Wireless Sensor Systems for Space and Extreme Environments: A Review

Habib F. Rashvand, Ali Abedi, Jose M. Alcaraz-Calero, Paul D. Mitchell, and Subhas Mukhopadhyay

***Abstract*—This is a complementary contribution from Guest Editors of the Special Issue, Wireless Sensor Systems for Space and Extreme Environments (SEE) so that the reader of this Special Issue is supplied with basic fundamental points for a better appreciation of the need for 'space and other extreme environments' which means barrier breaking applications and associated challenging technologies. The paper includes the scanning of the critical development of wireless sensor systems and associated networking in three basic key areas of: (a) clarification of the fuzzy term of SEE that appears to be growing further with ambiguity and its role of directivity for future academic research activities, (b) positioning the 'wireless sensing' for its practical potential in future industrial prospective applications, and (c) highlighting significant problem areas facing wireless sensor systems and associated leading industries by example. It contains basic introductory definitions in Section 1, Section 2 briefs the networking aspects, and Section 3 looks at the synchronization issues. Then, Section 4 analyses the problem of spectrum sharing and interfering issues in space whilst Section 5 looks into the energy issues of SEE including medium access control as a way to reduce the use of scarce energy resources. Finally, Section 6 comes with a selective set of complementary typical examples leading to an encapsulating table with six groups of SEE based on the application scenarios and their working environments.**

***Index Terms*— Wireless Sensing, Wireless Sensor Systems, WSN, UWSN, WUSN, Space, Extreme Environments, Practical Applications, Classification, Unconventional Wireless Sensing**

I. Introduction

THE addressing of the challenges associated to wireless sensing in space and other extreme environments (SEE) is gaining momentum in the scientific community due to the potential benefits that these technologies can bring to the detailed study and analysis of these environments ranging from a complete ecosystem of information sources that better feeds command and control missions to control systems to protect and control human exposure to hazardous environments such as vacuum, acid or radio-active locations. So, in order to explore further detailed requirements for SEE let us first examine the basic concepts of conventions and directivity in wireless sensor networks (WSN).

Arising from traditional telecommunication networks and the Internet most people's general understanding of conventional WSN is a very large network interconnecting many thousands of ICT-enabled homogenous and similar smart sensors nodes. It is true that some eye-catching applications such as global environmental monitoring, pollution and other global level surveillance applications would require as many or even a much larger number of similar sensors to deal with the surge of collective information. Such sample applications need very high volume of data as required to ensure not to dismiss any critical atmospheric climate changes, which do not bring sufficient returns and benefits to justify our heavy R&D investments in the past quarter of century. The real industries as the backbone of industrial nations cannot survive very long without being able to provide real private user end products and services to the economic cycles.

Following its successful start at the end of 20th Century wireless sensing moved rather sporadically from strength to strength seeking proper positioning for its practical potentials, proper uses, and real breakthrough applications over the last decade whilst its efforts at its research ends was at its significant peak. In this period we have seen a variety of terms including the very common term of WSN, wireless sensor systems (WSS), wireless sensor and actuator networks (WSAN or WiSAN [1]), wireless underground sensor networks (WUSN), underwater wireless sensor networks (UWSN), wireless smart intelligent sensing (WSIS), wirelessly-connected distributed smart sensing (WDSS), wireless body sensor mesh network (WBSMN), space sensor/surveillance network (SSN), unmanaged aerial vehicle sensor networks (UAVSN) and an extension of its ambiguity to this critical advancement rather than helping with understanding the basic concept and its influence in other fields and disciplines.

The incorporating fields include recent known technologies of classic ICT at various levels of maturity progressing forward for their second waves of diffusion into our systems and therefore our life-style. We name a few such as wireless broadband, ultra-band, Internet and new unstructured

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networking such as dynamic ad hoc down to computing and interfacing with devices for integrating various advanced old and new interconnected devices including RFID, IoT, MEMS and nanotechnology. At the application end, due to the inclusion of many other fields merging into the construction of an overall system the number of possibilities becomes un-imaginable. One economically sensitive emerging field is the inclusion of medical devices and instrumentations for a good number of medical applications where smart shirts, low complex smart clinic and operational theatres for remote sensor-rich risk-free operations just count as tip of the iceberg.

It is appropriate for this review paper to highlight and examine wireless sensing application areas that cannot be properly addressed as the main important issues appear when a system faces working conditions beyond the classic designed working environment. That is, a huge amount research works for large WSN applications but does not seem to be helping very much in real economies and user needs and practical applications such as video surveillance, a space mission, smart bridge, or an underwater project. The working environment often is assumed transparent or ideal. We cannot assume all sensors can always enjoy easy communication with each other. At the device level, sensors can be easily tested for their expected performance under their particular working condition but their performance at the systems application level could vary extensively under different conditions and could vary even more by their working environment. For example, a complex WSN working in a moderate temperature in Europe may not last very long in a South American humid, bushy environment, and may not work in the hyper-arid climate of the North African desert. To this effect if we look for any recent technological developments using wirelessly distributed sensing (WDS) it is hard to find many [2]. That is, WSN once hailed as a new application paradigm is now becoming an economy black hole spreading fast and consuming global economy resources and wasting our young researcher's time with very little results to show. In other words, once entered with a promise of potential opportunities it has not been able to show sufficient innovative end products so it now required to be harnessed before too late [3] [4].

Looking for feasible solutions to land this rapidly growing falling snowball process we see that true practical impacts are hampered by the poorly defined WSN paradigm as it cannot happen under the existing ground rules for which we need to add some critically important refinements of addressing the unconventional under the flagship of WSS-SEE, to lead us to the practical approach of 'unconventional wireless sensing' (UWS). That is, a rejuvenating directed move into better position reactivate more useful research and development as required essential to inject flagship break-through applications where both academics and industries can visualise the real potentials of wireless sensor platforms that can only happen under new unconventional applications.

In order to locating a suitable placement to accommodate the new wireless sensing application paradigm we first need to redefine SEE or more appropriately EE in a compact format. For this we look further into the word 'environment' at its two distinct common meanings.

One is the word used for humans. We find many in the literature under abnormal conditions or 'human extreme living environments' usually classified as: acidic, alkaline, astrobiology, extremely cold, extremely hot, hypersaline, space, under pressure, under water, under heavy radiation, without water (waterless), without oxygen, without air (airless), and all other places on earth or beyond in short supply of basic needs for human survival E.g., [5].

Another meaning for the word is the way we use it for systems, which represents an environment falling well into the scope of our investigation applicable to our distributed systems of sensing and actuating. As for the system we prefer to use the term '*conventional*' instead of 'classic' or 'normal' as the one being commonly used by researchers. Hence conventional environment means ordinary, un-defined, or 'generic, assumed normal'. That is, most sensing devices and associated systems normally work well beyond the human and other living creatures. Unfortunately, under conventional most studies and research works have been taken on many assumptions over-simplifying the systems working environment resulting in pile of results and models that cannot be adequately used for most practical applications. In order to get a better insight for 'EE' working systems let's take three simple steps for redefining system's working environment: (1) Separate our systems working environment from human habitual environment, (2) Expand the specifications of the 'environment' into a dynamic form of system working ambience where the real applications means unconventional working conditions, and (3) As far as systems' behaviour is concerned there are no interactions with humans.

