Linear wireless sensor networks: Classification and applications

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Abstract
Wireless sensor networks (WSNs) constitute a rapidly growing technology, taking advantage of advances in electronic miniaturization that consume less energy for both processing and communication. The cost of these devices is also constantly decreasing, making it possible to use a large number of sensor devices in a wide array of commercial, environmental, military, and health care fields. Many of these applications involve placing the sensors in a linear form, making a special class of these networks which we define as a Linear Sensor Network (LSN). In this paper, the concept of LSNs is expanded, along with a set of applications for which this type of network is appropriate. In addition, motivation for designing specialized protocol is provided that explores linearity of the network to increase the communication efficiency, reliability, fault tolerance, energy savings and network lifetime. Furthermore, classification of LSNs from both topological and hierarchical points of views, is presented and various characteristics, research challenges and underlying opportunities are discussed. Simulation experiments are also presented to compare the performance and reliability of LSNs.

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1. Introduction

The advent of technology in computing and electronics evolving innovation of tiny wireless sensors has opened an unprecedented opportunity for a wide array of real-time applications. In recent years, wireless sensor networks (WSNs) have been emerging as a new suitable tool for a spectrum of new applications. These tiny sensor nodes are low cost, low power, easily deployable, and are self-organizing. They are usually capable of doing limited local processing. However, information collected from a large number of such nodes at a central location known as base stations (BSs) or sink nodes, before reaching a network control center (NCC) enables detailed representation of a given physical environment. Thus, a WSN can be described as a collection of sensor nodes which collaborate to arrive at some specific decision. Unlike traditional networks, a WSN depend on dense deployment and adequate co-ordination of data transfer to a BS. These unique characteristics make it very useful. WSNs were initially introduced for defense applications such as target detection, surveillance of enemy activities in a battlefield environment and counterterrorism. However, their advantages over traditional networks have resulted in many other potential civilian applications that range from infrastructure security to industrial control. Some examples are environment and habitat monitoring, health applications, home automation, traffic control, etc. Another possible example is protecting and monitoring a large pipeline system.

Research in the field of WSNs is relatively active and involves a number of interrelated issues, including efficient routing protocols (Akkaya and Younis, 2005, 2003; Akyildiz et al., 2002; Chong and Kumar, 2003; He et al., 2003; Schurgers and Srivastava, 2001; Soharabi and Pottie, 2000), QoS support (Jawhar and Wu, 2005), security (Fernandez et al., 2005), and middleware (Hadm et al., 2006). Most of these are investigated under the assumption that the network used for sensors does not have any infrastructure support. Fortunately, WSN needed for a monitoring linear infrastructures ought to be a structured network in which all sensor nodes are to be placed in a line. This characteristic can be utilized for enhancing the communication sequencing and reliability of the network.

We define LSNs as a new category of WSNs where the nodes are placed in a strictly linear or semi-linear form. A WSN is considered linear if one of the following conditions are true: (1) if all the nodes are aligned on a straight line, strictly forming a line, or thin LSN; (2) if all of the nodes exist between two parallel lines that extend for a relatively long distance as compared to their transmitting range and the distance separating them constitute a semi-linear or thick LSN. We introduced a general concept of LSNs along with some specialized routing protocols and addressing scheme in Jawhar et al. (2007).
The alignment of sensor nodes in a linear form can be used in many applications such as monitoring and surveillance of international boundaries for illegal crossing, or smuggling activities, monitoring of roads, or long pipelines carrying oil, gas and water resources, river environmental monitoring, etc. (Jawhar et al., 2007). This architecture utilizes a linear structure to address communication sequencing, reliability, and security problems. The objective of the design is to reduce the installation and maintenance costs, increase the network reliability and fault tolerance, enhance the battery life for sensors, and reduce end-to-end communication delay for better quality of service (QoS) support of sensitive data.

The contributions of this paper can be summarized as follows:

- Identify and define LSNs, which constitute special class of WSNs.
- Present sample applications of LSNs.
- Outline the reasons and motivation behind the need for new architectures and protocols for LSNs.
- Distinguish different possible control classes that indicate different types of LSNs from a topological and hierarchical points of views.
- Present a case study which illustrates a design with associated protocols that increase the efficiency and robustness of routing.

The rest of the paper is organized as follows. Section 2 provides an overview of related work in this field. Section 3 introduces some important applications for wireless LSNs. Section 4 discusses the reasons why new architectures and protocols are desirable for LSNs. Section 5 provides a topological and hierarchical classification of LSNs. Sections 6 offers a basic algorithm for routing messages in LSNs and Section 7 presents simulation experiments, which evaluate its performance under various network conditions. The last section concludes the paper and provides future directions for further research.

