distance between nodes (i.e., communication range) can be reduced and a node may have only few neighbors. This scenario, from the viewpoint of the design of networking protocols, also corresponds to a sparse network. In general, ad-hoc protocols are impacted in this scenario due to the reduced number of alternate routes for data-paths. Moreover, the protocols must deal with different bandwidth capabilities among the nodes. One scenario relatively similar to this one that can provide useful insights is related to Wireless Underground Sensor Networks (WUSN) [29], [30], [31], [32]. Therefore, it is clear that additional research in the area of ad-hoc communication and SA systems is still required and such study must consider the possibility of sparse networks and the dynamic selection of multiple wireless technologies.

C. *Through-The-Debris Communication*

As shown in Fig.2, a network in collapsed buildings is potentially subjected to the need of establishing wireless links through the debris. It is assumed that in this case, at least many

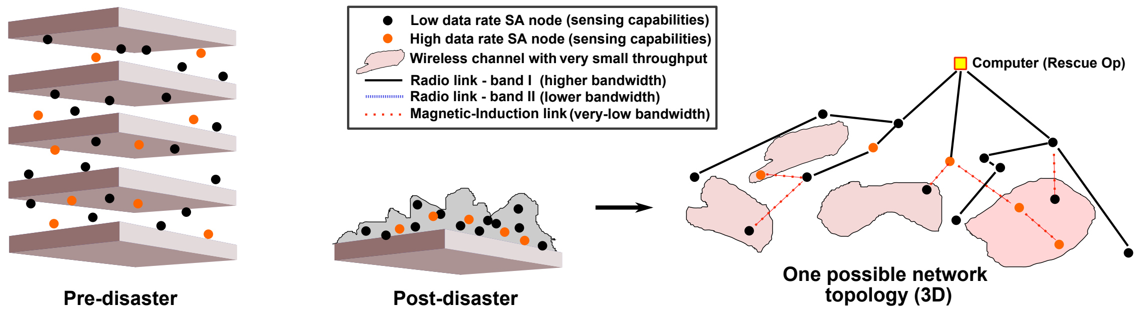

Fig. 2. Ad-Hoc protocols for SA systems must be adaptive in relation to the possibility of a very sparse network and the need of using different communication technologies with very distinct capabilities.

(ideally, the majority) of the nodes where not damaged. Such mechanical robustness can be expected if the design of the nodes' enclosure follow the principle similar to the *black box* used in planes as suggested in [6]. Nonetheless, such effort is voided if the antennas of the SA node are damaged. Therefore, research is required in order to design robust antenna schemes for the nodes assuming that a metallic enclosure is typically required for a SA node. Because a SA node can have two antennas (explained next), such effort must be duplicated. One research line to be investigated is a scheme where one of the antennas is only exposed to the exterior of the enclosure after the disaster event (also, in a regular functionality test). Nothing similar for WSN nodes has been reported so far.

In relation to the communication through the debris, empirical and theoretical research work must be done. Due to the need of dealing with different scenarios (normal and critical communication channel performance), it is recommended that each SA node uses at least two communication modules. Studies related to the radio propagation through concrete can be found in [33]. Also, communication through soil, using both electromagnetic radiation and magnetic induction techniques can be found in [29], [30], [31], [32]. It is expected that the WUSN scenarios represent a worst case basis for the analysis of communication through the debris. The bottom line is that a significant reduction of both data rate and inter-node distance is expected in comparison with an over-the-air link, no matter the through-the-debris communication technology which is being used.

D. Radio Frequency Spectrum for SAs

An expected remarkable characteristic of a SA node is its capability to dynamic adapt itself to the scenario encountered by the node after the disaster. It was already mentioned that it must be prepared to deal with the communication in a very critical under-debris or similar scenario. Moreover, the node must also be used as a discovering tool (i.e., a *sniffer*) in relation to the existence of any wireless device which is operating nearby. In this case, it is possible that a person is alive and he is trying to communicate. In this sense, the SA node relays this information to a base station outside the affected area. In an ideal scenario, the SA node could work as a relay agent to allow, at least, text-based communication (e,g., GPRS) with the survivor. Unfortunately, there is no reported study in relation to such aspect and it is an open research topic.