The first step provides a realistic condition by separating a systems working environment from the commonly perceived human living environment. Systems are normally less flexible, highly rigid, but generally more resilient than humans to the environmental changing parameters. This may reduce some environmental acceptance features but due to lack of human intelligence and associated flexibility it can actually expand the working range of systems' acceptable conditions to higher thresholds. This is mainly due to the fact that moving away from living body limitations we open up systems' behavioural prospects to lesser restrictions leading to wider opportunities normally restricting the scope by excluding the limitations for living intelligent. The second step generally allows the system to work far better than if confined and heavily restricted by living creatures. The third allows us to study systems' behaviour far more precisely upon a set of realistic and application-specific assumptions for better defined, solid, and more practical research. Following are some brief examples for wireless sensing systems working under the definition of 'EE systems working parameters operating beyond conventional conditions':

- The space represents an EE due to its unpredictable features. For the aerospace wireless sensor technology we can add to the list of possibilities out of scale distances between the systems with serious propagation problems, LOS, lack of air pressure, and variable gravity, they all must work under the energy scarcity. Although all systems are tested in the Laboratory and on terrestrial earth environment may not behave in the same way under extremely low pressure, different gravity and without atmosphere during the mission. Due to the extensive cost of any possible failure, NASA, for example, uses Skylab in space and underwater facilities (NEEMO) for testing space parts, components, and systems before their final assembly as well as other activities. The man-made satellites are a dominant potential for being upgraded with better use of wireless sensors. Now, with thousands of them, many under-used, if equipped with sensors and used properly they could improve human life on earth significantly. Most aeroplanes really need better wireless sensing.

- The systems working underwater or immersed in in any fluid represent EE. The classic terrestrial EM radio waves are not suitable for such environments therefore other less developed wireless techniques such as acoustic and (ultrasound) should be deployed. Most importantly, the underwater systems face possibility of being interrupted by natural movements, and obstacles, if unmanned or remotely supervised.

- It may be worth mentioning that due to the remoteness of access to deep-ocean any wirelessly operated sensing requires possible encounters for which rigid enclosures could degrade the signal. All these conditions and many other practical factors make underwater systems behave very differently from the conventional environment. Typical cases are underwater surveillance, marine ecology, and offshore explorations [6].

- Extending use of smart sensors in the ground, hidden, or covered in other places can enable many new and advanced applications such as securing mines, improved agriculture where such uses of strong cover create EE conditions [7].

- Medical applications of WSS due to their special working conditions mostly can be regarded as EE. EE medical cases are many and scope for applications are plenty and mostly versatile. WSS medical applications often require secure and reliable connectivity of various systems and devices to work properly. Sensitive operations require an extra measure of confidence for a fully functional condition throughout the operation. One may consider that 'smart shirts' using wireless connectivity should be examined under EE requirements [8] [9].

- Non-conventional wireless sensor applications include those involved in heavy and sensitive industrial environments. Examples are oil wells, refineries, chemicals, hazardous, and atomic energy where human safety would require special attention. Industrial disasters, surveillance, and emergency applications impose particular difficulties associated with time where speedy process and following certain measures of sequencing the events and actions impose particular requirements where a designer should consider it as a special EE. One example is monitoring railways at its sensitive location instead of a whole network. Antarctica and other extremely cold spots and places on earth as it is the case with hot and arid areas that in fact cover some third to a quarter of the surface of planet earth represent EE [10].

We argue that we should be able to revamp the process and create a paradigm of new chain of applications under the flagship of WSS-SEE for unconventional wireless sensing (UWS) to highlight the importance of environment, not just for its perception of what surrounds the system but also to include any possible factors creating unconventional circumstances. As we will explain further in Section 6 of the paper from the environmental point of view we classify our wireless sensing systems into six groups. These six environmental groups each should come with its own specific areas of application where the working condition represents the type of EE unconventional working conditions, as below:

1) Group 1 represents those free from terrestrial dominating factors (space).

2) Group 2 represents those immersed or controlled by liquids usually water's dominating factors (underwater) – they can be extended to any size from a small container to rather large water-farming or aquaculture lake.

3) Group 3 represents those buried in covering materials as their main performance is limiting factors such as the ground where they have the problem of communicating with each other or systems outside the soil. Deep mines, body-implants, and many agricultural applications are included in this group.

4) Group 4 represents those loosely confined to a restricted area so that their performance is controlled by specific enclosed dominating factors when inside (indoors) – a wide range of applications such as systems working inside tunnels, subways, block buildings, and caves fall into this group.

5) Group 5 represents sensors on the move, also called mobile sensor systems (MSS).

6) Group 6 covers all *remaining* sensing cases working under special and specific environments such as energy sensitive systems, data sensitive and harsh Antarctica, arid, mountains and desert, volcanoes, etc.

The rest of this paper organised with Section 2 briefs the networking aspects of SEE, Section 3 looks at the synchronization issues, Section 4 looks into the problems of spectrum sharing, and interfering issues in space whilst Section 5 looks into the energy of wireless sensing and an associated medium access control solution. Finally, Section 6 comes with a set of typical examples leading to a major classification table dividing the WSS-SEE application sensor systems into the earlier mentioned six groups based on their uses and associated working environments.

II. WIRELESS NETWORKING FOR SEE

Ever-larger numbers of people are relying on the technology directly or indirectly as it enables the deployment of networks of densely distributed sensors and actuators for a wide range of environmental applications encompassing a variety of data types including acoustic, image and various chemical and physical properties. Wireless sensor network topology may be divided into 3 topologies: Star Topology, Cluster Tree Topology and Mesh Topology. The remote configuration of the sensing node should ensure that it should continuously transmit digital sensor data to other coordinators located in the nearby area. For wider applications especially in space and extreme environment, the networking should be smart, efficient and also it should be a low-cost, low-power system. The low cost allows the technology to be widely deployed in wireless control and monitoring applications and the low power-usage allows longer life with smaller batteries. The mesh networking is usually the preferred choice as it provides high reliability and a larger range.

The network routing is a basic element of closed-loop, real-time sensing and control and its implementation is challenging due to dynamic, uncertain link or path delays. The delays lead to instability, estimation error and low data delivery in the performance of the system. A multi-timescale adaptation (MTA) routing protocol has been proposed in [11] taking into consideration multi-timescale estimation (MTE) based on accurately estimating means and variance per packet transmission time. The architecture of MTA-based real-time routing is depicted in Figure 1. It is important to emphasize that the *packet dispatcher* is using time synchronization and delay estimation techniques in order to adapt the networking layer to the environmental conditions. The challenges related to time synchronization will be discussed in the next section. However, at this point it is worth noting the intentional closed-loop available between data and the control plane in MTA protocol enabling the reinforcement of real network performance metrics into the control plane in order to re-adapt the networking layer to perform well in extreme conditions in which either packet delays are being unusual or time synchronization is being affected.

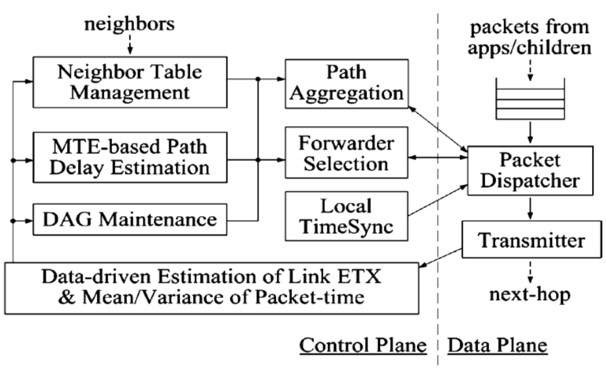

Figure 1: Architecture of MTA-based real-time routing [11]

Distributed radar sensor networks (RSN) grouped together in an intelligent cluster headwork on ad hoc fashion provide spatial resilience for target detection and tracking [12]. The RSN may be used in EE such as tactical combat systems that are deployed on airborne, surface, and subsurface unmanned vehicles in order to protect critical infrastructure from terrorist activities. An orthogonal constant frequency (CF) pulse waveform model has been proposed which eliminates interference between radar sensors. A distributed estimation and control approach for wireless sensor and actuator networks (WSAN) has been proposed accounting for noisy condition as well as packet loss and it shows that the mean and variance of estimation errors are bounded [13]. One of the challenging issues for integration of wireless sensor networks and radio-frequency identification systems is the low efficiency of communication due to redundant data. The five-layer system architecture along with a data-cleaning algorithm proposed to achieve synergistic performance [14]. The developed algorithm can eliminate redundant data effectively and thereby save energy of data communication and avoids time delay. The coverage of sensing area becomes dynamic if there is a continuous movement of sensors. Dynamic area coverage and intrusion detection capability of a mobile sensor network has been reported in [15]. Delay synchronization, elimination of redundant data and dynamic sensing areas are some of the critical routing challenges that WSN needs to address when deployed in SEE environments. In this context, Xue et al. [16] have proposed a velocity-based routing protocol with a reliability and energy-efficiency routing scheme to enhance the network real-time routing performance, energy efficiency and transmission reliability. The proposed method has made use of some intelligent functions including (a) selection of an eligible relay node using two-hop neighbourhood information, (b) estimated delivery velocity and (c) energy aware-based energy-cost.

