A Hierarchical and Topological Classification of Linear Sensor Networks

Imad Jawhar and Nader Mohamed
College of Information Technology
UAE University, Alain, UAE
Email: {ijawhar, nader.m}@uaeu.ac.ae

***Abstract*— Considerable advancements in the technology of wireless sensor networks (WSNs) are taking place due to smaller, and more efficient electronic devices which are capable of increased processing power, and communication capabilities. In addition, the cost of such devices is constantly decreasing, which makes it possible to employ large quantities of networked sensors in numerous commercial, environmental, military and health care applications. A lot of these applications involve lining up the sensor nodes in a linear structure giving rise to a new class of WSNs, which is defined in this work as Linear Sensor Networks (LSNs). This paper identifies some of the applications that might use such networks and offers a classification of the different types of LSNs from a topological and hierarchical points of view. Finally, a motivation for designing specialized protocols that take advantage of the linearity of such networks in order to increase reliability, efficiency, energy savings, and network lifetime is offered along with the new research issues, challenges and opportunities that exist in this field.**

Keywords: Ad hoc and sensor networks, routing, applications of wireless sensor networks, networking frameworks.

I. Introduction

In recent years, wireless sensor networks have been emerging as a suitable new tool for a spectrum of new applications. These tiny sensor nodes are low cost, low power, easily deployable, and self-organizing. Each sensor node is capable of only a limited amount of processing, but when coordinated with the information from a large number of other nodes, they have the ability to measure a given physical environment in great detail. Thus, a sensor network can be described as a collection of sensor nodes which co-ordinate to perform some specific action. Unlike traditional networks, sensor networks depend on dense deployment and co-ordination to carry out their tasks. These unique characteristics make them advantageous over traditional networks. Sensor network applications were originally used for military applications such as target detection, surveillance of enemy activities in a battlefield environment and counterterrorism; however, their many advantages over traditional networks resulted in the development of many other potential applications that range from infrastructure security to industrial sensing. Some examples are: environment and habitat monitoring, health applications, home automation, traffic control, etc. Another possible example is using wireless sensor networks for protecting and monitoring pipeline systems.

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Research in the field of Wireless Sensor Networks is relatively active and involves a number of issues that are being investigated. These issues are efficient routing protocols for ad hoc and wireless sensor networks [12], QoS support [11][12], security [4], and middleware [6]. Most of these issues are investigated under the assumption that the network used for sensors does not have a predetermined infrastructure [3][5][7][8][14][18]. Fortunately, the wireless sensor network needed for monitoring linear infrastructures is a structured network in which all sensor nodes are distributed in a line. This characteristic can be utilized for enhancing the communication quality and reliability in this kind of networks.

This paper presents LSNs, which is a new category of WSNs where the network nodes are aligned in a linear formation. Different important potential applications that exhibit this form of node structure is offered along with a classification of the different categories of LSNs from hierarchical and topological points of views. This paper also provides the background, motivation, and advantages for using LSNs. As mentioned earlier, this kind of alignment of sensors can come up in many applications such as the 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, as well as many other such uses [9]. This architecture utilizes the special linear structure of the networks to solve some communication reliability and security problems. The objective of the design is to reduce installation and maintenance costs, increase network reliability and fault tolerance, increase battery life for wireless sensors, reduce end-to-end communication delay for quality of service (QoS) support of sensitive data, and increase network lifetime by utilizing the special linear structure of the network.

The rest of the paper is organized as follows. Section II provides some related work in this field. Section III introduces some important applications for wireless linear sensor networks. Section IV discusses the reasons why new architectures and protocols are needed for linear sensor networks. Section V provides a topological and hierarchical classification of linear sensor networks. The last section presents the conclusion and future research.

II. Related Work

There is some work that was done in designing and analyzing linear networks; however, most of this work is either

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for wired or general wireless networks that are not designed for sensor applications. 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 such as a long downtown street to enable mobile users to use the Internet [1]. Another example is using linear wired sensor networks for monitoring and controlling pipelines. Sensors are distributed along long pipelines to report the status of the pipelines such as temperature, pressure, flow speed, etc. These networks are usually constructed using copper or fiber optic cables [16][22]. Wireless technology was proposed to be used to enhance the reliability of connectivity in long wired networks for pipelines [15].