Another aspect that requires urgent attention is the allocation of frequency bands for SA systems. It is clear that a SA node must have the capability of using ISM bands in order to achieve communication with additional devices at the disaster area. However, reserved frequency bands are also required to SA systems in order to avoid interferences. As a reasonable alternative, shared bands can be employed. In this case, the users of such bands are temporarily prohibited to use these bands at the region close to the disaster area. Again, further studies in this area are recommended. Moreover, besides the allocation of bands for SA systems, non-traditional higher equivalent isotropically radiated power (EIRP) may be associated with the radio modules in a disaster area.

E. WSN with Dual Mode of Operation

In order to achieve very high network performance in terms of high data throughput, low data latency, and high reliability, the networking protocols typically are associated with a significant amount of energy consumption. For instance, in a moment when no application data is flowing through the network, the network traffic is typically non-zero. Moreover, even sleeping 99% of the time at this non-application data period of time, a node still needs to wake-up multiple times per second when typical WSN protocols are used. As a result, besides the significant increase of the network overhead (and its associated high energy consumption), many interesting energy-efficient hardware techniques cannot be employed in order to save energy. One of these techniques is the power hibernation which is possible when a module, such as a radio, is completely turned-off as opposed to be put in standby or sleep mode [34], [35].

Therefore, it is important to translate the above facts to the context of a SA node. On the average, only the typical Medium Access Control (MAC) protocols represent an network overhead of more than 5% [36]. If we add the overhead of the remaining networking protocols, a significant higher value for the overhead is achieved. Such overhead does not critically impact if the application data rate is significantly high, such as in the case of the network operating in a post-disaster event. However, if the event does not occur, the application data rate is pretty low and the network overhead potentially dominates the energy consumption of the nodes. Accordingly, the framework design goal that is being analyzed now is exactly the one that can prevent such unnecessary waste of energy. To the best of our knowledge, this is the first time that such goal is being proposed in the context of SA systems. One possible reason why such proposal was not done before is the fact that the reduction of the network overhead typically impedes the network to achieve the expected performance for a SA system by means of a suited choice of protocols.

Therefore, in this framework, it is being proposed a novel technique: the Dual Mode of Operation. More specifically, it is possible to put the network in one of these modes: Limited Operation (LO) and Full Operation (FO). While in FO mode, the network performance and all the protocols are exactly the same as originally designed for that SA system. That is, no modification is necessary in the ad-hoc protocols. However, as already discussed, this mode is not the most energy-efficient one and it is used only when the networks operates in a disaster scenario (real case or verification test scenario).

On the other hand, it is possible to command the network in FO mode to change to LO mode. In this way, the network achieves very high energy efficiency. One can argue why not simply turning-off the network and activating it when the disaster event occurs. However, such proposal implies a higher risk to have a network not operating properly exactly when it is needed. A more sound, reliable, and balanced solution is to *virtually* deactivate and activate the network regularly, multiple times per day. In this way, a continuous check of the network health is performed without significant energy sacrifice. This is exactly how a node in LO mode is expected to behave. Even when active for a couple of seconds, the SA node continues in LO mode but it has the opportunity to send its state to a central server that controls the SA application. In short, the SA node in LO mode achieves its maximum energy performance.

Such discussion for a SA node is very important because the goal is to have an overall SA solution that does not require frequent exchange of batteries (e.g., $<$1 year). Besides the low network overhead under the LO mode, the node can still hibernate in this mode. An example of how the LO mode can be implemented is described in [35] and it is in fact part of our ongoing project, although not related to a SA system. This solution is based on a cross-layer protocol called BETS which imposes a segmentation of the network and a 2-Tier architecture based on a cluster-head and regular sensor nodes. In a SA system, such segmentation can be realized in a logical way, by designating distinct frequency channels and logical address for the nodes operating in LO mode. Once returning to FO mode, such architecture is removed and the WSN network returns to its native mode of operation and topology. Any solution similar to the BETS approach can also be employed to realize the implementation of the LO mode for SA nodes, such as the LEACH protocol approach in [37]. The main point to highlight is that during the LO mode, the traditional WSN protocols are not in operation and the network operates with very low duty-cycles that are based on very long schedules, such as 30min. The effective network overhead is expected to be smaller than $<$1%.

