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**WIRELESS SENSOR NETWORKS DESIGN FOR THE
SIGNALLING SYSTEM OF ETHIO-DJIBOUTI RAILWAY
LINE**

**A Thesis in Degree of Master of Science in Electrical Engineering for
Railway Systems**

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A Thesis

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

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ABSTRACT

The Addis Ababa-Djibouti route which is the backbone of the Ethiopian Rail Network has both single and double tracks, serves to both freight and passenger trains. Moving trains at this track have different speeds, passenger trains relatively run at high speed. Introduction of Wireless Sensor Networks for the signalling system in the Ethio-Djibouti railway line will be a perfect choice to ensure safety, efficiency, increasing line capacity, with reduced power consumption and cost relative to the current system.

Congestion mitigation can be solved by shortening the train interval on the basis of earlier and correct information of trains. Thus we can run 3 or 4 trains in between two stations at a time. Rapid train which cuts the trip time will provide efficient passing facilities. Direct through operation over multiple lines will improve the traffic convenience. 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. Thus, it achieves high degree of safety.

Ring routing protocol is used, which enables to have an energy-efficient system and it is compared with other routing techniques such as Line Based Data Dissemination and Railroad method. And a Gravitational Search Algorithm (GSA) will be conducted to achieve a low cost center. For the future, it leads to automation in railway engines and trains can be operated without drivers and manual interference. Also the proposed system is easy to deploy and maintain in case of any failure.

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LIST OF ACRONYMS

3GPP	Third Generation Partnership Project
ATP	Automatic Train Protection
BSC	Base Station Controller
BSS	Base Station Subsystem
BTS	Base Transceiver Station
CBTC	Communication Based Train Control
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
EIRENE	European Integrated Radio Enhanced Network
eMLPP	Enhanced Multi-Level Precedence and Pre-emption
EoMA	End of Movement Authority
ERA	European Railway Agency
ERC	Ethiopian Railway Corporation
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
FA	Functional Addressing
FDD	Frequency-Division Duplex
GD	Gaussian Distribution
GSA	Gravitational Search Algorithm
GSM	Global System for Mobile Communication
GSM-R	GSM-Railways
HLR	Home Location Register
HSPA	High Speed Packet Access
HSS	Home Subscriber Register
ICI	Inter-Carrier Interference
LBDD	Line Based Data Dissemination
LDA	Location Dependent Addressing
LTE	Long Term Evolution
MOO	Multi-Objective Optimization
MOP	Multi-Objective Problem
PS	Pareto Set

PSD	Packet-Switched Data
PSO	Particle Swarm Optimization
WiMAX	Worldwide Interoperability for Microwave Access
WSN	Wireless Sensor Networks

Chapter 1 INTRODUCTION

1.1 Background

The Addis Ababa-Djibouti Railway is a standard gauge international railway that serves as the backbone of the new Ethiopian National Railway Network. Ethiopia is a country which is locked with land borders and has no link to the sea. Hence, this railway line gives the country access to the sea, by linking Addis Ababa which is the capital city of Ethiopia with Doraleh which is the port of Djibouti. More than 95% of Ethiopia's trade passes Djibouti accounting for 70% of the activity at the port of Djibouti. The railway is expected to transport 24.9 million tons of freight in 2025, alongside increases in cargo capacity at the port of Djibouti.



Figure 1-1: Ethio-Djibouti route: red and purple line [1]

1.1.1 Overview

Type	Heavy Rail
System	Ethiopian Railway Network and Djiboutian Railway Company
Status	In trail service
Location	Ethiopia, Djibouti
Termini	Sebeta, Ethiopia; Port of Doraleh, Djibouti
Stations	25(Passengers)

Operation	full testing on 9May,2017
Line Length	756Km (470mi)
Number of tracks	Single-/double-track
Track gauge	1435mm(4ft 8 ½ in) standard gauge
Loading gauge	5300mm
Electrification	Overhead line 25Kv AC/50Hz
Operating Speed	120Km/h (75mph) (Passenger), 80Km/h (50mph) (freight)
Signalling	Automatic block and ETCS-2
Highest elevation	2356m (7730ft)
Maximum Incline	1.83%

Table 1-1: Overview of the line [41]

Automatic block signalling (ABS) was invented in America and first used by the Eastern Massachusetts in 1871. It is a railroad communication system that consists of a series of signals that divide a railway line into a series of sections or blocks. It feeds the information of the current state of the track to approaching trains.

In ABS system, each signalling system requires one relay for its own track and an additional relay for each block in its control length. Essentially the circuit works by applying a voltage across the two rails in a track section. The two major downfalls of this system are:

- I. The system basically works by applying voltage between the trains, wheels and the rail. Hence, any blockage in the flow of current through the axles can disable the system from the detecting trains and therefore can lead to a very serious problem.
- II. Loss of connection or damage in the wire which connects the earth rail to the circuitry may result in that part of the wire to loss electrical contact which in turn makes that section to be idle or not be able to detect trains.

European Train Control System (ETCS) is the signalling and control component of the European Rail Traffic Management System (ERTMS). ETCS is the standardized signalling, control and train protection system for ERTMS. It offers a signalling system

that enables high speed trains to cross borders seamlessly. ETCS has three levels that defined based on the functions and features implemented on each level.

Level 1 is about the communication between the track and train, level 2 is about the communication between radio block center and the train whereas level 3 applies the concept of moving block. ERTMS allows smooth migration from one level to another. However, Picking up one ETCS level to operate the network depends on factors such as: the maximum speed allowed, capacity upgrades, existence of another signalling system and locating GSM-R equipment.

Movement authority and other signal aspects are displayed in the cab for the driver. The train detection and train integrity supervision still remain in place at the trackside. Train movements are monitored continually by the radio block center using the track side derived information. The movement authority is transmitted to the vehicle continuously via GSM-R together with speed information and route data.

GSM-R utilizes circuit switching technology which limits the radio network capacity that is once the channel is dedicated between two nodes it cannot be shared for other services. As indicated in some studies, GSM-R causes severe interference and capacity limitations. Hence, GSM-R cannot offer an effective solution for the future expansion either by supporting more trains or providing supplementary services, hence new system is needed.

In this paper a safe, cost effective and efficient solution is introduced for the signalling system of Ethio-Djibouti railway line by increasing the line capacity.

1.2 Statement of the Problem

Addis Ababa-Djibouti comprises both single and double tracks, which serves to both freight and passenger trains. The longest path of route is a single track it is only from Sebeta- to- Adama is a double track. And the trains moving in this total track have different speeds, passenger trains moving at 120 Km/hr and freight trains moving at 80Km/hr. Here the point is that the trains moving in the same track has different speeds. Also since they are moving in a single track there is a high degree of occurrence for head-on conflict of the outward and inward running trains.

However with a powerful signalling and control system the single track can be perfectly utilized by setting a proper management for the train collision, increase route capacity and supply proper power distribution.

The station master's responsibility is to provide a complete arrival of the train. Hence, any obstacle in the accomplishment of this task will result in a disastrous situation.

Block working with a task of establishing one train at a time is a system that has many signalling devices and hence has high construction cost. These signalling devices transmit electronic information for controlling the signal which will be transmitted using signal cables. Hence, many signalling cables are needed to realize a complex control.

Another problem is initial cost and maintenance costs of the system. Since, to transmit these signals a complex control is used which is realized using so many cables.

For information to be transmitted efficiently cables must be correctly connected, any error in connection will result in a crash of the train and an accident which leads to a derailment. Also the long downtime of this system will only be solved using a monitoring and maintenance system that can get the information about signalling equipment in real-time.

The problem in coverage and capacity of GSM-R is also another reason for deploying an efficient system.

1.3 Objective

1.3.1 General Objective

Study and Design Wireless Sensor Networks for the signalling system of the Ethio-Djibouti railway line

1.3.2 Specific Objective

- Study literatures about the current railway signalling system used in Ethio-Djibouti line.
- Reviewing literatures on railway signalling systems especially on emerging technologies.

- Comparing and selecting the systems based on key parameters like safety, cost, efficiency, power consumption and future development.
- Designing the system model: deciding the appropriate number of sensor nodes and number of trains in between stations.
- Selecting routing protocol, which is energy efficient.
- Study and use gravitational search algorithm to find the center in the routing protocol, which reduces cost and energy of the system.

Testing the model with Matlab software is the last step.

1.4 Literature Review

[1] Teklebrhan Aregawi (2015/2007)

This thesis designs a GSM-R radio coverage network for automatic train protection (ATP) system in the Ethio-Djibouti route. As studies indicate GSM-R is the standardized radio network for ERTMS and is stated in research papers as currently used in 38 countries in Europe, Asia and Northern Africa. From these areas data's showed that inference issues have been found in 400 locations around Europe from LTE mobile operators.

In this paper, the detailed geographical and morphological nature of the route is explained using actual pictures taken from the sites. In which the author used this data to calculate the radio coverage of the real route. To estimate the Link budget of the network Path loss model is used. From software applications MATLAB simulation software is used to select the appropriate path loss model and Atoll software is used to optimize the overall network.

However, there are concerns regarding the GSM-R capacity as the number of dedicated channels is not enough for future scaling. Added to the inference issues, GSM communication system is considered as outdated technology and the current trends toward the LTE. GSM-R in Europe as mentioned above operates in a dedicated frequency band, which introduce an interference issues caused by neighboring frequency bands and also due to its limited capability.

[2] Tewodros Abebe (2016)

This next paper analyzes, design and dimension the WiMAX network for advanced real-time two-way communications services for the case of Addis-to-Djibouti. Basically the study is concentrated on WiMAX network coverage and capacity calculation. Based on the calculations the reasonable choice of positions is made for the transmitters along the route.

The author selected qualitative, quantitative and analytical data analysis methods. Among the data presentation methods graphs, charts, tabular and word formations are included. The work is discussion concerning only, and the final outputs of the study focus on the technical measures which enable the Ethiopian Railway Cooperation to update the speed of the communication system.

However power consumption is the first issue of WiMAX networks and it is clearly stated in researches that the power consumption of each access point of a WiMAX network is ranged between 9W-10.6W. This is a remarkable problem for Ethio-Djibouti railway line because of the long route is included in the rural areas where these much power will be very hard to provide. The cost of network itself is another problem.

[3] Farah Mourad (2016)

In the final paper the disadvantages of GSM-R technology are discussed and used as inputs in designing LTE radio coverage network for the Ethio-Djibouti route. Among the tasks that are accomplished in this work are: analyzing capacity and features of the LTE network, selecting LTE radio network design parameters and algorithms, selecting a path loss model for link budget calculation, and selecting Atoll software for simulation and optimization of the overall network.

From the result of the work it is seen that the whole line is covered in terms of signal strength. And the appropriate data rate capacity which is enough for the proposed applications is achieved.

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 signalling system has to adopt a new, effective and cost efficient mechanism.

Summary of Literature Review

Paper	Objective of thesis	Method used	Constraint	Proposed Solution
[1]	Designs a GSM-R radio coverage and capacity planning of the route	Okumura-Hata model, to model three different cell radius of the three terrain type and Atoll Software	Inference between domestic GSM and other networks with GSM-R network, also Insufficiency of data and related reference materials	Propose a solution how to optimize the wired network using a GSM-R radio communication
[2]	Attaining safe transportation	Cost-231 Hata Model	Difficult to address extra services in order to satisfy the passengers demand of BW real-time control of station and train speed	Reduced risks due to same cell radius calculated along throughout route
[3]	Design LTE radio coverage and capacity for Addis-Djibouti route	Okumura-Hata model as a propagation model	End-to-End transmission performance offered by LTE network or how to provide voice communication over LTE	Access network and interface dimensioning of LTE network

Table 1-2: Literature review summary

1.5 Methodology

Allocation of Base Stations, the design and range of sensor devices, the network model, network topology and transmission techniques, communication medium or short and long range data transmission will be carefully selected. Also Routing protocols are carefully surveyed to choose the energy efficient protocol.

The signalling system consists of four basic components:

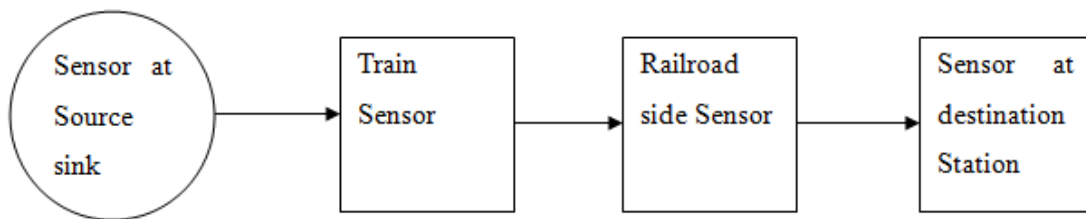


Figure 1-2: Signalling components of the system

Sensor at source sink: Initiates signals and at the time of departure it sends a departure signal to the train

Train sensor: send signal about its position and speed to the nearest sensor on railroad side

Railroad side sensors: receive the signal from the train sensor; it transmits these signals to both the stations on their sides in ad-hoc manner using other sensors on track.

Hence, source station can send a signal for departure to another train on the same track before first train reached the destination station. In this way we can run multiple trains in between two stations on the basis of location signals send by the trains.

Stations can communicate with each other using sensor network and send data when required. This communication between stations is done telephonically in existing system which is very slow and complex.

1.6 Scope

This paper studies in detail the current method of signalling in the Ethio-Djibouti railway line and also the related works. Wireless Sensor Networks architecture, parameters and their mathematical representations are studied briefly. Finally to weight the merits of the network above its demerits, an optimization process is used. From the Swarm Intelligence Optimization family, Particle Swarm Optimization is used for optimization of optimal deployment, node localization, and clustering and data aggregation.

1.7 Thesis Outline

Chapter 1 Introduction: In this chapter background of the line, the problem statement, objective, and review of related works, methodology and scope of the thesis are covered.

Chapter 2 Railway Communication: In this second chapter introduction of railway communication, topography and landform of the route, main technical standards of the route, train traffic of the line, and alternative communication technologies will be covered.