2. Related work

Akkaya and Younis (2005) provide a survey of routing protocols in WSNs. They identify three types of such protocols: data centric, hierarchical, and location-based. The data centric protocols include flooding, gossiping, directed diffusion, energy-aware, rumor, and gradient-based. The hierarchical protocols include LEACH (low-energy adaptive clustering hierarchy), PEGASIS (power-efficient gathering in sensor information systems), and APTEEN (adaptive threshold sensitive energy efficient sensor network protocol), and a detailed summary is given in recent text-books (Agrawal and Zeng, 2011; Cordeiro and Agrawal, 2011). The location-based protocols include SMECN (small minimum energy communication network), GAF (geographic adaptive fidelity), and GEAR (geographic and energy-aware routing). The protocols are classified based on the network structure into flat, hierarchical, and location-based. In addition, the protocols are classified according to their operation into multipath-based, query-based, negotiation-based, QoS-based, and coherent-based. On the other hand, in order to enhance the scalability, communication and energy efficiency of WSNs some research has been done to provide query and data aggregation. Madden et al. (2002) present techniques to implement various SQL aggregates (e.g., COUNT, SUM, AVERAGE, etc.) Kalpakis et al. (2003) present a solution to the maximum lifetime data gathering problem. Given the location of n sensors, a base station and available energy at each sensor, the algorithm provides an efficient method for gathering data from all the sensors and transmitting/forwarding it to the base station in a manner that maximizes the lifetime of the network. Krishnamachari et al. (2002) provide a model for data centric routing along with data aggregation strategies which provides improvement over the traditional end-to-end routing schemes with respect to the energy and delay efficiency. Petrovic et al. (2003) provide routing protocol which involves data funnelling with aggregation and compression for WSNs. Here, only one data stream is sent from a group of sensors to the NCC by having fewer nodes send longer packets as the stream gets closer to the NCC. Lossless data compression is also used to reduce the aggregate packet size further and achieve additional energy and communication bandwidth savings. The models and frameworks presented here are specifically tailored to LSNs while existing frameworks are designed for multi-dimensional WSNs.

Some work has been done in designing and analyzing linear networks. However, it is primarily either for wired or for general wireless networks without any reference to sensors. For example, linear wired or wireless networks are used for connecting emergency telephones on highways. Wireless mesh routers can also be installed in linear infrastructures along downtown streets to enable mobile users to access the Internet (Akyildiz and Wang, 2005). Another example of a linear wired sensor network is for monitoring and controlling pipelines. Sensors are distributed along the long pipeline to report the status of the pipeline such as temperature, pressure, flow speed, etc. Such a network is usually constructed using copper or fiber-optic cable (Mohamed et al., 2008; Tu and Chen, 1999). Wireless technology has been proposed to enhance the connectivity reliability of networks along the long pipeline (Mohamed and Jawhar, 2008). Another example of linear wired sensor networks is active tape (Tjang et al., 2004), which uses a wire to enable sensor nodes to use external power, and allows higher bandwidth and lower communication latency than wireless networks. Although wired sensor networks have some advantages, they are costly and not suitable for applications such as security applications that require monitoring sensors to be hidden and wires not exposed to the world. There is some work in studying the performance of linear wireless networks, and one example is given by MomClinic and Squillante (2008) where the performance-cost tradeoff is analyzed and investigates the relationship between the throughput and energy cost. However, all of the mentioned networks are not tailored for linear wireless sensor networks.

Some researchers studied the characteristics of one-dimensional ad hoc networks. DiGregorio et al. (2005) studied the characteristic of wireless capacity with the existence of mobility in one-dimension. Ghasemi and Nader-Esfahani (2006) provided an approximate relation for the connectivity probability in one-dimensional ad hoc wireless networks. Mirsajedi and Altman (2006) analyzed the connectivity issue in one-dimensional ad hoc networks using the queuing theoretical approach. None of these works provides a classification and characterization of various types of LSNs.

3. Applications of linear wireless sensor networks

This section presents a list of potential applications for LSNs.

3.1. Monitoring of oil, gas, and water pipelines

3.1.1. Above ground pipelines

One of the applications for LSNs is monitoring and protecting oil, gas and water pipelines. Long pipelines are used in many countries for a number of applications such as transferring water from desalination plants usually located close to the sea to cities that are far from the sea. In the Middle East, a big city like Riyadh, home to over four million people, is completely dependent on the water transferred through huge and long pipelines from the
3.1.2. Underwater pipelines

There are several long underwater pipeline systems used for different applications around the world. One of the longest pipelines in use is the Langeder pipeline that extends for 1200 km from the Ormen Lange field in Norway to the Easington Gas Terminal in England under the North Sea and is used to transfer natural gas to England. This pipeline started operating in October 2007 and can carry 25.5 billion cubic meters of natural gas per year and supplies around 20% of the natural gas demand in England. Another long pipeline is located between Qatar and UAE under the Arabian Gulf and owned by Dolphin Energy Limited of Abu Dhabi. It is used to transfer processed gas from Qatar's offshore North field to the UAE. It extends for 367 km through the Gulf and transfers a high percentage of UAE's gas needs. In addition, pipelines are intensively used in the Gulf of Mexico to transfer oil. There are around 30,000 miles of underwater pipelines in the Gulf of Mexico and several of these pipelines have been damaged by hurricanes in 2005. It is a very difficult and time consuming process to inspect the pipelines and find the location and type of damages inflicted by the hurricanes. With the existence of sensor networks, pipeline infrastructures can be remotely monitored, easily controlled, and quickly inspected. The economic feasibility of using underwater pipelines for transferring gas, oil and water encouraged many countries to plan projects to build a number of new underwater pipeline infrastructures. One example is building a pipeline to transfer gas from Oman to India under the Arabian See. This project requires a 1200 km pipeline, extending under the Arabian Sea at depths as low as 3500 m in some locations. In another planned project, underwater pipelines are to be built in Australia to eliminate the need for oil extraction platforms set in dangerous areas for primary oil processing. With the new pipeline, the cost of oil production will be reduced as the natural gases will be transported directly to refineries situated on Australia's coast lines. Northern Cyprus also is considering building an underwater pipeline to transfer water from Turkey. The objective is to overcome any water shortage problem in the island by bringing water from the Dragon River in Turkey to the Turkish Cypriot coastal city of Girne (Kyrenia) through a 105 km pipeline, 78 km of which will be built 250 m under water.