All these mechanisms used in the LO mode to save energy, such as the creation of a hierarchy for the nodes and a time-division method of access [35], [37], come with a price: network performance penalties, in particular data latency. Therefore, the LO mode cannot be used to satisfy the performance metrics of SA system. Accordingly, the framework provide a way to make the network to return to FO mode when it is necessary. In fact, while in LO mode, a node can still be commanded by a Base Station to return to its FO mode. This is the case, for instance, when scheduled SA functionality tests must be realized. It is very important to highlight that, due to the need of implementing the Dual Mode operation aiming energy savings, all nodes must have local sensors that can identify disaster events in order to force the node to return to its full operation (FO mode). In addition, when a disaster-event is detected by a node, it will try to disseminate such information through the network. In the next section, the mechanisms used to force all nodes in a network to quickly return to FO mode are discussed.

But before moving to the next section, a justification for the Dual Mode operation must be given by translating the practical meaning of the expression *energy savings* for a SA node. Two different power system cases are considered: with the use of non-rechargeable and rechargeable batteries. First, assume that a node is powered by non-rechargeable batteries. In this case, a continuous operation of the node in FO mode would impose the need of exchanging the batteries very often, potentially after just a few months. We are assuming here the use of a single D-size cell and insights behind this example can be found in [34].

Now, assume that an energy harvester is used, such as a photo-voltaic (PV) panel in conjunction with rechargeable batteries. The continuous operation of the SA node in FO mode, that is, without implementing the proposed Dual Mode operation feature, can potentially lead to two issues. The first problem is related to the life expectancy of a rechargeable cell, typically smaller than 1 year. As already discussed, under FO mode and without significant application-data traffic, the energy consumption is governed by the network protocols. Therefore, it is highly expected that the batteries have to be charged multiple times per day, although this conclusion actually depends on the stack of protocols being used and the network topology, among other factors. Because the lifetime of the cell is also governed by the number of charge cycles, the battery can potentially have its lifetime strongly shortened. The second issue related to FO mode and rechargeable batteries is related to the form of energy harvesting. If PV panels are used, it is possible that during many periods of time the SA node is consuming more energy than what it being harvested. In this case, if the rechargeable batteries reach a low energy level exactly when the disaster event occurs, the SA solution becomes compromised. Therefore, it is secure to state that typically some sort of energy-saving provision for a SA system must be in place, such as the Dual Mode presented here.

F. Ultra-Low Power Wake-Up Radio (WOR)

An ultra-low power Wake-Up on Radio (WOR) device has the capability of detecting a wake-up signal (beacon) and wake-up a microcontroller (MCU) from its sleeping period [38]. This technology is closely related to the previous mentioned design aspect of this framework, the Dual Mode of operation. While in FO mode, a SA node does not need a WOR because the MCU is constantly accessing the network and all SA nodes can potentially detect disaster-related events and quickly disseminate the information in the network. However, the challenge is related to the LO mode. As already explained, in this mode, the SA node is mainly hibernating for the majority of the time. Therefore, the challenge is to conciliate the energy-performance of the LO mode with the expected readiness metric for the detection of events followed by the mode switching to FO mode.

The above goal is achieved by means of two components: the intelligent sensor and the WOR. As already explained, the intelligent sensor has the capability to quickly wake-up an individual SA node which is hibernating in LO mode as soon the event is detected. However, this node must now wake-up its cluster-head (CH) node (or similar controller node) and this task is realized by means of its Beacon transmitter. Such transmitter is, in general, distinct from the other transceivers/antennas that the SA node has. Once the CH node wakes-up, more nodes are awaken by the same method. Without this technology, the LO mode would have to use shorter schedules, such as 1-min, in order to mitigate the delay between the disaster-detection moment and the fully readiness of the SA system. However, the solution would still be highly penalized in terms of energy in a long-term perspective.

IV. Conclusions

In this work, a framework for the design of Situational Awareness (SA) systems based on WSNs is presented. It is mainly governed by practical aspects related to the feasibility of deploying such system. Six foundations, or design goals, are considered in conjunction with the related work. It is concluded that many topics are still open to research. However, we believe that the feasibility of SA systems is very likely because many of the necessary key-technologies are already in place or they are being currently investigated.

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