Another example of linear wired sensor networks is Active Tape [21]. Active tape uses a wire to enable sensor nodes to use external power, and allows higher bandwidth and lower latency communication than wireless networks. Although wired sensor networks have some advantages, they are costly and not suitable for some applications such as security applications that require hidden sensors for monitoring. There is some work in studying the performance of wireless linear wireless networks in general, and one example is in [17]. The authors analyzed the performance-cost tradeoff in such networks. They investigated the relationship between throughput and energy cost in large wireless linear networks. However, all of the mentioned networks and work are not for linear wireless sensor networks.

III. Applications of Linear Wireless Sensor Networks

This section presents a list of potential applications for linear sensor networks.

A. Oil, gas, and water pipeline monitoring

One of the applications for linear sensor networks is oil, gas and water pipeline monitoring and protection. Long pipelines are used in many countries for a number of applications. For example, long pipelines are used to transfer water from desalination plants, which usually are 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 dependant on the water transferred through huge and long pipelines from the Shoaiba Desalination Plant in Al-Jubail in the eastern part of Saudi Arabia. Saudi Arabia is now the world's largest producer of desalinated water supplying major urban and industrial areas through a network of water pipes which run for more than 3,800 km. Furthermore, Oil and gas Industries in the Arabian Gulf heavily depend on oil pipelines for connecting shipping ports, refineries, and oil and gas wells. For instance, in the United Arab Emirates, there are 2,580 km of gas pipelines, 300 km of liquid petroleum gas pipelines, 2,950 km of oil pipelines, and 156 km of refined products pipelines (2006). The paper in [9] presents a framework for using wireless sensor networks for oil, gas, and water pipeline monitoring. Our paper extends the model and architecture discussed in [9]. More details on the background, motivation, advantages, and applications for using linear structure wireless sensor networks can be found in that paper.

There could be many types of parameters that need to be monitored in order to provide for proper protection, early response, maintenance scheduling, as well as operational control. Some of these parameters are fluid temperature, fluid pressure, fluid velocity, fluid viscosity, chemical traces of some important elements that may indicate metal corrosion, physical deformation (bending), 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) [2].

B. Railroad/subway monitoring

One of the applications of linear sensor networks is in the monitoring, surveillance and control of railroads and subways. For example, some researchers in [13] have investigated the deployment of fiber-optic sensors on fatigue-critical components in the superstructure of a railroad bridge. The sensors can monitor dynamic strains caused by the passing of trains as well as provide early detection of critical and dangerous cracks. Fiber Fabry-Perot interferometers (FFPI) strain gages were adhesively bonded to the stainless-steel strip by spot welding. These sensors were also installed on the railroad/subway strips on the approach to the bridge. Furthermore, for performance evaluation, electrical resistive strain gages were installed with the fiber-optic sensors on the bridge. Fiber-optic continuity sensors that can detect cracks were bonded at critical locations in the structure. Currently, phone lines are used for transmission of the gathered telemetric information. In order to improve deployment cost, maintenance, and scalability, wireless sensors and other nodes at higher levels of the communication system hierarchy can be used. Such wireless systems would allow monitoring to be done along the entire length of the rail road system for significant improvements in monitoring and control capabilities.

More research needs to be done in this area in order to investigate the 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 communication points of view.

C. Monitoring of AC Powerlines

Another area of interest where linear sensor networks can be used is in the monitoring of AC powerlines overhead and underground [23]. The collected information would be useful to the electric utility company in order to anticipate outages that can occur due to faulty equipment and overloading of AC powerlines. Such outages result in loss of service for large numbers of customers, and cause significant financial losses to the utility companies due to high maintenance costs. In addition to these losses, there are also losses due to costly damages to the reputation of the utility as well as added danger to its employees. By monitoring certain electrical conditions, utility companies can better anticipate equipment failures and unexpected outage conditions and create better maintenance schedules and replacement of powerlines which are more likely to loose power as a result of an overload or fault. This increased predictability can significantly reduce maintenance cost which is caused by overtime pay.

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. Also, in this particular application, the sensors can communicate their information back to the control center using the powerline itself as well. In addition, the installation of these sensors is done relatively quickly and easily without interrupting or affecting service to 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 alignment of the sensors in order to improve network performance, reduce installation and maintenance costs, and increase network reliability and security.