Chapter 3 Wireless Sensor Networks: In the chapter of Wireless Sensor Networks, Introduction to Wireless Sensor Networks, system model including system architecture, signalling in the proposed system, merits of the proposed system, node deployment in WSNs and necessary calculation will be discussed in detail.

Chapter 4 Routing and Lifetime of a WSN: In this 4th chapter routing in WSNs, routing algorithms including LBDD, Railroad method and ring routing are covered along with gravitational search algorithm, and lifetime of a WSN.

Chapter 5 Multi-Objective Optimization (MOO): In this chapter, Multi-Objective Optimization including the parameters (12 basic parameters), techniques of MOO, and optimizers (Particle Swarm Optimization and Gaussian distribution) will be well discussed.

Chapter 6 Results, Conclusions and Recommendations: Results of the GD and PSO Matlab simulation will be displayed. Also conclusion and recommendations are stated in the chapter.

Chapter 2 **RAILWAY COMMUNICATION**

2.1 **Introduction**

In the railway technology communication evolved from electrical telegraph towards many advanced technologies. Before wireless radio and color light signals put to use by advanced railway operations, the usual means for signalling in this transportation technology was hand signals, ball signals, and Aags, telegraph, semaphore, and position lights.

The advancement towards more reliable technologies leads towards digital wired and wireless networks such as Ethernet and GSM-R. With these advancements a new type of communication besides the usual one is introduced. In this system a real-time communication between the central traffic control unit and the computer unit of the locomotive can be achieved. So, these systems enable the user of the system to develop supporting supervision for the train drivers using command-control systems. The in-cab signalling is a feature supporting the driver by providing detailed information about the speed limits and the distance to the End of Movement Authority (EoMA). Since this information is now displayed right on the driver desk, there is no risk that a driver will miss a trackside signal.

The European Train Control System (ETCS) and the Communication Based Train Control (CBTC) are categorized under the category of communication-based command control systems. They can provide different kind of feature such as in-cab signalling. ATP also offers moving block operation which will reduce in trackside equipment and emergency communication. The Automatic Train Protection prevents the train from passing the stop signal which will significantly reduce risk of human error. Another type of CBTC systems is called Unattended Train Operation (UTO), which enables the perfect elimination of human drivers. These systems are highly supportive for high-speed railways such as high-frequency metro railways.

2.2 Ethio-Djibouti Railway Line

Addis Ababa-Djibouti railway line is located in the mountain areas between the central plateaus of Ethiopia and Djibouti border. The line originates westward from Sebeta at southwest of Addis Ababa. It runs eastward through Labu, Indode, Gelan, Dukem, Bishoftu, Mojo, Adama, Welenchiti, Metehara, Awash, Asebot, Mieso, Mulu, Afdem, Bike, Gota, Dire Dawa to Dewele, reaches Djibouti. Then it passes Ali-Sabieh and Holhol, and finally ends at Nagad [4].



Figure 2-1: Overview of Ethio-Djibouti Railway line [41]

Ethio-Djibouti railway line is an electrified railway line designed for both passenger and freight trains. The length of the whole international railway line from Sebeta-Nagad is 743.245km. The section from Sebeta -Adama (included) is double track railway, with a length of 113.836km, 7 stations, and an average distance between two stations 16.26km. The section from Adama (excluded) - Mieso (included) is single track railway, with a length of 213.418km, 12 stations, and an average distance between two stations 17.78km. The section from Mieso (excluded) - Dewele (included) is single track railway, with a length of 334.014km, 21 stations, and an average distance between two stations 15.91km. The section from Dewele (excluded) - Nagad (included) in single track railway, with a length of 81.977km, 5 stations and an average distance between two stations 16.4km. In the initial stage (2020), 20 stations will be constructed; conditions are reserved for construction of 5 stations in short term (2025) and 20 in long term (2035) [28] [4].

2.3 Structure and Landform of the Route

2.3.1 Sebeta-Meiso Section

The section from Sebeta-Meiso is governed under the Ethiopian landform and comprises many cities. It is a low mountain and shallow hill area with moderate forest coverage and river valley landform.

Around Awash it has a tunnel with 380m distance. The elevation of road surface is about 850~2300m. This section has a tunnel with 380m distance around Awash [28] [4].

2.3.2 Meiso -Dewele Section

The line from Mieso-Dewele belongs also to the Ethiopian plateau platform and shallow hill landform. Part of the zone has low mountain and river valley landform, the ground is wide and the topographical relief is not great. Meiso to Dire-Dawa has small hills with moderate vegetation coverage and the section from Dire-Dawa to Dewele has almost no vegetation coverage.

The elevation of road surface is about 700~1200m, and the relative elevation difference is scores of meters. The climate is hot and the surface tropical plant is scarce with coverage of approximately 10% to 30%. There is dry riverbed [1].



Figure 2-2: Meiso-Dire Dawa Section [28][4]



Figure 2-3: Dire Dawa –Dewele Section [28][4]

2.3.3 Dewele- Nagad Section

This section belongs to alluvial plain, hills and plateau landform. There are arid and semi-arid plain and desert with low altitude of usually 15~800m. It has low relative elevation and flat terrain. The vegetation is rare [28].



Figure 2-4: Gallile-Nagad Section

2.4 Main Technical Standards

Scope	Sebeta-Adama	Adama-Djibouti
Track Gauge	1435mm	1435mm
Number of mainlines	Double-Track	Single-Track
Speed Track Value	Passenger Transport 120Km/h; Freight Transport 80Km/h	Passenger Transport 120Km/h; Freight Transport 80Km/h
Minimum radius of curve	800m	800m
Maximum Grade	Ruling Grade 9%, Pusher Grade 18.5%	Ruling Grade 9%, Pusher Grade 18.5%

Type of Traction	Electric Traction	Electric Traction
Type of Tractive	Passenger Train: ss9* Freight Train: ss4*	Passenger Train: ss9* Freight Train: ss4*
Tractive Tonnage	Preliminary 3500T Long-Term 4000T	Preliminary 3500T Long-Term 4000T
Length of Arrival- Departure Track	850m(Dual-locomotive 880m)	850m(Dual-locomotive 880m)
Block Type	Semi-Automatic Block	Semi-Automatic Block

Table 2-1: Main Technical Standard of the Addis-Djibouti Line [28] [4].

*SS9: The Shaoshan 9 is a type of electric locomotive used on China Railways for passengers.

**SS4: The Shaoshan 4 is a kind of AC-powered electric locomotives used in China for freight.

2.5 Train Road traffic of the line

2.5.1 Freight Traffic Volume

Based on the analysis on economic development, foreign trade and port transportation of Ethiopia and Djibouti, the freight volume of each section along the line is shown in the table below [29]. It has been combined with the analysis on the current status and future development trend of the traffic corridor where the line is located, and substation traffic volume forecast of each station.

Section	Direction	2020	2025	2035
Indode-Adama	Up direction	530	780	1610
	Down direction	190	290	420
Adama-Awash	Up direction	439	697	1503
	Down direction	136	211	314
Awash-Dire Dawa	Up direction	456	775	1653
	Down direction	144	238	351
Dire Dawa-	Up direction	479	800	1700

Djibouti	Down direction	148	242	358
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Unit: 10^4t

Table 2-2: Freight Flow density of each section [29] [4]

The design traffic volume for the line shows that, the up direction (i.e. Djibouti Port~Addis Ababa) of cargo transport is heavy loaded, which fits the situation of resources and current transport condition of the country. Djibouti-Dire Dawa section possesses the maximum cargo traffic volume; freight flow density is 8 million tons per year in the short term and 17 million tons per year in the long term [29] [4].

2.5.2 Passenger Traffic Volume

The table below shows the density of passenger flow by section based on surveys undertaken by Ethiopia. The passenger movement in Addis Ababa-Adama section is very heavy. That is why this section is double track.

Section	2020	2025	2035
	Single direction		
	Density of passenger flow (10^4 persons/year)		
Addis Ababa-Adama	137.5	165	275
Adama-Dire Dawa	55	55	82.5
Dire Dawa-Dewele	27.5	27.5	55

Table 2-3: Density of passenger flow by section and pairs of passenger trains [29]

2.5.3 Total Train Traffic

The line is designed for both passenger and freight trains. Based on the forecasted freight and passenger traffic volume along the route, the organization of freight and passenger trains in each term stage is shown below.

Study year	Section	Pair of Trains (Pair/Day)			
		Passenger Train	Freight Train	Pick Up and Drop Train	Subtotal
Initial Stage	Sebeta-Adama	5	5	1	11
	Adama-Awash	2	5	1	8

	Awash-Dire Dawa	2	5	1	8
	Dire Dawa-Nagad	1	5	1	7
Short Term	Sebeta-Adama	6	7	1	14
	Adama-Awash	2	8	1	11
	Awash-Dire Dawa	2	9	1	12
	Dire Dawa-Nagad	1	9	1	11
Long Term	Sebeta-Adama	10	16	1	27
	Adama-Awash	3	17	1	21
	Awash-Dire Dawa	3	19	1	23
	Dire Dawa-Nagad	2	19	1	22

Table 2-4: Pair of Trains [30] [4]

A total of 60 trains will be moving along the line every day. Thirty trains will be moving in the up direction (Djibouti-Sebeta) and the other thirty will be moving in the down direction (Sebeta-Djibouti). 20 trains will be for train passengers, 2 trains for Pick-up and drop trains and 38 trains will be for freight trains.

2.6 Assessment of Alternative Techniques

2.6.1 Intrinsic worth and Imperfections of GSM-R

GSM-R is not a perfect choice for the case of Ethio-Djibouti railway line. Although it provides basic train operation and protection and also enough for the initial stage and the short term the GSM-R technology doesn't meet the long term forecast of Ethiopian Railway Corporation and also not appropriate for the range of single railway track lines in the total area. In addition to this the proposed communication network is a wired one, hence, the probability that some incident could happen is not risk of ignoring. If a problem happens, the communication system becomes compromised therefore the railway operation completely stops or works in a degraded mode reducing its efficiency.

To elaborate the demerits of GSM-R consider two basic reasons based on the discussion of studies conducted before and the recommendation of the Chinese whose are enrolled in this specific area of work.

First, the signalling system uses Semi-automatic block which is hard to handle when in the future the demand of the line increases above the forecasted one. Specifically in the section from Addis Ababa- Adama the demand will surely increase from the forecasted one this deduction is based on experience on the daily basis, due to this the section encounters a degraded line capacity.

Secondly, for the freight forecast of the Ethiopian Railway Corporation again taking as a sample the Addis Ababa- Adama it is expected to increase above the forecasted amount. Hence as a solution the Chinese come up with the idea of building a second track which is not cost effective. Rather, building an efficient system which will solve these problems and the like with the existing infrastructure is a perfect choice to handle this type of contradictions with the Ethiopian Railway Corporation forecast.

2.6.2 Universal Mobile Telecommunications System (UMTS)

Universal Mobile Telecommunications System (UMTS) is a third generation mobile cellular system for networks based on the GSM standard. Developed and maintained by the 3GPP (3rd Generation Partnership Project). It uses wideband code division multiple access (W-CDMA) radio access technology to offer greater spectral efficiency and bandwidth to mobile network operators.

UMTS is a third generation wireless telecommunication system. It is indeed the successor of GSM and GPRS and offers much more improvement over GSM-R. It uses a more evolved radio interface as well as the backbone network. Some countries like Australia adopted this technology. Although UMTS might be a good candidate for replacing GSM-R, the major performance comparison metrics are cost, reliability, safety, ease of complexity of the system. Hence, wired mediums are not much of a choice, rather consider advanced wireless and simpler systems. Our country Ethiopia is building the railway to enable the society get benefited from the affordable cost at the rate of high service reliability and safety hence, reducing the cost of building the signalling system is of high concern. There is an existing infrastructure so, an engineer should be studying about the availability of advanced technologies which will get rid of the complex circuits but not demanding additional infrastructure which will be built on the existing infrastructure.

2.6.3 IEEE 802.16 (WiMAX)

WiMAX systems provide an economic choice for the replacement of wired medium.

WiMAX is an industry trade organization formed by leading communications, component, and equipment companies to promote and certify compatibility and interoperability of broadband wireless access equipment that conforms to the IEEE 802.16 standards. WiMAX would operate similar to Wi-Fi, but at higher speeds over greater distances and for a greater number of users. WiMAX has the ability to provide service even in areas that are difficult for wired infrastructure to reach and the ability to overcome the physical limitations of traditional wired infrastructure. WiMAX was formed in April 2001, in anticipation of the publication of the original 10-66 GHz IEEE 802.16 specifications [20][26][4].

WiMAX is to 802.16 as the Wi-Fi Alliance is to 802.11. WiMAX constitute best candidate for railway communication considering its main feature [20] [26] [4]:

- I. WiMAX is a packet-switched technology offering large bandwidth and efficient data communication.
- II. Realistic data rates reach 16 Mbit/s, while theoretical ones reach 78 Mbit/s.
- III. Radio interface in WiMAX is based on Orthogonal Frequency-Division Multiplexing (OFDM), which is significantly more efficient and flexible than the TDMA mechanism used in GSM-R.
- IV. WiMAX supports a range of modulation schemes (up to 64QAM), which can be dynamically chosen based on the radio conditions.
- V. WiMAX offers group-calls and push-to-talk voice communication.
- VI. Multi-hop mesh networking is available, which could be used as a cost effective method for connecting remote base stations.
- VII. WiMAX also offers QoS mechanism for prioritizing different flows in the network, which is important if the transmission resources are shared between critical and non-critical applications.

Despite its numerous advantages, WiMAX did not have a large commercial success. Indeed WiMAX gained only about 25 million subscribers globally as the currently deployed WiMAX networks are usually small and they serve private institutions, local

communities or small towns [26]. As a consequence from the railway perspective, this may lead to higher maintenance cost since WiMAX cannot guarantee a long-term wide industry support.

2.6.4 Long Term Evolution (LTE)

Long Term Evolution (LTE) is the latest family of mobile communication standards developed by Third Generation Partnership Project (3GPP).