An unstructured multi-hop radio network model, with asynchronous wake-up, no collision detection and little knowledge on the network topology, has been proposed for capturing the harsh characteristics of initially deployed wireless ad hoc and sensor networks [17]. The issue of a local broadcasting problem has been dealt with by adopting the physical interference model and without any knowledge of the neighbourhood to obtain a new randomized distributed approximation algorithm. This scenario proposed in [17] deals efficiently in environments in which there is a high degree of uncertainty, which is an inherited feature of SEE.

The conventional WSN consisting of a large number of heterogeneous sensors deployed over a wide, unstructured, harsh and time-varying environment presents various interesting problems. A system of tracking mobile robots and mapping an unstructured environment, using 25 wireless sensor nodes in an indoor setting environment has been reported [18]. The sensor nodes are deployed into an unknown environment. Three sensor nodes known as anchor nodes are mounted in a triangle frame, and two nodes are mounted on two of the mobile robots. The sensor nodes form an ad hoc network of beacons and localize themselves with respect to the anchor nodes using the pairwise ranging data. The localized sensor nodes are then used to track the locations of the mobile robots in the field [18]. In WSN, there are possibilities of attacks from inside the network by malicious and non-cooperative selfish nodes or by any unwanted outside nodes. A ubiquitous and robust access control (URSA) solution for mobile ad hoc networks has been presented in [19]. It uses tickets to identify and grant network access to well-behaving nodes and thus effectively enforces access control in the highly dynamic, mobile ad hoc network. Using a handheld computing device with wireless access to have anytime, anywhere access to the latest factory floor information has been proposed [20]. These authors have designed and implemented an energy-efficient and intrusion-resilient authentication (ERA) protocol, which can achieve security self-recovery when strong adversaries compromise either a user's handheld device or a factory authentication server to obtain the authentication secrets. Implementation of a low-cost, data access-efficient, sample and easy to deploy, waterproof, and heatproof outdoor cable access point (CAP) device for ubiquitous network applications has been presented in [21]. The whole purpose of the CAP device is to effectively extend the coverage of the outdoor wireless access link and to further provide a data access-efficient service for construction of a ubiquitous networking environment in the metropolitan area.

A movement-aware vertical (MAV) handover algorithm between WLAN and mobile WiMAX for seamless ubiquitous access has been addressed in [22]. The purpose of the development of the algorithm is to exploit the movement pattern to avoid unnecessary handovers in the integrated WLAN and mobile WiMAX networks. Sometimes, it is quite difficult to extract accurate information from raw sensors data and feature extraction techniques become quite useful for this situation. A novel feature extraction technique based on a nonlinear manifold learning algorithm for autonomous navigation systems has been reported in [23]. Transmitting the wireless data in the presence of extreme dense environments poses the question of how to exploit wireless networks more efficiently. This efficient management of handovers works well in SEE scenarios where it is critical to have a constant monitoring of variables, for example, due to human exposure hazards, and it requires soft handover techniques for continuing the session along different wireless technologies.

III. SYNCRONIZATION AND COOPERATIVE TECHNIQUES

While the previous Section provides a brief review of different robust networking protocols, this Section is focused on different challenges that appear explicitly under extreme environments and are directly related to the management of the wireless network and the synchronization and cooperative collaboration of the nodes.

The idea is to provide the reader practical examples based on real deployments to appreciate the possibility of such local solutions and a better understanding of the network operational management under SEE conditions.

A. TIME SYNCRONIZATION

One of the critical aspects associated to distributed sensing is the imperative necessity of performing an accurate time synchronization between all the involved nodes of the network in order to associate the sensed data with the time in which such data was sensed in order to aggregate and correlate the data gathered to be distributed by the different nodes. A simple error in the time synchronization will not only lead to non-accurate data but also a severe case will invalidate the complete series of data along the sensed period. Almost all the current wireless sensor nodes used in the vast majority of the real deployments carried out so far are using time measurement instruments, which are very sensible to errors when they are exposed to slight variations in the environmental conditions. So, environmental monitoring of specific geographical areas considered SEE is a representative example of the application to be analysed as an example of WSN deployment associated to extreme working conditions. This environment monitoring is directly associated to some scenarios in which WSNs are deployed with the intention of monitoring extreme temperatures such as volcano monitoring, glacier monitoring, nuclear-plan thermal monitoring, industrial monitoring, thermal monitoring of chemical products and aerospace thermal monitoring. These scenarios usually use such synchronization twofold: a) To enable the efficient correlation between the metrics gathered distributed by all the nodes; b) To perform an efficient energy management of the WSN in order to prolong the lifetime. These are some well-known time synchronization protocols for WSN like reference broadcast synchronization (RBS) [24], timing-sync protocol for sensor network (TPSN) [25] and flooding time synchronization protocol (FTSP) [26], to name a few. All these protocols heavily rely on the usage of crystal oscillators where the actual frequency of oscillation depends on many factors such as the type and the cut of the crystal, capacitance, and specially temperature. Figure 2 shows two sensors, the first one is exposed to a constant temperature while the second one is exposed to a range of temperatures (-40º to +40º) in steps of 10º. It is also representing the time synchronization error to see how this error is directly related to the temperature due to the crystal oscillator used. As the reader can see in Figure 2, the variance in the temperature lead to a significant increase in time synchronization errors, this fact emphasizes the clear need of using alternative time measurement instruments for deployments in SEE or at least trying to minimize the variance of the interference by means of isolation techniques, correction techniques, redundancy techniques, etc.

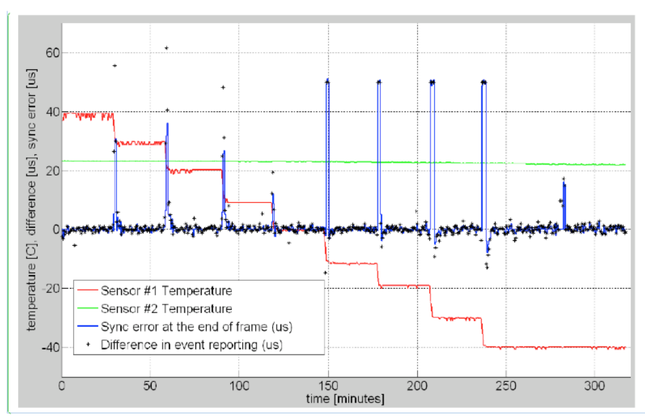

Figure 2: Results associated to SCS protocol provided by Raskovic et al [27]

Another approach to achieve efficient time synchronization is provided by Raskovic et al [27]. They have provided the sliding clock synchronization (SCS) protocol suitable for time synchronization under extreme temperatures. The key aspect of this protocol resided in the inclusion of special nodes called central node sending periodically time synchronization beacons. Then, the node measures the time between two consecutive beacons as well the time measured locally. They also periodically measure the echo time to determine the time it takes a message of fixed size to reach the central node and to be returned back. The calculated ratios gathered from all these measures are averaged enabling the identification of the differences in crystal frequencies to be taken into account. This cooperation between nodes results in SCS offering a significant reduction of the error rate when sensors are exposed to high temperatures, thus providing a better network operational management. Table 1 shows the comparison between the different protocols analysed.

