Monitoring of Power Transmission Lines through Wireless Sensor Network in Smart Grid

By

Malik Ali Judge

CIIT/SP15-REE-016/ISB

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A Graduate Thesis submitted to Department of Electrical Engineering as partial fulfillment of the requirement for the award of Degree of M.S (Electrical Engineering).

Name	Registration Number
Malik Ali Judge	CIIT/SP15-REE-016/ISB

Supervisor

Dr. Moazzam Islam Tiwana,
Assistant Professor,
Department of Electrical Engineering,
COMSATS Institute of Information Technology (CIIT),
Islamabad Campus.
June, 2017

Co-Supervisor

Dr. Nadeem Javaid,
Associate Professor,
Department of Computer Science,
COMSATS Institute of Information Technology (CIIT),
Islamabad Campus.
June, 2017

Final Approval

This thesis titled

Monitoring of Power Transmission Lines through Wireless Sensor Network in Smart Grid

By

Malik Ali Judge
CIIT/SP15-REE-016/ISB

has been approved

For the COMSATS Institute of Information Technology, Islamabad

External Examiner: ____
Dr. Muhammad Sher
Professor, Department of Computer Science & Software Engineering, IIU, Islamabad

Supervisor: ____
Dr. Moazzam Islam Tiwana
Assistant Professor, Department of Electrical Engineering, Islamabad

Co-Supervisor: ____
Dr. Nadeem Javaid
Associate Professor, Department of Computer Science, Islamabad

HoD: ____
Dr. M. Junaid Mughal
Professor, Department of Electrical Engineering, Islamabad

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I Malik Ali Judge**, CIIT/SP15-REE-016/ISB** hereby declare that I have produced the work presented in this thesis, during the scheduled period of study. I also declare that I have not taken any material from any source except referred to wherever due that amount of plagiarism is within acceptable range. If a violation of HEC rules on research has occurred in this thesis, I shall be liable to punishable action under the plagiarism rules of the HEC.

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____

Malik Ali Judge
CIIT/SP15-REE-016/ISB

Certificate

It is certified that Malik Ali Judge, CIIT/SP15-REE-016/ISB has carried out all the work related to this thesis under my supervision at the Department of Electrical Engineering, COMSATS Institute of Information Technology, Islamabad and the work fulfills the requirement for award of MS degree.

Date: _________________

Supervisor:

____
Dr. Moazzam Islam Tiwana
Assistant Professor

Co- Supervisor:

____
Dr. Nadeem Javaid
Associate Professor

Head of Department:

____

Dr. M. Junaid Mughal
Professor, Department of Electrical Engineering

DEDICATION

I am deeply obliged to acknowledge and thank to those people who put their ever-best contribution in my thesis. First, I am thankful to my Almighty Allah for blessing me this beautiful life and everything that He has provided me.

Secondly, I cannot forget the appreciation and encouragement from my family especially from my mother, respected teachers and friends that they gave throughout my academic life. I also feel great and valuable by being a part of COMSATS University.

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Malik Ali Judge
CIIT/SP15-REE-016/ISB

ABSTRACT

Monitoring of Power Transmission Lines through Wireless Sensor Network in Smart Grid

Smart Grid (SG) faces several challenges to efficiently and effectively transmit power from generation to end users. So, a robust monitoring mechanism is essential to monitor the transmission lines and towers. Numerous state-of-the-art techniques are available in literature which timely and precisely locate the problem. In this thesis, we present a three-tier hybrid model composed of wireless, wired and cellular technologies that can ensure real-time data monitoring of transmission lines. In this regard, we developed a mathematical framework to measure the feasibility of our model in term of minimal time delay. Further, we formulate the placement problem to locate the optimal position of cellular enabled towers in regard to minimize the delay of data delivery. We also scrutinize the associated energy consumption of data transmission. Additionally, we map our scenario in order to adjust power allocation for achieving minimal energy consumption. For ensuring the feasibility of our proposed work, theoretical analysis is done to compute feasible regions for the performance parameters which are confirmed via observable results through simulations. Results show that proposed model is effective in delivering information at minimum delay.

LIST OF PUBLICATION

1. Judge, M.A., Manzoor, A., Ahmed, F., Kazmi, S., Khan, Z.A., Qasim, U. and Javaid, N., 2017, July. Monitoring of Power Transmission Lines through Wireless Sensor Networks in Smart Grid. In *International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing* (pp. 162-170). Springer, Cham. Download

2. Manzoor, A., Ahmed, F., Judge, M.A., Ahmed, A., Tahir, M.A.U.H., Khan, Z.A., Qasim, U. and Javaid, N., 2017, July. User Comfort Oriented Residential Power Scheduling in Smart Homes. *In International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing* (pp. 171-180). Springer, Cham. Download

3. Ahmed, F., Javaid, N., Manzoor, A., Judge, M.A., Feroze, F. and Khan, Z.A., 2017, June. Cost and Comfort Based Optimization of Residential Load in Smart Grid. In *International Conference on Emerging Internetworking, Data & Web Technologies* (pp. 563-572). Springer, Cham. Download

4. Ahmed, F., Manzoor, A., Judge, M.A., Hussain, H.M., Khan, Z.I., Z.A., Qasim, U. and Javaid, N., 2017, September. Building energy and comfort management: A state-of the-art Survey. In *International Conference on P2P, Parallel, Grid, Cloud and Internet Computing*, Barcelona, Spain. Download

5. Ghulam Hafeez, Abdul Wahab, Malik Ali Judge."Optimal residential load scheduling under utility and rooftop PV units in the smart grid." *12th international conference on 2P2, Parallel, Grid, Cloud and Internet Computing (3PGCIC-2017),* Nov 5-7, 2017 in Palau Macaya, Barcelona, Spain. Download

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Chapter 1

Introduction

Energy efficiency is one of the key parameters in the zone of power sector, therefore, research community is devoted continuously to bring improvement in the requirements of the users. For energy efficiency to improve the performance of the grid, an infrastructure is needed which can tolerate disturbances like transients, harmonics, voltage sags or swells, voltage surges and voltage imbalances. Energy efficiency can be accomplished by developing more energy efficient technologies and by making system more reliable.

Currently, the transmission line infrastructure is highly vulnerable to natural disasters, manmade mishaps, etc resulting in instability of the grid. So, there is an impending need to modify the transmission lines with efficient communication system to support several reviews like real time monitoring, faster fault identification and exact fault diagnosis. In this regard, communication systems enabled with IoT based Wireless Sensor Networks (WSNs) are integrated into Traditional Grid (TG) and transforms it to Smart Grid (SG). SG refers as two-way communication technologies, distributed energy resources and generation, smart technologies and advanced electricity storage system. The aforementioned features make SG more reliable, less stringent, self-healing and less vulnerable as compared to TG. Smart grid infrastructure is illustrated in Figure 1.1.

