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Wireless Sensor Networks for Building Robotic Paths - A Survey of Problems and Restrictions

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ABSTRACT

The conjugation of small nodes with sensing, communication and processing capabilities allows for the creation of wireless sensor networks (WSNs). These networks can be deployed to measure a very wide range of environmental phenomena and send data from remote locations back to users. They offer new and exciting possibilities for applications and research. This paper presents the background of WSNs by firstly exploring the different fields applications, with examples for each of these fields, then the challenges faced by these networks in areas such as energy-efficiency, node localization, node deployment, limited storage and routing. It aims at explaining each issue and giving solutions that have been proposed in the research literature. Finally, the paper proposes a practical scenario of deploying a WSN by autonomous robot path construction. The requirements for such a scenario and the open issues that can be tackled by it are exposed, namely the issues of associated with measuring RSSI, the degree of autonomy of the robot and connectivity restoration.

Keywords: *Wireless sensor network (WSN); Coverage; Connectivity; Limited energy supply; Routing; Node deployment; Localization of nodes; Connectivity Restoration; Autonomous robot path construction*

INTRODUCTION

A wireless sensor network (WSN) is a group of small sensor nodes, that are distributed in a space and wirelessly connected to each other, forming a network. Such a network allows measuring environmental points of interest using the sensors equipped in the nodes. Each node is a small device that can be thought of as a tiny computer being equipped with a wireless radio, one or more sensors, its own processor and a power supply. The processor of a sensor node makes up a processing unit which generally has a small storage unit. The sensors make up a sensing unit generally equipped with an analog-to-digital converter (ADC), which is responsible for converting the analog signals from the observed phenomenon to digital ones [1].

Figure is a representation of the general sensor node architecture.

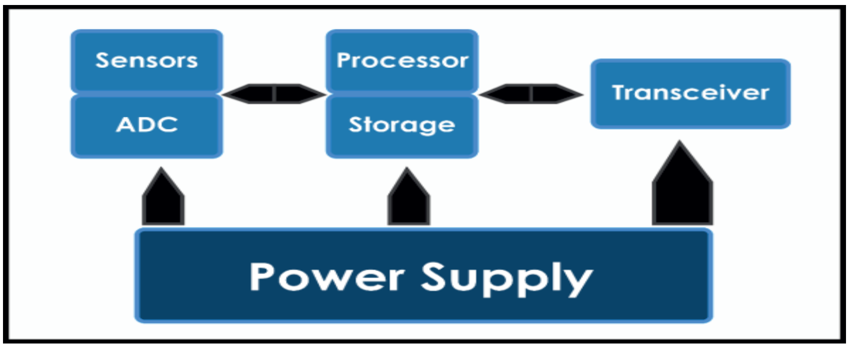

Figure1. *Sensor Node Architecture*

Such a sensor node architecture guarantees that each node has communication, sensing and computing capabilities [2]. The nodes may be mobile, with unpredictable or deterministic movement patterns, or stationary [3]. Developments in micro-electrical-mechanical systems technology and digital electronics allowed for the creation of these small nodes, that have the multiple functions described. They can be acquired for low-cost, have low energetic requirements and can communicate effectively in short distances. These are the conditions that allowed for the emergence of wireless sensor networks [1][4].

The fact that each node has its own processor also means that sensor nodes can cooperate in collecting data and process the raw data in order to send only the required information, diminishing the computing requirements at the receiving ends [1].

A sink node is the node that receives data from the WSN and routes it to a computer, reaching the end user directly, or to the Internet and from there to the end user. Figure 2 represents this process, in which sensors scattered in a sensor field route data to a sink node that in turn sends it to an end device.