Table 1: Comparison Of SCS [27] With Other Synchronization Algorithms

	TPSN [4MHZ]	RBS [7.37 MHZ]	FTSP [7.37 MHZ]	SCS [4 MHZ]
AVERAGE ERROR	20US	1.85US	0.5US	0.32US
WORST CASE ERROR	50US	4.41US	2.3US	3.25US

Another example is sensing underwater using wireless sensing which is also a very challenging scenario associated to extreme conditions due to the intrinsic nature of the medium in which high frequency (HF) radio waves are strongly attenuated. Traditional radio modules operating in MHz and GHz cannot be used underwater which is an acoustic-based and optical-based communication therefore the emerging technologies cannot work for these scenarios. Martinez and Hart [28] proposes a way for understanding of sub glacial processes, especially to investigate their links with climate change, as well as developing the next generations of environmental sensor networks. They perform the real deployment of sensors for the monitoring of glaciers in the arctic by means of the deployment of 30 nodes in valley glaciers in Briksdalsbreen, Norway and 8 nodes in Skalafellsjökull, Iceland between 2003 and 2006. A diagram of the deployment undertaken is depicted in Figure 3

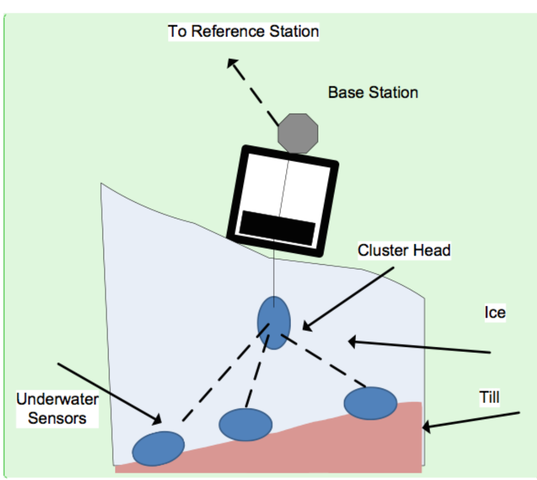

Figure 3: Sensor Deployment provided by Martinez and Hart [28]

The base station is located outside the water with the transceiver placed into the water and the rest of the sensors are in the water. The main geological objectives are to provide a long term record of water pressure changes in the ice and sub glacial sediment to enable the investigation of the relationship between water pressure, till strength and till temperature in order to understand till sedimentation. Operational conditions are between -40 º and +20º and a lifetime of four years must be ensured. The sampling rate of the sensors is fixed at once per four hours, partly because changes are expected to be slow but also to save power. Long radio-disconnection periods are expected but glaciologists wanted every data sample, even if this data is delivered months later. So, a large ring buffer (6,000 readings) for the data is used in each node in order to store data for up to a year. The sensing platform acts as remote sensing architecture in which all the monitored information is stored in the internal memory.

A GPS device is attached to the base station and a broadcasting of the GPS time to all motes is done daily as a way to keep synchronization within seconds and save power by narrowing safety margins on wake-up scheduling. Power management is a key to satisfying the requirement for long-term system life. Since a daily data transfer is acceptable, the radios on every unit are completely off most of the time and limited time windows are given to those tasks that used them. After several trials, the authors decided to insert the transceiver of the base station into the water because otherwise the loss of signal is significant and it is impossible to establish connections so far at 20 meters (testing several frequencies such as 868 MHz, 433 MHz, 172 MHz). This transceiver is standardized around the Radiometrix BiM unit tuned to 173.25 MHz but powered at 100mW rather than the default 10mW. The key cooperative aspect of this deployment is the usage of a well-known windows time frame in order to perform the daily coordination and synchronization between all the nodes in order to increase significantly the lifetime of the network and to reduce the usage of communication links.

B. FAULT-TOLERANCE OF SENSING NODES

Another good example of cooperative technique directly associated with SEE is proposed by Wenning et al [29] with the environmental monitoring aware (EMA) protocol which takes into account the realistic fact that a deployment of a WSN in extreme conditions such as forest fire scenarios which can destroy the sensors devices in any moment due to the fire. This fact has direct implications for the network lifetime, performance and robustness. They focused on node failures caused by the sensed phenomenon itself proposing a resilient method aware of node destruction being able to adapt the network topology accordingly before node failure results in broken routes, delay and power consuming recovery actions. EMA uses as routing criteria different key metrics: a) health status; b) received signal strength indicator (RSSI); and c) hop count. The key aspect in this deployment is the health status defined to be a value between 0 and 100. 0 indicates the worst and 100 the best health. If the temperature of the node is below a lower threshold then the health status is 100. Then, the health status is being decreased using a directly proportional relationship between temperature and health status. The upper threshold is setup in a temperature in which the node is likely to fail within a very short period of time. Then, nodes identified in bad health status condition can initiate a self-healing recovery method for the sensed data and also for the network topology improving the operational management of the network.

Another critical aspect in space missions and SEE conditions is to enable sensor nodes to take over the damaged functions of their neighbour sensor nodes automatically. This collaborative approach ends up with a high reliable WSN that never stops monitoring even in extreme conditions and does not require maintenance if some sensor nodes suddenly die. Figure 4 shows a WSN with some nodes performing different functions. A different coloured node represents different functions, for example, sensing functions. The links are routes established using any of the dynamic routing protocols already available. Then, when a node dies, Miyazaki et al [30] proposes a protocol for enabling other nodes to take over the function being carried out of the dead node.

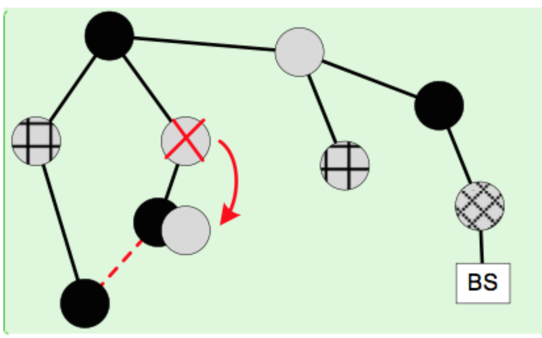

Figure 4: Concept of Function Alternation proposed by Miyazaki et al [30]

Miyazaki et al [30] proposed an architecture in which each node has a table, named a neighbour management table (NMT) that manages the status of the functions of its neighbourhood. This table has an entry per each different neighbour function. Each entry has an associated timestamp. A ‘notice list’ the list of nodes that can take over the function being carried out by this node. Then, the protocol sends periodically broadcast HELLO packets to their neighbour (not flooded) as any routing protocol does in order to notify its existence to its neighbours. This HELLO packet has the list of functions that this node can take over. When a timeout is expired and no new HELLOs are received or HELLOs are received with fewer functions, this node has died or some functions have been damaged. If a node detects such function damage it can take over the function, the node floods a NOTICE packet to notify other nodes that it is a candidate for the damaged function alternative. The NOTICE packet contains the ID of the die node and a value indicating the node suitability to assume such an alternation function. This value is calculated for balancing energy and the distribution of sensor functions. After waiting for NOTICE packets from neighbour nodes for a threshold time, the node with best suitable value floods a TAKEOVER packet to all of the nodes to inform them that the alternation function has been executed. This simple cooperative method improves significantly the reliability and resilience of the WSN, which is especially welcome for space missions and scenarios in extreme conditions where WSN needs to be at the highest level of reliability.

C. NETWORK MANAGEMENT FOR SEE

An important aspect of network management related to the usage of WSN in extreme conditions is generally the difficulty associated to the deployment of the sensors in the sense field. Once the WSN is deployed, it is highly difficult to remove the sensors from the field, especially in SEE. So, these sensors need to be provided with reconfigurable and re-programmable processing techniques enabling the decoupling of the sensing infrastructure from the applications running on top of it. Deluge [31] provides a reliable dissemination protocol for distributing a large amount of data through WSN. It uses full image replacement strategy for updating all sensor nodes. So, as soon as the whole image-data received by the sensor nodes the network starts the update procedure to replace the old image by this new one. Scenarios in extreme conditions demands different design principles in which data transmission is minimized due to the hard network conditions and also in which recovery mechanisms are considered a critical part of the protocol just in case the updating process of the nodes ends up in failure due to the extreme conditions. The former can be tackled using two-stage differential update, Diff [32]. In essence, both the old and new version of images is compared on a host machine sending only the different components or contents to all sensor nodes for updating. The latter addressed by Lien and Chiang [33], who have also provided a recovery mechanism for the reprogramming of WSNs. The main design principles for this recovery technique are: a) It must have as much data retransmission as possible; b) Recovery process must be performed locally in sensor nodes to minimize the communication. The main approach presented by Lien and Chiang is depicted in Figure 5.