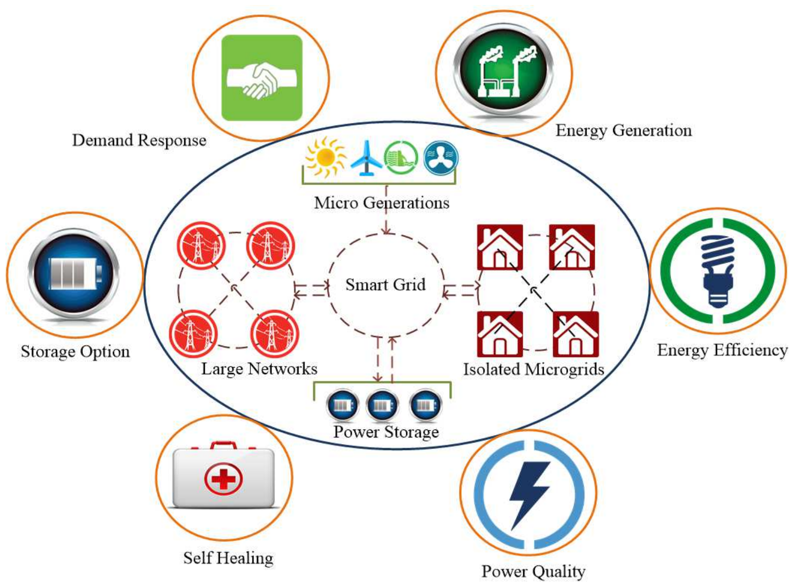

Figure 1.1: Smart grid infrastructure

SG is comprised of various components like Control Center (CC), substations, transmission lines, towers and with advanced information and communication technologies. Due to long distance between generations and end users, transmission lines are supported by towers and employ to carry power. Substation transmits information to CC every few seconds. The speed of communication link between the substation and CC is quite slow [1], thus there is need to improve the communication links. Due to improvements in technologies, it is anticipated that more power companies will use higher bandwidth and low latency communication links, e.g. optical fiber [2]. Nowadays, optical communication provides better option than other communication links due to its better capacity, low latency and high reliability while one factor that overshadow the performance of optical fiber is its high installation and maintenance cost. However, it is impossible to deploy optical fiber communication links along the transmission lines, thus a wireless communication idea is proposed in [3]. A wireless communication technology provides cheaper, less complicated and highly flexible solution than that of optical fiber. However, wireless technology is widely used in smart grid.

WSNs play a significant role in the monitoring of transmission lines. For real time status monitoring, different types of sensors are placed at various location of transmission lines. Theses sensors are responsible for collecting fine monitoring data and employ short range communication for data transmission to relay node. Due to short range of communication between sensors and relay nodes, sensors are installed near to the transmission towers, while relay nodes on top of the towers. All relay nodes communicate with each others and transmit accumulative data to substations. Thereafter, data will be transmitted from substations to CC through optical fiber. At the CC, data will be compared with the existing data and correct decision will be taken after comparison. Delivering the fine monitoring data to CC with cost efficient and timely manner is a critical challenge for an intelligent smart grid.

How to deliver data in timely fashion to the CC is the biggest challenge for an intelligent SG. In this thesis, we study the wireless communication based infrastructure for the monitoring of transmission lines. We propose a mathematical relation to judge the feasibility of our model in term of minimal time delay. We also investigate the associated energy consumption of cellular networks and sensor nodes for data transmission.

The rest of the thesis is organized as follows: Section 2 comprised of state of the art work. Thereafter, section 3 presents the working of system model to support future smart gird. In section 4, we formulate our problem and developed a quadratic equation to find the optimal position of direct cellular link. Further, we calculate feasible region for both the scenarios under the consideration of variable number of nodes in section 5. Section 6 is composed of simulations and discussions of our work where we explore the relationship between total energy consumption and time delay as well. Furthermore, we perform scalability analysis to measure the performance of system. Finally, section 7 summarizes the entire work with conclusion and some future directions.

Chapter 2

Related Work

Redundant behavior of power consumption leads to increase the losses of transmission line; thus, it is necessary to monitor the various parameters of transmission lines. Monitoring of transmission lines have attained the focus of researchers and substantial work has been carried out to overcome the problems.

Nordman *et al.* utilized the WSNs to support the monitoring network of substation [4]. Authors of [5] and [6] are responsible to extend the application of WSNs for monitoring the transmission lines. The main theme of these papers are to deploy sensors at different points along the transmission lines. Moreover authors also observed those locations of transmission lines which are far away from the substation and authors proposed a prototype for transmission line sensors in order to validate the feasibility of its work [7]. In [8], authors first discussed the feasibility of linear network model and conclude the result that this model is infeasible in delivering information timely and then proposed reconfigurable network model. In aforementioned model, authors set two direct links for information delivery and minimized the time delay to some extent. This model still has some space of improvement regarding positioning of direct links. Further, time delay can be minimized by appropriate selection of direct links. However, in [9] authors proposed a quadratic equation to find the optimal number and position of direct links aiming to reduce the time delay in delivering the information. Hence, in this regard authors proposed a mathematical model to understand relation between time delay and direct links. Moreover, authors also investigated the associated energy consumption of delivering the data.

In [10], the authors developed a hybrid hierarchical model which is composed of wired, cellular and wireless technologies that can ensure low cost data monitoring. Authors also developed an objective function aiming to minimize the total installation and operational cost of cellular network. Moreover, the authors formulated the problem to find the optimal number and position of cellular links and formulation is solved by using integer linear programming. Further, authors presented the several diverse scenarios to measure the feasibility of proposed hierarchical model. In order to felicitous measurement Feng ye *at al.* presented a model [11] to monitor real time status of transmission line. Authors proposed different centralized schemes with the objective to minimize the power consumption of all sensors in data transmission. Authors also proposed a distribution power allocation strategy for dynamic data traffics thus results of the centralized schemes used as a benchmark for the distributed strategy. Authors also conducted the case study to measure the feasibility of distributed strategy. Results demonstrated that distributed power allocation strategy consumes less power and gratifies the delay requirement effectively.

Wide area network plays a significant role in the monitoring of transmission lines. In [12], authors proposed an efficient technique called optimal placement for the quality of service and robustness to maintain and improve the quality and robustness of transmission lines. The major objective of the proposed model is to minimize the cost while respecting the constraints of the quality of service and robustness. The proposed technique uses a canonical genetic algorithm to find an optimal location, quantity, and types of wide area network to be installed. The results validated that the proposed technique has efficiently achieved the desired objective with minimum computational time as compared to the exhaustive search. Venkatasubramani *et al.* in [13], has proposed a hybrid model comprised of three technologies: wired, wireless and cellular. The proposed model aimed at cost-efficient monitoring of several mechanical parameters which affect the transmission lines. Moreover, the optimal placement of cellular communication towers has also been addressed to minimize the deployment and operational cost. In [14], the problem of determining the minimum number of connecting lines and buses have been addressed. The traditional optimization problem has been converted into two stages and the problem of finding the minimum numbers of connecting lines has categorized the upper level. Moreover, line redundant factor has also been proposed at the upper level and introduced penalty factor to penalize the excessive lines. In this way, the entire transmission lines and buses are directly and continuously monitored.

Yun *et al.* presented Brillouin Optical Time Domain Reflectometry (BOTDR) sensing system for on-line monitoring of transmission lines in [15]. Authors measured the temperature of electrified and non-electrified transmission lines at different times and monitored the variation in temperature. Authors also studied the temperature with fixed and variable sensing position. Further, authors also discussed the experimental results that show the line temperature increases as the length of line increases. Results show that BODTR sensing system can be successfully implemented to monitor the temperature of transmission lines and support several technical things for future SG. A comprehensive study showing real-time monitoring of transmission lines is presented in [16]. Authors discussed the wide range monitoring device which is used to determine the thermal rating of transmission lines. The device used for real time monitoring of transmission lines is evaluated for two system modes: normal operation and system contingency. Authors evaluated strength and weakness of different methods and concluding that some methods perform well during system normal mode while others are effective in system contingency mode. A hybrid architecture is presented in [17] to overcome the limitations of linear topology. Authors used sensor to control and monitor power distribution network. Authors investigated the extensive utilization of relay nodes in hybrid architecture and proposed fault tolerance mechanism to monitor the transmission lines. Optimization techniques are applied to decide numbers of backup and cellular nodes to achieve minimal cost. Moreover, authors also examined the exact deployment position and timely action will be taken to remove the fault.