Most existing and planned underwater pipeline projects are considered important infrastructures for economic stability and social growth. Having a reliable unmanned monitoring and control system for these infrastructures can significantly help in monitoring and inspecting them. Underwater pipeline infrastructure needs to be protected from damages which may negatively affect the environment, cause loss of production, and could present significant safety hazards. One main approach that can be explored for monitoring is a linear sensor network.

There could be many parameters that need to be considered in order to provide proper protection, early response, scheduled maintenance, as well as operational control. Some of these parameters are fluid temperature, pressure, velocity, viscosity, chemical traces of some important elements that may indicate metal corrosion, physical deformation (bending), and fluid or gas leakage through measurement of certain chemicals in the surrounding environment (e.g., atmosphere, or water in the case of sub-sea pipelines) (Carrillo et al., 2002).

3.2. Railroad/subway monitoring

One of the applications of LSNs is monitoring, surveillance and control of railroads and subways. Security of rail infrastructures forms a high concern for many countries (Hartong et al., 2008). For example, Lee et al. (1999) have investigated deployment of fiber-optic sensors on fatigue-critical components in the railroad bridge superstructure. The sensors can monitor dynamic strain caused by the passing trains as well as provide early detection of critical and dangerous cracks. Fiber Fabry–Perot Interferometers (FFPI) strain gages are adhesively bonded to a stainless-steel strip by spot welding. These sensors are also installed on the railroad/ subway strips on the approach to the bridge. Furthermore, electrical resistive strain gages with the fiber-optic sensors are installed on the bridge for performance evaluation. Fiber-optic continuity sensors that can detect cracks at critical locations in the structure. Currently, phone lines are used for transmission of the gathered telemetric information. In order to reduce the deployment cost, minimize maintenance, and enhance scalability of WSNs, higher levels of the communication hierarchy can be used. Such WSNs would allow monitoring along the entire length of the rail road system and significantly improve its monitoring and control capabilities.

More research needs to be performed in order to determine optimal parameters for such systems, including monitored metrics, density, and distance between the various nodes in the hierarchy, data rates, and appropriate sensor technology from structural and communications points of view.

3.3. Monitoring of AC powerlines

Another area of interest where LSNs can be used is in monitoring AC powerlines, both overhead and underground (Wiesman et al., 1995). The collected information would be useful by the utility company to anticipate outages that can occur due to faulty equipment and overloading of AC powerlines. Such outages result in loss of service for a large numbers of customers, and could cause significant financial losses to the companies due to high maintenance costs. In addition to these losses, there are also indirect losses due to impact on the utility's reputation as well as added risk to its employees. By monitoring electrical conditions, utility companies can possibly anticipate equipment failures and unexpected outage conditions and create better maintenance schedules. This improved predictability can significantly reduce the maintenance cost.

New research in this area have lead to the development of AC powerline sensors which sense electrical parameters such as power, voltage, and current. In this particular application, the sensors would acquire their energy from the powerline itself by drawing low power through non-contacting transformer action. The sensors can communicate their information back to the control center using the powerline itself. In addition, installation of these sensors is done relatively quickly and without interrupting or affecting the service for the end customers. The linear structure of these sensor networks provides some interesting research questions and issues in order to select the right
communication protocols, technology, framework, and architecture that would take advantage of the linear placement of sensors (Cordeiro and Agrawal, 2011) in order to improve the network performance, reduce the installation and maintenance costs, and increase the network reliability and both physical and data security.

3.4. Driver-alert network

Other applications of LSNs include free-way-based road-side networks that can be used to monitor vehicular activities along the roads such as speeding cars, accidents, and more. Cars can have communication capabilities with other fixed wireless nodes along the road-sides which can alert them to potential problems ahead, traffic conditions, as well as give quick life-saving warning to car controls so as to alert a sleepy driver in case the car is about to be driven off the road. In fact, the car controls can even take critical actions before the driver can respond in time.

Some researchers have already considered the idea of making car driving safer by working on preventing many dangerous and life threatening accidents through the use of car-to-car and car-to-roadside communication which allow cars to alert drivers of danger in crossing an intersection or detecting a situation where the vehicle is about to be driven off the road. LSNs having nodes with different hierarchical positions, capabilities and responsibilities have a great potential in car-to-roadside network communication. Information from or about far away cars can be gathered and transmitted along the linear network to a control center, or other cars. This information can be used to avoid accidents, alert drivers to certain driving, weather, emergency, or traffic conditions, among many other potentially time, or life saving situations.

3.5. Border monitoring

Another important application of LSNs is in monitoring international borders for different activities such as illegal smuggling of goods, or drugs, unauthorized border crossings by civilian or military vehicles or personnels, or any other kind of activities. In order to establish the network for monitoring borders, different deployment strategies can be used. One of the strategies could be to deploy sensor nodes by dropping them in a measured and controlled fashion from a low-flying airplane or a UAV (unmanned aerial vehicle). The resulting topology of the sensor nodes will then have that of an ad hoc network with a relatively uniform density distribution. Subsequently, the data relay nodes, and sink nodes can then be deployed in a linear formation at predetermined distances between the nodes. The distances would be chosen in a way that allows a multipath communication between the relay nodes as discussed later in this paper. Similarly, the distance between the sink nodes would be determined by taking into account the nature of the terrain, the available infrastructure, and the desired level of performance and reliability of the network.