The key merits towards LTE are: The major change in LTE is the adoption of an all-IP approach. First, LTE network is based on packet-switched transmission. Hence, packet switched transmission is more flexible in managing available network resources, thus increasing network utilization and reducing waste of limited network resources. Second, the network infrastructure is simplified with fewer elements than in the GSM standard all based on a common technology (IP). This will help reducing the packet delay. Third, LTE includes Quality-of-Service mechanisms that provide packet differentiation. Fourth, LTE introduces a new radio interface that offers much higher spectral efficiency than any other legacy mobile communication standard. This is due to the advanced multiplexing (OFDMA), modulation (up to 64QAM) as well as usage of Multiple Input Multiple Output (MIMO). Lastly, LTE can operate in different bandwidths: 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz or 20 MHz (and more with carrier aggregation in LTE-Advanced).

Added to this merits, there are some network performance issues that should be evaluated. This includes:

1. The Doppler shift effect in LTE downlink and uplink channel performance

The subcarrier interval of OFDM in LTE standard shall allow avoiding the Inter Carrier Interference (ICI) on LTE performance.

2. The effect of high speed in resource scheduling

The radio resource management functionalities optimize the radio resource assignment by means of algorithms that schedule the channel use both in time and frequency domains. This scheduler process is based on the control signalling information provided by the user equipment in terms of ACK/NACK and channel state reports (CQI). In a high

speed environment, the channel measurements for channel estimation may not be able to adapt fast enough to channel variations and schedulers also lose the diversity gain, which decrease system performance.

3. Handover mechanisms in LTE

Depending on evaluation results, other types of handover mechanisms like soft handover ones to avoid packet loss while minimizing handover interruption time can be implemented. Hence, connection and re-association time shall be reduced while minimizing the handover failure rate in high speed environments.

Chapter 3 WIRELESS SENSOR NETWORKS

3.1 Introduction

The fundamental definition of Wireless Sensor Network is that they are smallest devices which have their own power source, processing unit, sensing unit and communication unit. Wireless sensor networks consist of a large number of small battery-operated devices with sensing capabilities that communicate by the means of short range wireless transceivers. Recent advances in wireless communications and electronics have enabled the development of low-cost, low-power, multifunctional sensor nodes that are small in size and communicate with in short distances.

These tiny sensor nodes, which consist of sensing, data processing, and communicating components, weight the idea of sensor networks. Networks represent a significant improvement over traditional sensors. Wireless sensor networks usually consist of several thousands of sensor nodes and are being deployed for a wide variety of applications including military sensing and tracking, environment monitoring, patient monitoring and tracking, smart environments etc.

The fact that the Wireless Sensor Network is relied on extremely reserved resources like battery life, bandwidth, data processing and storing capabilities makes the network really distinguished from other networks. Although battery life a distinguishing feature for the network, but the requirement of operating in unattended way for a long period of time raise the issue of energy-efficiency and it has to be carefully dealt with.

Usually, nodes have limited hardware characteristics, such as low-cost hardware, limited processing capabilities, low communication bandwidth and a weak communication signal that operates at a frequency that is shared with other wireless devices. It is made up of four basic components: a sensing unit, a processing unit, a transceiver unit and a power unit. There can be application dependent additional components such as a location finding system, a power generator and mobilize.

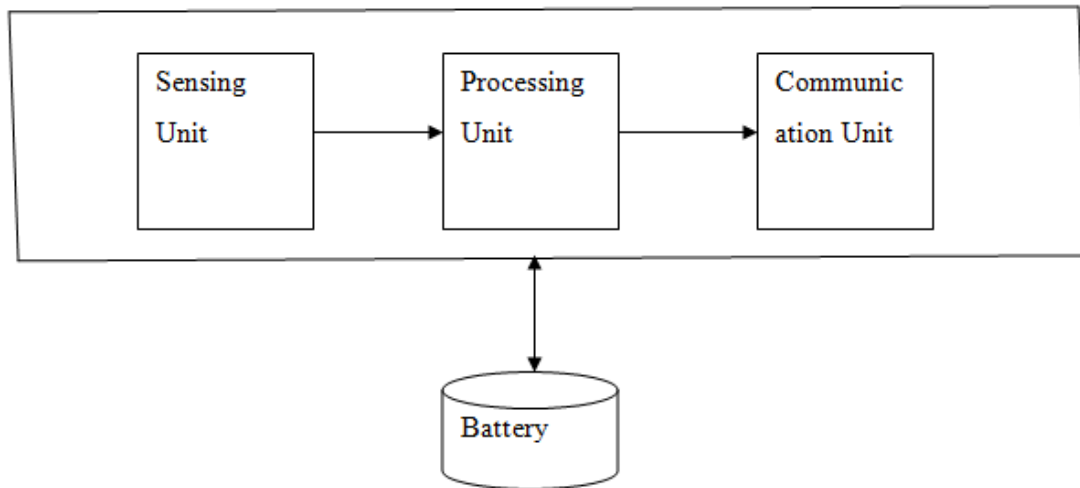


Figure 3-1: Architecture of Wireless Sensor Nodes

3.2 WSN Model

3.2.1 WSN Architecture

This system uses wireless communication medium, which is of in ad-hoc manner. And it uses range of communication distance to be 200m, in this way a reliable communication can be achieved between nodes. Bearing this in mind, for the smallest average distance between railway stations which is taken to be 10Km, there will be 50 sensor nodes that will be deployed. In figure below, S shows the wireless sensor node situated at a railroad side at a distance of 200 meters from each other. Sensors used here are Transmit Only Sensors. Wireless Sensor Nodes have the problem of power consumption since; they are using battery as an energy source. Later on the final chapters optimization techniques to mitigate these problems will be discussed on detail. For now a reasonable a choice of sensor node type is made to be Transmit Only Sensors because, consume they very less energy that increases the lifetime of the sensor.

Every station will work as a sink for sensor nodes, in this way the network coverage will be increased. And the fact that one sensor node will at least be covered by one sink node is maintained All sensor nodes send data in ad-hoc manner and can be used for inter-station communication. Each Train has its own train sensor which will receive data, process the data, display it in the cab for the driver and send also its speed and position

information to nearest railroad side sensor. Sensors near the railway track and in the train can send and receive data to and from the sensors within their range of communication. For this reason, the communication and network range have to be maintained.

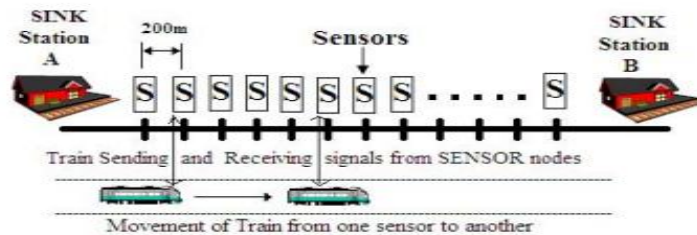


Figure 3-2: System Architecture [5]

3.2.2 WSN Signalling

The system of wireless sensor nodes will not use any light signals to pass orders and signals in between communication. The flow of communication will mostly depend on sink stations at the source and destination stations at the end-to-end communication sites. Signals are initiated by the sink at station, transmit by the sensors on railroad side and received by the sensor in the train. Data received by the Train Sensor will be display on the screen in the train after processing. In existing signalling system we can only send a signal to the trains but we cannot receive any signal from the trains. In the system of Wireless Sensor Networks we can retrieve speed and location information from train sensor. Stations can communicate with each other using sensor network and send data when required.

In more precise words: First, the sink node at the source station will initiate the process by sending a departure signal to the train at the time of departure. After departure, the train sensor will send information about its position and speed to the nearest sensor on the railroad side. Then, the sensors on the railroad side will send the signals received from the train sensors to both the stations on their sides in ad-hoc manner using other sensors on the track. Using the received information, the source station will send another train on the same track before the first train reached the destination station. So, the system enables to run multiple trains in between two stations.

The four sections of the whole route are divided as: Sebeta-Adama (Included): It is a double track division with a length of 113.836 Km, and an average distance between

stations to be 16.26Km. Adama (Excluded) - Mieso (Included): It is a single track division with a length of 213.418 Km, and an average distance between stations to be 17.78Km. Mieso (Excluded) - Dewele (Included): It is a single track division with a length of 334.014 Km, and an average distance between stations to be 15.91Km. Dewele (Excluded) - Nagad (Included): It is a single track division with a length of 81.977 Km, and an average distance between stations to be 16.4Km. Added to the existing stations and taking the average distance between stations to be 10Km the resulting number of total stations will be 77.

3.2.3 Merits of the WSN System

Considering the demand of Ethiopian Railway Corporation and the customers from both Ethiopia and Djibouti corridors, the system of WSN has enormous benefits to customers and service providers. By increasing line capacity, safety, and reliability and insuring power savings. More discussions on the benefits and processes to achieve these benefits are listed below:

Increase capacity, accomplished by increasing the frequency of trains which is due to increase of signals to shorten the train interval. The real time information of the trains will enhance the traffic convenience by providing accurate information. Rapid train for cutting the trip time is introduced which provides efficient passing facilities, used to improve the traffic convenience. The system achieves a high degree of safety by avoiding slow telephone communications between stations. The other advantage is that, the system will work very fine in any kind of weather condition because there is no visibility problem and drivers will get all the information on their system screens. Added to this the existing system is not suitable for future upgrading options rather, the system of WSNs can lead to automation in railway engines and trains can be operated without drivers and manual interference. The other fantastic feature of WSN is that it can be used to have voice communication with the driver in running train using ad-hoc network devices and signals can be passed through sensors deployed on track side. Finally, maintenance in the existing system will require long time and operation will be closed for a while, this might result dissatisfied customers and huge loss of money, but having a system that did not require the whole system to be closed for maintenance will ensure undisrupted and continuous operation which will satisfy customers and results in the reliability of the system.

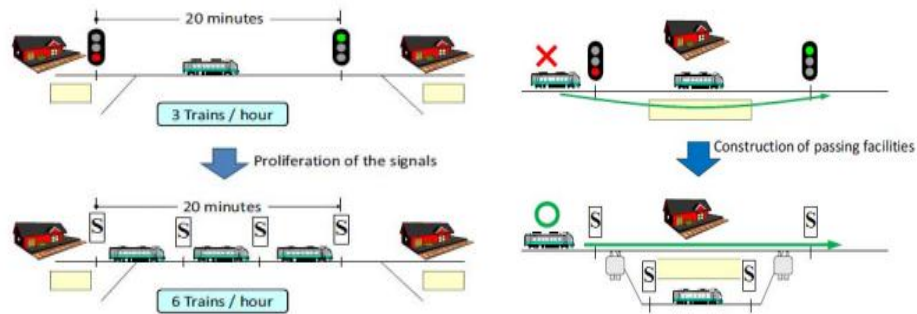


Figure 3-3: Increasing of frequency of the trains for congestion mitigation and Introducing of the rapid train for cutting the trip time [5]

3.3 Node Deployment in Wireless Sensor Network

The twelve fundamental metrics that needs to be dealt with are: network coverage, network connectivity, network lifetime, energy consumption, energy efficiency, network latency, differentiated detection levels, number of nodes, fault tolerance, fair rate allocation, detection accuracy and network security. Covering the two first most basic metrics that are network coverage and network connectivity means addressing all the other metrics in indirect way. For this reason we need to study in detail the Node deployment of a WSN.

Node deployment is a fundamental issue in Wireless Sensor Networks (WSNs) since; 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 a 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 set up. For these tiny sensor nodes to gather and transmit information the first

requirement is that: one node shall be covered by at least one cluster head. This way connectivity will always be maintained and no data will be lost.

In WSN nodes are deployed according to the demand of application. In the application for railway systems specifically for the route from Ethiopia to Djibouti, the distribution is not uniform. Because of no uniformity of the landform in the area that is governed both under the Ethiopian landform, and under the alluvial plain, hills and plateau landform. Uniform deployment of sensor nodes means that, the nodes are placed manually at fixed spot and routing paths are predetermined. While random way of sensor node distribution is allowing the random scattering of nodes in the specified area of placement. Since, random sensor node deployment is the right choice for the route energy efficiency is the main issue. To deal with this issue a perfect choice of the cluster head deployment has to be carefully conducted. This is accomplished with a right choice of routing algorithm. From the types of routing algorithms ring routing is the energy efficient algorithm. Using ring routing algorithm along with the gravitational Search Algorithm for finding the center of the routing protocol will result in an energy efficient and effective sensor nodes (i.e. effective with respect to localizing and coverage).

Sensor nodes are small in size so they have limited power supply to the overall process of sensing, processing and transmitting the information via a wireless communication. The lifetime of the sensor node is totally dependent on the battery. Once the battery is depleted the sensor node will be dead it causes change in topology rerouting of data.

Data delivery models and data aggregation are another key issues that needs to be discussed in these subchapter. Continuous, data driven, query driven and hybrid models are the types of the data delivery models. Continuous model is a model where the data is send periodically to the sink. Data transmission is occurred when the event happens explains event driven data delivery model. Or data is transmitted when sink generates a query to the node in query driven delivery model. Whereas the combination of the above listed methods is by itself a model and known as Hybrid model. Data aggregation is a method of suppressing different packets of data from the many sensors that are deployed in certain area. The main task of data aggregation is to combine the information from these sensors then the routing protocol use this information to consume the battery life by using data compaction.

3.4 Necessary Calculations

In this system of WSNs we use the inter station distance of 10Km to keep the sensing range and the coverage range in the range of appropriate communication. This average distance estimation is based on the general specification of sensor nodes (i.e. the distance between two sensor nodes must be 200m for an efficient communication). Considering the number of sensors to be deployed may vary accordingly for different topology of the land, we take an average of 50 sensors to be deployed in between stations. Then for 50 sensors to be deployed around one cluster head the average distance between stations (cluster head positions will be 10Km).

The total length of the line is 743.245Km.

