Wireless Sensor Networks for Environmental Monitoring

Ismael Filipe Maia Gonçalves da Trindade
ismael.trindade@tecnico.ulisboa.pt

Instituto Superior Técnico, Lisbon, Portugal

November 2021

Abstract

Wireless Sensor Networks (WSNs) are regarded as one of the most rapidly developing information technologies, with a wide variety of potential applications. Their capacity to sense and transmit without a permanent physical infrastructure, makes them an appealing technology for use in monitoring systems, particularly in Environmental Monitoring.

This thesis will introduce some fundamental concepts of WSNs, their design challenges and applications. Moreover, an overview of several prominent standardization initiatives for open standard protocols for Wireless Sensor Networks will be presented. This study provides a document that will help electronic circuit design researchers in their search for a protocol. Currently, there are numerous protocols in the market, however, the focus of this study will be on the open standards. Furthermore, ZigBee and Bluetooth Low Energy protocols will be explained in greater depth to better comprehend the functioning of a protocol and assist in the development of a proposed protocol.

Finally, this dissertation discusses a simple proposed protocol for environmental sensing, which monitors humidity and temperature, and is intended for experimental purposes. Considering that the sensor nodes are projected to have a battery autonomy of several years, it is critical to simplify the network management and the communications energy consumption. Therefore, this protocol aims to reduce network energy consumption and management. Applications of this system will include environmental and precision agriculture monitoring, as well as fire detection capability by tracking a sudden temperature increase over a certain threshold. These applications will benefit society in a variety of ways.

Keywords: Wireless Sensor Networks, WSN Standards, Environment Monitoring, Bluetooth Low Energy, ZigBee.

1. Introduction

Over the past few years, there has been an increase in weather conditions as a consequence of climate change. For this reason, it emphasizes the importance of a thorough understanding of our environment and its development for human beings. Wireless Sensor Networks (WSN) have been used in a variety of industries and can also be used in environmental monitoring applications.

Environmental monitoring using WSN is of most importance to help prevent natural catastrophes and predict climate change. Late detection of a wildfire allows it to grow to larger proportions, making it more difficult to extinguish. WSNs would detect and send a fire alarm as soon as possible, increasing firefighters' performance.

Furthermore, it can be used in a variety of applications, in order to assist people in their work and reduce cost and time. In agriculture, WSNs are capable of measuring the humidity and temperature present in the fields. These sensed measures allow the farmer to determine whether or not it is necessary to irrigate the crops, thereby conserving valuable natural resources such as water, which are becoming increasingly scarce.

Currently, there are many technologies suitable for Wireless Sensor Networks, making the decision of selecting one to be implemented much harder. However, some protocols excel in comparison to others, most notably those that are open protocol standards. These standards are open to the public and are maintained through a collaborative and consensus driven process. Thus, facilitating interoperability, data exchange between devices and they are designed for widespread adoption. Therefore, the initial motivation was to make a study on the available open protocol standards suitable for WSNs, in order to help the electronic design circuit researchers to choose one for their future projects.

Moreover, a protocol is necessary to test in the field the functioning of the electronic circuit, designed by the researchers. Furthermore, the importance of balancing energy consumption with transmission time cannot be ignored. Thus, this thesis proposes a simple protocol for environmental sensing.

2. Introduction to Wireless Sensor Networks

Wireless Sensor Networks (WSNs) are self-configured wireless networks that do not require any infrastructure. They are designed to monitor physical parameters or environmental conditions such as temperature, humidity, sound, vibration, pressure, motion, or pollutants and transmit the sensed data across the network to a centralised location or *sink*, where it can be viewed and analysed [26]. A sink, also referred to as a base station, is a special node responsible for collecting, processing, and controlling data from a group of sensor nodes. One can obtain information from the network by inserting queries and retrieving results from the sink.

A wireless sensor network can be as small as a two-node network or as large as thousands of nodes connected. The actual network size will vary depending on the application and deployment, but it is expected that a WSN will have a significant number of nodes in general.

Sensor nodes are devices that have at least one sensor and may include actuators, as well as processing and networking capabilities for data processing and wireless access. Sensors measure an observation's physical property and quantity, converting the measure into a signal that may be electrical (e.g. current, voltage, power, resistance, etc.), mechanical (e.g. pressure, flow, liquid density, humidity, etc.) chemical (e.g. oxygen, carbon monoxide, etc.), acoustic (e.g. noise, ultrasounds, etc.), or any other signal type. Actuators are devices that can respond to a stimulus(caused by an input signal) by performing an action (e.g. turning on a light, triggering an alarm, turning off an irrigation system, etc).

Radio signals allow the sensor nodes to communicate with each other. Sensing and computing devices, radio transceivers, and power components are all integrated into a wireless sensor node.