D. Driver-Alert Network

Other applications of linear wireless networks include roadside networks that can be used to monitor vehicular activities along 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 to alert a sleepy driver in case the car is about to be driven off 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 a lot of dangerous and life threatening car 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 as mentioned earlier. Linear sensor networks 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 conditions.

E. Border monitoring

Another important application of linear sensor networks is monitoring international borders for different activities such as illegal smuggling of goods, or drugs, unauthorized border crossings by civilian or military vehicles or persons, 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 the sensor nodes by dropping them in a measured and controlled fashion from a low flying airplane. The resulting topology of the sensor nodes will then be 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 multihop communication between the relay nodes as will be discussed later in the paper. Similarly, the distance between the sink nodes would be determined by taking into consideration the nature of the terrain, the available infrastructure, and the desired level of performance and reliability of the network.

F. Additional applications

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

IV. Why New Architectures and Protocols are Needed

There are many reasons why new frameworks and architectures are needed for the different categories of wireless linear sensor networks.

A. Increased routing efficiency

The first reason is the ability to take advantage of the linear nature of the network in order to significantly increase the efficiency of the routing protocols that are used. This is the case since the two-dimensional routing protocols that exist in the literature [19] 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 costly in using important resources which are scarce in the wireless environment such as bandwidth and node processing. In addition, it causes delay in path acquisition and maintenance. Routing protocols that are designed for linear sensor networks will not need to use such a costly process for route discovery. In fact, they can exploit the linearity of the network to possibly eliminate or drastically reduce the route discovery process. For example, the protocols in [10] 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 the information in the node addresses to overcome node failures. It is important to note here that address assignment is done only once at network initialization.

B. Increased network reliability

Another reason for using new more specialized protocols for linear wireless sensor networks is the ability to adapt such protocols to take advantage of the structure of the network to achieve significantly increased reliability. The existing multi-dimensional protocols such as DSR and AODV react to node failures by either re-initiating a new route discovery process or can do local repair in some variations. In either case, more overhead is needed, but more importantly, if no other alternative links are available, the connectivity of the network is compromised and the communication of that part of the network is stopped. This does not have to be the case if the network has a linear structure. This is because for this particular structure specialized solutions can be employed to overcome node failure. In [10], several solutions are presented. One of the solutions is to immediately use the opposite direction from the failed node to reach an alternative sink node. Another solution is to increase the range of the node before the failed node in order to jump over it and reach the next node in line. This increased range cannot only allow the overcoming of only one node, but of several nodes along the way. Even the failure of multiple adjacent nodes can still be overcome by increasing the transmission range accordingly with easily available corresponding technology in sensor nodes.

This ability of the network to efficiently and quickly overcome node failures can only be taken full advantage of by designing specialized protocols and architectures for linear sensor networks.

C. Better handling of node heterogeneity

Existing multi-dimensional routing protocol can support heterogeneous ad hoc and sensor networks. However, they are not adapted to linear structures. They assume a multi-dimensional deployment and distribution of the various types of nodes. Their route discovery and maintenance process for example, does not exploit the linearity of a particular sensor network. This 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 overhead. In addition, the data transmission process can be made more efficient in various aspects. In [10] the data that is collected by the sensors is disseminated to the control center in parallel at the data dissemination nodes. This significantly decreases the end-to-end delay. Furthermore, the parallel dissemination of the data increases the reliability of the data delivery process. This is because a disconnection of one or more segments of the network only affects the very limited area where this disconnection takes place.

D. Improved location management algorithms

In addition, algorithms for locating faults can be much more easily designed by taking advantage of the linear structure. In order to help in this regard, a higher level addressing scheme which includes information about the node location inside the address, can be used. This strategy would 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 take appropriate repair and maintenance actions.

E. Increased network robustness

As mentioned earlier, designing specialized protocols for wireless linear sensor networks also allows these protocols to increase the robustness of the network in reaction to different conditions such as node failures and variations in traffic intensity in different modes of operation (normal and emergency mode).

F. Increased network security

Security in wireless sensor networks is an important issue that needs to be considered when designing such systems. Although the criticality of the security provisioning is expected to vary depending on 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. There has been some research with respect to security in wireless sensor networks. However, most of the work assumes a multi-dimensional network. Significant improvement in the effectiveness, efficiency, and security protocol overhead reductions can be achieved by adapting these protocols and designing new ones for wireless linear sensor networks. These improvements could rely on the pre-determined knowledge of the behavior of the routing and message transfer processes. This information can be used to characterize normal operation and detect abnormal behavior which can typify certain attacks.