The stations will be divided according to the above information:

- I. Sebeta-Adama (Included): It is a double track division with a length of 113.836 Km, and an average distance between stations to be 16.26Km.
It has 7 stations in the existing system structure.
Hence, the Wireless Sensor Network will be using the existing stations along with the additional stations to be added as a place to put the cluster heads.
 $114\text{Km}/10\text{Km} = 12$ stations which is $12 - 7 = 5$ additional stations
- II. Adama (Excluded) - Mieso (Included): It is a single track division with a length of 213.418 Km, and an average distance between stations to be 17.78Km.
It has 12 stations in the existing system structure.
Hence, the Wireless Sensor Network will be using the existing stations along with the additional stations to be added as a place to put the cluster heads.
 $214\text{Km}/10\text{Km} = 22$ stations which is $22 - 12 = 10$ additional stations
- III. Mieso (Excluded) - Dewele (Included): It is a single track division with a length of 334.014 Km, and an average distance between stations to be 15.91Km.
It has 21 stations in the existing system structure.
Hence, the Wireless Sensor Network will be using the existing stations along with the additional stations to be added as a place to put the cluster heads.
 $334\text{Km}/10\text{Km} = 34$ stations which is $34 - 21 = 13$ additional stations

IV. Dewele (Excluded)- Nagad (Included): It is a single track division with a length of 81.977 Km, and an average distance between stations to be 16.4Km. It has 5 stations in the existing system structure.

Hence, the Wireless Sensor Network will be using the existing stations along with the additional stations to be added as a place to put the cluster heads.

$82\text{Km}/10\text{Km} = 9$ stations which is $9-5=4$ additional stations

Now the overall update of stations can be summarized in table below:

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

Table 3-1: Station calculations summary

Chapter 4 **ROUTING AND LIFETIME OF A WIRELESS SENSOR NETWORK**

4.1 **Routing in Wireless Sensor Networks**

Routing is necessary to the deployment of sensor nodes in many reasons but to mention a few, consumption of the battery life of the node. Since the battery of the node with large data traffic will drain quicker than other nodes. Basically, routing provides the network a hierarchy of communication that will provide an alert when a node is out service. Hence, uninterrupted service of delivering data from source to destination will be enabling by a means of these hierarchical methods of communication. Again for the railway application there needs to be a wise choice in the type of the routing protocol to be used. The choice of routing protocol is accomplished to find out the method that will enable high node coverage and connectivity with energy efficiency. An energy efficient node placement also depends on the place of the sink node. High degree of reach ability of the sink node enables consumption of the battery of sensor nodes by reducing the path of communication (intermediate communication between that specific node and the sink). The routing protocol guarantees to access the channel efficiently by the user to increase the throughput of the network. The routing protocol used the concept of memorization of past traffic to increase the reliability of the network. In the routing procedure the first step of classifying the whole network into divisions is very important. The most known method of classifying the network is based on clusters-based divisions.

4.2 **Routing Algorithms**

For routing algorithms clustering methods are the majorly adopted aimed to solve the above listed problems. Clustering means dividing the whole region into regions of limited area and associated sensor nodes with that area, where network connectivity keeps maintained. Here, networks are classified into categories: Homogenous network where all nodes are assumed to have identical battery energy and hardware configuration and Heterogeneous network topology where variable node resources and different

topology of the network is enabled, this is the more practical network topology also because of increased network reliability and lifetime.

According to recent studies heterogeneous methods are dealt with in many approaches: DECHA which is used for all the nodes that distributed uniformly here position information of nodes is taken into consideration. Density of each node as the number of its neighbor nodes, and together with the energy capacity is defined, which is an important asset for electing candidate cluster heads, seeking for more proper cluster heads, thus promote both lifetime and energy-efficiency. LEACH is a method based on weighted election probabilities of each node to become cluster heads.

There are many approaches for issue of routing in a wireless sensor network with mobile sinks; the most important method that has been extensively used is hierarchical mobile sink routing protocols. The purpose of these methods is reducing the load of sink position notification to the network by creating a layer of hierarchical nodes imposing different dynamic roles to sensor nodes. Some of the methods to be compared are stated below:

4.2.1 Line-Based Data Dissemination Method (LBDD)

The line-based data dissemination protocol is a protocol which uses a geographic routing and assumes that each node knows the physical coordinates of the interest area. LBDD defines a wide vertical strip of nodes that are called in-line nodes that are horizontally centered on the area of deployment. The band that the in-line code lies on represents an area of engagements for queries and data storage. The nodes can access the line by a clear-cut mechanism. The operation of LBDD consists of two main steps: one is spreading which means when a node detects a stimulus, the data is generated and sent to the nearest inline-node and the other one is collection is when to collect different data, the sink sends a perpendicular query to the band.

With enough expansion of the line LBDD depends on spreading the data search along the path. Hence, for large grids in-line current may considerably increase total energy. Energy consumption is the main challenge in WSN, and this method fails to provide a means to consume the battery life of the node.

The first in-line node which receives the query will propagate it in both directions of the band to attain the nodes with the required data. The data will be then sent directly to the sink [9].

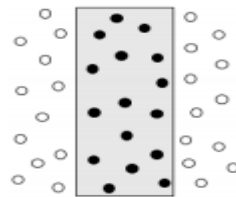


Figure 4-1: Line-Based Data Dissemination Architecture [9]

4.2.2 Railroad Method

This method will construct a structure which will look a lot like the rail, which is a closed loop of strip of nodes called rail nodes. Here, the sink search on the rail is by single molds unlike that of LBDD which uses dissemination. One condition to be satisfied is that station must cover the width of the rail; this use of stations will reduce the need to extended disseminations in the rail and assist the protocol scalability.

When a node has sensor data, it sends some information about this data to the nearest rail node that constructs a station, which is a portion of the rail centered on the rail node. The sink searches the rail for data and when it attains to station node, it notifies the source from sink position and data is directly sent to the sink [9].

The disadvantage of this method is that, since searches might travel by a much longer structure than the LBDD, a delay might happen while delivering the data that is higher than the LBDD. And again the data is stored in the database, so when a search attains to a station the source node must be informed from the sink position to begin data dissemination. Therefore, this may increase the delay for data delivery.

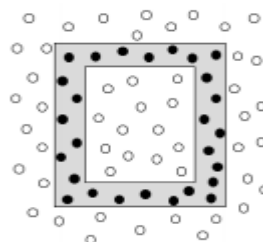


Figure 4-2: Ring routing architecture [9]

4.2.3 Ring Routing Method

Ring Routing creates a ring structure and its purpose is combining the easy accessibility of grid structures with the capability of easy change in the column structures [9].

It uses a simple and efficient mechanism for sharing the sink position notification among ring nodes, hence, reducing the repeated routing protocol packages by combining the minimum quantity of nodes in the ring structure. Unlike, other methods it depends on a minimum inept dissemination value. For a mobile sink and a fixed number of sensor nodes ring routing is a protocol for a wide-scale wireless sensor network like the railways. Its easily accessible and easily configurable hierarchical routing protocol with an advantage of security and energy efficiency and high speed data delivery which is a requirement for high speed networks like that of the railways.

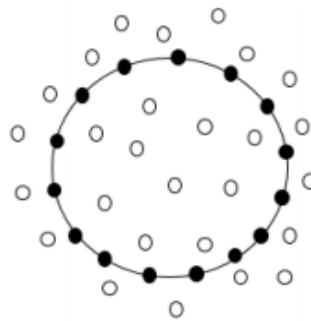


Figure 4-3: Ring routing architecture [9]

In a various studies, a simulation result shows that the performance of ring routing is better than the existing mobile sink routing protocol in terms of battery consumption, lifetime, and delay for delivering the data. To achieve higher performance in terms of increasing the lifetime of the network a gravitational search algorithm is used to initially select the ring.

In the ring structure there are three types of nodes ring node, normal node, and anchor node. The nodes that form the circular path with the width of the node are called ring nodes.

4.2.3.1 Formation of the Ring Structure

The formation of the ring structure involves the following steps: First, noticing the sink position to the ring, second, normal nodes obtaining the information about sink position from the ring at any time required and lastly, nodes disseminating their data by anchor nodes performing as factors for connecting the sink to the network.

These three roles of sensor are not fixed; it means that the role of sensor nodes might be changed during operation from wireless receiver network. The network center is marked with an “X” in various example ring structures shown in figure below [9].

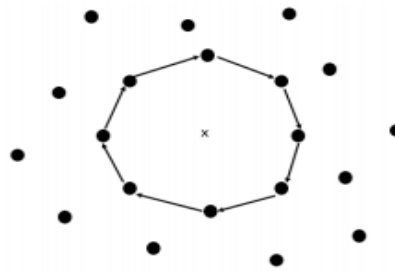


Figure 4-4: Structure of a ring [9]

For starters, a ring is made by determining the radius of the initial ring after the founding of the network. Nodes closer to the ring that has been defined by this radius and the center of grid are determined by a specific threshold to act as a nomination for converting to the ring node.

By beginning from a specific node (for example, closest node to the left side of the point in the ring), by geological transmission in a given direction (in clockwise/ counterclockwise direction), ring nodes are selected by using gravitational search random optimization algorithm to attain the beginning node and complete the closed ring as indicted in the below figure. More, we explain gravitational search algorithm (GSA) detailed as below.

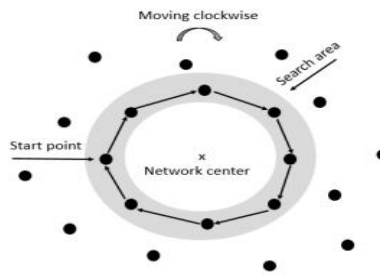


Figure 4-5: Creation of a ring [9]

4.3 Gravitational Search Algorithm

From the family of nature-inspired algorithms, that that is based on Newton's law of gravity and the law of motion is used in this work for determining the first position of the cluster which aimed to decrease the battery usage of the nodes.

This method put to use the combination of searcher agents that interact with each other through the gravity force. Here, any mass (factor) has four characteristics including place, inertial, gravitational passive and gravitational active masses. The place of the mass is according to the solution of the problem and gravitational and inertial masses are determined by using the fitness function. Some masses (factors) are considered as objects and their performance is measured as their mass, all such objects attract themselves by gravity and this force may cause the movement of all objects towards heavier masses. According to this law, heavier masses move slower than lighter objects.

On the contrary, for any mass to provide a solution, an algorithm is developed by properly setting the inertial and gravitational masses. To provide an optimal solution for search space, objects are expected to be attracted towards heavier objects as stated above. Steps for gravitational search algorithm are summarized as follows:

- I. Identifying the exploration space and random initialization
- II. State minimization or maximization problems, and evaluate the problems for all agents at every iteration.
- III. Changing the gravitational constant in the order of *max* and *min* value and calculating the general force in different directions and calculating the velocity and acceleration;

- IV. Repeating steps c to g until stopping the conditions has been attained;
- V. End.

The exploration space Y is defined over the interval i as follows:

$$Y_i = (Y_{i1}, \dots, Y_{id}, \dots, Y_{in}) \text{ for } i = 1, 2, \dots, N \dots \dots \dots (1)$$

Y_{id} Represents the positions of the i^{th} agent in the d th dimension, while n is the space dimension

Minimization and maximization problems with best and worst value of t are explained below:

Minimization problems:

$$best(t) = \min_{k \in \{1, \dots, N\}} fit_k(t) \dots \dots \dots (2)$$

$$worst(t) = \max_{k \in \{1, 2, \dots, N\}} fit_k(t) \dots \dots \dots (3)$$

Maximization Problems:

$$best(t) = \max_{k \in \{1, \dots, N\}} fit_k(t) \dots \dots \dots (4)$$

$$worst(t) = \min_{k \in \{1, 2, \dots, N\}} fit_k(t) \dots \dots \dots (5)$$

Changing the gravitational constant, $G(t)$, $best(t)$ and $worst(t)$ in the order of max and min value, fitness proportional to factor “ i ” in time “ t ” and mass value of $M_i(t)$ with $i = 1, 2, \dots, N$;

$$Gr(t) = Gr(Gr_o, t) \dots \dots \dots (6) \text{ where } Gr \text{ is the gravitational constant}$$

$$M_{ai} = M_{pi} = M_{ii} = M_i \dots \dots \dots (7)$$

$$m_i(t) = \frac{fit_i(t) - worst(t)}{best(t) - worst(t)} \dots \dots \dots (8)$$

$$M_i(t) = \frac{m_i(t)}{\sum_{k=1}^N m_k(t)} \dots \dots \dots (9)$$

The total force, velocity and acceleration can be equated as:

$$f_i^d(t) = \sum_{k=1, k \neq i}^N rand_j f_{ik}^d(t) \dots \dots \dots (10) \text{ where } f_i^d(t) \text{ is the total force}$$

$$V_i^d(t+1) = rand_i X V_i^d(t) + a_i^d t \dots \dots \dots (11)$$

$$a_i^d t = (F_i^d(t)) / M_{ii}(t) \dots \dots \dots (12)$$

In gravitational Search Algorithm, marking of neighboring nodes is obtained after the initial nodes have been selected. Anchor nodes that are selected to the movement of their

neighbors perform as a representative to manage the communication between sink and sensor nodes. Due to the presence of anchor node, when a source node obtains the fixed location of the current anchor node, it could directly transmit its data by geographical transmission to it and the anchor node will reflect these data to the sink and completes data dissemination.

4.4 Lifetime of a Wireless Sensor Network

According to their usage on harsh environments and cost effectiveness, wireless sensors have received increased attention in the past years. They have been used in many applications including military applications, environmental applications, health applications, and home applications. But the main parameter that should be taken into consideration is the battery life of the sensor node. After the depletion of the battery life they are no more useful. To estimate the lifetime of the wireless sensor network the estimation of the battery life is very essential. Along with this estimation the proper algorithm to increase the battery life should be taken into consideration too. The two most known network lifetime metrics that will be depicted in seconds and are expensive when using together is:

- (1) N_a is the first metric that gives the accumulated network lifetime as the sum of all times that $n(t)$ is fulfilled, stopping only when the criterion is not fulfilled for longer than Δt_{sd} seconds.
- (2) N_t Is the second metric, known as the total network lifetime that gives the first point in time when the liveliness criterion is lost for a longer period than the service disruption tolerance Δt_{sd} .

An efficient method for the lifetime of a network is enabling node scheduling technique, node enabling technique allows the node to operate in a scheduled manner. That when one node is at operating mode the neighboring node right next to it will be set to a sleep mode. Hence, nodes in the network will have two states: operating state and sleep state.

