PJET, Vol. 3, No. 1, October 2024: 38-49

Poly Journal of Engineering and Technology

journal homepage: https://journals.bdu.edu.et/index.php/PJET/index

ORIGINAL ARTICLE

Wireless sensor network node deployment strategy in the case of Ethio-Djibouti railway

Temesgen Getnet Fenta [1], *Edom Tsegaye Desta*[2], *Fareeza Fayaz* [3]

[1] Faculty of Electrical and Computer Engineering, Bahir Dar Institute of Technology, Bahir Dar University, Bahir Dar, Ethiopia

[2] Faculty of Electrical and Computer Engineering, Bahir Dar Institute of Technology, Bahir Dar University, Bahir Dar, Ethiopia

[3]Department of Biomedical Engineering, Dr. M. G. R. Educational and Research Institute, Chennai, India.

ABSTRACT

The EthioDjibouti route is a standard gauge international railway with a single track covering 639 kilometre s of the total length. This paper introduced Wireless Sensor Networks for the Ethio-Djibouti route, for their advantage of low cost, ease of complexity in installation and maintenance, low energy consumption, increased line capacity, and real time monitoring data. But, depletion of nodes energy is a major concern since it creates a phenomenon called "Energy Hole", which decreases the lifetime of the network. Non-uniform node deployment strategy is used to mitigate the problem of network lifetime. It is a random node deployment technique which allows non-uniform distance between nodes. And the nodes create shortest paths between neighbouring nodes to ensure data transfer between source node and destination node with reduced power consumption, which in turn minimizes the effect of energy hole. In the MATLAB computation result the optimum communication range is twice of the sensing range of the sensor nodes.

Keywords: Non-Uniform Node Placement Algorithm, Wireless Sensor Network, Transmission range, Communication Range, Energy Hole, Signalling

https://doi.org/10.20372/pjet.v3i1.1877

Corresponding Author: Temesgen Getnet

Faculty of Electrical and Computer Engineering, Bahir Dar Institute of Technology, Bahir Dar University, Bahir Dar, Ethiopia

Email: getnettemesgen@gmail.com

1. Introduction

Through the Addis Ababa-Djibouti Railway Ethiopia conducts ninety-five percent of its commercial transactions through Djibouti. Railway signaling together with efficient communication systems play a vital role for optimizing freight transport while guaranteeing safety operations and solving capacity-related issues. Automatic Block Signaling (ABS) along with European Train Control System (ETCS) faces existing operational limitations. The effectiveness of ABS systems comes with an increased number of relays per track section thus making the system difficult to maintain. The dependency of ETCS on GSM-R leads to limitations because this technology experiences interference and capacity restrictions as well as inefficient circuit-switching mechanics that constrain future growth potential. This paper evaluates the shortcomings of ABS and ETCS within the Addis Ababa-Djibouti Railway while developing a premium signaling and communication framework that enhances operational effectiveness and augments cargo capability and enables easy future infrastructure development.

Overview of Ethio-Djibouti railway line [8]

A wireless sensor network (WSN) is a network of autonomous, geographically dispersed devices that use sensors to collaboratively monitor. These nodes are tiny electronic components with sensing, communication, and processing capabilities. Data are often sent to the server to track the environment or the necessary phenomena. In order to cooperate transfer their data to a sink or central place where it can be viewed and evaluated, wireless networks monitor environmental or physical factors such as sound, temperature, pressure, vibration movements, or contaminants [2].

In the paper [3], shows the main drawbacks of GSM-R technology which will help in designing LTE radio coverage network for the Ababa-Djibouti route. LTE can be a reasonable replacement for GSM-R. However, a dedicated frequency band must be allocated to LTE-R to prevent any interference with public mobile networks, and this requires a huge cost. Hence, our signaling system has to adopt a new, effective and cost efficient mechanism.