The sensor nodes in a WSN possess very limited processing speed, storage capacity, and communication bandwidth due to their design constraints.

After being deployed, the sensor nodes are responsible for self-organising an adequate network infrastructure, which typically includes multi-hop communication. The inbuilt sensors then begin collecting data of importance. Wireless sensor devices also respond to requests for specific instructions or sensing samples given from a control site. Actuators can be added to wireless sensor devices, in order to perform certain tasks in response to particular situations. This kind of network has a more specific term, which is Wireless Sensor and Actuator Networks (WSAN).

WSNs can be stand-alone networks, although connecting them to other networks (such as the Internet) for remote access and management may be beneficial. In this situation, a Sensor Network Gateway can provide communication between the WSN and another network.

Wireless sensor networks enable innovative applications and require nontraditional protocol design paradigms, due to numerous limitations. An appropriate balance between communication and signal/data processing capabilities must be achieved, because of the demand for minimal device complexity along with low energy consumption. This has motivated a massive effort in research, standardization, and industrial investments in this area [26].

2.1. Applications of WSNs

WSN technology allows a wide range of control and monitoring Sensor Network Applications (or use cases) in a variety of contexts, including environmental monitoring, healthcare and assisted living, sports and fitness, critical infrastructure monitoring, logistics, home automation, industrial monitoring, smart metering and urban monitoring [18].

Figure 1: Applications of WSN across different sectors (this image was designed using resources from [19, 17, 13]).

2.2. Design challenges in Wireless Sensor Networks

The deployment of sensor networks has numerous obstacles. Without any infrastructure, sensor nodes communicate on wireless, lossy lines. Another concern is the sensor nodes' limited, usually non-renewable energy supply. To ensure that the network will last as long as possible, the protocols must be developed from the beginning with the goal of effective energy resource management.

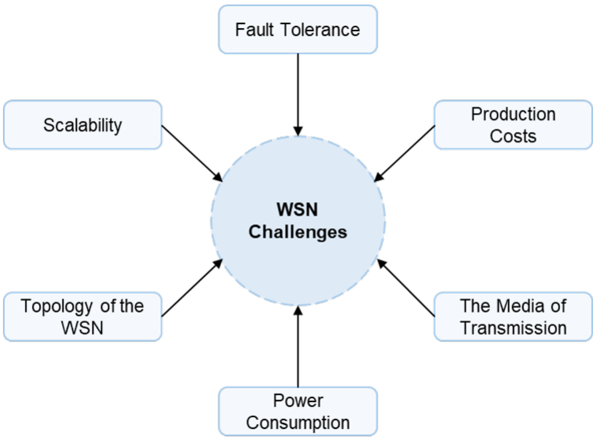

Figure 2: Design challenges in WSN.

Many aspects impact sensor network design, including scalability, fault tolerance, manufacturing costs, hardware restrictions, WSN topology, transmission media, and power consumption [2, 26, 14].

3. WSN standardization Initiatives

The standard specifies the functionalities and protocols that sensor nodes must use to communicate with different networks. There are a variety of standard WSN architectures, each of which is further characterised by amendments and upgrades. True interoperability between devices and applications requires universally accepted specifications and protocols, which can only be achieved through standardization. This section highlights some of the most prominent WSN standardization initiatives.

3.0.1 The importance of Open Standards

In essence, open standards offer greater value to the end-user. Closed standards may be used by product managers and developers who believe that they will provide additional security, guarantee interoperability between their products, or force consumers to purchase more of their own products in order to get the most value out of the products they have already purchased. However, consumers desire alternatives, and the industry is recognising that proprietary ecosystems are no longer feasible. Nowadays, the vast majority of WSN manufacturers use open and standardised networking protocols, allowing the freedom of choice to the consumers [4].

There are protocols that gain market dominance without going through the standardization process. These protocols are referred to as *de facto* standards, which are common in emerging markets or monopolised markets, and are capable of holding a market to deter potential competition. standardization is as a countermeasure to the negative effects of *de facto* standards. There are positive exceptions, like Linux, operating system, a *de facto standard* operating system, which does not have this negative market grip, because the sources are published and maintained openly, inviting competition.

3.1. IEEE

The Institute of Electrical and Electronics Engineers (IEEE) is a not-profit organisation committed to engineering, computing, and technology development [21]. The IEEE supervises several publications, conferences, technical standards, and professional and educational events.

Figure 3: The Institute of Electrical and Electronics Engineers (IEEE) logotype (extracted from [21]).

IEEE's major standard for WSNs is *IEEE 802.15.4*, which defines the physical (PHY) and Medium Access Control (MAC) layer functions of a low power radio interface. It was created to optimise battery life in wireless sensor systems used in short-range communication. The physical layer supports low bands of 868/915 MHz and high bands of 2.4 GHz. For managing access to the radio channel, the MAC layer employs CSMA/CA.The IEEE 802.15 Task Group 4 was formed to study a low data rate solution with multi-month to multi-year battery life and very minimal complexity.