Chapter 5 MULTI OBJECTIVE OPTIMIZATION

5.1 MOO Metrics of Wireless Sensor Networks

Here we will discuss the metrics in two basic categories: basic metrics and the others are discussed as other left metrics below.

5.1.1 Basic Metrics

1. Network Handling

The network handling calculation is based on the assumption that, all points within a disk centered at the node are considered to be covered by the node. A point A is regarded to be covered by at least a node B if their Euclidean distance is less than the sensing range R_s of node B. Given a set of nodes, finding the optimal positions of these nodes to achieve maximum coverage is in general a NP-Complete problem.

Consider a total area T, represented by a rectangular grid, which is divided into $C=XY$, rectangular cells of identical size and let (X_i, Y_i) denote the coordinate of node K. Network coverage $C_v(x)$ is defined as the percentage of the adequately covered cells over the total cells of T.

$$N_c(x) = \frac{\sum_{x'}^x \sum_{y'}^y c(x', y')}{XY} \dots\dots\dots (1)$$

$$N(x', y') = \{1, \text{if } \exists k \in \{1, \dots, N\}, d(x_k, y_k), (x', y') \leq R_s \text{ and } 0, \text{otherwise} \dots\dots\dots (2)$$

Where N- number of nodes

$N(x', y')$ - monitoring status of the cell centered at (x', y')

R_s – Sensing range of a node

$d(x_k, y_k), (x', y')$ – Distance from the location of node k to the cell centered at (x', y') .

While having a higher probability of detecting the event monitored, there is a better coverage.

2. Network Connectivity

Network connectivity is achieved if and only if the location of any active node is within the communication range of one or more active nodes. And again two sensor nodes are directly connected if the distance of the two nodes is smaller than the communication range R_c . In Cluster-Based architecture all nodes in the same cluster can directly communicate with each other via a single hop and all nodes in the same cluster can communicate with all nodes in the neighboring clusters via the cluster head. Here connectivity issues tend to hinge on the number of nodes in each cluster (because a cluster head can only handle up to a specific number of connected nodes).

For an area represented by a rectangular grid xYy let:

R_{ck} - Communication range of the k^{th} node

R_{sk} - sensing range of the k^{th} node

Each sensor node is placed within the communication range of at least another sensor node and to prevent sensor nodes from becoming too close to each other, the objective function associated with the network connectivity can be expressed by:

$$f_{con} = \sum_{i=1}^{xYy} \mathbf{1} - e^{-(R_{ck}-R_{sk})} \dots\dots\dots (3)$$

Where $R_{ck} - R_{sk} > 0$ has to be satisfied for achieving network connectivity

Maintaining network connectivity means ensuring that the messages are propagated to the appropriate sink node or base station. Loss of connectivity means end of networks lifetime. Network connectivity closely related to coverage and energy efficiency in WSNs. A future scaling in the area of sensor nodes will require the appropriate use of nodes battery life. Substantial energy savings can be achieved by dynamic management of node duty cycles in WSNs having high node density. Some nodes can be scheduled to sleep (enter a power-saving mode) while others remaining active nodes provide continuous service. A significance method to utilize the battery life of sensor nodes is the use of node scheduling. The main idea behind this algorithm is that the nodes will not operate at the same time rather, they will work on schedules. While a node is working the neighboring node will enter a sleep node so that energy is conserved. Fundamental problem is to minimize the number of active nodes while still achieving acceptable QoS.

Maintaining an adequate sensing coverage and network connectivity with the active nodes is a critical requirement in WSNs. Relationship between coverage and connectivity hinges on the ratio of the communication range to the sensing range. For a set of nodes that cover a convex region, the network remains connected if $R_c \geq 2R_s$.

3. Network Lifespan

Network lifetime is the duration between the times when the network is putted to use for the first time to the time when any of the sensor node on the network runs out of battery. Or it can be defined as the time duration from the applications first activation to the time instant when any of the sensor nodes in the cluster fails due to its depleted energy source.

The objective function formulated as;

$$T_{net} = Tk \dots \dots \dots (4)$$

Where $k = 1, 2, N$

Lifetime of a sensor node is partially determined by the source rates of all the sensor nodes in the network and it is inversely proportional both to the average rate of its own information generated and to the information relayed by this node. Both the radio transceiver unit and sensor unit of each node have to be energy-efficient, to maximize the attainable network lifetime.

4. Energy Depletion

Each node consumes some energy during its data acquisition, processing and transmission phases. Energy consumption of a WSN depends on both Shannon capacity of channels among the nodes and on these nodes functionality. Energy consumption of a path P is the sum of energy expended at each node along the path $E(P)$ of a given path is:

$$E(P) = \sum_{i=0}^L (t_i^a + t_i^p) * P_i^o + P_i^t * t^m \dots \dots \dots (5)$$

Where t_i^a and t_i^p – Time durations of data acquisition and processing taking place at node i

L – Number of nodes on the given path

t^m – Message transmission time

P_i^o and P_i^t – Operational power and transmission power dissipation of node i

5. Energy Proficiency

Energy proficiency closely related to network lifetime. Energy efficiency of node I is the ratio of the transmission rate to the power overindulgence.

$$\eta_i = \frac{W \log_2(1+\mu_i)}{P_i} \dots\dots\dots (6)$$

W – Communication Bandwidth

μ_i – Signal-to-interference-plus noise ratio (SINR) at the destination receiver relative to node i

P_i – Transmission power of node i

Two approaches to deal with the energy conservation of problem in WSNs are: To plan a schedule of active nodes while enabling the other nodes to enter a sleep mode and dynamically adjust the sensing range of nodes for the sake of energy conservation.

5.1.2 Other Metrics

1. Network Expectancy

Latency will be reduced by creating more paths (i.e. this is achieved by increasing the number of nodes) for simultaneously routing packets to their destinations. Hence, this will also increase the latency that is due to the proportional increase of sensor nodes on the target paths. This is due to additional controversy for the wireless channel when the node density increases, as well as owing to routing and buffering delays. Delay between source node U_{so} and sink node U_{si} is the time elapsed between the departure of a collected data packet from U_{so} to its arrival at U_{si} . And it's given by:

$$DU_{so, U_{si}} = (T_q + T_p + T_d)XN(U_{so}, U_{si}) = CXN(U_{so}, U_{si})\alpha N(U_{so}, U_{si})\dots\dots\dots (7)$$

Where T_q – Queue delay per intermediate forwarder

T_p – Propagation delay

T_d – Transmission delay

$N(U_{so}, U_{si})$ – Total number of data disseminators between U_{so} and U_{si}

Therefore minimizing of delay corresponds to minimizing the number of intermediate forwarders between the source and the sink.

2. Node Recognition

Different geographic areas require different densities of deployed nodes. Differentiated sensor network deployment is also an important issue. In many real WSN applications, such as underwater sensor deployments or surveillance applications, certain parts of the supervised region may require extremely high detection probabilities if these parts constitute safety-critical geographic area. However, in the less sensitive geographic area, relatively low detection probabilities have to be maintained for reducing the number of nodes deployed, which corresponds to reducing the cost imposed. Therefore, different geographic areas require different densities of deployed nodes, and the sensing requirements are not necessarily uniformly distributed within the entire supervised region. Let us use $d((m, n), (i, k))$ to denote the Euclidean distance between the coordinates (m, n) and (i, k) . A probabilistic node detection model can be formulated as:

$$P((m, n), (i, k)) = \begin{cases} e^{-ad((m,n),(i,k))}, & d((m, n), (i, k)) \leq R_s \\ 0, & d((m, n), (i, k)) > R_s, \end{cases} \dots\dots\dots (8)$$

Where a - is a parameter associated with the physical characteristics of the sensing device

R_s - is the sensing range

3. Amount of Nodes

Each sensor node imposes a certain cost, including its fabrication, organization and upkeep. As a result, the total cost of the WSN increases with the number of sensor nodes. When deploying a WSN in a battleground, sensor nodes have to operate as cautiously as possible to avoid being noticed by the enemy. This implies that the number of nodes has to be kept at a minimum in order to reduce the probability of any of them being discovered. Minimizing the number of active nodes is equivalent to maximizing the following objective [104]:

$$f'(N) = 1 - \frac{|N'|}{|N|} \dots\dots\dots (9)$$

Where $|N'|$ - is the number of active nodes and

$|N|$ - is the total number of nodes

4. Error Acceptance

Error in sensor nodes or a failure in the sensor node might occur due to the surrounding physical conditions or the depletion of their energy. Replacing the existing nodes might be difficult and hence the error acceptance rate has to be as high as possible. Error acceptance is nothing but the network's operation without disruption in case of any failure, and it is typically implemented in the routing and transport protocols. Error acceptance or reliability $R_k(t)$ of a sensor node can be modeled using the Poisson distribution in order to capture the probability of not having a failure within the time interval $(0, t)$ as [1]:

In a K -connected WSNs, k -connectivity implies that there are k independent paths in the full set of the pair of nodes. For $k \geq 2$, the network can tolerate some node and link failures. Due to the many-to-one interaction pattern, k -connectivity is a particularly important design factor in the neighborhood of base stations and guarantees maintaining a certain communication capacity among the nodes [6].

$$R_k(t) = e^{-\lambda_k t} \dots\dots\dots (10)$$

Where λ_k – is the failure rate of sensor node

And t - is the time period

5. Unbiased Ratio Share

For a limited bandwidth, the amount of information that the sink node receives has to be in a proportioned rate so that all the nodes are using the bandwidth in unbiased manner. The exactitude of the expected source information depends on the allocated source rate. Simply maximizing the total quantity of the network is insufficient for ensuring the specific application's performance, since this objective may only be achieved at the expense of sacrificing the source rate supposed to be allocated to some nodes. For example, in a sensor network that tracks the mobility of certain objects in a large field of observation, lower rates impose a reduced location tracking accuracy and vice versa.

By simply maximizing the total throughput instead of additionally considering the above fairness issues among sources, we may end up with a solution that shuts off many

sources in the network and enables only those sources whose transport energy-cost to the sink is the lowest. Hence, considering the fairness of rate allocation among different sensor nodes is of high significance. An attractive methodology of achieving this goal is to adopt a network utility maximization (NUM) framework, in which a concave, non-decreasing and twice differentiable utility function $U_i(x_i)$ quantifies the grade of satisfaction of sensor node i with the assigned rate x_i , and the goal is to maximize the sum of individual utilities. A specific class of utility functions that has been extensively used for achieving fair resource allocation in economics and distributed computing is formulated as

$$U^\alpha(x) = \begin{cases} \log x, & \alpha = 1 \\ \frac{1}{1-\alpha} x^{1-\alpha}, & \alpha > 1 \end{cases} \dots \dots \dots (11)$$

Where $x = (x_i, \forall i)$ and the functional operations are element wise. When we have $\alpha = 1$, the above utility function leads to the so-called proportional fairness, whereas when $\alpha \rightarrow \infty$, this utility function leads to max–min fairness.

6. Recognition Accurateness

Having high target detection accuracy is also an important design goal for the sake of achieving accurate inference about the target in WSNs. Target detection accuracy is directly related to the timely delivery of the density and latency information of the WSN. Assume that a node k receives a certain amount of energy $e_k(u)$ from a target located at location u and K_o is the energy emitted by the target. Then, the signal energy $e_k(u)$ measured by node k is given by

$$e_k(u) = \frac{K_o}{1+\alpha d_{Kp}} \dots \dots \dots (12)$$

Where d_K - is the Euclidean distance between the target locations of node K ,

P - Is the path loss exponent that typically assumes in the range of [2, 4],

While α - is an adjustable constant

7. Network Safe keeping

Sensor nodes may be deployed in an uncontrollable environment, such as a battlefield, where an adversary might aim for launching physical attacks in order to capture sensor nodes or to deploy counterfeit ones. As a result, an adversary may retrieve private keys

used for secure communications by eavesdropping and decrypt the communications of the legitimate sensors. Recently, much attention has been paid to the security of WSNs. There are two main types of privacy concerns, namely data-oriented and context-oriented concerns [29]. Data-oriented concerns focus on the privacy of data collected from a WSN, while context-oriented concerns concentrate on contextual information, such as the location and timing of traffic flows in a WSN. A malicious node of the WSN abuses its ability of decrypting data in order to compromise the payload being transmitted in the case of data analysis attack. In traffic-analysis attacks, the adversary does not have the ability to decrypt data payloads. Instead, it eavesdrops to intercept the transmitted data and tracks the traffic flow on a hop-by-hop basis. Based on information theory loss of privacy can be calculated as:

$$\zeta = 1 - 2^{-I(S-X)} \dots\dots\dots (13)$$

Where $I(S - X)$ is the mutual information between the random variables S and X .

More specifically S represents the current position of the node of interest, X is the observed variable known to the attacker and correlated to S ,

While, $I(S - X) = H(S) - H(S|X)$ with $H(\bullet)$ denoting the entropy. Studies indicate that minimizing the probability of eavesdropping in a Wireless Sensor Network can improve network security.

5.2 Techniques of MOO

Wireless sensor networks (WSNs) are networks of autonomous nodes used for monitoring an environment. Developers of WSNs face challenges that arise from communication link failures, memory and computational constraints, and limited energy. Many issues in WSNs are formulated as multidimensional optimization problems, and approached through bio-inspired techniques.