This paper [4] proposes a system that utilizes a combination of sensors to constantly monitor railway tracks and detect any potential hazards. The proposed system uses ultrasonic sensors to detect cracks and infrared sensors to detect obstacles on railway tracks. The GPS location of the detected hazard is also recorded, and communication is facilitated through a GSM modem. One potential drawback of the proposed system is the communication system require compl ex installation and off-hour maintenance.

In this paper [5] different methods for railway maintenance and inspection are proposed and a new algorithm that uses wireless acoustic sensors to detect cracks and breakages in railway tracks. The system is designed using the Laboratory Virtual Instrument Engineering Workbench (LABVIEW). The proposed system relies on wireless acoustic sensors, which may require frequent maintenance and calibration to ensure accurate detection.

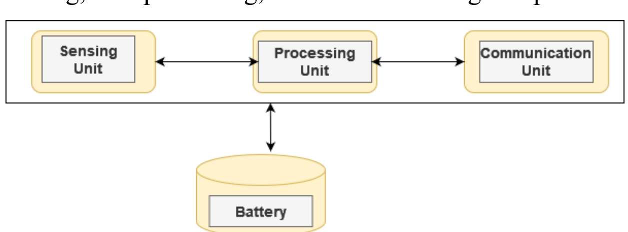
The paper [6] proposes a system that use Wireless Sensor Networks, RF, and Wi-Fi communications to monitor and track real-time parameters of trains. The proposed system has the potential to significantly improve train safety, security, and reliability by providing real-time monitoring and tracking of parameters. However, the hardware and software required for telemetry systems can be expensive, ongoing mainte ance and upgrades can also be costly. Another potential problem is data loss or corruption. Finally, telemetry systems may also raise privacy concerns if they are used to collect and transmit sensitive data.

The paper [7] proposes an optimization of railway tunnel radar defect detection through the combination of multisensor technology and active interference suppression algorithm to optimize railway tunnel radar defect detection. A railway tunnel detection simulation experiment is conducted using the multisensor system combined with the active interference suppression algorithm. The experimental results are analyzed to determine the accuracy of the proposed method. The experimental results show that the use of multi-sensors combined with active interference suppression algorithm to optimize radar detection can improve the accuracy of railway tunnel defect detection. The detection accuracy of this paper has reached 98.8%, which is a significant improvement over traditional methods. However, the interference suppression algorithm is that it may not be effective in all situations. The algorithm is designed to suppress unwanted signals and noise, but it may not be able to completely eliminate all interference.

In the case of Ethio-Djibouti Railway, the deployment strategy of WSN nodes is a critical factor that affects the overall performance of the system. The related work suggests that a strategic deployment of WSN nodes can improve the reliability and efficiency of the railway system. The placement of WSN nodes should be carefully planned to ensure maximum coverage, minimal interference, and optimal network connectivity.

2. Methodology

Wireless sensor networks consist of a large number of small battery-operated devices with sensing capabilities. These tiny sensor nodes, consist of sensing, data processing, and communicating components.



Overall System Architecture

In this paper the overall advantages of wireless sensor networks for the Ethio-Djibouti route are described. The topography and landform of the route is investigated to decide the type of node deployment strategy for the route. Using non-uniform node deployment technique, the optimal communication range in between the source and destination stations is obtained.

A. Wireless Sensor Networks for Ethio-Djibouti Route

The Ethio-Djibouti route is an international standard gauge railway line composed of both single and double track lines. The single-track line with passing loops covers wider range of the route, which has a higher possibility of head-on conflicts between outward and inward running trains. In systems like the railways which has no tolerance for failures, the existing signaling system have safety and reliability and economic disadvantages. The existing signaling system of the route is Automatic Block Signaling and ETCS level 2, which has high construction cost due to the requirement of many signaling devices for a complex control to transmit electronic information using many signal cables. The other main issue is the use of block working, which has the following problems: slow operation of trains, high construction cost, and unexpected disaster that it causes in case of any failure in any part of the system.