Residential, industrial, and environmental monitoring, control, and automation are among the wireless sensor applications that use this standard. IEEE 802.15.4 has essentially become the *de facto* radio interface for WSNs [8].

3.2. IETF

The Internet Engineering Task Force (IETF) is an open multinational community of network designers, operators, manufacturers, and academics concerned with the development and efficient operation of the Internet. The IETF designs and updates Internet protocols and architectures [22]. The specifications developed by the IETF are not official standards, but they are *de facto* standards, which means that a wide community accepts and uses their specifications.

Figure 4: The Internet Engineering Task Force (IETF) logotype (extracted from [22]).

3.3. ITU

The International Telecommunications Union (ITU) is the United Nations organisation responsible for issues related to information and communication technologies. ITU-T is the organisation in charge of telecommunications standards [24].

Figure 5: The International Telecommunications Union (ITU) logotype (extracted from [24]).

Ubiquitous Sensor Networks (USNs) were the focus of a ITU-T research aimed at identifying viable technologies for standardization work within the organisation [30]. On the other hand, the ITU released a technical paper on the applications of WSN in next generation networks [25].

3.4. ISO and IEC

The International Organisation for standardization (ISO) develops and publishes international standards on a wide range of topics. Organisations from both the public and private sectors are members of ISO [23]. Similarly to ISO, the International Electrotechnical Commission (IEC) is a non-profit global membership organization whose work supports quality infrastructure and international commerce in electrical and electronic products [20].

Figure 6: The International Organisation for standardization (ISO) and the International Electrotechnical Commission (IEC) logotypes (extracted from [23, 20]).

The ISO/IEC Joint Technical Committee (JTC) 1 was founded as a result of a merging of ISO and IEC organisations with the objective of focusing on information technology. In 2010, the JTC 1 Work Group 7 was established to work on standardization in the areas of generic sensor network solutions and application-oriented sensor networks [1].

3.5. ETSI

Figure 7: The European Telecommunications Standards Institute (ETSI) logotype (extracted from [15]).

The European Telecommunications Standards Institute (ETSI) is one of the founding partners in *oneM2M*, a global standard initiative that covers requirements, architecture, API specifications, security solutions, and interoperability for M2M and IoT technologies. The number of connected devices is rapidly increasing (26 billion end 2020, 900 million five years ago) and it is expected to increase in the following years.

According to ETSI, oneM2M communication is present in eHealth,connected vehicles, home automation and energy management, public safety and industrial process control, and smart cities, which are applications that are commonly related to WSN [15].

3.6. Industry alliances efforts for standardization

There are multiple industrial alliances built around individual technologies that encourage the adoption of a certain technology as a *de facto* standard. The ZigBee Alliance, Bluetooth SIG, LoRa Alliance, WEIGHTLESS SIG, DASH7 Alliance are a few examples of such special interest groups (SIGs) or alliances that develop open standards.

3.6.1 LoRa Alliance

LoRa is a proprietary wireless RF technology that is also one of the driving forces behind the LoRa Alliance, which is working on the open LoRaWAN (Long Range Wide-Area Network) protocol and ecosystem. Since its establishment in 2015, the LoRa Alliance has grown to hundreds of members(Cisco, IBM, Actility, Sagemcom, Microchip Technology,Orange, KPN, Swisscom, SingTel, Proximus, and many others) [32].

Figure 8: LoRaWAN Alliance logotype (extracted from [32]).

The LoRaWAN open standard architecture was designed by the LoRa Alliance to provide a medium access control mechanism and allow End-Devices (ED) to connect with one or more gateways with the primary goal of enabling mainly uplink communication. As illustrated in Figure 9, LoRaWAN specifies the data link layer protocol on top of the LoRa physical layer protocol. The LoRa protocol specifications are shown in Table 1 [7].

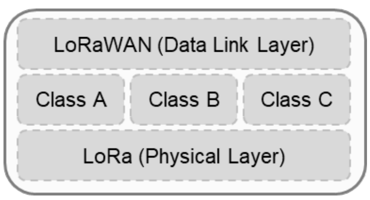

Figure 9: LoRaWAN protocol architecture.

Table 1: LoRa protocol specifications.