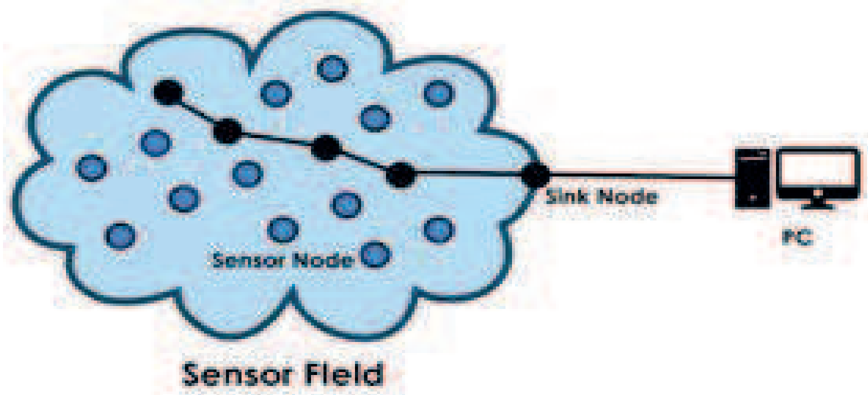

Figure2. *Sensor Node Field Architecture*

There are other important concepts which have been widely studied in the context of WSNs, such as coverage and connectivity. The concept of coverage is related to the sensors of each node and their sensing range. It is said that a target area is covered if all the points of the area are inside the sensing range of at least one of the sensors. Whereas connectivity is related to the communication between nodes and is affected by the communication range of each node. It is said that an area has connectivity if every single node is connected to the sink node either directly or through a multi-hop path [5].

The main goal of this paper is to offer a comprehensive understanding of WSNs and introduce a practical scenario that may help to answer challenges associated with these networks. It means to achieve this by firstly exploring the background of WSNs: the wide areas of application of WSNs, providing examples in each, and the challenges faced by WSNs, explaining each challenge and giving examples of proposed solutions founded in the literature. After picturing the background of WSNs it presents our proposed scenario of autonomous robot path construction. It mentions both the requirements and the open issues that can be given answer through this scenario. The rest of the paper is organized as follows: Section 2 presents the background of WSNs, Section 3 focus on our scenario of autonomous robot path construction, Section 4 concludes the paper.

WSNs Background

Throughout recent years these networks have been used in many different fields in various applications. Due to their characteristics they can be very useful and adaptable. We explore the fields in which they are used and give examples of specific applications for each of these fields. Due to their specific limitations and wide range of applications WSNs also face many different challenges. We mean to expose these challenges in categories and present solutions for these problems found in the literature.

Applications of WSN

Wireless sensor networks allow us to monitor environmental conditions with a higher degree of precision than ever before. Examples of conditions that can be measured are temperature, sound, humidity, wind, vehicular traffic, among many others. There are many and growing fields of applications for these types of networks, such as military, health, home, disaster relief, machinery monitoring, environment monitoring, volcanic monitoring, vehicle tracking, weather monitoring and network monitoring [2][1][5]. Figure 3 shows the general areas of WSNs applications.

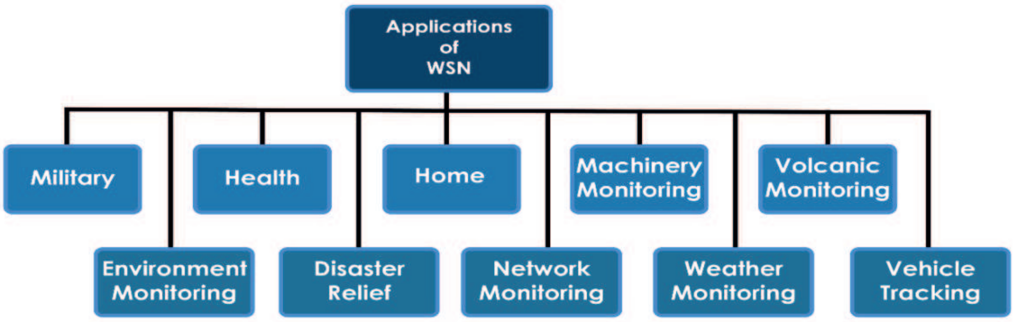

Figure3. *Applications of WSNs*

Military applications were the first that motivated research and progress in the field of WSNs [6]. They take advantage of certain properties of these networks like the fact they can be deployed rapidly, they can have self-organization capabilities and the redundancy of nodes creates several routing paths which provides tolerance to failure of individual nodes. This allows them to be used for monitoring friendly forces, monitoring equipment and ammunition, communications, battle field surveillance, reconnaissance, targeting systems, battle damage assessment or chemical attack detection [1][4].