V. Topological and Hierarchical classification of Linear Sensor Networks

From a **topological point of view**, linear sensor networks can be classified into several categories according to the linearity of the different levels of the node hierarchy: *thin, thick and very thick LSNs*. This section presents these categories and discusses the characteristics and limitation of each one of them. In addition, from a **hierarchical point of view**, linear sensor networks can be classified into several categories: *one-level, two-level, and three-level LSNs*. This classification depends on the way the sensor and communication support nodes are geographically deployed. This section presents and discusses each of these categories. Therefore, depending on the application, a particular linear sensor network can belong to one category from a hierarchical point of view and to another category from a topological point of view. The table in Figure 3 presents the different categories of linear sensor networks according to these two classifications.

Before discussing these categories of linear sensor networks, three types of nodes are identified and defined. Each of these types of nodes has different functions to perform in the data collection, routing and final dissemination to the **Network Control Center (NCC)**.

- **Basic Sensor Nodes (BSN):** These are the most common nodes in the network. Their function is to perform the sensing function and communicate this information to the data relay nodes.
- **Data Relay Nodes (DRN):** These nodes serve as information collection nodes for the data gathered by the sensor nodes in their one-hop neighborhood. The distance between these nodes is determined by the communication range of the networking MAC protocol used.

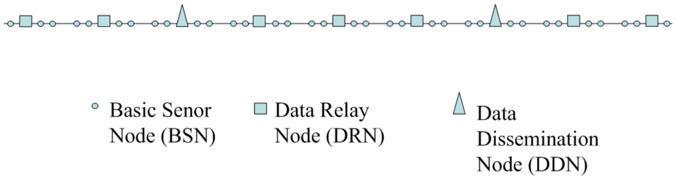

Fig. 1. A representation of a linear sensor network with a three-level hierarchy.

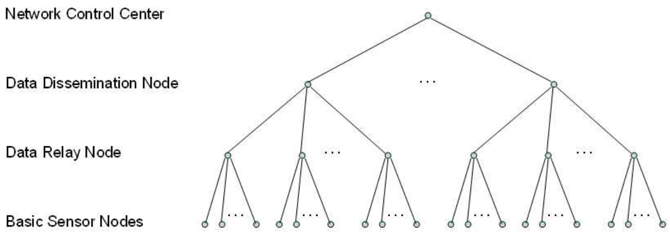

Fig. 2. A hierarchical representation of the linear structure sensor network, showing the parent/child relationship of the various types of nodes.

Linearity / No. Of Nodes	Thin	Thick	Very Thick
One-Level	BSN nodes lined up strictly linearly	BSN nodes lined up randomly between two parallel lines	N/A
Two-Level	BSN and DRN nodes lined up strictly linearly	BSN nodes randomly placed and DRN nodes are linearly. All nodes are between two parallel lines	BSN and DRN nodes randomly placed between two parallel lines
Three-Level	BSN, DRN, and DDN nodes lined up strictly linearly	BSN nodes randomly placed, DRN, and DDN nodes are linearly placed between parallel lines.	BSN, DRN, and DDN nodes randomly placed between two parallel lines.

Fig. 3. Classification table of linear sensor networks.

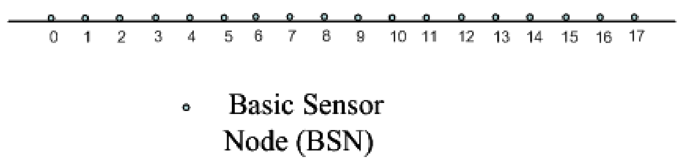

Fig. 4. Illustration of a thin/one-level linear sensor network.

- **Data Dissemination Nodes (DDN):** These nodes perform the function of discharging the collected data to the NCC. The technology used to communicate the data from these nodes to the NCC center can vary. Satellite cellular technology can be used for example. This implies that each of the DDN nodes would have this communication capability.

The DDN nodes provide the network with increased reliability since the collected sensor data would not have to travel all the way along the length of the pipeline 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 possible failures, unacceptable delay, higher probability of error, and security attacks. The DDN nodes allow the network to discharge its sensor data simultaneously in a parallel fashion. Additionally, the distance between the DDN nodes is important and affects the reliability of the network. A small distance between the DDN nodes would increase the equipment cost of the network, as well as 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 sensor network. As shown in the figure, multiple BSN nodes transmit their data to one DRN node. In turn, several DRN nodes transmit their data to a DDN node. Finally, all DDN nodes transmit their data to the Network Control Center.