Specification	LoRa Technology Support
Standard	LoRa Alliance
Operational Frequencies	Unlicensed ISM band 868 MHz, 915 MHz
Modulation	Chirp Spread Spectrum (CSS)
Coverage Range	2 km - 5 km (urban) / 15 km (rural)
Data Rate	0.3 - 50 kbps (EU) / 0.9 - 100 kbps (US)
Topology	Star

3.6.2 DASH7 Alliance

The DASH7 Alliance Protocol (D7AP) is an open standard protocol for wireless sensor and actuator communication that operates in the unlicensed SUB-GHz bands. It is developed and maintained by the DASH7 Alliance, an industry consortium established in 2009 [6], its specifications are described in Table 2 [7]. D7AP is based on ISO18000-7, a specification for active radio frequency identification (Active RFID) used by the US Department of Defense. From ISO/IEC 18000-7, D7AP obtains the default settings of 433MHz active air interface connection, an asynchronous Media Access Control (MAC), and a presentation layer that exclusively utilizes highly organised data components. D7AP expands the functionality of the standard from RFID systems to WSN environments by making it a full stack , implementing the complete OSI model, that provides compatibility between different providers from the physical layer to the application layer [31].

Figure 10: DASH7 Alliance protocol logotype (extracted from [6]).

Table 2: DASH7 protocol specifications.

Specification	DASH7 Technology Support
Standard	Inherited ISO/IEC 18000-7
Operational Frequencies	Unlicensed ISM band 433MHz, 868MHz, 915MHz
Modulation	2-GFSK
Coverage Range	1 km - 2 km (rural/urban)
Data Rate	9.6 kbps(Low), 55.555 kbps(Normal), 166.667 kbps(High)
Topology	Tree, Star

3.6.3 Weightless Special Interest Group

The Weightless Special Interest Group (Weightless SIG), which was established in 2012, is a non-profit organisation that develops and maintains a group of standards that were initially intended to encourage LPWAN communications in TV white space (TVWS) [27]. Among the founding members of the Weightless-SIG are: Accenture, ARM, M2COMM, Sony-Europe, and Telensa [16].

Weightless SIG has established three separate open standards, as shown in Table 3, each with different technical capabilities. [28, 11]

Figure 11: Weightless Special Interest Group logotype (extracted from [12]).

Table 3: Weightless protocols specifications.

Specification	Weightless Technology Support		
Standard	Wheightless-W	Wheightless-N	Wheightless-P
Operational Frequencies	TVWS 470-790 MHz	ISM SUB-GHz EU (868 MHz), US (915 MHz)	SUB-GHz ISM or licensed
Modulation	16-QAM, BPSK, QPSK, DBPSK	UNB DBPSK	GMSK, offset-QPSK
Coverage Range	5 km (urban)	3 km (urban)	2-5 km (urban)
Data Rate	1 kbps-10 Mbps	30 kbps-100 kbps	200 bps-100 kbps
Topology	star	star	star

3.6.4 ZigBee Alliance

The ZigBee Alliance is a non-profit organisation that manages and develops the ZigBee open standard. The alliance was established in 2002 and is currently formed by more than 450 companies [3].

Figure 12: ZigBee Alliance logotype (extracted from [4]).

The ZigBee standard is a set of high level communication protocols that use low power radios based on IEEE 802.15.4 and operates in the unlicensed bands of 2.4 GHz, 900 MHz, and 868 MHz. At 2.4GHz (16 channels), raw data throughput rates of 250Kbs are possible, 10Kbs at 915–921Mhz (27 channels), and 100Kbs at 868Mhz (63 channel). Depending on the power output and environmental conditions, transmission distances range from 10 to 100 meters. The transmission range of sub GHz channels is up to 1km [5]. The ZigBee network can be configured as a tree, star, or mesh topology.

ZigBee is ideal for network RF applications that require low data rates, low power and security. Zigbee is a protocol best known for connecting smart devices such as lights, plugs, and smart locks to a home network. The ZigBee protocol specification is shown in Table 4 [5].

Table 4: ZigBee protocol specification.

Specification	ZigBee Technology Support
Standard	ZigBee PRO Specification
Operational Frequencies	Unlicensed ISM Band 2.4 GHz, 868(Europe)/915(Americas) MHz
Modulation	BPSK/ O-QPSK
Coverage Range	10 - 100 m
Data Rate	10 kbps - 250 kbps
Topology	Star, Tree, Mesh

3.7. Bluetooth Special Interest Group

Bluetooth Special Interest Group (SIG) is a non-profit organisation, established in 1998, which has currently a global community of over 36.000 companies. The Bluetooth SIG's primary responsibilities include the publication of Bluetooth specifications as well as the protection and promotion of Bluetooth technology [10].

Figure 13: Bluetooth Special Interest Group logotype (extracted from [10]).

Bluetooth specifications are classified into two types: Bluetooth classic and Bluetooth Low Energy (BLE). The Bluetooth Classic, also known as Bluetooth Basic Rate/Enhanced Data Rate (BR/EDR), is a low power radio that transmits data via 79 channels in the unlicensed 2.4GHz ISM frequency band. Bluetooth Classic is the standard radio protocol used by wireless speakers, headphones, and in-car entertainment systems. It allows for device-to-device communication. [9].