3.6. Other applications

It is important to note that the list of applications discussed here is not comprehensive. There are several other sensor applications such as river and sea-coast monitoring which exhibit linearity in the structure of the network.

4. Why new architectures and protocols are needed?

There are many reasons why a new framework is needed for different types of LSNs.

4.1. Increased routing efficiency

The first reason is the ability to take advantage of the linear nature of the network that could significantly increase the efficiency of the routing protocol that is to be used. This is the case as many two-dimensional routing protocols that exist in the literature (Cordeiro and Agrawal, 2011), such as DSR, AODV, TORA and others perform their route discovery and maintenance using different strategies such as flooding, and multi-dimensional propagation of request messages from the source to the destination. However, this flooding process is expensive in using resources such as bandwidth, which are scarce in the wireless environment. In addition, it causes delay in path acquisition and maintenance. Routing protocols that are designed for LSNs need not use such a costly process of route discovery. In fact, the linearity of the network can possibly eliminate the route discovery process. For example, the protocols in Jawhar et al. (2009) use an addressing scheme in order to perform the routing without the need for route discovery. In addition, route maintenance is done automatically at the intermediate nodes by using available information about the node failures. It is important to note here that address assignment can done only once at the time of network initialization.

4.2. Increased network reliability

Another reason for using more specialized protocols for LSNs is the ability to take advantage of the structure and achieve significantly increased reliability. The existing multi-dimensional protocols such as DSR and AODV react to handle node failures by either re-initiating a new route discovery process or can do minor local repairs. If no other alternative links are available, the connectivity of the network is compromised and the communication to that part of the network is stopped. This does not have to be the case if the network has a linear structure. Jawhar et al. (2009) presented several solutions. One approach is to immediately use the opposite direction from the failed node to reach an alternative sink node. Another solution is to increase the transmission range of the node in order to jump over the failed sensor node and reach the next node along the line. This increased transmission range not only allow overcoming only one node, but several nodes along the way. Even the failure of multiple adjacent nodes can still be overcome by increasing the transmission range accordingly. This ability of the network to efficiently and quickly overcome node failures can only be achieved by designing specialized protocols and architectures for LSNs.

4.3. Better handling of node heterogeneity

Existing multi-dimensional routing protocol can support heterogeneous ad hoc and sensor networks. However, they cannot be easily adapted to a linear structure. They assume a multi-dimensional deployment and distribution of various types of nodes. The route discovery and maintenance process does not utilize the linearity of a particular WSN. Exploitation of this feature can significantly increase the efficiency of the installation, configuration, and initialization phases. It can also reduce the route discovery and maintenance overheads. In addition, the data transmission sequencing process can be made more efficient from various aspects. In Jawhar et al. (2009), the data that is collected by the sensors is disseminated to the network control center at the same time in parallel. This significantly decreases end-to-end delay. Furthermore, the parallel dissemination of the data from sink nodes to the NCC increases the reliability of the data delivery process. This is because a disconnection of one or more segments...
of the network affects only a very limited area where this disconnection takes place.

4.4. Improved location management algorithms

In addition, faults can be easily located by taking advantage of the linear structure. In order to make the system efficient, a higher level addressing scheme can be used that could greatly enhance the ability of the network to easily, quickly, and precisely locate faults and take corrective measures. This action can range from having the nodes automatically overcome the problem, or by quickly dispatching service personnel to do appropriate repairs and take quick maintenance actions.

4.5. Increased network robustness

As mentioned earlier, designing specialized protocols for linear WSNs also enables these protocols to increase the robustness of the network in response to different conditions such as node failures and variations in the traffic intensity in different modes of operation (normal and emergency modes).

4.6. Increased network security

Security in WSNs is an important issue that needs to be considered when designing any such system. Although criticality of provisioning any security is expected to vary as per the application, it remains important to secure these networks against different types of attacks such as eavesdropping, source spoofing, replays, message modification, denial of service, and black hole attacks (Banerjee et al., 2007; Deng et al., 2002). There has been some research on security in multi-dimensional WSNs. Significant improvement in the effectiveness, efficiency, and security protocol overhead reductions can be achieved by adapting these protocols and designing new ones for LSNs. These simplifications could be based on pre-determined knowledge of the routing behavior and message transfer process. This information can be used to characterize normal operation and detect abnormal behavior.

5. Topological and hierarchical classification of LSNs

From the topological point of view, LSNs can be divided into several categories according to the linearity of different levels of the node hierarchy: thin, thick and very thick. This section presents these categories and discusses the characteristics and limitation of each one of them. In addition, from the hierarchical point of view, LSNs can be classified into several categories: one-level, two-level, and three-level LSNs. This classification depends on the way sensors and the communication supporting nodes are geographically deployed. This section presents and discusses each of these categories. Therefore, depending on the application, a particular LSN belongs to one category from the hierarchical point of view and to another category from the topological point of view. Table 1 presents different categories of LSNs according to these two classifications.

Before discussing these categories of LSNs, three types of nodes are defined. Each of these types of nodes has different functions to perform in the data collection, routing and final dissemination to the NCC or BS.