To avoid any electrical connection between transmission lines, authors adopted non-contact capacitive coupling for voltage monitoring of overhead transmission lines in [18]. Authors proposed a technique which is based on non-contact capacitive-coupling and supported by magnetic field sensing. The proposed technique is implemented on single-circuit transmission line. Authors also investigated the affect of the several parameters such as ground wire, induction bar sensitivity, measurement of transients and associated capacitance of instrument. Moreover, spatial position of transmission lines is discussed with the integration of magnetic field sensing and stochastic optimization algorithm. To avoid glue aging problem Fiber Bragg Grating (FBG) is welded on the elastic element. A FBG load cell is used for monitoring the transmission line in [19]. This paper resolved the issue of low resolution and low sensitivity of existing optical sensor. Gubeljak *et al.* proposed the Overhead Transmission Line Monitoring (OTLM) system to measure additional inclination such as sag in [20]. An extra feature to calculate the sag on critical spans is also discussed. In this paper, mathematical model is developed for horizontal force and sag calculation.

We outline our contributions as follows: (1) We study the performance of both linear and direct link network architecture. (2) We design hybrid monitoring network with the combination of existing wired, wireless and cellular technologies. (3) To find the optimal location of cellular towers, we employ quadratic equation. (4) We calculate the feasible region for both scenarios. (5) We perform a scalability analysis to measure the performance of system under expanding workload condition. (6) We propose a power allocation scheme with the objective of minimizing the total power usage.

Chapter 3

System Model

3.1 Linear Network Architecture

In this section, we discuss the performance of linear network architecture. Figure 3.1 shows the visual image of transmission towers and one substations on both side. Different types of sensors are installed near the poles/towers. All the towers are spread linearly along with the earth surface and form a straight line as shown in Figure 3.1. We also assume that all towers have equal distance between each other. The total measurable distance between two substations is $50km$ [8]. On the other side, distance between two adjacent towers is no more than $0.5-1km$. However, there can be $30-100$ towers between two substations.

For interpole relaying, wireless communication technologies are used as a communication source between two adjacent towers. Wireless communication is most effective and reliable in terms of low installation cost and time. Many wireless communication technologies available in market and manufacturers are categorized them by their transmission range, throughput, total power consumption, subscription fee and wireless channel contention. Typically, higher the transmission range, lower the throughput and higher the total power consumption. For transmission over long distance, a dedicated channel is required due to high interference which is induced by high transmission power. However, excessive utilization of dedicated channel incurs huge charges about subscription fee. Characteristic of available wireless technologies outline in Table 3.1.

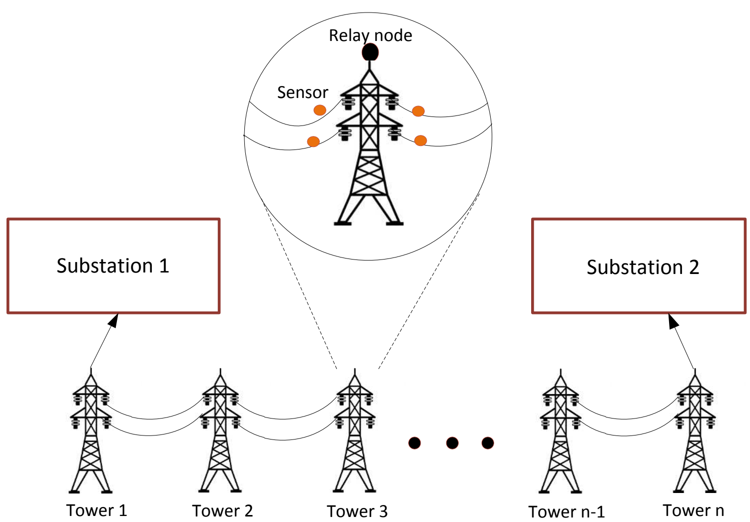

Figure 3.1: Overhead transmission line infrastructure between two substations

3.1.1 Description of linear network architecture

In order to sense, monitor, gather and transmit data from real time environment, n number of sensor nodes are randomly deployed over the desired area. We placed sensor nodes on the transmission lines and at the tower for relaying data of neighboring nodes and their own sensed data. If the short range communication technologies such as bluetooth, ZigBee are used then nodes are placed $100m$ away from each other [21]. However, pro ZigBee technology support communication up

Table 3.1: Characteristic of available wireless technologies

Properties	Cellular Network	ZibBee	WLAN	Bluetooth
Transmission Range	$100m - 10km$	$10m - 1.5km$	$100m - 250m$	$10m - 100m$
Throughput	$64kbps(2G) - 384kbps(3G)$	$20kbps-250kbps$	$11Mbps - 54Mbps$	$3Mbps$
Power Consumption	High	1 mW (standard range) 4−5 (extended range)	50mW	10mW
Wireless Channel Contention	No	Yes	Yes	Yes
Subscription Fee	Yes	No	No	No

to $10m - 1.5km$ [7]. Therefore, we have adopted pro ZigBee technology for long distance communication between sensor nodes. The data is passed to the CC via multi-hop communication which are connected through multiple substations.

Figure 3.2 depicts the high level of abstraction of linear network architecture based on several assumptions.

1) The substation is connected to the CC via high speed optical fiber link. A huge amount of data will be transferred to CC within no time.

2) Due to communication with large number of relay nodes, a relay node should be more powerful than sensor node in terms of computational power, transmission range, network lifetime, etc.

Figure 3.2 depicts the working of linear network architecture. It clearly indicates that some of the relay nodes are not directly connected to the substation and send their sensed data to its neighbor nodes which are near to the substation. For example, Relay Node 3 sends its data to Relay Node 2, Relay Node 2 appends its own data with the data received from Relay Node 3 and sends to Relay Node 1. Then Relay Node 1 adds all the receiving data from the predecessor nodes with its own data and sends to the Substation 1. All the process is also applied on Substation 2 where Relay Node n collects data from its neighbor Relay Node $n - 1$ and transmits whole data to the Substation 2.

3.1.2 Performance of linear network architecture

In this subsection, we evaluate the performance of linear network architecture in term of time delay. Several sensors such as magnetic field sensors, accelerometer, temperature sensors and strain sensors are deployed on various positions to monitor the span of the transmission lines. Table 3.2 categorizes different sensors based on their types and data collection rate. The data is sampled at the frequency of $500Hz$ while data collecting frequency is $2Hz$. Sensors shown in Table 3.2 cannot preprocess raw data while due to improvements in computational power of sen-

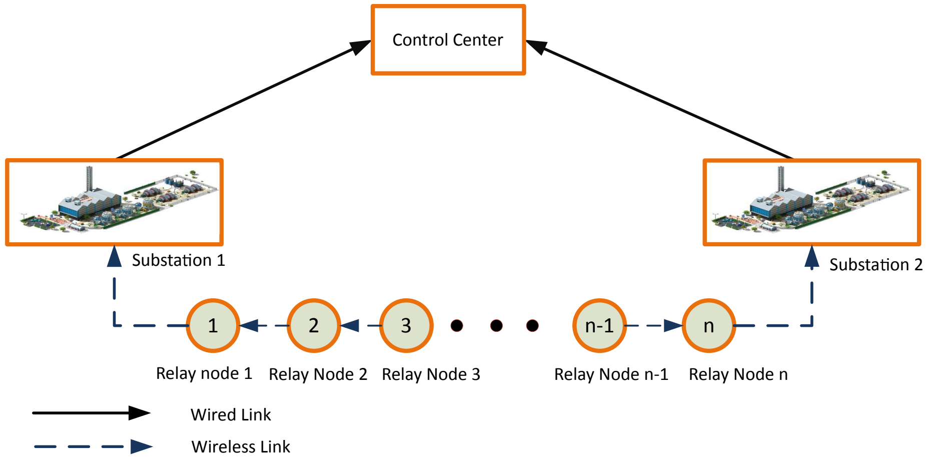

Figure 3.2: Linear network architecture

sors, it is anticipated that sensors can preprocess raw data to extract important information. In this work, we assume that sensors cannot preprocess raw data when the corresponding relay nodes receive data they extract important information and send back to the substation. Table 3.3 shows the list of some important attributes which are much important in monitoring application. The total size of processed data is $4kBytes$ while the size of unprocessed data is $16kBytes$. The size of processed data is almost quarter than that of unprocessed data.