Unlike Bluetooth Classic, BLE is designed for short range wireless communication with a focus on low data rate, energy constrained applications. BLE's purpose, in addition to being low power, is to enable the development of low cost, simplified radio transceivers for applications that are both cost and resource (i.e. memory) constrained.

The BLE, like ZigBee, uses the 2.4 GHz ISM band to transmit. It provides a maximum data throughput of 2 Mbps and it has 40 channels with 2 MHz spacing. To avoid interference from other devices, the BLE employs frequency hopping. Unlike classic Bluetooth, BLE devices, on the other hand, run at the same frequency over longer periods of time to simplify timing requirements [29]. BLE offers a variety of network topologies, including point-to-point, broadcast, and, most recently, mesh, allowing Bluetooth to support the development of reliable, large scale device networks [9].

BLE is suited for several WSN applications, such as building automation, health care, home automation, agriculture and smart cities [10]. BLE can also be used in applications that require direct communication between the device and a smartphone. The Bluetooth protocols specifications are shown in Table 5 [9].

Table 5: Bluetooth protocols specifications.

Specification	Bluetooth Technology Support	
Standard	Bluetooth Low Energy (BLE)	Bluetooth Classic
Operational Frequencies	Unlicensed ISM Band 2.4 GHz	Unlicensed ISM Band 2.4 GHz
Modulation	GFSK	GFSK, $\pi/4$DQPSK, 8DPSK
Coverage Range	10 - 400 m	1 - 100 m
Data Rate	125 kbps - 2 Mbps	1 Mbps - 3 Mbps
Topology	Point-to-Point, Broadcast, Multicast	Point-to-Point(including piconet)

4. Discussion of a Simple Proposed Protocol for Environment Sensing

4.1. General Aspects

A simple proprietary protocol will be discussed with the goal of reducing network energy consumption and management, for experimental use. This protocol will be developed into a wide range wireless sensor network for temperature and humidity monitoring in the environment. Applications of this system will include environmental and precision agriculture monitoring, as well as fire detection capability by tracking a sudden temperature increase over a certain threshold.

4.2. Network Topology

The main aim of this proposed protocol is to be capable of establishing communications between the sensor nodes (SNs) and base stations (BSs) in the most possible simplified network management, in order to reduce the communication overall energy consumption. The SNs will be powered by a button cell battery, which is intended to have a battery autonomy of 5 to 7 years. The addition of a mesh type (such as BLE mesh) would require data retransmission by sensor nodes, consuming more energy and demanding a more complex network management.

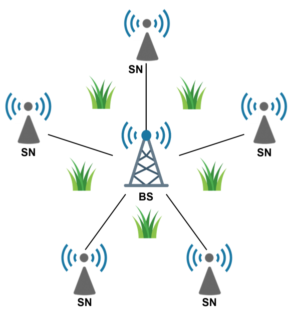

Figure 14: The one-to-many (1:m) star network topology to be used in the proposed protocol (this image was designed using resources from [19, 17, 13]).

Therefore, the one-to-many (1:m) star type network topology will be used, which means that each sensor node communicates only with the base station, as illustrated in Figure 14. Furthermore, communication is always initiated by the sensor node, never by the base station, which is always listening for SNs communications, since it is not so energy constrained. The SN measures temperature and humidity and stores the measurements in its internal memory. When the SN connects to the BS, it sends its stored measurements and clears its memory.

4.2.1 Link Layer

The proprietary communication protocol will be based on Bluetooth Low Energy (BLE) standard version 4.0, due to its simplicity. Nevertheless, it will be further simplified and optimised for this specific WSN application, temperature and humidity environmental monitoring. The Link Layer has a simple packet format as illustrated in Figure 15. The Link layer has been greatly simplified for experimental purposes. However, because the radio is programmable, larger packages can be built if necessary.

Preamble (1 octet)	Access Address (4 octets)	Packet Payload (27 octets)	CRC (3 octets)

Figure 15: The packet format to be used in the Link Layer of the proposed protocol.

The first field is the Preamble, which is one octet long and is used by the demodulator to detect the beginning of a packet. The second field is the Access Address (AA), which is four octets long and is used to identify radio communications node on the physical link. The third field is the Packet Payload, which contains the payload, with a value of 27 octets. The last field of the transmitted packet is the Cyclic Redundancy Check (CRC), which is an error detection code used to detect unwanted changes in a packet. It ensures data integrity for all packets sent over the air.

4.2.2 Physical Layer

The SN's integrated circuit is constituted by a radio transceiver that operates in the 2.4 GHz Industrial Scientific Medical (ISM) band, and it employs ultra low power circuits with low leakage technology to achieve a greater autonomy. In addition, in terms of Physical Layer, the radio transceiver is compliant with BLE's specifications.