Hence, the line needs an efficient and effective signaling mechanism to utilize the railway track safely, efficiently and with reduced cost for both freight and passenger trains. Introducing Wireless Sensor Networks for this route will then be profitable since they provide a system with low cost, ease of complexity in installation and maintenance.

Some of the benefits of the WSN signaling system are listed below [8].

- *For congestion mitigation*: In existing signaling system second train cannot be departed from the source station until first one reaches the next station on the track.
- *Accurate train positioning system*: By using WSN based signaling system an accurate view of train locations can be displayed to the enquiry handler on enquiry counter and the person there can handle passenger's queries more efficiently. This system avoids slow manual telephonic communication between stations.
- *High degree of safety*: Railway system has a very low tolerance for accidents, because of the potential big number of injury and death, huge financial losses and even worse social effects. Proposed system achieves a high degree of safety which one of the most important objectives of railway signaling system.
- *No visibility problem*: Existing Railway signaling system has the biggest drawback that it does not work accurately in bad weather like foggy days because it decreases the visibility of the signals but the signaling system will work very fine in any kind of weather condition and drivers will get all the information on their system screens.
- *Allow automation of the railways*.

However energy consumption is an issue, the above benefits can be exploited using proper node deployment and mitigation techniques.

B. Topography and Landform

Studies in the Ethio-Djibouti railway route divide the total route into three sections based on the topography and landform of the route. The first section from Sebeta-Mieso belongs to the Ethiopian Plateau Platform and low mountain shallow hill landform, the second section from Mieso-Dewele belongs to the Ethiopian plateau platform and shallow hill landform, and the third section from Dewele-Nagad belongs to the alluvial plain, hills and plateau landform. In the Fig. 3, 4, and 5 below the landform of the route is shown for 3 different sections of the line.

Mieso - Dire Dawa Section [7]

Dire Dawa - Dewele Section [7]

Dewele - Nagad Section [7]

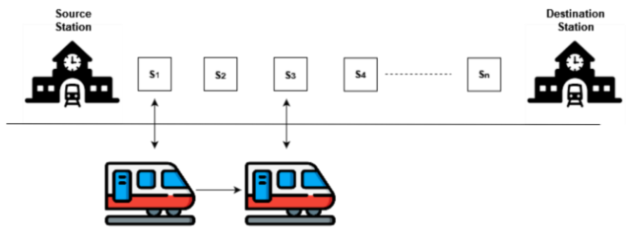
In the above figures it is shown that, different landforms are seen in the three different sections based on forest coverage, elevation, etc.

A. Proposed System

The system performs optimizations on base station deployment together with sensor development and network structure selection and transmission protocols to achieve optimised railway communication performance. Energy-efficient node deployment is prioritized. The signal processing begins at source nodes then uses trackside sensors for transmission to train sensors where the data is processed before final display. The method provides speed and location monitoring capabilities to train sensors through their direct connection to tracking units. The processes used are as follows [8]:

After receiving the departure signal from the source station the train immediately communicates its location and speed data to trackside sensors found in nearby areas. The trackside sensors transmit information instantaneously to both stations allowing the source station to grant departure permission to following trains ahead of time. The system permits numerous trains to run on shared tracks because it utilizes real-time position data. The existing slow telephone-based system is replaced by station-to-station data transmission that occurs without delays through sensor network systems.

In figure below, S shows the sensors.



The sensors deployed along the railway tracks will obtain power from electric lines and operate at 200-meter distances which would need up to 100 sensors for each 20-kilometer stretch. The sensors operate in an ad hoc system which functions as a replacement for present-day telephonic station communications. The sensors installed in each train use intelligence to present immediate data that assists the driver. Smooth communication and full sensor network coverage demands additional 32 stations to supplement the network across the railway length of 743.245 kilometers and its 45 existing stations.