- **Basic sensor nodes (BSNs):** These are the simplest nodes in the network. Their objective is to perform the sensing function and communicate this information to the data relay nodes.
- **Data relay nodes (DRNs):** These nodes serve as information collecting nodes for the data sent by the sensor nodes in their one-hop neighborhood. The distance between these nodes is determined by the communication range of the MAC protocol used.
- **Data dissemination nodes (DDNs):** These nodes perform the function of delivering the collected data to the NCC. The technology used to transfer data from these nodes to the NCC center can vary. For example, a satellite or a cellular technology can be used. This implies that each of the DDN would have such a communication capability.

The DDNs provide the network with increased reliability since the collected sensor data would not have to travel all the way along the length of the LSN from the sensing source to the NCC center. This distance is usually very long and can be hundreds of Kilometers which would make it vulnerable to a large number of

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<tr>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Classification of LSNs</strong></td>
</tr>
<tr>
<td><strong>Sub-categories</strong></td>
</tr>
<tr>
<td>One-level</td>
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<tr>
<td>Two-level</td>
</tr>
<tr>
<td>Three-level</td>
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possible failures, unacceptable delays, higher probability of errors, and potential security attacks. The DDNs allow the network to pass on its collected data simultaneously to the NCC in a parallel fashion. Additionally, the distance between the DDNs is important and affects the reliability of the network. A small distance between the DDNs would increase the equipment cost of the network, as well as the deployment and maintenance costs. On the other hand, a distance that is too large would decrease the reliability, security, and performance of the network. Figure 1 shows a graphic representation of the different types of nodes and their geographic layout. Figure 2 shows the hierarchical relationship between the various types of nodes in the LSN. As shown, multiple BSN transmit their data to one DRN. In turn, several DRNs transmit their data to a DDN. Finally, all DDNs transmit their data to the NCC.

More details about these node categories, as well as their functions and hierarchical relationships are available in Jawhar et al. (2007, 2009). In the following sections, we discuss different categories of LSNs.

5.1. Thin LSNs

The most basic LSN is the one where the sensor nodes and other communication nodes are lined up in a one-dimensional linear form. One of the applications that might use this kind of alignment of the nodes is oil, gas and water pipeline monitoring, road side networks, and railroad monitoring networks (Jawhar et al., 2009). Some of these applications have been discussed in earlier sections. Networks that have this structure can take advantage of the linearity of the nodes and the predictability of the structure to enhance the routing and communication efficiency, minimize the energy consumption, and increase the network reliability. A detailed framework for examples of this kind of LSNs is provided in Jawhar et al. (2007). Furthermore, three different subcategories of thin LSNs can be identified from a hierarchical point of view. Table 1 shows a summary of the thin LSN categories.

5.1.1. Thin one-level LSNs

This category is the simplest form of LSNs where all of the sensor nodes are of the same type and have the same responsibilities. In this case, each node acts as both a sensor and a data relay node. Data collected by each sensor has to be propagated by the other sensors until it reaches the sink node on one end of the network. Figure 3 shows a representation of a one-level LSN and is acceptable for networks covering a relatively short distance. One of the applications could be nodes around a structure whose perimeter does not extend beyond a few Kilometers.

Even though this type of network can have some useful applications, one-level (flat) hierarchy is not very good for a generic sensor network application as it is vulnerable and can be relatively unreliable with long distance. For example, in some area, one or more sensor nodes could be moved out of range with respect to each other by a storm or any other kind of natural or man-made action, making the network disconnected. Even though there could be routing provisions that could survive the failure of one or more adjacent (i.e., 1 hop-neighbors) or non-adjacent nodes (Jawhar et al., 2007, 2009); if enough nodes fail, and disconnection occurs on both sides of a segment, then the whole segment of the network could become isolated. In order to overcome this problem, data must be disseminated to the NCC every k meters, where k is a parameter that can range from few hundred meters to several kilometers, depending on the application in hand. This solution is provided in the subsequent LSN subcategories.

5.1.2. Thin two-level LSNs

In this category of LSNs, the network has two types of nodes: BSNs, and DRNs. The nodes in each group of BSNs have the responsibility of collecting information and transmitting it to their parent DRN. The DRNs pass on the data to the sink node located at the end of the network via multi-hop through neighboring DRNs. In this model, the BSNs are relieved from routing duties which can consume a considerable amount of energy. This significantly increases their battery life, a feature which is highly desirable in a WSN. DRNs, which are expected to have higher energy and transmission capacity, perform the routing as well as possible data aggregation duties (Banerjee et al., 2007). In addition, different routing strategies can be deployed to overcome DRN failures as presented in Jawhar et al. (2009). This two-level hierarchy can be useful for not only extending the lifetime, but...
also the efficiency of the network. However, it still suffers from vulnerability of the network partitioning in case one or multiple successive DRNs fail, especially if the network is long and extends to several hundred kilometers. Also, since the data hops across too many DRNs to reach the NCC at the end of the network, it can be subjected to higher end-to-end probability of errors as the number of traversed links increases before the data is consumed.

5.1.3. Thin three-level LSNs

In this type of LSNs, three types of nodes exist. Figure 1 shows an illustration of this category of networks. At the bottom of the hierarchy, the BSNs sense the information and transmit it to their parent DRNs. Then, each group of DRNs transmit their collected data to their parent DDN in a multi-hop fashion. Finally, the DDNs transmit the data to the NCC using the available wireless technology at that level.