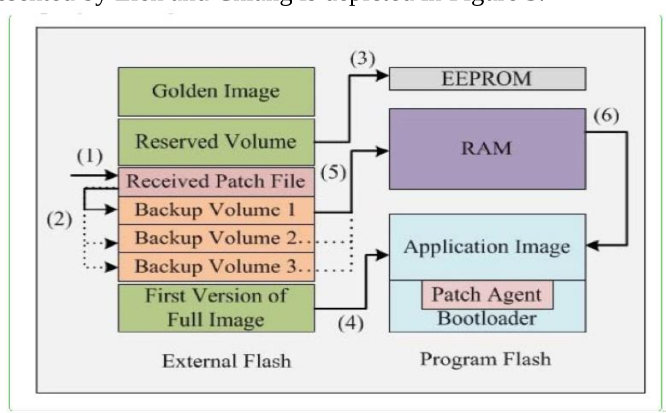

Figure 5: Flow for incremental recovery proposed by Lien and Chiang [33]

The figure shows several volumes located in the ‘external flash device’. The authors use four backup volumes for the updating process. The first backup volume is used to receive a patch file sent from the host machine (see signal point 1 in Figure 5). After the sensor node finishes receiving patch file, it will copy the file into another backup volume according to the current backup pointer (see signal point 2 in Figure 5). The backup pointer always points to the next volume address for receiving a new patch file. Since there are total three backup volumes to store three versions of patch files (the first one is used to store received file), the backup pointer must rollback to the first backup volume address for starting the next backup cycle. After three incremental updates, the fourth will rollback the pointer address back to the first backup volume. Then, the reprogramming flag is set and writes the backup pointer address into EEPROM (see signal point 3 in Figure 5). Sensor node will later reboot and start to execute the boot loader for reprogramming. The boot loader will perform the Two-Stage Diff update mechanism according to the patch file. If any error occurs during the reprogramming, the authors proposed that incremental recovery mechanisms would be executed to recover the failed sensor node. These incremental recovery mechanisms start from setting a recovery flag and write the flag into EEPROM. A sensor node will later reboot and perform the recovery mechanism according to the recovery flags. If any error occurs during diff-based reprogramming, the recovery mechanism will set version N recovery flag. After rebooting, the boot loader checks N recovery flag and performs the recovery mechanism. First, it will load the oldest fully executable image from external flash into program flash (see signal point 4 in Figure 5). According to how many patch file versions are stored, the mechanism will perform incremental recovery by patching the old full image many times until the current version. If the N recovery mechanism fails, the N-1 recovery mechanism is performed (see signal points 5 and 6 in Figure 5). It ensures that at least the node can rollback to the previous version which has been previously functional in the past in order to be able to replace the corrupted image with a more appropriate one.

IV. Dynamic Spectrum Sharing in Space and Extreme Environments

A. Motivations

There seem to be far less wireless devices in space than on earth, but it is expected that there will be a need in orders of magnitude for more wireless sensors in space than those we have on earth today. This calls for robust and reliable dynamic spectrum sharing schemes in space and of course this applies to other extreme environments. Since there is no federal communication commission (FCC), nor any action from the international telecommunications union (ITU) to regulate the spectrum in space, the sharing issue would be even more critical than it is in terrestrial systems. Noting that safety, security, and reliability of space habitats is dependent on wireless sensors, the importance of studying spectrum sharing in space becomes more evident. That is, we need smart structures that can withstand harsh space conditions and still have modes of failure prone to micrometeoroids and space debris impacts. Wireless sensing systems such as:

- Structural integrity and shape monitoring sensors
- Leak detection and localization sensing systems
- Impact detection and localization sensor networks

are just a few examples of wireless sensor systems that will be installed in space habitats and space vehicles. There wireless sensors in close proximity to each other need to operate in harmony on a limited frequency spectrum in concert with various other on board radios and wireless communications systems for surface and deep space networks.

Spectrum sensing enables efficient sharing of this scarce resource. Although a spectrum may seem plenty in space, due to the aforementioned arguments, the large number of users makes the sharing problem too challenging to handle.

Extreme environments in their own terms need to deal with the problem of spectrum sharing. Due to limitations caused by environmental conditions such as extremely high or low temperatures, or harsh chemical vapours present in the vicinity of sensors, special types of material needs to be used in sensors design. For instance, UMaine's new start-up company, Environetix is developing high temperature wireless sensors that can withstand above 1000 degrees Centigrade inside jet engines [34]. The material than enables operations in such environments but works at specific frequency bands, limiting spectrum access even further.

This section is organized as follows. Wireless sensors without batteries that can withstand harsh space and extreme environments are reviewed first. The interference problem in a network of wireless sensors is modelled next. Some recent interference mitigation solutions that can be applied in space and extreme environments are discussed afterwards. Finally a comprehensive review of literature in spectrum sharing with sensing errors is presented before we conclude this section.

B. Wireless Sensors for Space and Extreme Environments

Batteries are the most limiting factor in the operation of wireless sensors systems for SEE. On board battery power can be saved with implementation of multi-state operation such as off, sleep, or standby power states, lowering the operating voltage, precision hardware control, and power efficient use of the wireless spectrum [35]. Scaled down modulation schemes can be used to save power as well [36]. Alternatively, minimizing overhead in sensor data packets based on properties of the sensor data can also help overcome the limited battery on board [37].

The battery power saving is the least of our concerns in extreme environments where even having a battery, due to harsh environmental conditions, is questionable. That is why passive or battery-free wireless sensors can be very attractive for using in these environments. Weight and cost savings is another reason that makes passive sensors a good choice in space applications.

One example of using battery-free sensors in space applications is monitoring temperature at several points on the mirrors of the space telescope (Figure 6). For a fine-resolution imagery we require an array of small mirrors to remain focused and keep their structural integrity. The harsh space environment with high dynamic range of the temperature causes the mirrors to expand and shrink. Using battery-free wireless sensors can enable temperature correction by turning localized heaters on and off as needed. The problem of spectrum sharing becomes an issue as the number of sensors grows.

Figure 6: Space Telescope. (Picture courtesy of NASA GSFC)

Another example is embedding sensors in the heat shield of re-entry vehicles including inflatable decelerators (Figure 7). Extremely high temperatures at the re-entry need to be tolerated by the wireless sensors for their effective operation. Any unusual, locally high temperature outside of the normal window can be detected and catastrophic conditions may be avoided by directing cooling liquid to those specific locations.

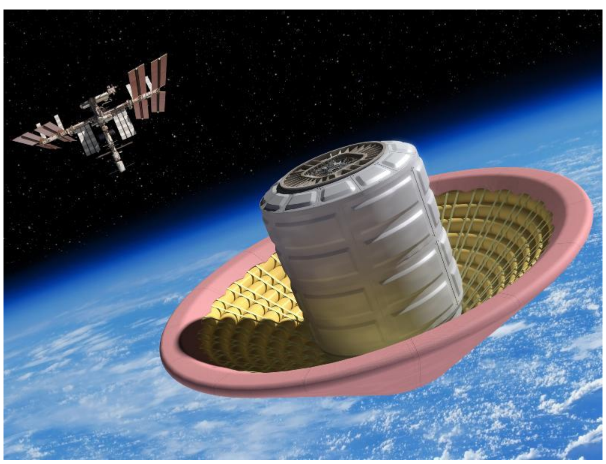

Figure 7: Inflatable Decelerator. (Picture courtesy of NASA GSFC)

Passive wireless sensors may be realized using multiple technology platforms such as semiconductor based sensors, piezoelectric substrates, and inductive sensors. Surface acoustic wave (SAW) based sensors are one of the widely used technologies that are based on concentration of the travelling wave on the surface of the piezoelectric based sensors [38]. Prior implementations of SAW devices were for one sensor operation at a time. Recently, a coded SAW sensor system was proposed in [39], where a multiple-access feature was added using coded sensors. More information on passive wireless sensors can be found in the references listed in this section.