Optimization covers almost all aspects of human life and work. In practice, there is an increasing demand and the resources are limited, hence optimization is important. Most research activities in computer science and engineering involve a certain amount of modeling, data analysis, computer simulations and mathematical optimization. This branch of applied science aims for finding the particular values of associated variables,

which results in either the minimum or the maximum values of a single objective function or multiple objective functions. A typical optimization process is composed of three components: the model, the optimizer/algorithm and the evaluator/simulator, as shown in Fig below:

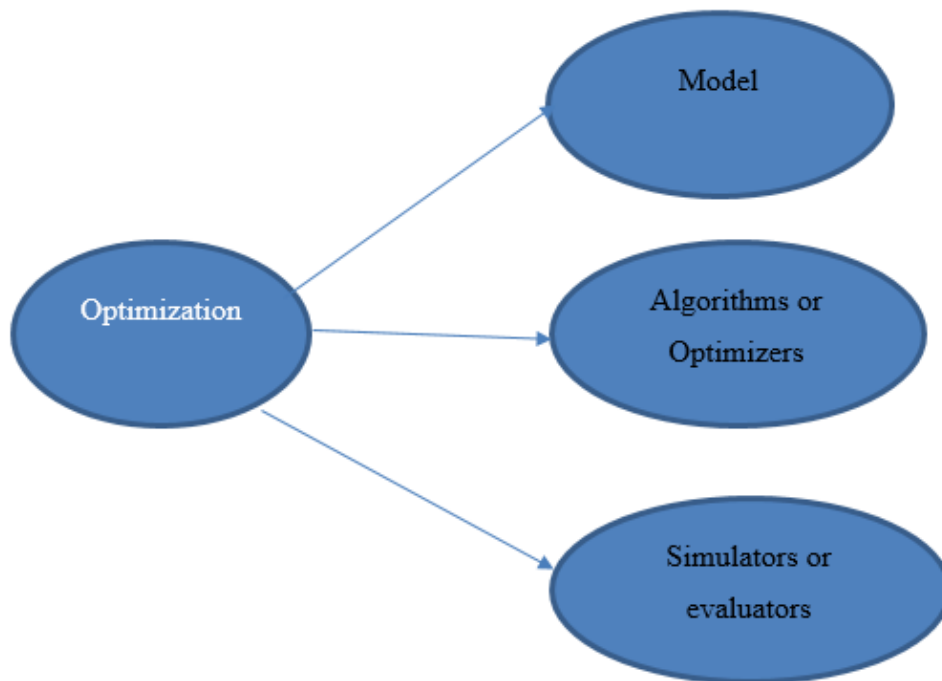


Figure 5-1: A simple illustration of optimization process

An optimization process has 3 basic steps: a model, an algorithm which is the optimizer that will be used for that specific problem and a simulator or evaluator to test the procedure of the network and check the result. The model is either a mathematical or numerical model which will describe the physical phenomenon. The optimizers used for different types of problems vary according to the problem and they are categorized under: derivative free, derivative based, population based, trajectory based, deterministic, stochastic, memoryless, history based and bio-mimic.

Finally the resulting optimized model of the phenomenon will be tested using one of the evaluators or simulators: direct calculation, numerical simulator and experiment or trail-and-error.

The representation of the physical problem is carried out by using mathematical formulations to establish a mathematical model. As an important step of solving any

optimization problem, an efficient optimizer or algorithm has to be designed for ensuring that the optimal solution is obtained. There is no single algorithm that is suitable for all problems. Optimization algorithms can be classified in many ways, depending on the specific characteristics that we set out to compare. In general, optimization algorithms can be classified as:

1. Finitely terminating algorithms, such as the family of simplex algorithms and their extensions, as well as the family of combinatorial algorithms.
 - Convergent iterative methods that evaluate Hessians (or approximate Hessians, using finite differences), such as Newton's method and sequential quadratic programming;
 - Evaluate gradients or approximate gradients using finite differences (or even sub-gradients), such as quasi-Newton methods, conjugate gradient methods, interior point methods, gradient descent (alternatively, "steepest descent" or "steepest ascent") methods, sub-gradient methods, bundle method of descent, ellipsoid method, reduced gradient method, and simultaneous perturbation based stochastic approximation methods;
 - And evaluate only function values, such as interpolation methods and pattern search methods.
2. Heuristics/Metaheuristics that can provide approximate solutions to some optimization problems. Recently, bio-mimetic heuristics/Metaheuristics based strategies have been widely used for solving MOPs, since they are capable of obtaining near-optimal solutions to optimization problems characterized by non-differential nonlinear objective functions, which are particularly hard to deal with using classical gradient- or Hessian-based algorithms.

A general MOP consists of a number of objectives to be simultaneously optimized and it is associated with a number of inequality and equality constraints. Without loss of generality, a multi-objective minimization problem having n variables and m ($m > 1$) objectives can be formulated as

$$\begin{aligned} \min f(x) = \min[f_1(x), f_2(x), \dots, f_m(x)] \dots \dots \dots (14) \\ s. t. h_i(x) \leq 0, i = 1, 2, 3 \dots \dots \dots m_{ie} \end{aligned}$$

$$g_j(x) = 0, j = 1, 2, 3 \dots \dots \dots m_{eq}$$

Where $X \in R_n$ with R_n being the decision space and

$f(x) \in R^m$ represents the objective space.

Explicitly, the improvement of one of the objectives may result in the degradation of other objectives, thus it is important to achieve the Pareto-optimality, which represents the conditions when none of the objective functions can be reduced without increasing at least one of the other objective functions. For the minimization of m objectives $f_1(x)$, $f_2(x)$... , $f_m(x)$, we have the following definitions.

• **Non-dominated solutions:** A solution a is said to dominate a solution b if and only if:

$$f_i(a) \leq f_i(b) \forall i \in \{1, 2, \dots, m\}, \dots \dots \dots (15)$$

$$f_i(a) < f_i(b) \exists i \in \{1, 2, \dots, m\}, \dots \dots \dots (16)$$

Solutions that dominate the others but do not dominate themselves are termed non-dominated solutions.

• **Local optimality in the Pareto sense:** A solution a is said to be locally optimal in the Pareto sense, if there exists a real $\epsilon > 0$ such that there is no other solution b dominating the solution a with $b \in R_n \cap B(a, \epsilon)$, where $B(a, \epsilon)$ shows a bowl having a center a and a radius ϵ .

• **Global optimality in the Pareto sense:** A solution a is globally optimal in the Pareto sense, if there does not exist any vector b that dominates the vector a . The main difference between global and local optimality lies in the fact that for global optimality we no longer have a restriction imposed on the decision space R_n .

• **Pareto-optimality:** A feasible solution is said to be Pareto-optimal, when it is not dominated by any other solutions in the feasible space. PS, which is also often referred to as the efficient set, is the collection of all Pareto-optimal solutions and their corresponding images in the objective space are termed the PF. The PF of an MOP is portrayed both with and without constrains in figure below.

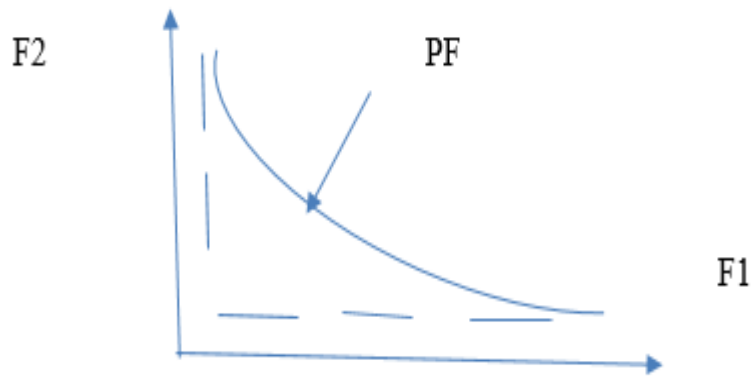


Figure 5-2: PF of Unconstrained MOP

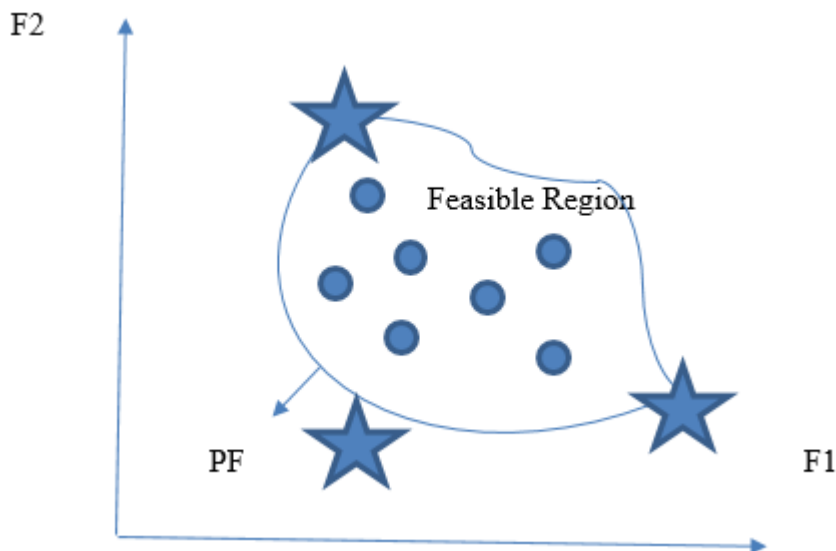


Figure 5-3: PF of Constrained MOP

Pareto-optimal solutions of the objective functions in the PF (marked as asterisk) provide better values than any other solution in R_m . The ideal solution in the unconstrained MOP which is difficult to reach indicates the joint minimum of the objective values f_1 and f_2 . The remaining solutions are all dominated by at least one solution of the PF.

In contrast to the unconstrained scenario of in Fig. 5-4, the curve illustrates the PF of a constrained MOP. The feasible solutions are represented by solid circles which are in the feasible region. While the remaining points outside the feasible region are regarded as infeasible.

WSNs need various complex MOPs to be solved. For each metric we need a different optimization algorithm due to the complex nature of the optimization problem. One optimization problem which enhance a certain metric will reduce the performance of another matrices.

Optimization algorithms are more diverse than the types of objective functions, but the right choice of the objective function has a much more grave impact than the specific choice of the optimization algorithm. Nevertheless, the careful choice of the optimization algorithm is also vital, especially when complex MOPs are considered. There are various methods that will be used to generate the multi-objective optimization problems. There are various classes of methods designed for generating the PSs of MOPs, such as mathematical programming based scalarization methods, nature inspired Metaheuristics, and so forth. Although we are writing different MOP algorithms for different matrices, they problems should be stated or formulated using a single-objective optimization problem whose optimal solutions are also Pareto-optimal solutions to the MOP. Additionally, it is often required that every Pareto-optimal solution can be reached with the aid of specific parameters of the scalarization.

5.3 Optimizers

5.3.1 Particle Swarm Optimization

Particle Swarm Optimization is a family of Swarm Intelligence optimization which is descended from the main family of Nature-Inspired Metaheuristics Algorithm. An optimization algorithm that is inspired by social behavior movement dynamics of insects, birds and fish. It exploits the collective behavior of self-organized, decentralized systems that rely on a social structure, such as bird flocks, ant colonies and fish schools. It is global gradient-less stochastic search method suited to continuous variable problems. It has a performance comparable to genetic algorithms and has successfully been applied to a wide variety of problems like the neural networks, structural optimization, and shape topology optimization.

PSO simulates animal's social behavior including insects, birds, herds and fishes. These swarms conform a cooperative way to find food and each member in the swarms keep changing the search pattern according to the learning experiences of its own and its

neighbors. Main design idea of the PSO algorithm is closely related to two researches: EA (Evolutionary Algorithm) which uses a swarm mode that makes it to simultaneously search large region in the solution space of the optimized objective function and AL (Artificial Life) which studies the artificial systems with life characteristics.

In studying the behavior of social animals with the artificial life theory, for how to construct the swarm artificial life systems with cooperative behavior by computer, it was proposed five basic principles. These principles include the main characteristics of the artificial life systems, and they have become guiding principles to establish the swarm artificial life system. First, proximity: the swarm should be able to carry out simple space and time computations. Second quality: the swarm should be able to sense the quality change in the environment and response it. Third diverse response: the swarm should not limit its way to get the resources in a narrow scope. Fourth stability: the swarm should not change its behavior mode with every environmental change. And finally adaptability: the swarm changes its behavior mode when this change is worthy. Assume that there was a “cornfield model” on the plane, i.e., food’s location, and birds randomly dispersed on the plane at the beginning. In order to find the location of the food, they moved according to the following rules by first assuming the position coordinate of the cornfield. The assumed position coordinate of the cornfield is (Y_0, Y_0') , and position coordinate and velocity coordinate of individual bird are (m, n) and $(V_y, V_{y'})$, respectively. Distance between the current position and cornfield is used to measure the performance of the current position and speed. The further the distance to the “cornfield”, the better the performance. On the other hand, when the distance to the cornfield is closer the performance is worse. Like the wireless sensor node each bird has the memory ability and can memorize the best position it ever reached, denoted as $pbest$. The velocity adjusting constant is referred as a , $rand$ denotes a random number in $[0, 1]$, change in the velocity item can be set according to the following rules:

$$\text{If } X > pbesty, V_y = V_y - rand \times a, \text{ otherwise } V_y = V_y + rand \times a \dots\dots\dots (17)$$

$$\text{If } Y > pbesty, V_{y'} = V_{y'} - rand \times a, \text{ otherwise } V_{y'} = V_{y'} + rand \times a \dots\dots\dots (18)$$

Then assume that the swarm can communicate in some way, and each individual is able to know and memorize the best location (marked as $gbest$) of the total swarm so far. And b is the velocity adjusting constant; then, after the velocity item was adjusted according to above rules, it must also update according to the following rules:

$$\text{If } Y > gbesty, V_y = V_y - rand \times b, \text{ otherwise } V_y = V_y + rand \times b \dots \dots \dots (19)$$

$$\text{If } Y' > gbesty', V_{y'} = V_{y'} - rand \times b, \text{ otherwise } V_{y'} = V_{y'} + rand \times b \dots \dots \dots (20)$$

Computer simulation results show that when a/b is relatively large, all individuals will gather to the “cornfield” quickly; on the contrary, if a/b is small, the particles will gather around the “cornfield” unsteadily and slowly. Through this simple simulation, it can be found that the swarms can find the optimal point quickly. After this trial and error methods an evolutionary optimization algorithm was deployed, and they finally fixed the basic algorithm as follows:

$$V_y = V_y + 2 * rand * (pbesty - y) + 2 * rand * (gbesty - y) \dots \dots \dots (21)$$

$$y = y + V_y \dots \dots \dots (22)$$

They abstracted each individual to be a particle with only velocity and position but without mass and volume, so they called this algorithm “particle swarm optimization algorithm.” On this basis, PSO algorithm can be summarized as follows: PSO algorithm is a kind of searching process based on swarm, in which each individual is called a particle defined as a potential solution of the optimized problem in D-dimensional search space, and it can memorize the optimal position of the swarm and that of its own, as well as the velocity.