Dissemination of data at these DDN points provides better network reliability, increased robustness, improved scalability and added flexibility. In addition, it provides better communication efficiency and reduced end-to-end delay. Such parameters could be relatively important for some delay sensitive applications. In addition, this model benefits from the addition of the DDNs, which allow collected data at their corresponding network segments to be transmitted in parallel to the NCC which improves the network performance. Also, the data collected by the BSNs, and routed by the DRNs to the nearest DDN do not have to travel the entire length of the linear network. The reduced route in the physical length and the number of DRN hops reduces the overall end-to-end delay and hence the probability of error. Additional robustness is also gained. Specifically, if there could be too many failures of DRNs in some segment of the network, then only that segment will be disconnected from the system, while the rest of the network can continue to operate normally. For a large network, three-level LSN model is an efficient way even for the thin LSN model. Furthermore, this category provides increased security, since data collected by each segment of the network is disseminated in a parallel manner by the DDNs to the NCC and does not have to be transmitted along the entire path, which would otherwise make it highly vulnerable for various attacks. It is useful for applications that cover long stretches of the linear networks (several hundred kilometers or more) and in situations where the network is subject to different types of natural or human-made attacks at different geographic locations that might affect specific segments of the network. Therefore, the added overhead in the installation and cost of using DRN as well as DDNs is justified.

5.2. Thick LSNs

Another type of WSNs are thick LSNs where linearity does not exist at all the levels. Specifically, only the upper two levels, namely the DRN and DDN levels exhibit a linear structure. In fact, the BSNs can have a two- or three-dimensional geographic distribution as illustrated in Fig. 6. As is the case in the previous model, the BSNs gather the required data from their local environment and transmit it to their parent DRNs. In order to discover and maintain routes from the BSNs to their parent DRNs which act as multiple sinks before sending data to the NCC, the BSNs use one of the two-dimensional routing algorithms that exist in the literature such as DSR, AODV, and others (Cordeiro and Agrawal, 2011). Once the data is gathered by the DRNs, it is routed to the higher level DDN sink nodes. Subsequently, the DDNs transmit the collected data to the NCC.

This kind of topology can be present in many applications such as when the WSN is responsible for monitoring a geographic area. For example, the network can have the responsibility of monitoring international borders between countries (D'Costa et al., 2004) and detect illicit activities. As mentioned earlier, such activities can involve border crossings by smugglers of different illegal goods or substances, military crossings by individuals, or vehicles, etc. The inexpensive sensors can be deployed by throwing them from an airplane moving at a constant but low speed or a UAV. The dropped sensors end up in a semi-random geographic form and could follow a linear structure. The DRN sink nodes with increased capabilities can also be deployed at various locations and are separated by some specified average distance. This deployment of the DRNs can be done in many different ways. They could also be thrown from a low-flying airplane, placing them at locations which are separated by approximately the same average distance, or they can be installed (Wang and Agrawal, 2008) in a precise fashion by the network personnel if the terrain is easily accessible. Table 2 shows a summary of the thick LSN categories.

From a hierarchical point of view, depending on the number of levels in the hierarchy, three types of thick LSNs can be identified.

5.2.1. Thick/one-level LSNs

Figure 4 shows an illustration of a thick/one-level LSN. Only BSNs exist in this case. They are scattered in a two-dimensional random form between two parallel lines which extend for a long distance. In this type of network, the sensor nodes have the responsibility of both sensing the information and routing it through their neighbor nodes along the “thick line” of BSNs to finally reach the sink node (NCC) at the end of the network. In this case, the BSNs have sensing, aggregation, compression, as well as routing responsibilities.

5.2.2. Thick two-, and three-level LSNs

In this type of sensor networks, the linearity exists at the DRN and DDN levels. The lower level containing the BSNs can be two- or three-dimensional. The BSNs at the lowest level can be scattered in an ad hoc fashion or arranged in a multi-dimensional mesh, hexagon, or triangular form (Wang and Agrawal, 2008). As in the case of a two-level LSN, it can use different existing multi-dimensional routing algorithms to reach their parent DRNs, which is usually the nearest one to the corresponding BSN. In turn, the DRNs can also be scattered in an ad hoc fashion or arranged in a multi-dimensional mesh form.

Depending on the existence of a third level of DDNs or not, there are two types of thick LSNs: thick/two-level, and thick/three-level. Figure 5 shows a thick/two-level network where only BSNs and DRNs exist. In this case, the DRN multi-hop the information to the final sink on either side of the linear network. The sink collects the information and provides it to the NCC.

On the other hand, thick/three-level LSNs contain DDNs in addition to the BSNs and DRNs. Multiple DDNs are placed at regular intervals in the network. Once the data is collected by a DRN, it is then routed through the other DRNs to the nearest DDN. The DDNs will then transmit the data to the NCC using the technology which takes advantage of the existing communication infrastructure as is the case with its counterpart, thin/three-level LSN mentioned earlier.
5.3. Very thick LSNs

In this type of LSNs, nodes at all levels of the hierarchy are randomly placed, but they are located between two parallel lines that extend linearly for a long distance. Figure 6 shows a representation of this kind of sensor networks.

Only two types of very thick LSNs are identified: very thick/two-level and very thick/three-level. This is because the very thick/one-level LSN is basically the same as the thick/one-level LSN. The other two categories are discussed below. Table 3 shows a summary of the very thick LSN categories.

5.3.1. Very thick/two-level LSNs

These are sensor networks where the BSN as well as the DRNs are deployed in a two-dimensional form. The LSN presented in Fig. 6 falls under this category. The BSNs can use existing routing protocols to reach their parent DRNs which will then use a multi-hop routing strategy to reach the sink node at the edge of the network.