BLE was adopted because the modulation is simple to implement and it was possible to develop a demodulator that consumes very low energy, which only operates with GFSK modulation. Therefore, in terms of hardware energy consumption, it was decided that BLE with this modulation and frequency would be most desirable.

For WSN communications, a subset of three BLE channels (Ch1, Low Frequency; Ch2, Mid Frequency; Ch3, High Frequency) will be used. The main objective of using three channels is not to communicate with multiple SNs at the same time, but to select the best propagation conditions for a particular communication. Table 6 contains an overview of the proposed protocol specifications.

Table 6: Specifications for the Simple Proposed Protocol.

Proposed Protocol	
Modulation	GFSK
Frequency	2.4 GHz ISM Band
Subset of Channels	Ch1: Low Frequency Ch2: Mid Frequency Ch3: High Frequency
Topology	Star (1:m)

4.3. First time installation of a Sensor Node

The first time a sensor node is installed, it must be rebooted in order to connect to the base station for the first time. The BS will recognise a new SN's first time communication since all SNs will have the same initial ID. Subsequently, the BS will provide and store a unique ID in the SN, which will be selected from a previously stored list. This ID might probably be the Access Address of the BLE protocol.

Furthermore, the BS will configure the SN's Real-Time Clock (RTC), establish a daily schedule for temperature and humidity measurements, as well as predefined time slots for transmitting the sensed data to the BS. Regular communications between each SN and BS occurs at a predefined and unique time slot.

Finally, once all SNs have been installed by the operator, the BS's list with the GPS coordinates of all SNs must be updated. This will be accomplished through the use of the BS's direct cable connection. The configuration of the BS requires a direct cable (USB type) connection. This method may be used to reconfigure the configuration parameters of SNs and BSs. Figure 16 shows the steps involved in setting up a sensor node for the first time.

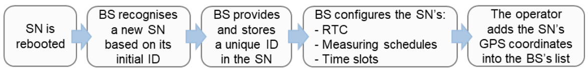

Figure 16: The procedures for the first time installation of a sensor node.

4.4. Regular communications

When an SN wishes to communicate, it shall first check the three predefined channels for the lack of communications. Although each SN has a predefined time slot, collisions may occur due to SN's RTC delays or advances, or radiation perturbations from other communication services.

In the event that the SN connects successfully with the BS, the SN shall restart its RTC, allowing it to schedule future time slots and compensate for the time difference. Additionally, after delivering its measurements, the SN shall clear its stored measurements.

Figure 17 represents a flowchart depicting the decision process that a SN must execute in order to initiate regular communications with the BS.

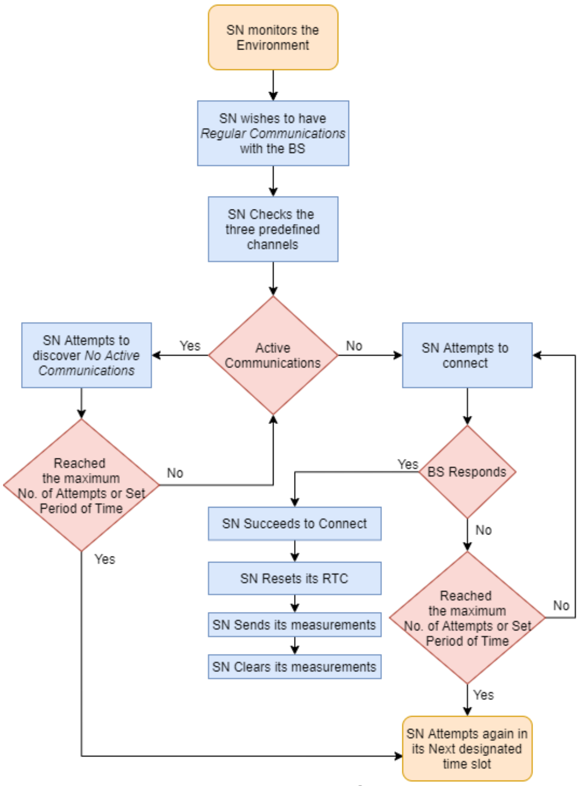

Figure 17: Flowchart describing the SN's decision process to establish regular communications with the BS.

4.4.1 No Active Communications

If there are *No Active Communications*, the SN attempts to contact the BS in the following order: Ch1, Ch2, and Ch3. The BS determines which channel to use based on the highest received power signal. The selected communication channel will be the one in which the BS replies.

- If the *BS does Not Respond*, a maximum predefined number of attempts will be performed by the SN over a set period of time.
- If the *SN Succeeds*, the previous description applies; if it does not, it will attempt again in its next available time slot.