An example of health applications of WSN is recording and transmission of biosignals, namely the electrocardiogram, pulse wave and body weight, which are important parameters for cardiovascular monitoring [7]. Another example is an in-vehicle WSN platform capable of monitoring health risk factors due to long time sitting and driving [8]. It is also possible to monitor Electromyogram sensors in a Wireless Body Area Network so that the results can be determined and analysed by a physician or expert, despite the distance apart from patients [9]. A good use in hospital premises is the tracking of doctors and patients activity and health, through stationary and wearable sensors [10].

Examples of environmental applications of WSNs are animal tracking such as monitoring wildlife with the goal of preserving endangered species [11], and also monitoring endangered animals that live in areas where human access is difficult, like polar regions [12]. Other environmental applications are the use of WSN to monitor conditions for irrigation and for precision agriculture, resulting in reducing water consumption and increasing the yield of crops by giving them uniform water [13][14][15]. WSNs are also used for chemical detection, such as heavy metal monitoring [16] and monitoring toxic gases in the environment [17].

Detection of forest fires is another important use of WSNs, both through flame sensor modules, that aim at early detection of fire [18], and through analysing the noise power spectrum of forest fires, which can determine the type of forest fire and help in fighting it [19]. Flood detection is another important environmental application of WSNs, as they are used to build flood prediction systems [20] and flood warning systems [21]. Finally WSNs are also used to monitor water [22] and air pollution [23][24] [25].

Home applications are based on home automation and smart automation, such as monitoring and controlling environmental, safety and electrical parameters of the house [26], with uses such as fire detection, gas leakage detection and determination of whether any door is closed or open [27].

Challenges in WSNs

WSNs have specific challenges presented in Figure 4. Such as limited energy supply, localization of nodes, node deployment, limited storage and routing [5]. These and other research challenges are discussed in the next subsections.

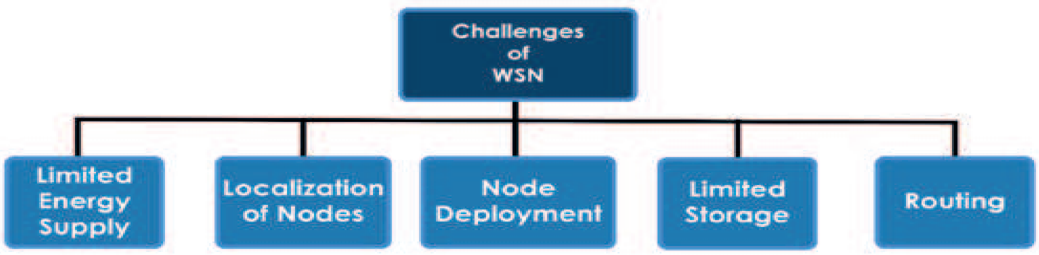

Figure4. *Challenges in WSNs*

Limited Energy Supply

Many times the area where the network is to be deployed does not have infrastructure to supply energy to the sensor nodes [2]. Hence arises the problem of the limited energy supply of each node. The fact each sensor node needs to be equipped with a battery makes them susceptible to failure if the battery is depleted. Changing batteries may not be an option in situations like monitoring volcanoes, battlefields or earthquakes. In the case of node failure, due to depletion of its energy supply, the network may suffer from coverage holes and data may not reach the sink node, breaking network connectivity [5]. It is also important to guarantee that network lifetime is enough to accomplish what is required by the network application in question [28]. These problems bring our attention to the need to conserve energy, so that we can prolong network lifetime and avoid problems of coverage and connectivity.

In order to present possible solutions, it is first important to understand how energy is spent in a sensor node. First the communication unit has a much higher consumption than the computing unit. The radio transceiver spends about the same in reception, transmission or while in idle mode, but a lot less when in sleep mode. The sensing unit may also spend a considerable amount of energy, but this heavily depends on the specific application of the network [28].

Attempts at reducing energy consumption can be categorized in three main techniques: duty cycling, data-driven approaches and mobility [28]. Duty cycling is based on turning off the radio transceiver or changing it to sleep mode when it is not required [29]. Data-driven approaches focus on avoiding sending redundant data, for example samples with high spatial and temporal correlations, and using special nodes called cluster heads to perform aggregation techniques that minimize data size and forward it to the sink node [30]. Data-driven approaches also propose reducing the consumption of the sensing unit, by limiting the amount of sampled data, while trying to maintain enough sensing accuracy for the purpose of the network application [31]. Mobility approaches focus on having the mobile nodes collect the data from stationary nodes, creating a communication in proximity and not through a multi-hop path to the sink node, thus reducing energy spent in communication [32]. If the energy spent in making nodes mobile is too high, than sensor nodes can be attached to mobile entities that move around the sensing filed, such as vehicles or animals [28].