C. Interference Problem in Dense Wireless Sensors Networks Deployed in SEE

The large number of wireless sensors deployed in space habitats and vehicles creates an interesting and challenging scenario under the general spectrum-sharing problem. The interference created by adjacent sensors when one particular sensor being read by an interrogator. Various techniques such as time, code, and frequency diversity may be used to address this issue to some extent. The model below is based on the results presented in [40].

Let us assume functions *M(.)* and *N(.)* refer to matching (autocorrelation) and non-matching (cross-correlation) responses from desired and interfering sensors, respectively. Denoting each orthogonal code in a network of n sensors with C_j, $j=1,..,n$, the received response at the interrogator can be formulated as,

$$\mathrm{R}_1 = M(C_i) + \sum_{j=1, j\neq i}^{n} \mathrm{N}(C_j)$$

This is assuming that all n sensors respond to the interrogating signal, which is true in practical cases, if they are all within the reading range of the interrogator. Now, the question is that: ‘How many sensors can be placed within reading range of an aggregator?’ The number of sensors is limited to the point that aggregated cross-correlation signals from all sensors masks the autocorrelation peak of the desired sensor response. Noting that the relative location of the peak(s) is related to the measured parameter, peak detection can be a challenge if too many large side lobes are created.

The interference mitigation method described here is reported in [41] and based on multiple outputs generated from a bank of matched filters combined with a novel iterative interference cancelation method. The filter bank consists of n matched filters with the same codes as n sensors in the network. Only one of the filters’ outputs will have high amplitude autocorrelation peak, and the rest will only have cross-correlation signals with no obvious peaks. We note that from n detected signals only one desired to be accurately decoded. In order to start the interference mitigation, we first sort all filters based on their output highest peak value in descending order. The first filter indicates the desired sensor response. Starting from the second filter, which has the highest interfering signal, we remove its response from the received signal and update the filter bank outputs with this modified signal. This process is repeated until all interfering responses are removed iteratively. At this stage the output of the first filter will be much closer to the interference-free response compared to the initial received signal.

As seen in Figure 8, dynamic spectrum sharing while dealing with multiple sensors responding simultaneously can be managed using interference mitigation techniques. This is a paradigm shift from conventional spectrum sensing/interference avoidance methodology. Allowing interference to happen and resolve the issue later might lead to more cost effective sensor fabrication technologies.

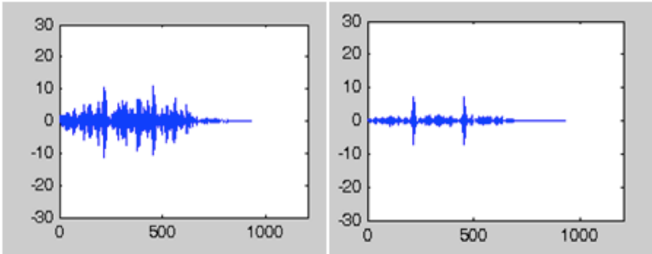

Figure 8: Sensor response with five interfering sensors (left) and after interference mitigation (right).

In order to find average interference caused by one or two sensors not knowing which sensor is interfering at each time slot, the following equations may be used:

$$f_1 = M(C_i) + \frac{1}{n}\sum_{j=1, j\neq i}^{n} N(C_j)$$

$$f_2 = M(C_i) + \frac{1}{n^2}\sum_{j=1}^{n}\sum_{k=1}^{n} N(C_j) + N(C_k)$$

These equations can be generalized to include m interfering sensors.

$$f_m = M(C_i) + \frac{1}{n^m}\sum_{j_1}^{n}..\sum_{j_m}^{n} N(C_{j_1}) +..+ N(C_{j_m})$$

A reduced complexity method for calculating the approximate value of (5) for a large wireless network is proposed in [41]. As seen in Figure 8, peaks of the signal are much easier to detect after interference mitigation is applied to the aggregate response.

D. Dynamic Spectrum Sharing with Sensing Errors

A totally different form of interference in spectrum sharing literature is called, primary-secondary interference. The main idea dates back to Simon Haykin's original paper introducing cognitive radio [42] where the operation of secondary users (un-licensed) while primary users (licensed) are silent is permitted. This is subject to interference mitigation methods to make sure primary users who paid for the licenses spectrum do not get harmed by ad hoc secondary users.

This elegant scheme has not been widely used yet, since errors in spectrum sensing are unavoidable and there is no incentive for primary users to allow access to secondary users. Recently, a reputation-based Stackelberg game approach for spectrum sharing is proposed in [43]. In this work, concept of cognitive cooperation is introduced, where secondary users act as relays for primary users to help them when their main channel and has low quality providing more spectrum holes in future time slots. The price to pay for possible interference is relaying. Time allocation to various phases of transmission (primary only, secondary relay for primary and secondary only) has been optimized keeping fairness in the network.

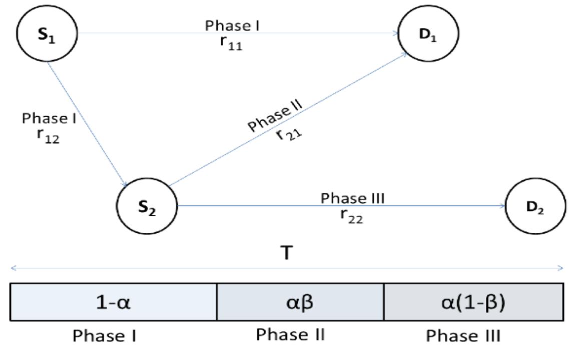

Figure 9: Network model and time frame model for cognitive cooperation [43]

The problem of spectrum sharing in space and other extreme environments in the context of wireless sensor networking are few in the literature with much more remaining as future research directions. The interference in passive sensors versus interference concept in cognitive radio networks mentioned above is also for future research where the combination of these two concepts and cognitive interrogation systems for passive networks should be studied.

V. ENERGY CHALLENGES AND ENERGY EFFICIENT MULTIPLE ACCESS

Reliable and efficient multiple access remains a significant research problem for mission-critical applications in SEE characterised by challenging and highly dynamic environmental conditions [44]. It is well known that medium access control (MAC) plays a crucial role in providing high channel utilisation efficiency, low delay and energy-efficient communication in wireless networks. Outages due to energy shortages and adverse propagation conditions are significant problems in SEE, calling for highly adaptable and energy-efficient MAC protocols. Sensing systems designed for operation in space or underwater face additional challenges, notably long and potentially variable propagation delays, which severely inhibit the throughput capability and delay performance of conventional MAC schemes. This section reviews some of the challenges associated with reliable and efficient multiple access in SEE, focusing on underwater sensing systems.

A number of multiple access schemes have been proposed for resource constrained wireless sensor networks [45]. Emphasis has often been placed on energy-efficiency, based upon the use of battery powered sensing nodes, which permit flexible deployment, typically outdoors and in potentially remote and/or inaccessible locations. Efficient duty cycling and the use of low power sleep modes are commonly employed at the MAC layer [46]. Although such approaches extend the lifetime of wireless sensing systems, nodes will ultimately fail without some form of ambient energy harvesting technology. This is, of course, a critical issue in SEE environments where battery replacement may not be feasible. Informative surveys of the possibilities, technologies and challenges associated with ambient energy harvesting for wireless sensor networks can be found in [47] [48]. Solar, mechanical and thermal are the most promising energy sources but their availability is heavily environment dependent and the physical size of typical sensing devices is a significant constraint. Attempts have been made to produce optimal sleep and wakeup schedules based upon the assumption of fixed recharge rates from energy harvesting devices [49]. Although such optimisation methodologies have merit, the amount of energy generated from a harvesting device is heavily dependent on ambient conditions. The time varying availability of energy needs to be considered to avoid outages, and if batteries are used, their recharge characteristics need to be accounted for. Other forms of energy storage may be beneficially employed, such as super-capacitors [50]. A good comparison of the characteristics of super-capacitors in comparison to Li-ion batteries and hybrid devices can be found in [51]. Table 2 summarises some of the key characteristics. It is worth noting that super-capacitor charging characteristics are particularly suitable for long term use in extreme environments, since they can operate at more extreme temperatures, offer much lower charge times and a greater number of charge cycles. They are significantly more expensive but the amount of energy available will, however, be significantly reduced.