More details about these node categories, as well as their functions and hierarchical relationships are available in [9] and [10]. In the following sections, the different categories of linear sensor networks are discussed.

A. *Thin LSNs*

The most basic type of linear sensor networks is one where the sensor nodes and other communication nodes are lined up in a one-dimensional linear formation. 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, and other applications [10]. Some of these applications were 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 routing and communication efficiency, minimize energy consumption, and increase network reliability. A detailed framework for examples of this kind of linear sensor networks is provided in [9]. Furthermore, three different subcategories of thin LSNs can be identified from a hierarchical point of view.

Thin/One-level LSNs:

This category is the simplest form of linear sensor networks where all of the sensor nodes are of the same type and have the same responsibilities. In this case, all of the nodes are lined up in a linear formation and each node acts as both a sensor and a data relay node. Data collected by each sensor has to be propagated or relayed by the other sensors until it reaches the sink node on one end of the network. Figure 4 shows a representation of a one-level linear sensor network. This category is acceptable for relatively short LSNs. One of the applications could be nodes around a structure whose perimeter does not extend beyond a few kilometers needs to be monitored.

Even though this type of network can have some useful applications, a one-level (flat) hierarchy is not very good for all sensor network applications. In this case, the network is vulnerable and can be relatively unreliable, especially, with

LSNs that extend for long distances. For example, if in some area, the sensor one or more nodes are moved out of range of each other with a storm or any other kind of natural or man-made action, then the network becomes disconnected. Even though there could be routing provisions that survive the failure of one or more consecutive or non-consecutive nodes [9][10]; if enough nodes fail, and network disconnection happens on both sides of the network, then the whole segment of the network could become isolated. In order to overcome this problem, there must be a dissemination of the data to the control center every k meters, where k is a parameter that can range from few hundred meters to several kilometers depending on the application involved. This solution is provided in the subsequent LSN subcategories.

Thin two-level LSNs:

In this category of LSNs, the network has two types of nodes: BSN, and DRN nodes. The nodes in each group of BSN nodes have the responsibility of collecting the information and transmitting it to their parent DRN node. The DRN nodes multi-hop the data along their neighbor DRN nodes to the sink node at the end of the network. In this model, the BSN nodes are relieved from routing duties which can use a considerable amount of energy. This significantly increases their battery life, a feature which is highly desirable in sensor networks. DRN nodes, which are expected to have higher energy and transmission capacity would perform the routing as well as possible data coalescing duties. In addition, different routing strategies can be deployed to overcome DRN node failures as presented in [10]. This two-level hierarchy can be useful for not only extending the lifetime and efficiency of the network, but also to increase its physical length. However, it still suffers from the vulnerability of network partitioning in case one or multiple consecutive DRN nodes fail, especially if the network is long and extends to several hundred kilometers or more. Also, since the data is hopped across too many DRN nodes to reach the destination at the end of the network, it can become more subject to higher probability of error as the number of links that are traversed before data is consumed increases.

Thin three-level LSNs:

In this type of LSN networks, three types of nodes exist. Figure 1 shows an illustration of this category of networks. At the bottom of the hierarchy, the BSN nodes collect the information and transmit it to their parent DRN nodes. Then, each group of DRN nodes multi-hop the collected data to their parent DDN node. Finally, the DDN nodes transmit the data to the control center using the available wireless technology at that location.

The dissemination of the data at these DDN points, provides higher reliability, robustness, scalability and flexibility of the network. In addition, it provides for better communication efficiency and end-to-end delay. Such parameters could be relatively important for some delay sensitive applications. In addition to the advantages gained by the inclusion of the DRN nodes which were mentioned in the thin two-level LSN model, this model benefits from the addition of the DDN nodes. The DDN nodes allow the data collected at their corresponding network segments to be transmitted in parallel which increases network performance. Also, the data collected by the BSN nodes, and routed by the DRN nodes to the nearest DDN node do not have to travel the whole length of the linear network. The reduced route in physical length and number of DRN hops reduces the overall end-to-end delay, as well as the accumulated probability of error. Additional reliability and robustness properties are also gained. Specifically, if there are enough failures of DRN nodes in a certain segment of the network, only this segment of the network will be disconnected from the system, and the rest of the network can continue to operate normally by transmitting the collected sensor data through the rest of the DDN nodes. The three-level LSN model is the most efficient one of the thin LSN models presented. 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 attacks that might damage certain segments of the network. These attacks can be caused by natural phenomena or can be human made. In this case, the added overhead in installation time and cost of using DRN as well as DDN nodes is justified due to the significant number of important advantages that were stated earlier.