Table 3.2: Summary of available sensors data rate

Types of sensors	Number of sensors	Number of channels per sensor	Size of each sample per channel	Data per cycle
Accelerometer	4	2	$4Bytes(1Float)$	$8kBytes$
Magnetic Field Sensor	2	2	$4Bytes(1Float)$	$4kBytes$
Strain Sensor	1	2	$4Bytes(1Float)$	$2kBytes$
Temperature Sensor	1	1	$4Bytes(1Float)$	$1kBytes$

In [8], authors explain the feasibility of linear network architecture in delivering the data. To evaluate the performance of the network, authors consider several assumptions such as $n = 100$ towers in between two substations, these towers have equal distance between each other and available uniformly spaced in linear alignment. For data relaying between relay nodes, half side of towers such as Tower 50 to Tower 1 is considered. Relay node of Tower 50 receives data from its corresponding sensor and sends it to relay node of Tower 49. Relay node of Tower 49 adds its data with the data received from relay node of Tower 50 and sends to relay node of Tower 48. Suppose each sensor sends H_d Bytes to its corresponding relay nodes. Then, relay node of Tower 50 sends H_d Bytes to relay node of Tower 49 while relay node of Tower 49 sends $2H_d$ Bytes to relay node of Tower 48. In this way, we conclude that relay node of Tower 2 sends $49H_d$ Bytes to relay node of Tower 1. So, we express a relation of total number of Bytes that is transmitted from relay node of Tower j to relay node of Tower $j-1$ as $[n/2-(j-1)]H_d$, where

j should be $1 \leq j \leq 50$. Let us denote the data transmission rate for interpole relaying as Z_i. Hence, total time for data transmission of relay node of tower 50 is given as.

Table 3.3: Summary of important monitoring parameters

Monitoring Parameters	Types of sensor	Total Size
Inclination	Accelerometers	$16 Bytes (4 Floats)$
Cable Tilt	Accelerometers	$8 Bytes (2 Floats)$
Magnetic Field	Magnetic Field Sensors	$16 Bytes (4 Floats)$
Cable position	Accelerometers	$8 Bytes (2 Floats)$
Extension and strain	strain Sensor	$8 Bytes (2 Floats)$
Temperature	Temperature sensor	$4 Bytes (1 Floats)$
Current	Magnetic Field sensors	$4 Bytes (1 Floats)$
Power quality Graph	Magnetic Field Sensors	$4kBytes(4Floatsx250Datapoints)$

$$\sum_{j=1}^{50} \frac{(51-j)H_d}{Z_i} = \sum_{j=1}^{50} \frac{jH_d}{Z_i} = \frac{\frac{50 \times 51 H_d}{2}}{Z_i} \tag{3.1}$$

Where sensor data generation rate is denoted by H_d and generation rate is 4kBytes. Table 3.4 depicts several system parameters that are used in the calculation above. To find the delay, we use ZigBee communication technology for data transmission between relay nodes and it supports data rate up to $31.25 kBytes/s$. However, total time for reaching the data of relay node of Tower 50 will be $50 \times 51 \times 4/2 \times 31.25 = 163.2s$. Moreover, to avoid data packet collision, channel access time is considered. Due to shared medium of wireless channels, one device may has to wait for data transmission because channel has already occupied by some other devices. Typically, channel access time is $41ms$. After the inclusion of channel access time, total time for delivering the data to CC in linear network architecture is $50 \times 41ms + 163.2s = 165.25s$.

Table 3.4: Major parameters for computing delay

Number of towers	n
Message size per pole	H_d
Total data from tower j to tower $j-1$	$[n/2-(j-1)]H_d$
Interpole data relaying	Z_i

3.2 Direct Link Network Architecture

In linear network architecture, delay is one of the aspects that affects the efficiency of linear network architecture while linear network architecture also suffers due to imbalance of workload. Those relay nodes which are closer to the substation need to tackle a lot more information. However, to support those relay nodes extra power is needed, so it is required to find another way to efficiently send information to CC. Authors in [9] proposed a way in which they establish several direct links for information delivery from directly relay nodes to CC as shown in Figure 3.3. In this way, information sends directly to the CC without depending on neighbor nodes. Figure 3.3 shows that all relay nodes send information directly to CC. A CC is located at several kilometers far away from towers. For data transmission, direct links rely on cellular technologies such as $GPRS$, GSM and $3G$. For example, GSM data rate is $8kBytes/s$, thus, total time to transmit information is reduced significantly to $\frac{4kBytes}{8kBytes/s} = 0.5s$. If we use $3G$ instead GSM delay can further be reduced.

By using GSM technology on each tower, the time delay of sending information will be reduced significantly and imbalances caused by workload will be more balanced. Nevertheless, network is very expensive in terms of installation and subscription cost of direct links. Additionally, extra energy consumption is also a dominating factor that degrades the performance of direct link architecture. To make network more balanced, instead of enabling all towers with direct links, we should enable some of them with cellular capabilities. Those towers which are not directly linked to CC should send their monitoring data to one of the towers that have cellular capabilities. It is obscure that how many direct links we should establish to achieve a desired time delay requirement. However, selection of optimal number and position of direct links, we can significantly reduce time delay. For example, it is not favorable to establish direct link on relay node of tower 3 because data of relay node of tower 50 still requires to go long way to reach at the relay node 3.

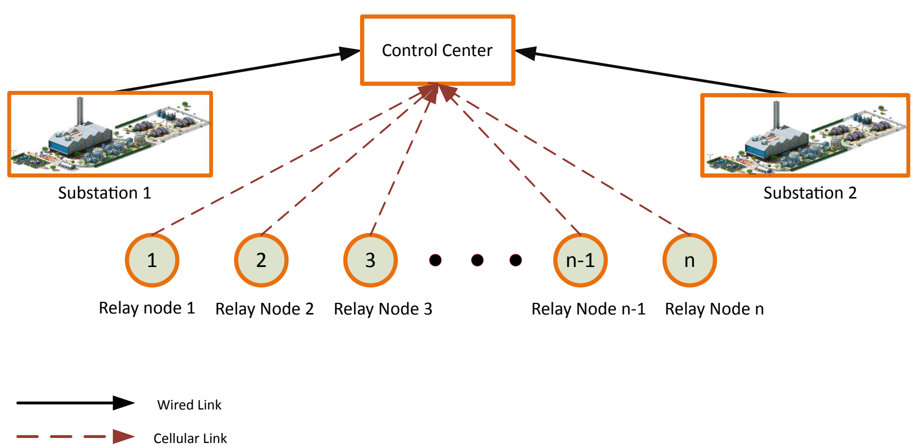

Figure 3.3: Direct link architecture

We developed three stage hybrid monitoring network for real time status awareness of transmission lines. Our proposed model includes the installation of WSNs, optical fiber and wide area network like cellular. We suppose that all towers are linearly available and have equal distance between each others.

3.3 Description of system model

In monitoring infrastructure, WSNs play key role and provide both low cost and low data rate communication while wide area networks impart high data rate communication at the expense of enormous installation and maintenance cost. The proposed model utilizes existing optical fiber link to send its monitored data from substation to CC. Further, in this model, we strategically utilized the cellular network for transmission of sensed data from particular transmission tower to the CC directly. Each stage is comprised of different types of sensors and transceivers such that accumulatively they reach to the targeted behavior. In this model, a set of sensors uses to take fine monitoring data in real time. Figure 3.4 depicts the infrastructure of system model which includes the number of transmission towers, two substations on both sides of transmission tower and a single CC. We divide all towers in four different groups such as $G1$, $G2$, $G3$ and $G4$. Where $G1$ and $G4$ are near to Substation 1 and Substation 2 respectively. We also select representative in each group named as $r1$, $r2$, $r3$ and $r4$ as shown in Figure 3.4. These representatives are directly connected to CC through wireline and cellular technology. Both substations are always known as a representative because they are directly connected to CC. All sensors that exist in $G1$ and $G4$ send their data through hop-by-hop to $r1$ and $r4$ respectively while nodes in $G2$ and $G3$ that are not directly connected to representative nodes send their data hop-by-hop to $r2$ and $r3$ respectively.