4.4.2 Other Communications are Active

If *Other Communications are Active*, a maximum predefined number of attempts will be performed by the SN over a set period of time, in order to discover *No Active Communications*.

- In *case of Success*, the previous point applies.
- In *case of Lack of Success*, the SN will try again at its next available time slot.

4.4.3 Observations

- When communication efforts fail, there should be enough temporal separation (a short delay) between the time slots of surrounding sensors to prevent communication attempts from overlapping, so that the SNs communicate roughly at the same time, but not simultaneously. Figure 18 illustrates this observation. This spacing will also be determined by the number of sensors and the time it takes each one to transmit a signal.

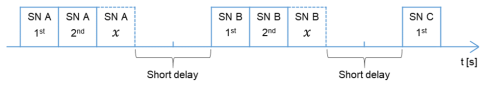

Figure 18: Representation of a short delay between the time slots of SNs to ensure that there is no overlapping between them in case of x attempted failed communications, x being the maximum number of attempts within a set period of time.

- If Low Energy Power Control (LEPC) is used, it will provide a method for SNs and BSs to alert each other when received signal strength is too high or too low, and request that the other adjust transmission power accordingly. This implies that a connection can be optimised, decreasing the need for retransmissions, reducing overall power consumption, and allowing applications to function more smoothly. This benefits both the involved SNs and BSs, as well as general 2.4 GHz coexistence because by not over transmitting, there is less risk of interfering with other 2.4 GHz protocols, such as Wi-Fi.

4.5. Precision Agriculture

In order to apply this protocol to a WSN for precision agriculture, sensor nodes must be strategically deployed over a field to monitor humidity and temperature. Based on the sensed information provided by the SNs, farmers will be able to evaluate and determine how to manage their crops, such as the optimal time of day to irrigate the fields. Furthermore, this collected data helps to analyse and have a better understanding of the impact of climate change in this area. Figure 19 depicts the two previously discussed advantages.

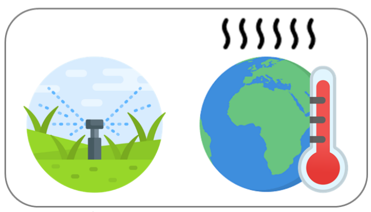

Figure 19: The data from the sensor nodes allows researchers to estimate the best time to irrigate fields and the influence of climate change in the area (this image was designed using resources from [19, 17, 13]).

Depending on the type of crop and the climate of the region in which it is deployed, a sensor node could monitor humidity and temperature more or less frequently, as illustrated in Figure 20. It might also be worthwhile to reconfigure the SNs for a specific time of year in order to extend the device's lifetime by measuring more or less frequently. In Portugal, for example, monitoring humidity and temperature more often throughout the summer is particularly important, due to the shortage of water resources and the increased risk of fire. On the other hand, it would not be necessary to monitor as often during the winter season.

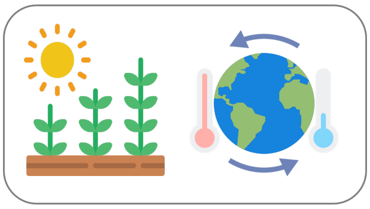

Figure 20: Depending on the crops and the seasons, the sensor nodes could be programmed to monitor more or less frequently (this image was designed using resources from [19, 17, 13]).

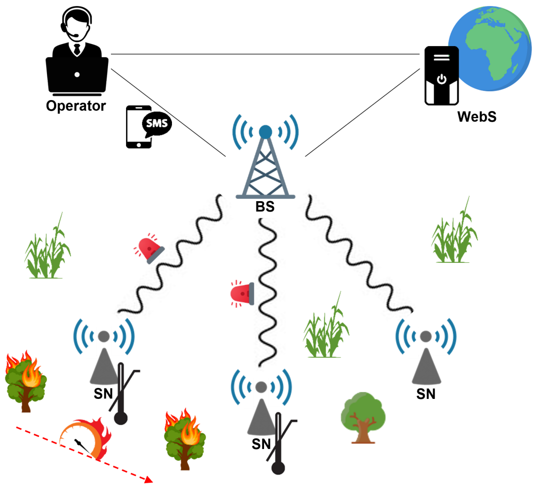

Figure 21: In case a sensor node detects an above threshold temperature, the Emergency Communications procedure will be adopted. If another sensor node reports the fire, it is possible to estimate the fire spread and its propagation velocity (this image was designed using resources from [19, 17, 13]).

4.6. Fire Detection and Emergency Communications

To implement this proposed protocol in a WSN for fire detection, sensor nodes must be strategically placed throughout the forest to detect fires efficiently. The SNs must constantly monitor the temperature, and if it exceeds a certain temperature threshold, it is an indicator that a fire is starting. This temperature threshold should be high enough to prevent false detection, such as the SN overheating due to the UV radiation from the Sun. Therefore, the SN should be strategically placed, for example on a tree's trunk, where it will be covered by the tree canopy and thus avoid the problem of overheating.