5.3.2. Very thick/three-level LSNs

In this type of LSNs, the BSN and DRNs are deployed in a two-dimensional formation. However, due to the physical requirements...
and AODV are not used due to the fact that they are designed for the classical routing protocols for wireless networks such as DSR. Messages are done at the DRN-to-DRN level. It is important to note that is more involved.

In case due to the fact, in case of failure of a parent DDN, finding provisioning of the network as discussed later. This would be the case due to the fact that, in case of failure of a parent DDN, finding alternative DDN for children DRNs has to be done differently and is more involved.

6. A basic algorithm for routing of messages in LSNs

As presented earlier, the main routing process of data messages is done at the DRN-to-DRN level. It is important to note that the classical routing protocols for wireless networks such as DSR and AODV are not used due to the fact that they are designed for multi-dimensional topologies and do not take advantage of the linear structure that is assumed. For example, DSR and AODV both use flooding from the source in order to discover paths to the destination. This is not necessary in our LSN once the network is initialized and the tree structure is created using localized flooding between the nodes and their parents (higher level nodes that are geographically closest to them). Also, DSR and AODV would have to deal with node failures by re-initiating the path discovery from the source, and do not have any provision of increasing the node’s transmission range in order to overcome failures in an efficient manner. They do not necessarily follow the concept of having two alternative destinations in opposite directions, a characteristic which can also be exploited in order to increase the network performance, reliability, and robustness under the presence of node failures. In addition, plain shortest path algorithms are not best suited for this environment either as they lack the flexibility of having increased node range, or choosing alternative destinations or sink nodes in response to faults in the network.

In order to illustrate the special nature of LSNs and the ability of the routing protocols to take advantage of its special characteristics, the following strategy is used to route the data in LSNs. Note that this is a basic routing algorithm, and further optimisations are the subject of additional research, which we are currently pursuing. The basic LSN routing algorithm is the

<table>
<thead>
<tr>
<th>Sub-categories</th>
<th>Characteristics</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-level</td>
<td>BSNs and DRNs randomly placed between two parallel lines.</td>
<td>Same as the thick two-level model with increased flexibility in both BSN and DRN deployment. Proper load balancing and scheduling can extend the network lifetime.</td>
<td>This added flexibility in deployment of DRNs in particular limits the ability of the routing protocol to take full advantage of the strict linearity of the topology. This leads to some reduction in reliability and efficiency aspects.</td>
<td>Useful for applications where highly flexible node deployment is important such as monitoring linearly structured geographic areas, natural or human-made structures, hostile, or uninhabitable territories that cannot be reached by human installation personnel for political, military, or natural reasons.</td>
</tr>
<tr>
<td>Three-level</td>
<td>BSNs, and DRNs randomly placed between two parallel lines. DDNs are lined up in a linear form.</td>
<td>Same as the other three-level models with increased flexibility in BSN and DRN deployment. Increased communication and energy efficiency, and a better overall QoS support.</td>
<td>Same as the other three-level models with increased complexity of routing among the DRNs. Reduced ability to exploit linearity of DRNs for increased reliability and robustness.</td>
<td>Useful for applications that have the requirements and characteristics of this model but with structures or areas that extend over very long distances and require increased performance, reliability, and security.</td>
</tr>
</tbody>
</table>

Table 3
Classification table of very thick LSNs. BSNs and DRNs placed between two parallel lines. DDNs are lined up in a strict one-dimensional linear formation. BSNs and DRNs can be inexpensively deployed (e.g., by throwing them from a low-flying airplane). Applications involve networks where easy and quick deployment is essential. Also, the coverage is for an area that is linear but requires a larger distance between the limiting parallel lines due to geographic topology requirements and the nature of the coverage. Note that except for the variations and adjustments that depend on the different topology, the general functions of the BSNs, DRNs and DDNs are similar to those mentioned for the thin LSNs.
following: A DRN transmits its collected data to its parent DDN using the intermediate DRNs in a multi-hop fashion. Connectivity between the DRNs is determined and maintained using periodically exchanged HELLO messages. When an intermediate DRN receives a data message, it forwards it to the next DRN neighbor node towards the DDN. In case of failure of the next DRN, the DRN can increase its transmission range in order to reach another DRN that is located further down the line. To achieve this, the range of the transmitting DRN is extended by multiplying it with a range multiplier (RM) variable. The extended transmission range is \( R_e = R_M \times R_i \), where \( R_i \) is the initial range of the DRN. The initial value of \( RM \) is 1. When the range needs to be extended, the value of \( RM \) is repeatedly increased to by one until a live DRN is reached, which transmits an acknowledgment to the sender informing it that it received the data correctly and that it will further propagate the data to the next DRN towards the DDN. If no live DRN can be reached even with \( RM \) increased to a pre-determined MAX\(_{RM} \) value, the message is dropped.

### 7. Simulation

As a case study, we compared the performance of one thin and two thick three-level LSNs with varying node densities per distance unit. We define \( D_{DRN} \) as the distance between two consecutive DRNs in the thin LSN, which is the unit of length in the simulation. The distance \( D_{DRN} \) varies depending on the communication protocol used for DRN-to-DRN communication. For the IEEE 802.15.14 (Zigbee) protocol, which is used by most sensor networks, the commonly used transmission range is 10 m. The segment length in each LSN was varied from 20 to 200 distance units. Also, we define the normalized density of DRNs per distance unit for the thin LSN as 1. Then, the two thick LSNs, named thick2 and thick3, which are used in the simulation are defined as having normalized densities of 2 and 3 DRNs per distance unit respectively. Table 4 presents the main simulation parameters that were used. In the simulation, the BSNs send their sensed data to their parent DRN in a periodic manner. Then, the DRNs use a the multi-hop approach described earlier to route this information to their parent DDN.