The first stage is composed of number of sensors and relay nodes. For real time status monitoring, different types of sensors are placed on various location of transmission lines. Due to short range of communication between sensors and relay nodes, sensors are installed near to the transmission tower, while relay nodes on top of the tower. Sensors can take fine measurements of different parameters and employ short range communication technology for data transmission. Distance between sensors and relay nodes is less than $100m$ and Bluetooth technology is sufficient for data transmission. At the end, relay nodes compress the received data and send it to the second stage.

Second stage is responsible for transmission of monitoring data from tower to substation. Those towers which are near to the substation send their monitoring data hop-by-hop to respective substation. As shown in Figure 3.4, $G1$ represents the groups of towers where tower 2 sends their date to tower 1 through wireless link such as ZigBee and then tower 1 appends its own monitoring data with the data received from tower 2 and sends to substation. Distance between two adjacent towers is far as $0.5 - 1km$ and ZigBee supports transmission range up to $1.5km$. Therefore, long range communication technology such as ZigBee suffices. Those towers which are away from substation and are not able to send their monitoring data due to low bandwidth of wireless link and high latency rate send their data by enabling one of the tower with cellular capability. All towers which are near to cellular enabled tower send their data directly to CC through cellular enabled

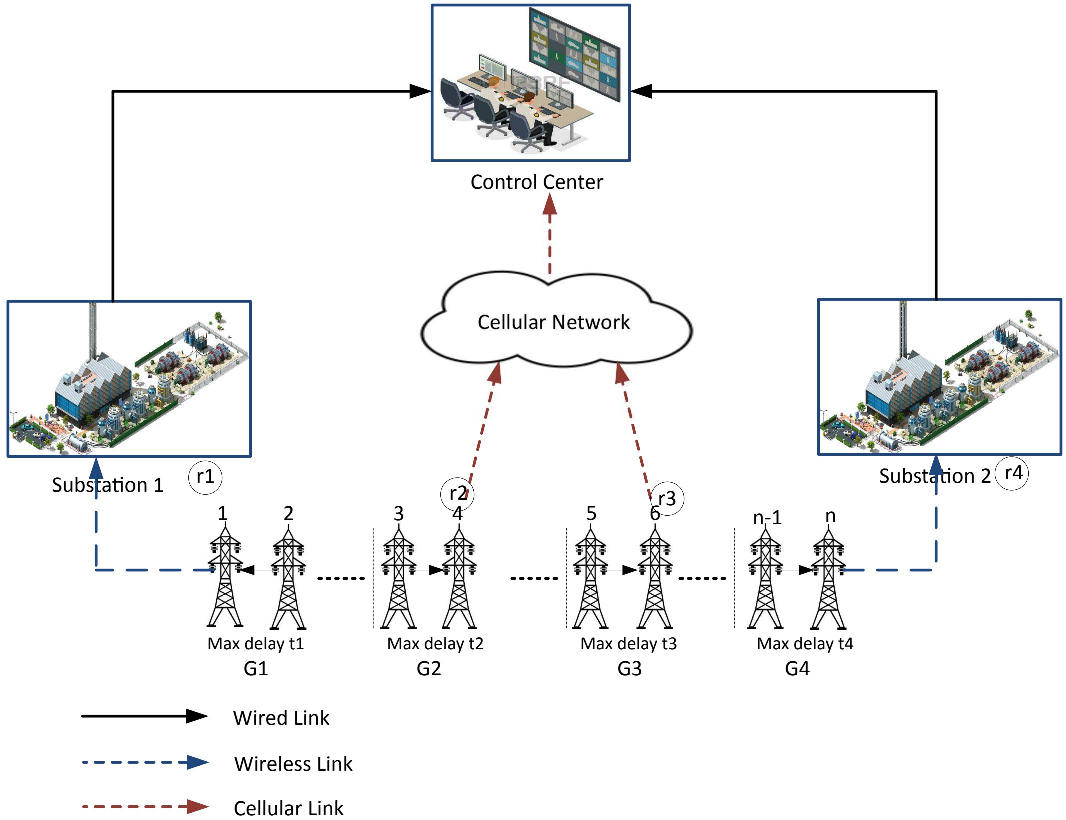

Figure 3.4: System model

tower.

Third stage is composed of two substations at the end of transmission lines, one CC and cellular enabled towers. Substation utilizes the existing optical fiber link and sends accumulative data to CC. Those towers that are unable to send their data to substation due to long distance and limited available link bandwidth employ wide area network and send monitoring data directly to CC.

Moreover, we modify our scenario where we ignore the cellular groups and depend heavily on wireless technology for data transmission. We also assume that it is not necessary to deploy sensors on each tower and distance between each tower is unequal as shown in Figure 3.5. Let $G = \{G1, G4\}$ be the total number of groups between $r1$ and $r4$, where $G1 = \{t_{T+1}, t_{T+2}, t_{2T-1}, t_{2T}\}$ includes number of towers that form linear network and transmits their data to $r1$ and $G4 = \{t_1, t_2, t_{T-1}, t_T\}$ includes another number of towers that also form linear network and transmits their data to $r4$. For simplicity, we only focus on towers in $G4$. In monitoring network sensors keep sending their monitoring data; therefore, sensors at tower t_{i+1} experience not only transmission signal but also interferences from nearby sensors, as shown in Figure 3.6. In general, sensors at tower t_{i+1} experience the interferences not only from $G4$ but also from other sensors in $G1$. Because sensors are deployed far away from each other, however, in practical interferences from these sensors are very low. Therefore, for the ease of discussion, we only consider the interferences from sensors in $G4$.