Localization of Nodes

The challenge of localization in WSNs means that many times it is necessary to know the location of each node after it's been deployed. This assumes the nodes are not manually deployed and their localization is not previously known. Such is the case in situations like natural disasters or military reconnaissance. The reason for the necessity of the location of each node is that without location information the sensing information given by a node might be imprecise or even useless. The location information is also the basis of many applications of WSNs like navigation, tracking or rescue operations [3][33][34].

There are many algorithms to deal with the localization problem, they can be classified in broad categories such as being centralized or distributed, anchor based or anchor less, range based or range free [35].

Centralized algorithms have a central base station. A base station is a special node that routes information from the network to a PC. This base station is also responsible for computing the localization of the nodes. The main problem with these algorithms is the computing overhead and increase in system cost [36][37][38].

In distributed algorithms the computing is done by each node. Each is responsible for figuring out their own location and the nodes communicate with one another to find their place in the WSN [39].

In anchor based algorithms there are several nodes whose locations are previously known, these are called anchor or beacon nodes. Each anchor node acts as a point of reference. Thus, more anchor nodes lead to a lesser average of localization errors. The problem with this approach is that the cost of the system increases because of having these special nodes with more capabilities [37][40][41][42].

The anchorless algorithms don't use special nodes but instead focus on creating a map of the nodes by measuring the distance between nodes [43][44][45].

Range-based algorithms uses range based techniques with the help of sensors and other node capabilities to estimate the absolute position of the unknown or non-anchor node. They have a good precision but might require additional sensors, increasing the cost of the system, might have a high complexity, increasing the computing overhead, and also have large communication overhead between nodes, which strains the energy limitation of each node [34][42][46][47].

Range-free algorithms do not measure absolute distance or orientation of the nodes but instead estimate the distance between two nodes using messages exchanged between them. Such algorithms have a lower cost, not requiring specific hardware, and low computation requirements, which is appropriate for larger WSNs. But if enough messages aren't exchanged between nodes the localization accuracy of these algorithms drops a lot [34][48][49][50].

Node Deployment

The problem of node deployment is very important because it affects critical network areas such as coverage, connectivity and network lifetime. The problem of optimal sensor deployment can be defined in two forms. The first is: given a sensor node with a certain sensing range to find the smaller number of nodes required to cover the entire area to be monitored. The second is: given a fixed number of sensor nodes to find the minimum sensing range that guarantees the area will be fully covered [51]. Deployment of the nodes can be done either in a deterministic way, in which the location of the nodes is previously known, or in a random way, in which the nodes possess self-configuration capabilities and should locate themselves properly, without any user assistance, in order to guarantee the desired network characteristics, such as coverage and connectivity. The latter is used in applications such as battlefield monitoring, disaster areas or underwater. The problem with random deployment is that it does not guarantee coverage of the whole area of interest or network connectivity. Nodes out of communication range will also reduce the possible routing paths, increasing energy consumption and decreasing the data throughput [52][53].

Many algorithms have been proposed to deal with the node deployment problem. They are usually specific to the application of the networks and the characteristics of the sensors. Examples of algorithms to deal with this problem are the artificial bee colony, particle swarm optimization, genetic algorithm and artificial immune system [54].

The artificial bee colony (ABC) algorithm is inspired by the behaviour of bees while foraging for food. Three types of bees are considered: employed bees, onlookers and scout bees. Employed bees exploit food resources and give information about food sources to onlookers when they return to the hive. Scout bees always look for new food sources. If the scout bees find a good quality food source, they do a dance when they return to the hive which informs the other bees about it, this dance is called the waggle dance. For the context of the algorithm each of the food sources is considered a solution to the problem and the quality of the food source is the fitness value of the solution. Firstly, employed bees are associated to random food sources or solutions, and in each iteration the bees evaluate food sources near its current food source and evaluate its quality or fitness value. And so, the food sources with more quality will have more onlookers. If quality does not improve over a certain number of iterations the bee becomes a scout [51]. The ABC algorithm is used to find optimal locations for sensor nodes, such as in [55], where the two main concerns are coverage of a target area and network connectivity.