In each generation, the particles information is combined together to adjust the velocity of each dimension, which is used to compute the new position of the particle. Particles change their states constantly in the multi-dimensional search space, until they reach balance or optimal state, or beyond the calculating limits. Unique connection among different dimensions of the problem space is introduced via the objective functions. Many empirical evidences have showed that this algorithm is an effective optimization tool. Flowchart of the PSO algorithm is shown in figure below.

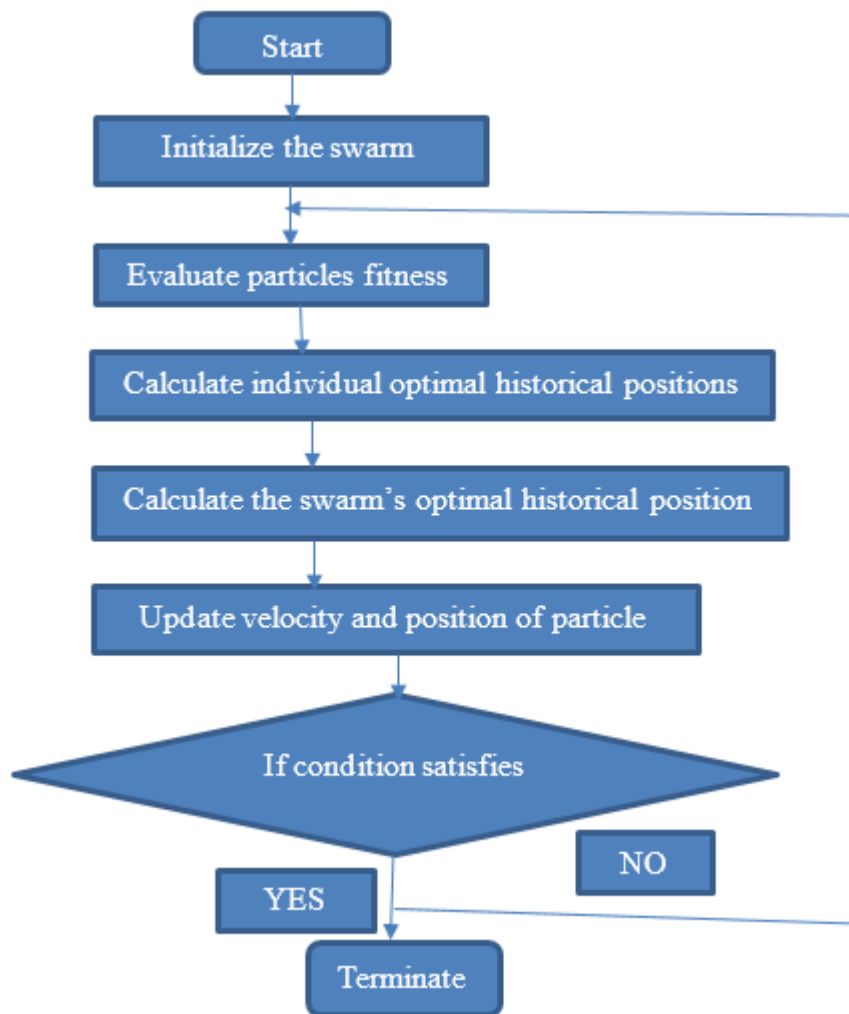


Figure 5-4: Flowchart of the Particle Swarm Optimization Algorithm YES NO

The following gives a relatively complete presentation of the PSO algorithm. In the continuous space coordinate system, mathematically, the PSO can be described as follows. Assume that swarm size is N , each particle's position vector in D -dimensional space is

$$Y_i = Y_{i1}, Y_{i2}, Y_{i3}, \dots, Y_{id}, \dots, Y_{iD},$$

$$\text{Velocity vector is } V_i = V_{i1}, V_{i2}, V_{i3}, \dots, V_{id}, \dots, V_{iD},$$

Individual's optimal position (i.e., the optimal position that the particle has experienced) is $P_i = P_{i1}, P_{i2}, P_{i3}, \dots, P_{id}, \dots, P_{iD}$, swarm's optimal position (i.e., the optimal position that any individual in this swarm has experienced) is represented as $p_g = p_{g1}, p_{g2}, p_{g3}, \dots, p_{gd}, \dots, p_{gD}$. Without loss of generality, taking the minimizing

problem as the example, in the initial version of the PSO algorithm, update formula of the individual's optimal position is:

$$P_{i,t+1}^d = \begin{cases} Y_{i,t+1}^d, & \text{if } f(Y_{i,t+1}^d) < f(P_{i,t}^d) \\ P_{i,t}^d, & \text{otherwise} \end{cases} \dots\dots\dots (23)$$

The swarm's optimal position is that of all the individual's optimal positions. Below it is stated respectively that update formula of velocity and position, the new velocity update formula became after the inertia weight was introduced to the velocity update formula are stated in the order of precedence:

$$V_{i,t+1}^d = V_{i,t}^d + C1 * rand * (P_{i,t}^d - Y_{i,t}^d) + C2 * rand * (P_{g,t}^d - Y_{i,t}^d) \dots\dots\dots (24)$$

$$Y_{i,t+1}^d = Y_{i,t}^d + V_{i,t+1}^d \dots\dots\dots (25)$$

$$V_{i,t+1}^d = \omega * V_{i,t}^d + C1 * rand * (P_{i,t}^d - Y_{i,t}^d) + C2 * rand * (P_{g,t}^d - Y_{i,t}^d) \dots\dots\dots (26)$$

Although this modified algorithm has almost the same complexity as the initial version, it has greatly improved the algorithm performance; therefore, it has achieved extensive applications.

Generally, the modified algorithm is called canonical PSO algorithm, and the initial version is called original PSO algorithm. By analyzing the convergence behavior of the PSO algorithm, researchers introduced a variant of the PSO algorithm with constriction factor χ which ensured the convergence and improved the convergence rate [42]. Then, the velocity update formula became:

$$V_{i,t+1}^d = \chi (V_{i,t}^d + \phi1 * rand * (P_{i,t}^d - Y_{i,t}^d) + \phi2 * rand * (P_{g,t}^d - Y_{i,t}^d)) \dots\dots\dots (27)$$

PSO algorithm has two versions the global version, where the two extremes that the particles track are the optimal position pbest of its own and the optimal position gbest of the swarm. Where as in local version, aside from tracking its own optimal position pbest, the particle does not track the swarm optimal position gbest, instead it tracks all particles' optimal position nbest in its topology neighborhood. For the local version, the velocity update equation in (26) became:

$$V_{i,t+1}^d = \omega * V_{i,t}^d + C1 * rand * (P_{i,t}^d - Y_{i,t}^d) + C2 * rand * (P_{l,t}^d - Y_{i,t}^d) \dots\dots\dots (28)$$

Where P_i was the optimal position in the local neighborhood. In each generation, iteration procedure of any particle is illustrated in figure below. From the velocity update formula, the first part is the influence of the particle's previous velocity which means that

the particle has confidence on its current moving state and conducts inertial moving according to its own velocity, so parameter ω is called inertia weight. The second part depends on the distance between the particle's current position and its own optimal position, called the "cognitive" item. It means particle's own thinking, i.e., particle's move resulting from its own experience. Therefore, parameter $c1$ is called cognitive learning factor (also called cognitive acceleration factor). The third part relies on the distance between the particle's current position and the global (or local) optimal position in the swarm, called "social" factor. It means the information share and cooperation among the particles, namely particle's move coming from other particles' experience in the swarm. It simulates the move of good particle through the cognition, so the parameter $c2$ is called social learning factor (also called social acceleration factor).

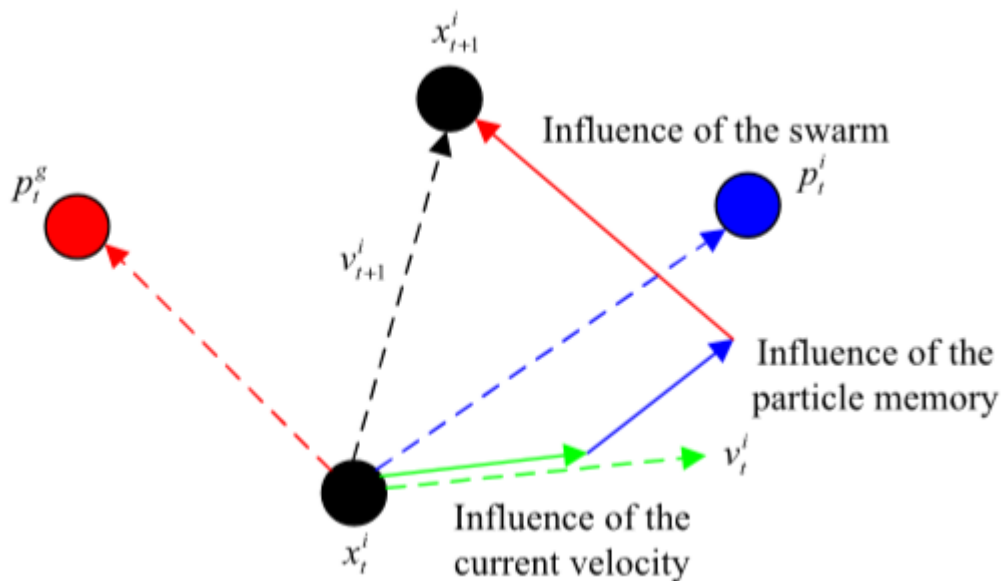


Figure 5-5: Iteration scheme of the particles [42]

5.3.2 Coverage and Lifetime Optimization of Wireless Sensor Networks with Gaussian distribution

A wireless sensor network (WSN) has to maintain a desirable sensing coverage and periodically report sensed data to the administrative center (i.e., base station), and the reporting period may range from months to years. Coverage and lifetime are two paramount problems in a WSN due to constraint of associated battery power. All previous theoretical analyses on the coverage and lifetime are primarily focused on the random uniform distribution of sensors or some specific network scenarios (e.g., a

controllable WSN). In this technique, an analytical framework for the coverage and lifetime of a WSN that follows a 2D Gaussian distribution is provided. The intrinsic properties of coverage/lifetime in terms of Gaussian distribution parameters, which is a fundamental issue in designing a WSN is also identified.

Next, we will define sensor deployment strategies for a WSN that could satisfy a predefined coverage and lifetime. Two deployment algorithms are developed based on using our analytical models and are shown to effectively increase the WSN lifetime.

Assumptions [34, 35, 36]

Coverage and Lifetime optimization

- ✓ The time until the first sensor is drained of its energy;
- ✓ The time until the first cluster head is drained of its energy;
- ✓ The time there is at least a certain fraction β of surviving nodes in the network
- ✓ The time until all nodes have been drained of their energy;
- ✓ K-coverage: the time the area of interest is covered by at least k nodes;
- ✓ The time each target is covered by at least one node;
- ✓ The number of successful data-gathering trips;
- ✓ The number of total transmitted messages;
- ✓ The percentage of nodes that have a path to the base station;
- ✓ The time until connectivity or coverage are lost;
- ✓ The time until the network no longer provides an acceptable event detection ratio;

Chapter 6 RESULTS, CONCLUSIONS AND RECOMMENDATIONS

6.1 RESULTS

6.1.1 Gaussian distribution Simulation Result

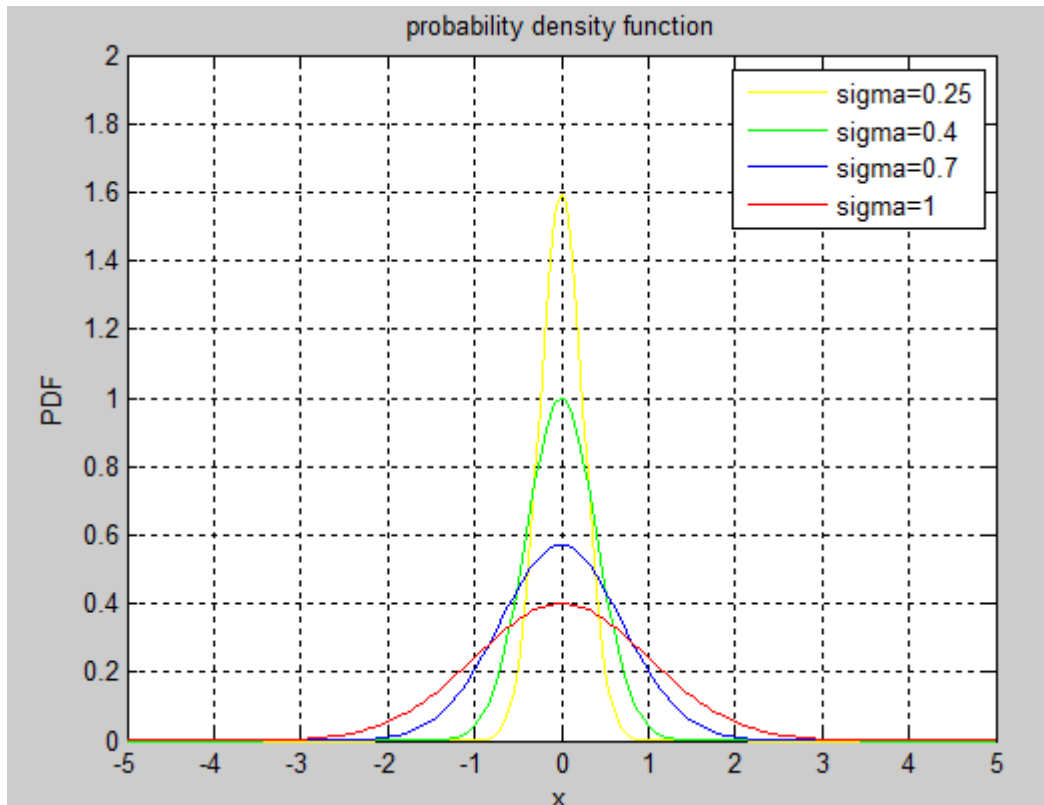


Figure 6-1: Gaussian distribution for the lifetime of the network

The MATLAB code for the Gaussian distribution is constructed using four lines: that is yellow, green, blue and red with sigma values of 0.25, 0.4, 0.7 and 1 respectively. The yellow curve with gradient 0.25, the green curve with gradient 0.4, and blue curve with gradient 0.7 shows the Gaussian distribution of the three types of terrain in the area in reference to the red line with gradient 1. Gradient one means ideal distribution for the lifetime of the sensor node.