Table 2: Key characteristics of super-capacitors and Li-ion batteries

Parameter	Conventional Supercapacitor	Hybrid Supercapacitor	Li-ion battery
Cycle life	High	Medium	Low
Charge time	Low	Medium	High
Energy density	2 to 6 Wh/Kg	10 to 50 Wh/Kg	120 to 200 Wh/Kg
Power density	1 to 10 KW/Kg	1 to 5 KW/Kg	0.1 to 1 KW/Kg

A new approach to power management is required to effectively support harvesting technology, which is geared towards using energy at the rate at which it can be harvested, with network protocols and functionality governed by this rate. This has been termed energy-neutral operation and it would ultimately support perennial operation [52]. The use of energy harvesting technology has important implications for medium access, since uncertainty surrounding the future availability of energy makes it difficult to arrange reliable duty-cycles, transmission/reception schedules or back-off times in the traditional way. Energy shortages may occur at critical times, for example when a node is scheduled for a period of activity. It may be counter-productive to wait, and decisions to transmit or to be available for reception may be better taken when sufficient energy is known to be available. A number of recent papers are devoted to evaluating the performance of existing MAC protocols with energy harvesting models. The impact of discontinuous energy availability on the performance of traditional time division multiple access (TDMA) and framed ALOHA schemes is investigated in [53] for a single hop wireless sensor network. Results show that the asymptotic packet delivery probability and time-efficiency (which relates to the achievable channel utilisation) of all the schemes is heavily dependent on the energy-harvesting rate. Unslotted carrier sense multiple Access (CSMA) has been shown to be more efficient than a slotted variant for a number of reasons [54]. The energy used for slot synchronisation calls for longer energy harvesting periods, which reduces transmission time (and potential throughput) on the channel. Energy overheads for sensing are lower in the unslotted scheme because a node can immediately enter a recharging state when a channel is sensed busy. In the same paper, a probabilistic polling scheme is proposed which adapts a contention (transmission) probability based on the energy harvesting rates. The throughput performance of the S-MAC protocol has been evaluated for an energy harvesting based WSN in [55]. An important trade-off in between throughput and remaining energy in the battery is shown. Based on minimum thresholds for these parameters, suitable bounds for the duty cycle can be determined to meet the quality of service and network lifetime requirements. New approaches are starting to emerge such as RF-MAC where energy is harvested through directed radio frequency waves [56]. RF-MAC is designed to effectively manage the transfer of data and energy in the same band. It is shown to offer an improvement in network throughput over a modified unslotted CSMA based scheme.

The challenges associated with long propagation delays are well understood for satellite systems. Demand Assignment Multiple Access (DAMA) is commonly employed as a means of achieving high channel utilisation efficiency, since capacity can be allocated to nodes in response to time-varying requirements. Many approaches are however limited to a minimum end-to-end delay bound of two/three hops for on-board and ground based schedulers respectively, corresponding to ~0.5s-0.75s for geostationary satellite systems. Underwater communication systems are often based on the transmission of acoustic waves, since electromagnetic waves suffer high levels of attenuation and only propagate over very short distances. The substantially lower propagation speed of acoustic waves (~1500m/s) introduces comparable delays to geostationary satellite systems with significant variation in delay if transmitters are located at different distances from a common receiver. The underwater propagation environment is particularly complex and MAC protocols remain a significant research challenge underwater [57]. The remainder of this section is therefore devoted to discussing the primary issues and potential solutions.

Underwater hardware development and sea installation is very expensive and commercial acoustic modems are only able to provide modest data throughput in networks. As a result, current deployments comprise low numbers of instruments recording data during a mission for later retrieval. A breakthrough in multiple access capability is required to fully exploit the exploration, sensing and monitoring capability that networks of mobile nodes can provide, yet most research in underwater acoustic communication deals with the physical layer. Existing multiple access techniques struggle to address the fundamental constraints, including long and variable propagation delays, the complicated space variability of the channel (e.g. shadow zones due to refraction), extensive multipath phenomena, and the fast time-variability of the channel, especially for mobile nodes.

A wide range of conventional MAC techniques have been considered for underwater networks and Table 3 summarises the primary advantages and disadvantages of alternative approaches. Power control is required to combat the near-far problem, challenging in an underwater environment given the rapidly varying channel conditions and long propagation delay. Provision of links with fixed bandwidth and data rate make FDMA and CDMA highly inflexible. Some form of adaptive TDMA is a natural solution for packet-switched communication but schedule-based schemes suffer from long reservation delays, restricting their ability to adapt to changing traffic requirements and propagation conditions. They also incur significant signalling and synchronisation overheads. Contention protocols based on CSMA can provide more rapid and flexible access to the communications medium, but the effectiveness of physical carrier sensing is significantly reduced with acoustic propagation, due to the highly variable propagation delays. Handshaking methods based on the principles of floor acquisition multiple access (FAMA) and multiple access with collision avoidance (MACA) have been extensively exploited to alleviate the hidden terminal problem [58] [59], akin to schedule-based schemes, but the time taken to exchange control packets prior to data transmission introduces notable delay and overheads at acoustic propagation speeds. ALOHA schemes represent a logical approach, but the absence of any form of coordination renders their throughput capability poor. Recent work to address such constraints has demonstrated the benefits of applying a stochastic transmission strategy to ALOHA, based on heuristic objective functions [60]. It has been argued that no single MAC protocol is able to satisfy the diverse requirements associated with underwater acoustic networks and that adaptation based on a suite of protocols is more appropriate [61].

Table 3. Summarises of advantages and disadvantages for different MAC approaches

Multiple Access Approach	**Advantages**	**Disadvantages**
FDMA	Simple to implement	Inflexible fixed rate allocation Susceptibility to fading
CDMA	Offers protection against fading	Inflexible fixed rate allocation Synchronisation required Power control required
TDMA	Suited to packet switched communication	Inflexible fixed rate allocation Synchronisation required
Adaptive TDMA/DAMA	Efficient variable rate allocation	Long reservation delays Signalling overheads
Free Assignment	Potential for minimising delay	Inefficient opportunistic allocation of resources
Random Access	Potential for minimising delay	Inefficient uncoordinated use of resources
Carrier Sensing	Potential for minimising delay High throughput potential	Hidden node problem Sensing inhibited with variable propagation delays
Handshaking (without sensing)	Alleviates hidden node problem	Long signalling delays
Handshaking (with sensing)	Alleviates hidden node problem	Long signalling delays Sensing inhibited with variable propagation delays

The development of efficient MAC protocols for underwater sensing systems is severely inhibited by the absence of suitable models for signal propagation. Virtual signal transmission recently developed and proposed in [62] is a significant step towards such a model, but it requires significant computation time and can only be used for relatively short signal transmission sessions. In [63], a different approach is proposed using waymarks over the trajectory of moving communication nodes. Based on local spline approximation of the time and space varying channel impulse response, this model allows simulation of infinitely long communication sessions. Crucially, it has the potential for real-time hardware implementation. Accurate models of underwater signal propagation need to be developed in order to provide the understanding required to design effective MAC protocols for such environments, especially for mobile systems in arbitrary acoustic environments.