A network segment is defined as the portion of the network residing between two consecutive DDNs. In the simulation, the percentage of successfully transmitted packets, which are able to reach the DDNs was measured as the length of the network segment was increased from 20 to 200 units. Since the reliability of the network is directly dependent on the reliability of the individual network segments, the simulation was done over one segment of the corresponding LSN. Two sets of experiments were conducted. Figures 7–9 show the results of the first set of experiments where the transmission range of the DRNs was fixed (\( MAX\_{RM} = 1 \)). Figures 10–12 show the results of the second set of experiments where the transmission range of the DRNs was variable with \( MAX\_{RM} = 2 \). In both sets of experiments, the percentage of successfully transmitted packets for the thin, thick2 and thick3 networks are compared.

#### Table 4

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of DRNs per DDN</td>
<td>20–200</td>
</tr>
<tr>
<td>Total number of BSNs per DRN</td>
<td>6</td>
</tr>
<tr>
<td>DRN transmission rate</td>
<td>1 Mb/s</td>
</tr>
<tr>
<td>Periodic sensing interval</td>
<td>10 s</td>
</tr>
<tr>
<td>DRN data packet size</td>
<td>512 bytes</td>
</tr>
<tr>
<td>MAX(_{RM})</td>
<td>1, 2</td>
</tr>
</tbody>
</table>

In order to study the reliability aspects of thin and thick LSNs and the impact of node density per unit distance, a number of DRN failures were intentionally generated using a Poisson arrival process and the exponential distribution with an average rate for the inter-arrival time between failures. The exponential distribution is reasonable to predict the arrival of failure events (http://www.math.uah.edu/stat/poisson/exponential.pdf; George and Chen, 2008; Gross et al., 1977; Zheng and Lan, 2009). It is worth noting here that
average number of nodes, is to provide consistency and fairness between the different experiments as the network length and consequently the number of DRNs increases. If we only chose a fixed average number of nodes to fail, then experiments with a larger number of nodes will have a smaller percentage of the nodes failing and unfairly enhance the probability of successful packet transmission for the corresponding network.

In Figs. 7–9, the segment length in each LSN was varied with a fixed DRN transmission range and the percentage of successfully transmitted packets was measured. The DRN failure rate was set to 6%, 8%, and 10% per year in the three figures respectively. The same set of experiments was conducted and presented in Figs. 10–12 with a variable transmission range and a $MAX_{RM}=2$.

It can be clearly seen that the thick3 LSN with the highest DRN density consistently performs better than the thick2 and thin LSNs. In fact, the performance of the latter one is very limited, even at the smallest failure rate of 6% per year, especially in the first set of experiments where a fixed DRN transmission range was used. This reasonable and expected pattern provides added validation to our model. The results also provide insight into the fact that for specific failure rates, and segment length ranges, increasing the density of the DRNs significantly improves the reliability of the network. However, beyond the normalized density of 3, the improvement in reliability is minimal. This demonstrates the importance of increasing the DRN density in the face of higher failure rates. Nonetheless, this normalized density increase, which also increases the overall cost of the network, is ineffective and would not be recommended beyond a certain level.

Additionally, the results show that as the length of the segment increases from 20 to 200 units, the percentage of successfully transmitted packets decreases for all three types of networks. This overall decrease in performance for all three cases as the length of the segment increases is expected due to the linear structure of the network. With the increased number of DRNs that a packet has to use to reach the DDN, the probability of encountering a situation with failures that prevents the message from going further, increases. As illustrated by the results, this decrease in the reliability as the overall network length increases can be compensated by either (1) increasing the density of DRNs per unit distance, or (2) decreasing the segment length and increasing the number of DDNs to service the same total network length. The former approach increases the cost of the network due to the increased number of DRNs per unit of distance, and the latter approach increases the cost of the network due to the installation of more DDNs. However, due to the increased parallelism in the dissemination of data to the NCC, the second approach provides the added benefit of increasing the overall network performance in addition to the increased reliability, as well as reducing the overall packet end-to-end delay. Therefore, when designing such a network, the density of the DRNs per unit distance and the number of network segments covering the required network length must be chosen carefully in order to meet the reliability and performance requirements that are needed. The choice of these parameters can also be an important factor, which is affected by the communication range of the DRNs used, as well as other desired quality of service (QoS) guarantees such as delay, bandwidth, and throughput. All of these requirements depend on the application, the particular type of monitored structure, and the desired specifications. These design issues require additional research, which we plan to conduct in the near future.

8. Conclusions and future research

In this paper, LSNs, which constitute a new and specific category of WSNs, are presented. The paper discussed some of

the applications that exhibit this kind of linear alignment and motivated the need for more research in this important area. Such research involves the design and testing of different networking and communication protocols which take advantage of the linearity of the network in order to increase the communication efficiency, energy savings, reliability and fault tolerance. In addition, a classification of the different categories of LSNs was presented. Simulation experiments are performed to evaluate the performance and reliability of three different LSNs. We believe that this field of research involves numerous applications, which impose specific challenges that need further investigation. We are currently working on the protocols and architectures tailored for specific LSNs.

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