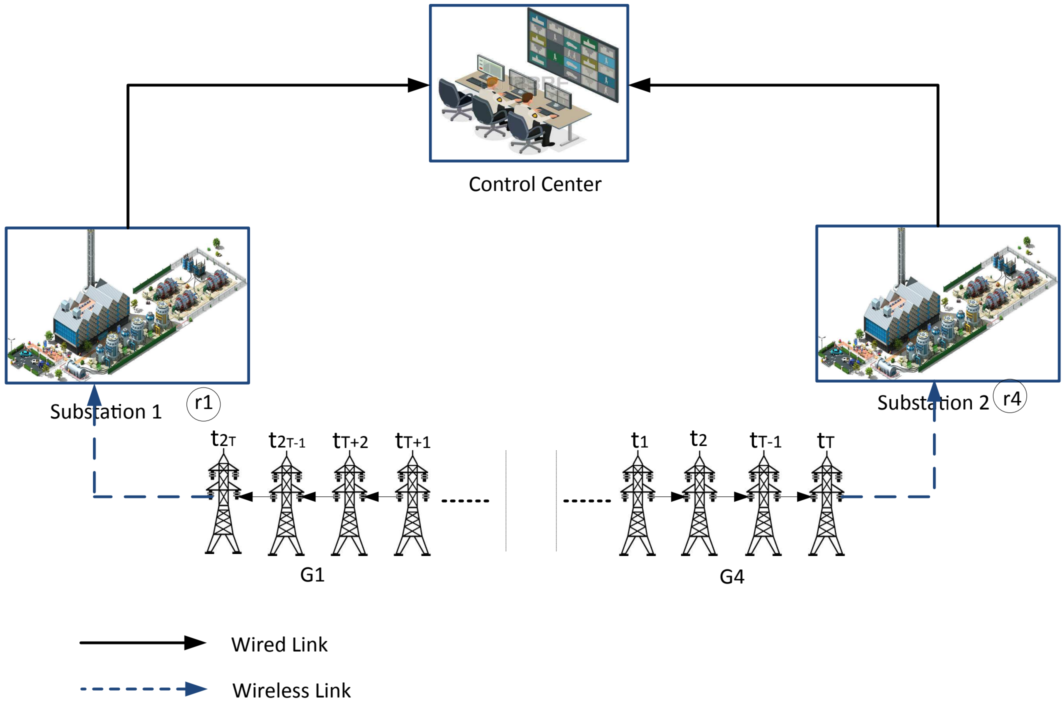

Figure 3.5: Modified system model

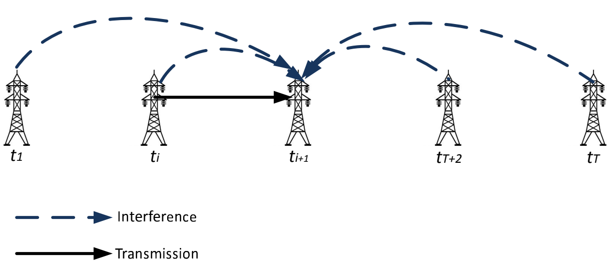

Figure 3.6: Interferences between different sensors

Chapter 4

Problem Formulation

Our objective is to minimize the total time delay of delivering the data to CC. Node that is deployed at the end of each group would suffer longest delay to deliver the data of its representative node. However, an appropriate position of representative node would lead to the desired goal. Furthermore, delay can be further minimized if we select representative node in the middle of groups.

4.1 Time delay analysis:

With the assumption that each sensor generates equal amount of data and number of nodes is equal both in $G2$ and $G3$ while nodes in $G1$ are also same as in $G4$. However, it simplifies our problem as $t_1 = t_4$ and $t_2 = t_3$. In direct cellular groups, time delay is calculated by two major components. Time includes when relaying all the group data to the representative node and from a representative node to a CC, as shown in equation (4.1).

$$t_{21} = \frac{H_d(1+2+3+\cdots+k)}{Z_i} + \frac{H_d k}{Z_i} \tag{4.1}$$

$$t_{22} = \frac{H_d(2k+1)}{Z_d} \tag{4.2}$$

$$t_2 = t_{21} + t_{22} \tag{4.3}$$

On the other side in $G1$, time delay is calculated by two major components. One is relaying all the group data to representative node such as $r1$ and from $r1$ to CC as shown in equation (4.2).

$$t_1 = \frac{H_d\{1+2+3+\cdots+[l-(2k+1)]\}}{Z_i} \tag{4.4}$$

Where t_1 and t_2 represent the total time of $G1$ and $G2$ respectively, k is the number of nodes in each group, l represents the position of last relay node in $G2$ and H_d is the sensor data rate. Further, Z_i is the relaying data rate such as ZigBeee whereas Z_d represents cellular data rate.

To reduce the maximum time delay of both groups $G1$ and $G2$. We consider delay of both group as $t_1 = t_2$ and establish a quadratic equation as follows:

$$\frac{H_d[3k^2-(1+4l)k+(l^2-l)]}{2Z_i} - \frac{H_d(2k+1)}{Z_d} = 0 \tag{4.5}$$

and convert into a standard quadratic form, we have

$$(\frac{3H_d}{2Z_i})k^2 - (\frac{H_d(1+4l)}{2Z_i} + \frac{2H_d}{Z_d})k + (\frac{H_d(l^2-l)}{2Z_i} - \frac{H_d}{Z_d}) = 0 \tag{4.6}$$

We enhance the idea where number of cellular groups are greater than 2. It is evident that increasing the number of nodes would affect the position of last node

Algorithm 1

Input: Number of nodes (k), Sensor data-rate (H_d), ZiBbee data-rate (Z_i), Cellular data-rate (Z_d), GSM data-rate (r_d), 3G data-rate (r_{d1})

Output:Maximum time delay

Initialization of parameter
Initialize cellular groups (g)
For i = 1 to 2
    If $Z_d = r_d$
        $Z_d \leftarrow r_d$
        else
        $Z_d \leftarrow r_{d1}$
    End If
    If Number of nodes = 100
        Min number of groups ← 2
        Max number of groups ← 20
    End if

For GSM

    If $g = 2$
        $k \leftarrow 14$
    else If $g = 6$
        $k \leftarrow 6$
    else If $g = 20$
        $k \leftarrow 2$
    End If

For 3G

    If $g = 2$
        $k \leftarrow 16$
    else If $g = 6$
        $k \leftarrow 7$
    else If $g = 20$
        $k \leftarrow 2$
    End If
    For i = 1 to 10
    Determine relaying delay
        Equation (2)
    Determine direct link delay
        Equation (3)
    Determine total delay
        Equation (4)
    End For
End For

index l. We calculate the position of last index by using equation (4.7).

$$l = \frac{n - g(2k+1)}{2} + (2k+1) = \frac{n - (g-2)(2k+1)}{2} \tag{4.7}$$

Where g represents the number of cellular groups. In general scenario, when there is a possibility of more than two direct links, our quadratic equation will be,

$$((\frac{H_d(g^2-1)}{2Z_i})k^2 + (\frac{H_d[g(g-n-1)-3]}{2Z_i} - \frac{2H_d}{Z_d})k + (\frac{H_d(n-g)(n-g+2)}{8Z_i} - \frac{H_d}{Z_d})) \tag{4.8}$$

4.2 Calculating energy consumption:

There are two major components that take part in calculating energy consumption. One is energy consumption of interpole relaying and second one is transmission energy of direct cellular link. Suppose there are g groups using direct wireless link and total data size of these groups is shown in equation (4.9). On the other side, data size of those groups which are connected to substation is shown in equation (4.10).

$$S_d = 2H_d(1 + 2 + \cdots + k) = H_d gk(k+1) \tag{4.9}$$

$$S_s = 2H_d(1 + 2 + \cdots + [l - (2k+1)]) = H_d(l - 2k - 1)(l - 2k) \tag{4.10}$$

Hence, total data size of the entire model is,

$$S_{tot} = H_d[gk(k+1) + (l - 2k - 1)(l - 2k)] \tag{4.11}$$

Therefore, the total energy consumes in relaying the group data is,

$$E_{rel} = H_d[gk(k+1) + (l - 2k - 1)(l - 2k)] \times E_{Ip} \tag{4.12}$$

Where E_{Ip} represents the total energy including the reception and transmission. For data transmission in direct wireless groups, all cellular technologies have their own energy consumption profile. Energy consumption increases as transmission range increases. Total energy consumption of GSM and $3G$ cellular technologies is calculated by using equations (4.13) and (4.14). In which first part represents the actual energy that needed for transmission, second part is the ramp down energy after transmission of data and third part is transmitter maintenance energy [22].

$$E_{gsm} = 0.036(x) + 0.25min(6, t_r - (\frac{x}{Z_d})^+) + 0.036t_r \tag{4.13}$$

$$E_{3g} = 0.025(x) + 0.62min(12.5, t_r - (\frac{x}{Z_d})^+) + 0.02t_r \tag{4.14}$$

Where x indicates the total data size of sensors which is measured in $KiloBytes$ and t_r represents the reporting interval.