Another algorithm used to deal with the node deployment problem is the particle swarm optimization. This approach consists of imitating the behaviour of a flock of birds. The idea is that a swarm of particles explores a spatial dimension looking for a solution to a certain problem, much like birds that regulate their direction by their neighbors and their own experience. The swarm intelligence approach used by this algorithm is very useful to find solutions to optimize real world problems that have a degree of uncertainty, for example optimizing the coverage area of the network [54]. It is also used to move the sensor nodes from an initial position, obtained from random deployment, to new positions obtained by the optimization algorithm, such as in [56], where new positions intend to maximize network lifetime.

The genetic algorithms are also used to deal with the node deployment problem. The basis of this algorithm is Darwin's theory of the evolution of species, in which genetic advantages are carried from generation to generation assuring the survival of the species that better adapt to the environment. It consists of several steps such as: selecting an initial population, representing the chromosomes, applying a fitness function, selecting chromosomes, applying crossover and mutation and eventually reaching a termination point. The genetic algorithm is used to deal with deployment problems such as in [57], in which the sensor nodes are randomly deployed at first and then re-positioned using the genetic algorithm to achieve maximum network coverage, removing the overlap between nodes.

Artificial immune system algorithms copy the functions of the biological immune system which recognizes and attacks pathogens. These algorithms typically use two main entities, antibodies and antigens, and go through several stages such as the clustering phase, the presentation phase, the activation phase, the clonation-mutation phase and the suppression phase. The cloning, mutation and selection is responsible for the long term adaptation, while short term adaptation is accomplished by the antibodies covering the zone where antigens are [58]. It is used in WSNs with mobile nodes as a way to redeploy nodes after initial random deployment, such as in [59], where it intends to maximize network coverage while minimizing the total distance of movement by sensor nodes.

Routing

One of the most important challenges in the context of WSNs is that of routing. A routing protocol aims to discover the best way between a source node and a destination node. It is what guarantees the communication between nodes and between nodes and a base station. Due to the specific characteristics of WSNs many problems arise when considering routing protocols. The goal would be to maximize the lifetime of the network, preventing degradation of connectivity. The challenges to this goal are the limitations in power supply of the nodes, transmission bandwidth and processing capability. Other challenges related to routing are that of node deployment, scalability, coverage, connectivity and security. Good routing protocols are required to deal with these challenges, being responsible for discovering and maintaining routes that are energy efficient and reliable [60][6][61].

Routing protocols can be categorized by different criteria. If we consider the structure of the network, we can distinguish three types of routing protocols, namely flat-based routing [62], in which all the nodes have the same functions, hierarchical-based routing [63], in which different nodes have different functions, and location-based routing [64], in which the locations of the nodes plays an important role in how to route the data. If we consider the protocol operation instead, we can classify routing protocols as multipath-based, query-based, negotiation-based, QoS-based or coherent-based [61].

Multipath-based routing protocols use multiple paths with the goal of improving network performance. The fact that more paths exist between a source and a destination can be used in the case that one path fails, because it increases the reliability of the network. The price to pay is that maintaining more paths increases energy consumption and thus reduces the lifetime of the network, in the case of each node having finite non-replaceable batteries, and increases network traffic, because the paths are maintained by periodic messages between nodes [65][66].

In query-based routing, the destination nodes emit a query for data to the whole network, the node that has the data will send it to the node that emitted the query [67][68][69].

Negotiation-based routing uses data descriptors that are used to eliminate redundant communi-cations. The decisions of communication are thus negotiated between the nodes and these decisions are also based on available resources [70][71].

In Quality of Service (QoS) based routing the network is forced to satisfy certain QoS metrics, such as delay, energy or bandwidth, when routing data to a base station [67][68].

In coherent routing, raw data is only minimally processed by local nodes. This processing usually means being time stamped and the suppression of duplicate data. Then, the data is sent to other nodes, called aggregators that will be responsible for the rest of the data processing tasks. It is a routing protocol that aims at improving the energy efficiency of the network by focusing heavy data processing task on special nodes [72][73][74].