Summary of Required Number of stations

Section	Length (Km)	Number of Stations Required		Total
		Initially built	Additionally required	
Sebeta-Adama (Included)	113.836	7	5	12
Adama (Excluded) - Mieso (Included)	213.418	12	10	22
Mieso (Excluded) - Dewele (Included)	334.014	21	13	34
Dewele (Excluded)- Nagad (Included)	81.977	5	4	9

For simulation two sites from the first section of the route (Sebeta-Adama) with a distance of 16Km apart are selected as a place for source and destination nodes. So, the number of nodes to be deployed will be 80.

C. Node Deployment

Node deployment is a fundamental issue to be solved in Wireless Sensor Networks (WSNs). A proper node deployment scheme can reduce the complexity of problems in WSNs. A sensor network generally consists of several tiny sensor nodes and a few powerful switch nodes also called base stations or sink. The nodes in the sensor network are compactly set up in a large area and communicate with each other through a wireless media. While working as team member these tiny sensor nodes are able to achieve worthy task of big volume. Information gathered by and transmitted on a sensor network of wireless networks describes conditions of physical environment of an area where the sensor network is setup. In WSN nodes are deployed according to the demand of application. In randomized way, the nodes are scattered randomly. This causes several issues such as optimal clustering and coverage. The position of the sink node or cluster head is an important factor in terms of energy efficiency.

Sensor nodes are small in size so they have limited power supply to the overall process of sensing, processing and transmitting the information. The lifetime of the sensor node is totally dependent on the battery. Once the battery is depleted the sensor node will be dead and it causes change in topology re-routing of data. The other key issues that needed to be defined are data delivery models and data aggregation.

Node deployment means placing sensor nodes that fully covered the target area and ensure connectivity to the sink node. The area to be monitored is said to be fully covered if every node within the sensing range is a neighbor to at least one node. Each node will sense events within its sensing range and transmits this information to the neighbors located in its communication range this will guarantee connectivity between nodes. The wireless sensor network is said to be connected if there is at least one path between the source and each sensor. Coverage without full connectivity will decrease quality of WSN because if connection is lost, there will be no guarantee that the data will arrive at the destination. Equation (1) defines Sensibility of nodes, where d (i, j) - is the Euclidean distance between neighboring nodes, C and k are positive sensor dependent constants.

$$(S, N) = C / \, d\,(i, j)^k \qquad (1)$$

The network coverage rate of a given area depend on the number of tasks performed by the nodes over the total number of tasks dedicated to the sensor nodes in the specified area of monitoring. Two nodes say i and j are connected, if their Euclidean distance is less than or equal to the communication range.

$$d\,(i\,, j) \leq R_c \qquad (2)$$

The network connectivity rate can be defined as the ratio of the number of nodes that can communicate with the source (destination) nodes to the total number of nodes.

D. Non-Uniform Node Placement Algorithm

The nodes can be deployed in the route either using uniform deployment method or non-uniform deployment method. In a uniform deployment method distance between two adjacent nodes on the same side of the line is equal and the number of sensor nodes to be deployed in a given monitoring area should be equal. In case of the Ethio–Djibouti railway line, the topography and landform of the route includes areas covered with mountain, hilly areas, areas with non-uniform percentage of forest coverage, elevation of road surface and also route in urban and remote areas.

The number of sensor nodes to be deployed in a given area will mostly depend on these factors since these applications demand high data transmission accuracy. To achieve this we need the sensors to communicate successfully with one another regardless of the type of area they are deployed in. Hence a relatively more number of sensor nodes needs to be deployed in a landform with non-linear appearance. In order to prevent loss of connectivity and improve the lifetime of the network.

In non-uniform node deployment, the track is defined as a rectangular monitoring region with length L and width h which is divided into sub monitoring regions of different areas. In areas with mountain, hills, or adequate forest coverage, the sensor nodes will send and receive relatively huge amount of data. To prevent unfair use of nodes and the creation of energy holes, the number of sensor nodes to be deployed in such cases must be increased relatively.