Algorithm 2

Input: Number of nodes (k), Sensor data-rate (H_d), ZiBbee data-rate (Z_i), Cellular data-rate (Z_d), GSM data-rate (r_d), 3G data-rate (r_{d1}), Reporting interval (t_r), Energy per byte (E_{IP})

Output: Associated energy consumption

Initialization of parameter
Initialize cellular groups (g)
For i = 1 to 2
  If $Z_d = r_d$
    $Z_d \leftarrow r_d$
  else
    $Z_d \leftarrow r_{d1}$
  End if
  For i = 1 to 9
    If Number of nodes = 100
      Min number of groups ← 2
      Max number of groups ← 20
    End if
    Determine the position of last node in G_2
      Equation (8)
    Determine the data size of cellular group
      Equation (10)
    Determine the data size of wireless group
      Equation (11)
    Calculate the total data size
      Equation (12)
    Determine total energy spent in relaying
      Equation (13)
    Determine energy consumption of GSM
      Equation (14)
    Determine energy consumption of 3G
      Equation (15)
    Calculate total energy consumption of GSM
      Equation (16)
    Calculate total energy consumption of 3G
      Equation (17)
  End for
End for

Therefor, total energy consumption in each round of cycle is,

$$E_1 = E_{gsm} + E_{rel} \tag{4.15}$$

$$E_2 = E_{3g} + E_{rel} \tag{4.16}$$

Where E_{gsm} and E_{3g} are the energy consumption of GSM and $3G$ technology respectively. Whereas E_{rel} represents the relaying energy. Both algorithm 1 and algorithm 2 are developed to calculate time delay of data delivery and associated energy consumption. We considered two cellular technologies such as $3G$ and GSM for direct data transmission from a particular towers to CC. We categorized 100 number of nodes into min and max groups as a 2 and 20 groups and applied the aforementioned equation to get the required result. While, algorithm 3 is developed to calculate SINR and the main idea is that we determine interfering nodes for the transmitting pair and then update the SINR.

Normally, a sensor is required to send its monitoring data at higher power and thus achieves higher Signal-To-Interference-Plus-Noise-Ratio (SINR). And theses interferences lead to increase the transmission rate because probability of higher transmission rate depends upon SINR. Hence, widely adopted transmission rate for transmitting sensor as [23] and [24].

$$T_i = R_i \times f(\alpha_i) \tag{4.17}$$

Where T_i is the transmission rate, R_i represents the theoretical transmission rate whereas SINR of sensors is indicated by α_i, which is computed by equation (4.18).

$$\alpha_i = \frac{p_i h_{i,i+1}}{\sigma^2 + \frac{1}{N}\sum_{j=1}^{i+1} p_j h_{i,j}} \tag{4.18}$$

Where p_i is the transmission power, N represents the processing gain, variance is indicated by σ and $h_{i,j}$ represents the path gain.

$f(\alpha_i)$ is denoted as frequency function which is S-shaped, increasing and continuous.

$$f(\alpha_i) = (1 - BER_i)^M, \gamma_i \geq 0 \tag{4.19}$$

Where M represents the packet length.

Path gain is based on physical distance between two sensors and carrier frequency. For the simplicity of discussion, we calculate $h_{i,j}$ [25] as,

$$h_{i,j}(dB) = 20log_{10}(d) + 20log_{10}(f) + 32.45 \tag{4.20}$$

Where d is the distance which is measured in kilometer between two sensors and f is the transmission frequency in megahertz. Let sensor t_i receives data from previous sensor and transmits to next sensor t_{i+1} with the maximum transmission frequency f_t. f_t should be high enough because it is unpredictable that how much data previous sensor t_{i-1} would send. Let d_i be the total data of sensor t_i and after the collection of data from predecessor sensors. The total data that is transmitted to t_{i+1} will be,

$$d_{total} = \sum_{i=1}^{total} d_i \tag{4.21}$$

Total delay for transmission data from t_i to t_{i+1} will be,

$$\tau_d = \frac{d_{total}}{T_i} \tag{4.22}$$

4.3 Relaying bandwidth constraint:

There is a moot point regarding how many nodes should be in group. The data rate of wireless technologies such as ZigBee must be higher than the data generation rate of entire groups otherwise overflow will arise due to excessive amount of data generation.

$$Z_i \times t_r > \frac{n - g(2k+1)}{2} H_d \tag{4.23}$$

Where Z_i is the data rate of interpole relaying whereas t_r is the reporting interval. Sensor data rate is denoted by H_d and k denotes the total number of nodes in a group.

4.4 Cellular bandwidth constraint:

Total number of nodes in a cellular group must be limited by its available cellular data rate.

$$Z_d \times t_r > (2k+1)H_d \tag{4.24}$$

Where Z_d is the data rate of cellular technologies.

4.5 Power consumption constraint:

Total power consumption of sensors must not exceed their maximum value.

$$p_r \leq p_{max} \tag{4.25}$$

Where p_r is the power consumption of sensor whereas p_{max} represents the maximum power consumption.

4.6 Transmission delay constraint:

Each sensor must transmit its aggregated data before the upcoming of new data.

$$\tau_d \leq \frac{1}{f_t} \tag{4.26}$$

Where time delay of sensor is represented by τ_d and f_t is the transmission frequency of sensors.

4.7 End-to-end delay constraint:

Let τ_{max} is the end-to-end delay of sensor for successfully deliver the information to substation. To deliver data in timely fashion, the time period must not exceed by its maximum limit.

$$\tau_{total} \leq \tau_{max} \tag{4.27}$$

4.8 Power allocation scheme:

To minimize the cost of network, total power consumption of all sensors should be less than by their maximum threshold.

$$P1 : min \sum_{i=1}^{T} p_r \tag{4.28}$$

In case of total time τ_{total} gets higher our solution will be minimized. However, we can relax our end-to-end constraint into equation (4.29).

$$\tau_{total} = \sum_{i=1}^{T} \tau_d = \sum_{i=1}^{T} \frac{d_{total}}{T_i} = \sum \frac{d_{total}}{R_i} (\frac{1}{f(\alpha_i)}) = \tau_{max} \tag{4.29}$$

In aforementioned equation $f(\alpha_i)$ is a variable which is continuous and increasing in nature with respect to α_i and $\alpha_i(p_i)$ is also a function with respect to p_i. So, minimizing the total power consumption can be viewed as minimizing the transmission data rate of each link. Therefore, we convert the previous minimizing problem into

$$P2 : min \sum_{i=1}^{T} f(\alpha_i) \tag{4.30}$$

S.t.

$$f(\alpha_i) \geq \frac{d_{total}}{R_i} f_t \tag{4.31}$$

$$f(\alpha_i) \leq f(\alpha_i^{max}) \tag{4.32}$$

Equation (4.31) shows the lower bound of normalized transmission rate below which the link would fail to transmit the new upcoming data. Equation (4.32) exhibits the upper bound of normalized transmission rate.

Algorithm 3 Algorithm to calculate SINR

Input: $G4_t = \{t_1, t_2, t_{T-1}, t_T\}$, $G4_r = \{t_1, t_2, t_{T-1}, t_T\}$

Output:SINR for each node

1: while $i < T$ do

2: while $j < T$ do

3: Schedule $G4_t$ and $G4_r$

4: For transmitting pair (t_i, t_j), determine the interfering nodes

5: Update SINR for t_i

6: end while

7: end while

Chapter 5

Feasible Region

Feasible region is defined as a possible set of outcomes that occurs in a specific region. We calculate the feasible region for both scenarios under the consideration of variable number of nodes. In first scenario, we take maximum time delay and total energy consumption while in second scenario we also take two parameters one is total transmission power and second one is delay between sensors for the feasible region. In first scenario, we first draw the feasible region for 100 nodes and then vary the number of nodes up to 1000. In second scenario, we first draw the feasible region for 10 nodes and then vary the number of nodes up to 100.

5.1 Feasible region of time delay for 100 towers

Figure 5.1 shows the feasible region of maximum time delay for 100 towers. Where p_1 and p_2 exhibit the minimum and maximum points of time delay at 2 number of groups while p_3 and p_4 depict the minimum and maximum points of time delay at 20 number of groups. At points p_1 and p_3, time delay of the groups is $29.73s$ and $1.756s$ respectively. As the number of nodes increases in those groups, the data size of entire groups also increases. However, sensors require larger time to deliver huge amount of data. At points p_2 and p_4, total number of nodes in those groups is maximum which is 100 in amount and depicts the maximum time delay is as $65.97s$ and $3.14s$ respectively.