The success and adoption of terrestrial radio systems is largely due to global standardisation efforts and the development of integrated physical (PHY) and MAC layer standards. The current treatment of the MAC layer in relative isolation is another significant issue. The variety of scenarios where underwater communication networks can be used dictates the need for the design of a universal PHY capable of adapting to different conditions [64] [65]. The most promising modulation schemes for underwater acoustic communications are considered to be schemes based on multicarrier modulation, such as OFDM and SC-FDMA. Drawbacks of such schemes include their sensitivity to the Doppler effect due to node movement and low spectral efficiency due to long guard intervals. However, as recently shown [66], these issues can be efficiently addressed. The development of a universal PHY layer in tandem with the MAC layer is now required, to enable intelligent and adaptive use of optimised channel sets in frequency and time as a means of providing flexible allocation of resources combined with time and frequency diversity

VI. Typical SEE Application Cases

To summarize our earlier discussions on SEE, their specific features, and their potential for promoting a new application paradigm upon the WSS and associated services under the unconventional wireless sensing requirements we follow up our six Section 1 environmental grouping by locating them into correct groups in their 'typical example' column of a new table. Here, Table 4 highlights each of six environmental groups divided consequently into few application areas upon the application working conditions, each supported by some typical examples from the recent literature.

Table 4: Grouping of sensor system environments. They are each, accompanied by some associated application areas. For which we have included some typical examples to show the unconventional EE working.

Environmental Group	Application Areas	Typical Examples
1 /Space /Sat /HAP	-Observation /Discovery /Interactive	-EG: Europa Mission [67], Sensors in Solar Space Missions [68], Advantages of using Integrated Wireless Sensing in Spacecraft Monitoring and Tracking [69] & [70], REMS: The Environmental Sensor Suite for the Mars Science Laboratory Rover [71], Distributed Space Satellite Sensor Networks [72], Distributed Intelligent Robotic [73], Space and Solar-System Missions [68]
2 /Underwater /Immersed /Submerged	-Monitoring /Discovery /Complex	**-EG:** Underwater Acoustic Networks [58], Coordinating Submerged Sensors for Distance Measurement and Localization Avoiding Acoustic Multipath Fading [6], Adaptive Error-Correction Coding and Modulation for UWA [65] & [64], Fast-Varying Acoustic Channels and Selectivity [66] & [63], Hidden Terminal Delay Problems [59], Underwater Wireless Sensing for Autonomous Underwater Vehicles (AUV) [46], Platform Dynamics and Emerging Technologies [74] & [61] & [62]
	-Aquaculture	**-EG:** Aquacultural breeding and harvesting [75]
3 /Underground /Buried /Hidden /Covered	-Monitoring	**-EG:** Magnetic Induction Through Soil [7], Under 1 GHz Wireless Soil Propagation Properties [76], Extreme Path Loss and Other WUSN Research Challenges [77]
	-Agricultural	**-EG:** Underground Sensor Channel Modeling, Agricultural, Other Applications (U2U, A2U, U2A) [78]
	-Mining	**-EG**: Underground Mine Sensing [79]
4 /Confined /Indoors	-Localization /Tracking /Navigation	**-EG**: Dynamic Localization of Moving Robots [80], Localization using Sensor Radars [81], Wireless Acoustic Sensor Networks Distributed Node Tracking [82]
	-Clinical /Wearable /BAN	**-EG**: Body Sensor Network Platform Clinical Monitoring [83], Foetal Movements of Pregnant Women [8], Implants [9], Smartphone Health Monitoring Laboratory [84], Intelligent RFID Wireless Body Sensor System [85], Body Mounted Sensor Modeling [86]
5 /Industrial /Robots	-Monitoring /Robotic (WSAN)	**-EG:** Real-Time Manufacturing Tracking and Monitoring [87] & [88], Railroad Alarm Monitoring [89], Robotic Rapidly Changing Env. [90]
	-SHM	**-EG:** Future of Structural Health Monitoring [91]
6 Others	-Energy /Conservation /Harvesting /Storage /Transfer	**-EG:** Suitability of MAC Protocols for Mission-Critical Applications [44], Adaptive Sleeping MAC for Energy Efficient Wireless Sensing [57], SMAC Energy Harvesting [55], Energy Harvesting Survey [48], Underground Harvesting, [h53], Game-Theoretic Energy Harvesting Management [49], Ambient Powered Energy Harvesting Survey [47] & [54], Single Hop Wireless Sensing MAC Protocols using Energy Harvesting Devices [53], Extended Lifetime Charging Supercapacitors [50], Wireless Power Transfer in Fiber-Reinforced Plastic [92], Wireless power transfer for embedded sensors [56]
	-Data Env.	**-E.G.:** Sensor Data Processing Platform [93], Privacy and Integrity of Sensor Data Aggregation [94], Trust and Uncertainty [4] & [95] & [96]
	-Special Cases (Antarctica, Arid, Mountains, Desert, etc.)	**-EG**: Terrestrial Pipe Protection [97] & [98], Desert Dust Devils Wireless Motes Measuring Temperature, Pressure, Humidity and Acceleration [99] & [100].

Although the entries and their classification are self-explanatory within our limited pages we have made upmost efforts not leave any important issues unclear. Some of the entries in the above Table have been discussed to some extent in previous Sections of the paper that we complement with the following.

Planet Jupiter also known as the gas giant or Jovian planet is the biggest of the four gaseous planets in the solar system and nearest to planet earth has been of scientific interest for one of main objectives of 2020 Europa Mission. However, for safeguarding the design and gathering basic information of scientific studies special sensors capable of collecting and analyzing radiation are employed. To name a few, energetic particle detector, heavy ion counter, composition measurement system, and low energy magnetospheric measurement system. These are, such as RadFET sensors, designed to monitor and provide context for the Europa Orbiter missions. [E.g., [67] Europa Mission.

Networking many similar wireless sensors in space could be used for many applications such as sustainable monitoring of properties such as weather, chemical, physical, and atmospheric sensing of the soils and surfaces of other planets using more economical space based networks (SB-WSN), applying the terrestrial concept to space [68].

Spacecraft monitoring and tracking associated industries such as space surveillance networking (SSN) are still premature. They can help to detect and track all new and existing detectable space objects, predict and characterize orbital movements for sensitive information such as country of origin, mission, alert or launch for any required activities [69] [70].

Over the period of the mission, the mars science laboratory (MSL) the REMS station requires to investigate habitability factors on a Martian surface, mainly: environmental temperatures, UV radiations, and water recycling system. Therefore, REMS sensors will record temperatures of the air and ground, measure the wind flows in various directions, pressure, and humidity, as well as ultraviolet radiations [71].

Plasma bubbles caused by ionospheric plasma depletions occur at low latitudes after local sunset with bubbles as large as thousands of kilometers propagating at speeds up to hundreds of meters per second can create unknown instabilities in low orbit systems. In order to investigate these we can use a special distributed space sensor (ionospheric multiple plasma sensor networks) of small systematically scattered sensing objects employed in two stages of (a) to set around spatial monitoring of plasma bubbles and (b) entered into the bubble forming a specific shapes allowing temporal monitoring of the plasma bubble evolution over time [72].

Under the concept of using robots to implement intelligent assembly work in space, also called iSpace, a space located distributed sensor network is deployed. In this system the robots simple follow a well-structured sequence procedure they sense gathering information about humans and other objects in the space and actuate appropriate functions based on "observe", "recognize", and "actuate" [73].

VII. Conclusions

This review conveys two distinct messages for viewers of this Special Issue: (a) to academic researchers in all engineering and associated disciplines including scientific research and developments, all industrial fields from light industries to heavy. Also, other global programs interested or involved in wireless sensing to understand the concept for practical applications and potentials of the real world of wirelessly connected smart and intelligent sensors for pushing the boundaries into virtually everywhere across the globe and beyond for improving their systems and better quality of life and (b) to engineers and industrial researchers to look for a wide range of possibilities that wireless sensing as an application paradigm for pursuing their innovative designs and application systems in the practical world of new technological developments.

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