Here, the Gaussian distribution function is used to illustrate the lifetime of the sensor, according to their usage in different types of terrain. Smooth communication is attained over a flat area or landform which means their battery consumption is lower relative to

their battery usage in landforms with higher gradients. This is due to the requirement for a continuous and fast communication to be attained in landforms with mountains and hills. The required numbers of sensor nodes in these areas are relatively high and their effort for smooth communication the data sensing, sending and receiving rate is also high. So, this will decrease their lifetime.

6.1.2 PSO Optimization Result

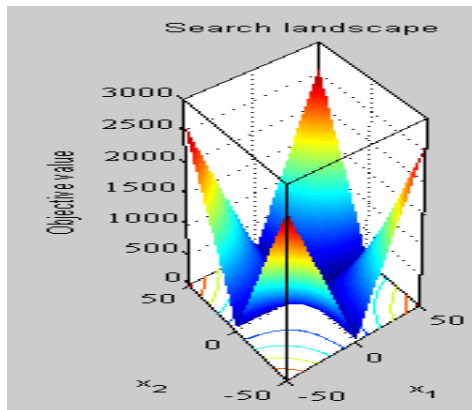


Figure 6-2: Ring routing model node deployment

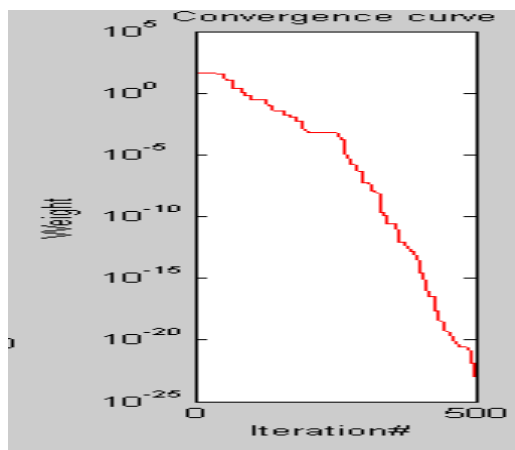


Figure 6-3: Convergence Curve

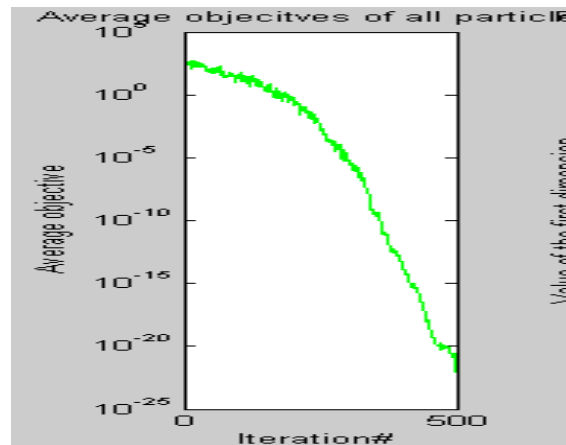


Figure 6-4: Average Objective

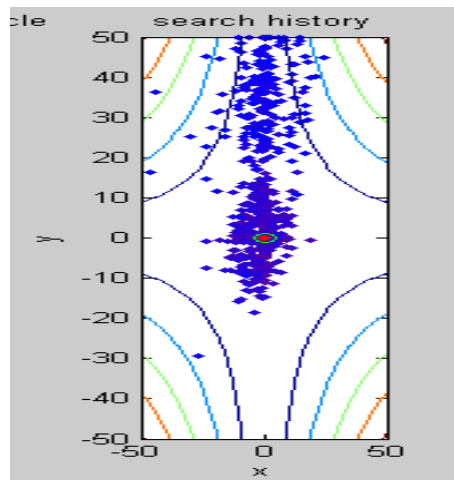


Figure 6-5: Result of the 500th iteration to find the cluster head

This PSO Matlab code can rush “collapse” of swarm for better local search at the cost of higher possibility of premature convergence.

The PSO is an efficient global optimizer for continuous variable problems (structural applications). It is easily implemented, with very little parameters to fine-tune. It takes the update of 500 iterations for the search of the best value of the objective function. The algorithm modifications improve PSO local search ability which can accommodate constraints by using a penalty method.

Parallel optimization algorithms allows higher throughput by solving more complex problems in the same time span. It has the ability to solve previously intractable problems of more sophisticated finite element formulations, with higher accuracy (mesh densities).

Improved convergence rate is achieved when p_i and p_g are updated after each fitness evaluation (asynchronous algorithm).

6.2 CONCLUSIONS

In this paper, the very fundamental parameters for the Ethio-Djibouti Railway is optimized and discussed briefly. Also, the mathematical models and descriptions of all the other parameters are mathematically described and defined well. To meet the sensing and coverage range requirements of the network, the number of required stations calculated based on the average distance requirement between stations.

The system of Wireless Sensor Networks is a powerful choice for countries like Ethiopia, since we do not need extra infrastructure for the deployment of these networks. We only need appropriate places to put the cluster heads. This paper studies and models the deployment and routing of Wireless Sensor Networks, the station calculations, system model and architecture, merits of the proposed Signalling system, routing algorithms carefully selected for its energy efficiency capacity and reliability and Gravitational Search Algorithm for an appropriate selection of the center of the routing protocol which is to be announced as a place for the cluster head.

A MATLAB simulation is done for investigating the distribution of the nodes in different types of topography; different gradients are taken to show the nodes are in the appropriate places for a uniform communication. Also a Particle Swarm Optimization technique is tested using MATLAB, which takes 500 iterations to find the best point and according to that point best solution is find.

6.3 RECOMMENDATIONS

With the increasing demand for quality of transportation, WSNs play an important role for the quality, cost and safety of railway transportation. For a subject with too many

objective functions dealing with individual functions might be tricky and almost impossible at one paper work since, improving one constraint might affect the other one and we are dealing with 12 metrics at the same time.

The topic is new and one of the emerging research areas for researchers across the globe. And from the papers that are surveyed for the completion of this thesis work, each metrics have to be covered and discussed in detail for the detailed documentation of a work. Hence, I strongly recommend for anyone who is interested in this field of study to model the rest of the metrics like energy consumption, data integration, security, reliability, and fault tolerance. For energy consumption, node scheduling technique (ON/OFF) system of nodes which uses shifting the operating state of the node to conserve the lifetime of the battery can be a future work.

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APPENDIX A

Code for Gaussian distribution

```
% Matlab Code for Gaussian distribution

clc; clear all; close all;

colors=['y','g','b','r'] ;
m = 0;
sig = [0.25 0.4 0.7 1];
y = -5:0.05:5;
f=zeros(1,length(y));

for w = 1:length(sig)
for ii = 1:length(y)

f(ii) = 1/(sig(w)*sqrt(2*pi)) .* exp(-((y(ii)-m)^2 / (2*(sig(w))^2)));

end

plot(y,f,colors(w))
hold on

end

ylabel('x');
y' label('PDF');
title('probability density function')
hleg1 = legend('sigma=0.25','sigma=0.4','sigma=0.7','sigma=1');
set(hleg1,'Location','NorthEast')
axis([-5 5 0 2]);
grid on
```

The main Code for PSO Algorithm (Parameter Definition)

```
% Main code for PSO

clear
close all
clc

% Problem preparation
problem.nVar = 2;
problem.ub = 50 * ones(1, 2);
problem.lb = -50 * ones(1, 2);
problem.fobj = @ObjectiveFunction;

% PSO parameters
noP = 4;
maxIter = 500;
visFlag = 1; % set this to 0 if you do not want visualization

RunNo = 30;
BestSolutions_PSO = zeros(1, RunNo);

[ GBEST , cgcurve ] = PSO( noP , maxIter, problem , visFlag ) ;

disp('Best solution found')
GBEST.Y
disp('Best objective value')
GBEST.O
```

Objective Function for PSO

```
% Objective function for PSO

function [ o ] = ObjectiveFunction (y)

    o = sum ( abs(y) ) + prod( abs(y) );

end
```

PSO Code and Plot Definition

```
% PSO code definition

function [ GBEST , cgCurve ] = PSO ( noP, maxIter, problem, dataVis )

% Define the details of the objective function
nVar = problem.nVar;
ub = problem.ub;
lb = problem.lb;
fobj = problem.fobj;

% Extra variables for data visualization
average_objective = zeros(1, maxIter);
cgCurve = zeros(1, maxIter);
FirstP_D1 = zeros(1 , maxIter);
position_history = zeros(noP , maxIter , nVar );
% Define the PSO's paramters
wMax = 0.9;
wMin = 0.2;
c1 = 2;
c2 = 2;
vMax = (ub - lb) .* 0.2;
vMin = -vMax;

% The PSO algorithm

% Initialize the particles
for k = 1 : noP
    Swarm.Particles(k).Y = (ub-lb) .* rand(1,nVar) + lb;
    Swarm.Particles(k).V = zeros(1, nVar);
    Swarm.Particles(k).PBEST.Y = zeros(1,nVar);
    Swarm.Particles(k).PBEST.O = inf;

    Swarm.GBEST.Y = zeros(1,nVar);
    Swarm.GBEST.O = inf;
end

% Main loop
for t = 1 : maxIter

    % Calcualte the objective value
    for k = 1 : noP

        currentY = Swarm.Particles(k).Y;
        position_history(k , t , : ) = currentY;

        Swarm.Particles(k).O = fobj(currentX);
        average_objective(t) = average_objective(t) +
Swarm.Particles(k).O;

        % Update the PBEST
        if Swarm.Particles(k).O < Swarm.Particles(k).PBEST.O
            Swarm.Particles(k).PBEST.Y = currentY;
            Swarm.Particles(k).PBEST.O = Swarm.Particles(k).O;
```

```
end

% Update the GBEST
if Swarm.Particles(k).O < Swarm.GBEST.O
    Swarm.GBEST.Y = currentY;
    Swarm.GBEST.O = Swarm.Particles(k).O;
end
end

% Update the X and V vectors
w = wMax - t .* ((wMax - wMin) / maxIter);

FirstP_D1(t) = Swarm.Particles(1).Y(1);

for k = 1 : noP
    Swarm.Particles(k).V = w .* Swarm.Particles(k).V + c1 .*
    rand(1,nVar) .* (Swarm.Particles(k).PBEST.Y - Swarm.Particles(k).Y) ...
    + c2 .* rand(1,nVar) .* (Swarm.GBEST.Y -
    Swarm.Particles(k).Y);

    % Check velocities
    index1 = find(Swarm.Particles(k).V > vMax);
    index2 = find(Swarm.Particles(k).V < vMin);

    Swarm.Particles(k).V(index1) = vMax(index1);
    Swarm.Particles(k).V(index2) = vMin(index2);

    Swarm.Particles(k).Y = Swarm.Particles(k).Y +
    Swarm.Particles(k).V;

    % Check positions
    index1 = find(Swarm.Particles(k).Y > ub);
    index2 = find(Swarm.Particles(k).Y < lb);

    Swarm.Particles(k).Y(index1) = ub(index1);
    Swarm.Particles(k).Y(index2) = lb(index2);

end

if dataVis == 1
    outmsg = ['Iteration# ', num2str(t) , ' Swarm.GBEST.O = ' ,
num2str(Swarm.GBEST.O)];
    disp(outmsg);
end

cgCurve(t) = Swarm.GBEST.O;
average_objective(t) = average_objective(t) / noP;

fileName = ['Results after iteration # ' , num2str(t)];
save( fileName)
end

GBEST = Swarm.GBEST;

if dataVis == 1
    iterations = 1: maxIter;
```

```
%% Draw the landscape
figure

Y = -50 : 1 : 50;
Y' = -50 : 1 : 50;

[Y_new , Y'_new] = meshgrid(Y,Y');

for k1 = 1: size(Y_new, 1)
    for k2 = 1 : size(Y_new , 2)
        X = [ Y_new(k1,k2) , Y'_new(k1, k2) ];
        z(k1,k2) = ObjectiveFunction( Y );
    end
end

subplot(1,5,1)
surf(Y_new , Y'_new , z);
title('Search landscape')
xlabel('N')
ylabel('M')
zlabel('Objective value')
shading interp
camproj perspective
box on
set(gca, 'FontName', 'Times')

%% Visualize the cgcurve
subplot(1,5,2);
semilogy(iterations , cgCurve, 'r');
title('Convergence curve')
xlabel('number of iterations')
ylabel('particles Weight')

%% Visualize the average objectives
subplot(1,5,3)
semilogy(iterations , average_objective , 'g')
title('Average objectitves of all particles')
xlabel('number of iterations')
ylabel('Average objective')

%% Visualize the fluctuations
subplot(1,5,4)
plot(iterations , FirstP_D1, 'k');
title('First dimention in first Particle')
xlabel('Iteration#')
ylabel('Value of the first dimension')

%% Visualize the search history
subplot(1,5,5)
hold on
for p = 1 : noP
    for t = 1 : maxIter
        x = position_history(p, t , 1);
        y = position_history(p, t , 2);
        myColor = [0+t/maxIter 0 1-t/maxIter ];
        plot(x , y , '.' , 'color' , myColor );
    end
end
```

```
        end
    end
    contour(x_new , y_new , z);
    plot(Swarm.GBEST.X(1) , Swarm.GBEST.X(2) , 'og');
    xlim([lb(1) , ub(1)])
    ylim([lb(2) , ub(2) ])
    title('search history')
    xlabel('x')
    ylabel('y')
    box on

    set(gcf , 'position' , [128          372          1634          259])

end
```