WSN for Autonomous Robot Path Construction

After an overview of WSNs uses and challenges we focus on one specific scenario. We intend to deploy this scenario in the real world and use it in an attempt at testing solutions to challenges that have been identified for WSNs.

Our scenario is to have a robot that moves from point A to point B, given that both points are indoor and be connected by a straight line. The robot achieves this goal by deploying a wireless sensor network. This robot, besides having movement capabilities, is also equipped with a node that has communication capabilities, is connected to a wireless network and can measure a received signal strength indication (RSSI).

There is one sink or master node, connected to a computer, through this node an end user can send movement commands to the robot and receive messages from the robot, for example getting the RSSI value. The robot will know when to deploy a new relay node based on the RSSI. If the RSSI value is below a predetermined threshold then the robot stops its movement and sends a message to the master node, informing it another stationary relay node needs to be deployed. The result is that the robot will construct a path of sensor nodes, that will allow him to move from point A to B, maintaining connectivity with the master node, as shown in Figure 5.

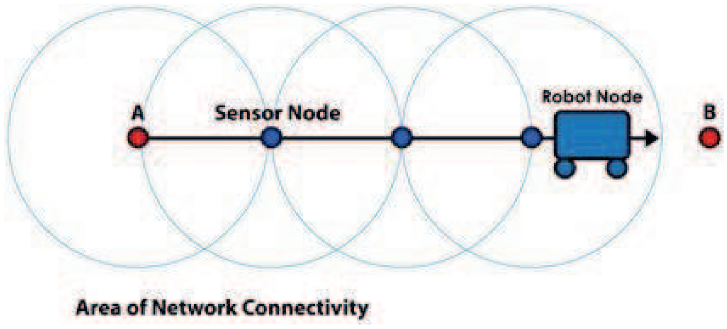

Figure5. *Autonomous Robot Path Construction*

This scenario fits into the definition of a Robotic Wireless Sensor Network (RWSN) given by [75]. Here RWSN is defined as a wireless network with mobile robotic nodes and sensor nodes, and assumes that all nodes have the capabilities to communicate wirelessly. A RWSN inherits challenges from both fields, robotics and WSN, but also has new specific problems, such as RSSI estimations when considering present and future locations of a robot [75].

We also find similar proposals such as [76], in which a WSN is deployed autonomously by a mobile robot, that can also restore the network by deploying additional sensor nodes. In this experiment a deployment and retrieval mechanism were mounted on the mobile robot. The mobile robot monitors the RSSI value to ensure communication between sensor nodes and deploys additional sensor nodes if a connectivity failure is detected.

Scenario Requirements

Following the above proposed scenario and assumptions, the requirements are discussed next.

Network Scalability

The system should support the deployment of a large number of sensors nodes so that it can extend a path long enough to meet the necessities of different applications.

Network Coverage

The sensing unit of each sensor node should have the capabilityto cover a target area required by different applications.

Light Routing Protocols

The system requires an efficient way to route packets through the sensor nodes that form the path back to the master node. Efficiency of routing is important for network applications and to guarantee that each sensor node does not waste too much energy routing packets, extending its life-time and thus the network life-time.

Energy Constraints

Each sensor node should be energy efficient as they are powered by a finite battery. Replacing or recharging batteries may not be an option. This means every node operation, such as routing, sensing or computing, must be sensible to energy constraints.

Connectivity Assurance

It is critical to maintain network connectivity because there is one routing path for packets to reach the master node. A single failure in connectivity compromises the entire network because any data beyond the point of failure will not be able to reach the master node. It is very important to build methods to detect failures and to restore connectivity in case of failure.

Quality of Service

The system should guarantee performance metrics that assure it can be used for different applications and in different environments.

Fault Tolerance

The system should be tolerant to failure in sensor nodes. It should incorporate a way to detect failure in nodes, due to depletion of battery, physical destruction or others. It should also have a way to restore the network once failure in a sensor node occurs.

Programmability

The sensor nodes and the robot node should be programmable in order to accommodate different applications, changes in scenario parameters or in the environment. Programmability augments flexibility of the system and widens the range of possible applications.