B. *Thick LSNs*

Another type of wireless sensor networks are thick LSNs. In this type of linear sensor networks, linearity does not exist at all levels. Specifically, only the upper two levels, namely the DRN and DDN levels exhibit the linear structure. On the other hand, the BSN nodes can have a two or three dimensional geographic distribution. As is the case in the previous model, the BSN nodes gather the required sensing data from their environment and transmit it to their parent DRN nodes. In order to discover and maintain routes from the BSN nodes to their parent DRN nodes which act as sinks, the BSN nodes use one of the multiple general wireless sensor network routing algorithms that exist in the literature such as DSR, AODV, and others [19][20]. Once the data is gathered at the DRN nodes, it is routed to the higher level sink DDN sink nodes. Subsequently, the DDN nodes transmit the collected data to the control center.

This kind of topology can arise in different applications such as when the sensor network is responsible for monitoring the boundaries of a geographic areas. For example, the network can have the responsibility of monitoring international borders between countries and detect different activities. Such activities can involve border crossings by smugglers of different illegal goods or substances, military crossings by individuals, or vehicles, etc. The sensors can be inexpensively deployed by throwing them from an airplane moving at a constant, low speed. In this case, the sensor end up in semi-random geographic formation. In other words, even though the sensors can fall in different, random locations, the overall formation of the sensors from a ”far enough distance” will follow a linear structure. The DRN sink nodes with increased capabilities can also be deployed at various locations which are separated by a certain average distance. This deployment of the DRN nodes can be done in different ways. They could be thrown

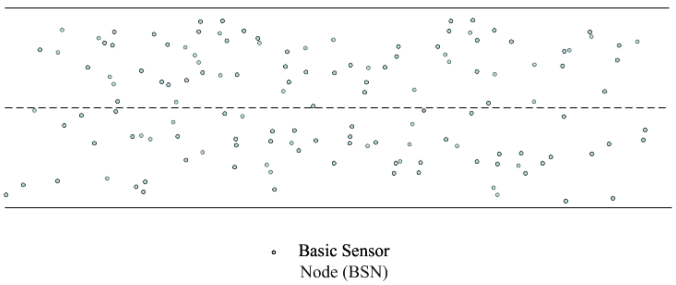

Fig. 5. Illustration of a thick/one-level linear sensor network.

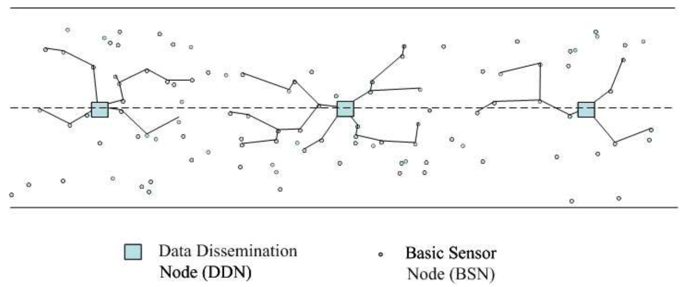

Fig. 6. Illustration of a thick/two-level linear sensor network.

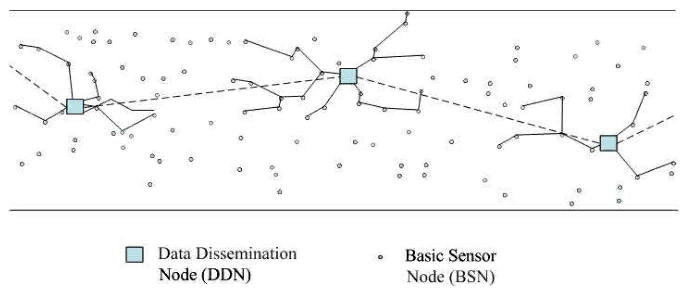

Fig. 7. Illustration of a very thick/two-level linear sensor network.

from an airplane placing them at locations which are separated with approximately the same average distance, or they can be installed in a more precise fashion by network personnel.