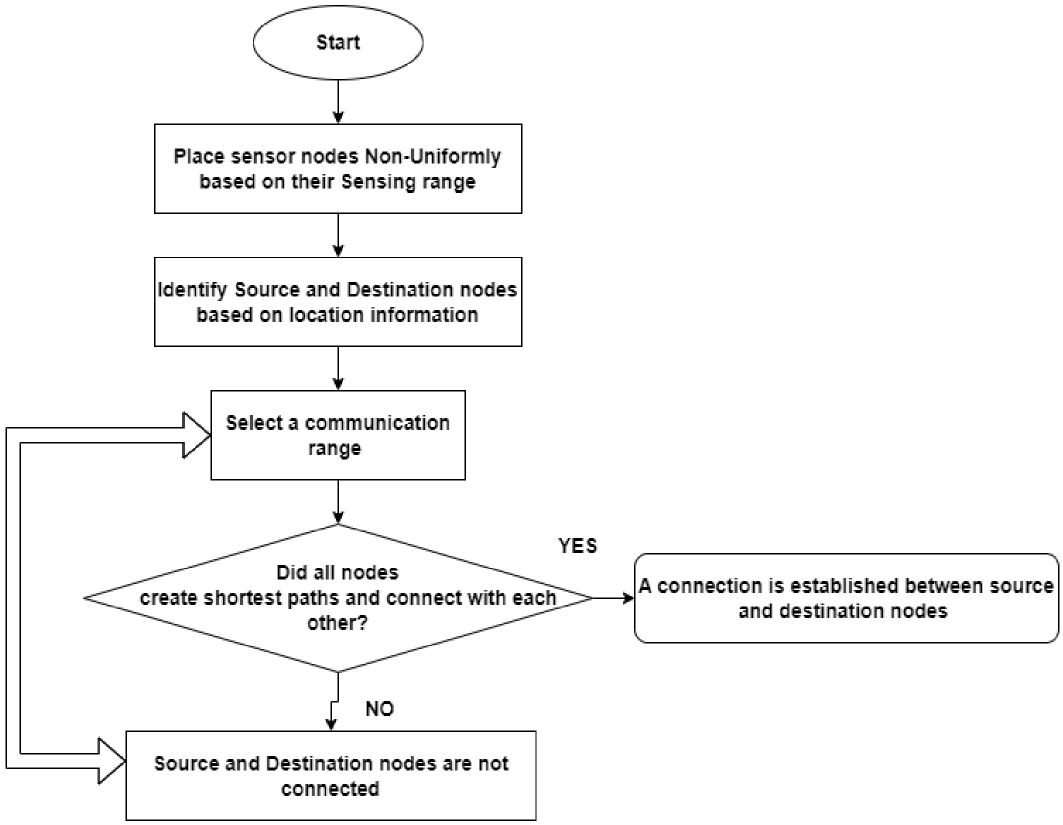
But the non-uniform deployment strategy allows nodes to be placed based on the characteristics of the area that they will be deployed in ensuring high data transmission accuracy by making the sensor nodes data acquisition rate uniform in each of the sub divided monitoring areas so that no sensor node will be used unfairly so this will minimize the occurrence of energy holes and increase the networks lifetime. This can be explained mathematically using the recursive formula in (3). If Ni is the number of sensor nodes to be deployed in a single region, Ai is the area of a single region, and (d0, d1, d(i-1)) are distances between the sensor nodes. Then the equation can be given by:

$$\frac{N_2}{N_1} = \frac{A_2}{A_1} = \frac{d_1}{d_0}$$
$$\frac{N_3}{N_1} = \frac{A_3}{A_1} = \frac{d_2}{d_0}$$
$$\frac{N_i}{N_1} = \frac{A_i}{A_1} = \frac{d_{(i-1)}}{d_0} \qquad (3)$$

Thus, in non- uniform deployment algorithm, the Euclidean distance between two neighbouring nodes will be described by the equation in (4). Where i and j ranges from 1: number of nodes in the network

$$d\ (i, j) = \sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2} \qquad (4)$$

In this model, the distance between nodes is not equal. The main idea behind this method is that, data acquisition rate of nodes in a monitoring region is the same hence; gap in consumption of energy will be reduced, which will in turn maximize the network lifetime. The general procedure for this algorithm is shown in the flowchart diagram below.