If a sensor node detects a temperature above the predefined threshold, it must promptly establish an *Emergency Communication* with the base station to report it, as explained in the flowchart depicted in Figure 22. The respective emergency communication package will include a *flag* to differentiate between an emergency event and a regular communication, so that the BS can prioritise and manage it immediately. Furthermore, in order to help confirm the emergency event, the SN must measure an additional maximum number of consecutive readings and transmit the results to the BS.

On the other hand, the base station must then send an SMS message to a predefined mobile phone informing the Operator of the alert, and transfer the data that triggered the emergency event to the Web Servers. This allows the operator to be quickly notified of an alert and to have an up-to-date information to further analyse and evaluate the emergency situation.

If a different SN also detects this fire alert, there are less doubts that there is a fire. Given the position of the SNs, it will be possible to predict where the fire is spreading. Additionally, by taking into account the time delay between the SNs' alerts and their respective coordinates, it is possible to estimate the distance the fire has spread and its propagation velocity, as portrayed in Figure 21.

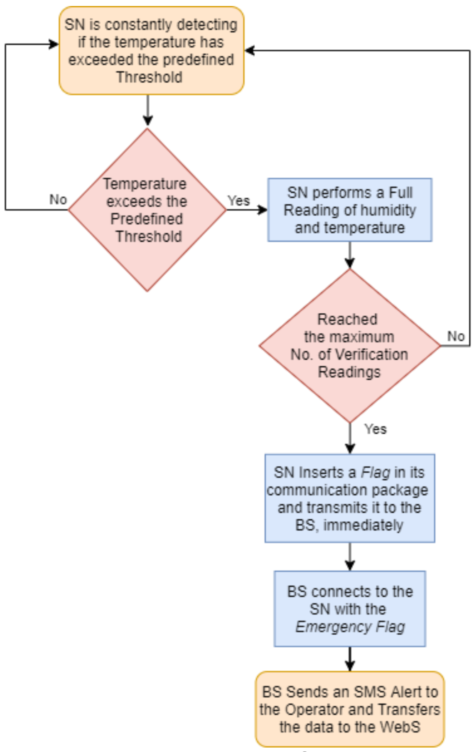

Figure 22: Flowchart describing the SN's decision process to establish Emergency Communications with the BS.

Although all developed sensor nodes are identical and continuously measure temperature, the ability to configure two classes of SN would allow the device to save energy and extend its life:

- *Precision Agriculture SN*: The SN is constantly detecting if the temperature has exceeded the predefined threshold, allowing it to detect a fire. Furthermore, it conducts several predefined daily temperature and humidity measurements, which are then communicated to the base station within its designated time slots.
- *Fire Detection SN*: The SN is constantly detecting if the temperature has exceeded the predefined threshold, allowing it to detect a fire. However, in contrast to the previous SN class, it will not conduct multiple daily temperature and humidity measurements and transmissions. It will perform a few daily temperature and humidity readings that will be transmitted to the base station within its designated time slots, merely to indicate that it is active and functioning properly. This will allow the SN to save more energy and extend its life.

5. Conclusions

The first objective of this thesis was to conduct a study of open standards for wireless sensor networks in order to help electronic circuit design researches. Resulting in a document that provides an overview of the most well known open standards for WSN, thus the first objective of the thesis was achieved.

The final goal is to discuss a simple protocol to be applied in a wireless sensor network with a star topology for environmental monitoring. This proposed protocol should be energy efficient, easy to implement and manage, with the objective of being used to test in the field the sensor nodes and the base station developed by the researchers. Their aim is to demonstrate that the radio communication system they designed consumes very little energy.

To accomplish this, the ZigBee and Bluetooth Low Energy protocols were studied in further depth. In order to better comprehend the functioning of these successful and similar protocols.

Through this approach, it became clear that BLE provided a better solution for the devices developed by the research team, because BLE's modulation allows the radio architecture and the demodulator developed by the researchers to consume less energy. Therefore, in light of this conclusion, the proposed protocol would be based on Bluetooth Low Energy standard version 4.0, due to its simplicity.

Finally, a simple proprietary protocol for experimental use was discussed with the goal of reducing network energy consumption and simplify management. The discussion focused in being applied to monitor temperature and humidity in order to be used for precision agriculture, as well as being capable of fire detection by reporting a temperature above a certain threshold.

After an overview and in depth study of open standards for wireless sensor networks, it was possible to develop a manual to assist researchers and provide contributions for an efficient and simple proprietary protocol for wireless sensor networks for environmental monitoring. Overall, the project was concluded with its main objectives fulfilled.

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