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

Thick/one-level LSNs

Figure 5 shows an illustration of a thick/one-level LSN. Only basic sensor nodes exist in this case. They are scattered in a 2-dimensional random formation between two parallel lines which extend for long distances. In this type of network, the sensor nodes have the responsibility of both collecting the information as well as routing it through their neighbor nodes along the ”thick line” of BSN nodes to finally reach the sink node at the end of the network. In this case, the BSN nodes have sensing, data collection, coalescing, compression, as well as routing responsibilities.

Thick two-level and three-level LSNs:

In this type of sensor networks, the linearity only exists at the DDN level. The lower levels containing DRN and BSN nodes can be two- or three- dimensional. The BSN nodes at the lowest level can be scattered in an ad hoc fashion or arranged in a multi-dimensional mesh formation. As in the case, of the two-level linear sensor networks, they can use different existing multi-dimensional routing algorithms to reach their parent DRN nodes, which is usually the nearest one to the corresponding BSN node. In turn, the DRN nodes can also be scattered in an ad hoc fashion or arranged in a multi-dimensional mesh formation.

Depending on the existence of a third level of DDN nodes or not, there are two types of thick LSNs: thick/two-level, and thick/three-level LSNs. Figure 6 shows a thick/two-level network where only BSN and DRN nodes exist. In this case, the DRN nodes 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 user.

On the other hand, thick/three-level LSN networks contain DDN nodes in addition to the BSN and DRN nodes. Multiple DDN nodes are placed at regular intervals in the network. Although in these kinds of networks, the placement of the BSN and DRN nodes is not linear, the DDN nodes are aligned in a linear fashion. Once the data is collected by a DRN node, it is then routed through the other DRN nodes to the nearest DDN node. The DDN nodes will then transmit the data to the control center using the technology which takes advantage of the existing communication infrastructure as is the case with its counterpart, thin/three-level LSN network which was mentioned earlier. It is worthwhile noting here that the linearity of the DDN nodes is only a product of the linearity of the structure or geographic area that is being monitored. If this structure or geographic area is not linear in nature, then the DDN nodes can be distributed in a multidimensional form that is appropriate for that environment without much impact over the communication protocols that are being used. This is the case since the DDN nodes do not use a multi-hop approach to communicate with the control center. However, the linearity of the DDN node can impact the reliability provisioning of the network as described in later sections. This would be the case due to the fact that finding alternative DDN nodes for children-DRN-nodes in case of failure of their parent DDN node has to be done differently and can become more involved.

C. *Very thick LSNs*

In this type of LSNs, nodes at all levels of the hierarchy are random, but they exist between two parallel lines that extend linearly for long distances. Figure 7 shows a representation of this kind of sensor networks.

Only two types of very thick LSNs can be defined: very thick/two-level and very thick/one-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.

Very thick/two-level LSNs

These are sensor networks where the BSN as well as the DRN nodes are deployed in a two-dimensional formation. Figure 7, shows a representation of this type of sensor networks. The BSN nodes can use existing routing protocols to reach their parent DRN nodes which will then use a multi-hop routing strategy to reach the sink node at the edge of the network.

Very thick/three-level LSNs

In this type of LSN networks, the BSN and DRN nodes are deployed in a two-dimensional formation. However, due to the physical requirements of the network, the DDN nodes are deployed in a linear structure. In this category, at the lower levels, the BSN and DRN nodes can use the existing multi-dimensional routing protocols to reach their corresponding DRN and DDN parent nodes respectively. Once the data arrives at the DDN nodes, they can perform different types of compression and optimization processing of the data then transmit it to the central station using various technologies that might be more available in that region of the network as is the case in the previous topologies.

VI. Conclusions and Future Research

WSNs has a vast amount of environmental, military, commercial, and health care applications. This paper presented LSNs, which constitute a new category of WSNs where the nodes of the network are aligned in a linear structure. The paper identified some LSN applications and offered a classification of the different categories of such networks. The classification was done from a topological point of view, which included thin, thick and very thick LSNs as well as from a hierarchical point of view, which included one-, two-, and three-level LSNs. The paper also motivated the need for more research in this important area, which involves the design of networking protocols that take advantage of the linearity of the network in order to increase reliability, efficiency, and network lifetime.

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