Flowchart of the non-uniform algorithm

3. Result and Discussion

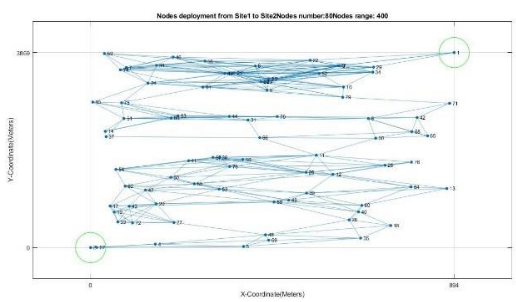
The non-uniform distribution of the nodes in a single section of the route from Site1 to Site 2 which is 16 Km long.

Simulation Parameter Values

Parameters	**Values**
Number of nodes	80
Number of neighbor nodes	5
Communication range	50-1000
Attenuation	1.8
Minimum energy	78.8
Maximum Energy	99.8

Energy consumption per circle	0.32
Energy recovery per circle	0.22
Energy factor	0.01
ST energy	1000

At a very low communication range, connection between the source and the destination will not be established.
As shown in the figures 8, 9, and 10 sufficient connection is established at 400m range, the source and destination nodes are connected. At increased communication ranges of 600m and 1000m extreme paths are established between sensor nodes.



Result at 400m communication range

Final Result at communication range of 400m, 600m and 1000m

Communication Range (meters)	**400m**	**600m**	**1000m**
Number of shortest paths	5	31	47
Number of hops (router nodes)	16	12	8
Number of packets sent	10789	39137	53555
Total number of dead nodes out of the total number of nodes deployed (Until the network losses connection)	3/80	29/80	44/80

As we can see from the above table, number of shortest paths, number of packets sent, and total number of dead nodes increased with increased communication range. As a result, there are fewer hops or router nodes that the data from the source node must go through before reaching the destination node.

The number of shortest path ways generated at a 400m communication range is the same as the predetermined number of neighbor nodes. There were a lot of router nodes utilized to transfer data from the source to the destination, but only three nodes are dead.

The reason that more than half of all nodes are dead at greater communication ranges is that, if the energy required for data transmission to reach a node at a distance of X meters is Y joules, then the energy required to reach a node at a distance of 2X joules will be 2Y. Nodes thus perish with each packet of delivered data.

4. CONCLUSION

In Ethio-Djibouti railway route high degree of safety and reliability is highly demanded due to the nature of the route. WSN provide an economic solution to provide a real time data for a reliable operation. The existing wired signaling system prevents utilization of full capacity of the system and will hugely delay the return of the investment.

This paper proposed a non-uniform deployment strategy for WSN in Ethio-Djibouti railway line. In situations like the railways, the track should be sensed in every few minutes range and neglecting a reasonable amount of sensed data might cause hazardous situation. Hence, nodes should be dispersed to cover the monitoring area fully and send real time information. Proper selection of the node deployment strategy will guarantee to exploit the WSN fully.

Finally, keeping the communication range at optimum, and using clustering algorithm that allows node scheduling will be a perfect choice for future expansion of the proposed strategy.

Author Contributions

Edom Tsegaye, Temesgen Getnet, Fareeza Fayaz, discuss about the overall model of the paper, designs the system model, and simulate the results in MATLAB.

System model, parameter setting, simulation, result and conclusion are all done in collaboration.

All the authors write the draft of the paper and edit the final documentation.

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