Open Issues

The value of RSSI is very important in our scenario because the robot uses it to decide when to deploy another stationary node, which affects how the path is built. Measuring RSSI faces problems because the signal is affected by characteristics of the physical environment such as obstacles and the medium of propagation, which may cause fading, shadowing or interference [75]. Future research should focus on building a generic model for interference. It would also be very useful to perform experiments and collect real world data that can help us understand radio frequency properties in different environments, such as mines, undergrounds or firefighting environments [75].

Another issue related to our scenario is the degree of autonomy of the robot. The main purpose of the robot is to autonomously deploy a network. But at times it may be useful for the robot to be commanded by a human user, that sends the movement commands, or even other commands via the master node connected a computer. The problem here is switching the robot from fully-autonomous mode to human-controlled mode and vice versa, how that switch is to be achieved and the consequences it may have on network connectivity, QoS and task allocation [77].

The problem of connectivity is a sine qua non of application functionality in WSNs. There are many reasons that may cause node failure, especially considering that in a lot of WSN applications the nodes are deployed in harsh environments, such as military applications in hostile areas. We can expect node failure from both internal limitations, such as limited battery life or mechanical flaws, and external forces, such as weather or intentional sabotage [78].

The biggest problem here is when node failure causes the network to be separated into disjointed segments, thus breaking network connectivity, and causing a part of the nodes to not be able to communicate with a sink node. The inability of nodes to make data reach end users causes negative effects to network applications and may result in incalculable loss, in applications such as rescue operations. Connectivity also affects the robustness and maximum throughput of network communication [79]. If we consider single path deployments, in which there is only one route to the sink node, then the network is even more susceptible to path failure and loss of connectivity, seeing as any one node failure may cause it [5]. Guaranteeing better connectivity in the network is usually attempted by increasing the communication range of each node or otherwise increasing the number of nodes in the area [79]. Other attempts are focused on restoring network connectivity after a node failure compromises it [80].

Many approaches have been tried in order to restore network connectivity and two main categories of approaches can be mentioned. The first is to deploy additional nodes to the location of the network failure. The second is to take advantage of the capabilities of a mobile node and move it to restore network connectivity, this obviously requires at least one node with moving capabilities in the network [81]. This approach is based on implementing a connectivity restoration algorithm in a mobile node for it to restore connectivity [78]. It is also important to locate the network discontinuity or network cut to be able to restore it [82]. Different methods based on mobile nodes to restore network connectivity have been proposed.

CONCLUSION

The emergence of WSNs allows for many new possibilities that are still being explored. These possibilities make use of the specific characteristics of WSNs, such as the low cost of sensor nodes, self-deployment, self-organizing capabilities and the ability to monitor our environment with a higher degree of precision than ever before. This not only helps research and monitoring efforts but also allows for informed decision making, as well as prevention and alarm systems. For these reasons WSNs have been used in innumerable fields of application, such as military, health, home, disaster relief, among others. WSN have thus become an intricate part of almost every aspect of modern life and will play an important role in the development of future smart cities.

Despite the large number of applications of WSNs, or maybe because of it, they still face many challenges. Nodes deployed in places without an energy infrastructure face the problem of limited energy supply. This and harsh environment conditions, in applications such as disaster relief or military applications, may both cause node failure, which in turn can result in coverage and connectivity problems for the network. Issues such as node deployment, how to know the location of nodes in the network and routing are also critical in WSNs. All these challenges motivate many research efforts, as this paper has tried to show, while summarizing different approaches that have been attempted to resolve each issue.

In order to give an experimental answer to some of the challenges described a practical scenario was proposed, in which a robot node deploys a wireless sensor network. Within this proposal some open issues were identified such as measuring RSSI, seeing as the signal is affected by the physical environment research to build a model for interference and collection of real-world data in different environments would be very helpful. Also, the problem of degree of autonomy of the robot, which should answer how to switch from fully autonomous to human controlled and vice versa and deal with its consequences to the network. Finally, the issue of network connectivity was identified, due to its critical importance to any application of WSNs. In fact, without the ability to make data collected by the network reach an end user the network becomes pointless. The area of connectivity restoration seems of interest in this regard, namely through efforts of implementing connectivity restoration algorithms in mobile nodes, used to heal the network.

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