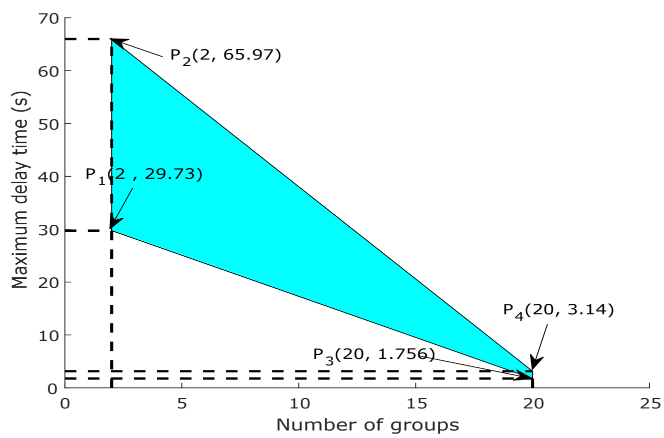

Figure 5.1: Feasible region of maximum time delay for 100 towers

5.2 Feasible region of time delay for 1000 towers

Feasible region of maximum time delay for 1000 towers is depicted in Figure 5.2. Where p_1 and p_2 exhibit the minimum and maximum points of time delay at 2 number of groups while p_3 and p_4 depict the minimum and maximum points of time delay at 20 number of groups. At points p_1 and p_3, time delay of the groups is $1422s$ and $1.756s$ respectively. As the number of nodes increases in those groups, the data size of entire groups also increases. However, sensors require larger time to deliver huge amount of data. At points p_2 and p_4, total number of nodes in those groups is maximum which is 1000 in amount and depicts the maximum time delay is as 4265s and 220s respectively.

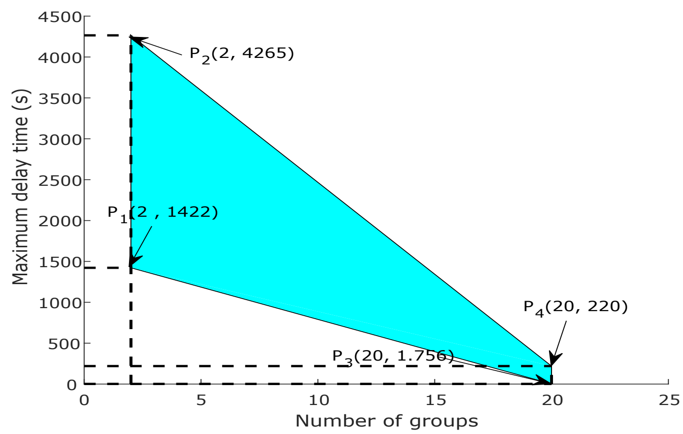

Figure 5.2: Feasible region of maximum time delay for 1000 towers

5.3 Feasible region of energy consumption for 100 towers

Figure 5.3 depicts the feasible region of total energy consumption for 100 towers and bounded by the points $P_1(2, 71.68)$, $P_2(2, 100)$, $P_3(20, 45)$ and $P_4(20, 62.9)$. Where $p1$ and $p2$ show the minimum and maximum points of energy consumption at 2 number of groups while $p3$ and $p4$ depict the minimum and maximum points of energy consumption at 20 number of groups. At points $p1$ and $p3$, energy consumption of the groups is 71.68J and 45J respectively. When we increase the number of nodes in those groups, total energy consumption of nodes also increases. At points $p2$ and $p4$, total number of nodes in those groups is maximum and consumes maximum energy is as 100J and 62.9J respectively to transmit the data.

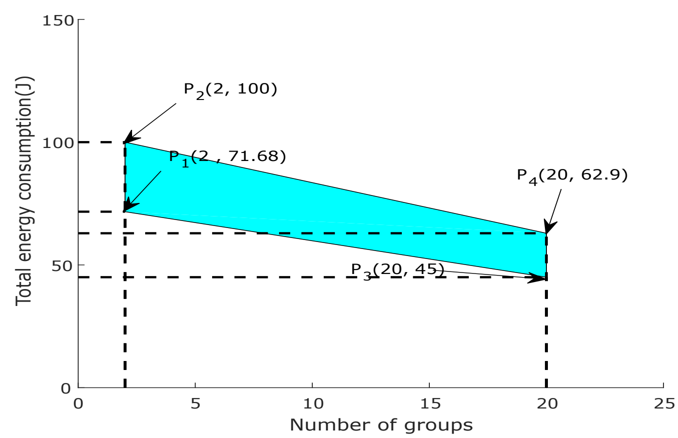

Figure 5.3: Feasible region of total energy energy consumption for 100 towers

5.4 Feasible region of energy consumption for 1000 towers

Figure 5.4 exhibits the feasible region of total energy consumption for 1000 towers and bounded by the points $P_1(2, 6155)$, $P_2(2, 8770)$, $P_3(20, 1002)$ and $P_4(20, 2815)$. Where $p1$ and $p2$ show the minimum and maximum points of energy consumption at 2 number of groups while $p3$ and $p4$ depict the minimum and maximum points of energy consumption at 20 number of groups. At points $p1$ and $p3$, energy consumption of the groups is $6155J$ and $1002J$ respectively. When we increase the number of nodes in those groups, total energy consumption of nodes also increases. At points $p2$ and $p4$, total number of nodes in those groups is maximum and consumes maximum energy is as $8770J$ and $2815J$ respectively for data transmission.

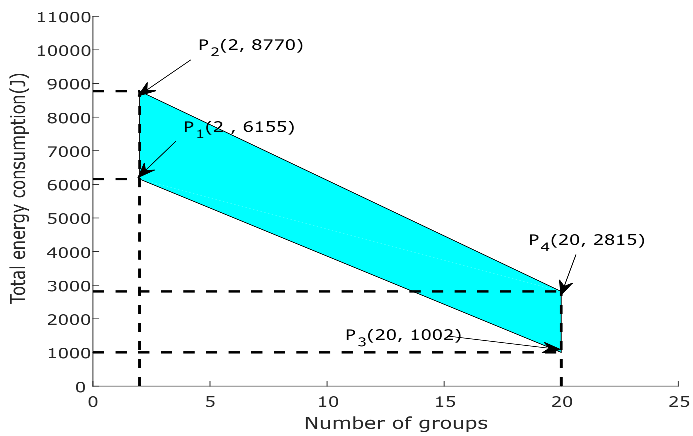

Figure 5.4: Feasible region of total energy energy consumption for 1000 towers

5.5 Feasible region of transmission power for 10 towers

A region bounded by points $P_1(2, 54.56)$, $P_2(2, 2.9)$, $P_3(10, 5.5)$ and $P_4(10, 0.55)$ exhibits the feasible region for transmission power for 10 towers as shown in Figure 5.5. Where p_1 and p_2 show the maximum and minimum points respectively of total transmission power at 1 number of sensor while p_3 and p_4 depict the maximum and minimum points respectively of total transmission power at 10 number of sensors. At points p_1 and p_3, total transmission power of sensors is $54.56W$ and $5.5W$ respectively. The region exhibits the linearly decreasing behavior because as the number of sensors increases, the distance between sensors decreases. However, due to short distance between each others, sensors consume less power for data transmission.

5.6 Feasible region of transmission power for 100 towers

A region bounded by points $P_1(10, 5.17)$, $P_2(10, 0.55)$, $P_3(100, 0.469)$ and $P_4(100, 0.19)$ exhibits the feasible region for transmission power for 100 towers as shown in Figure 5.6. Where p_1 and p_2 show the maximum and minimum points respectively

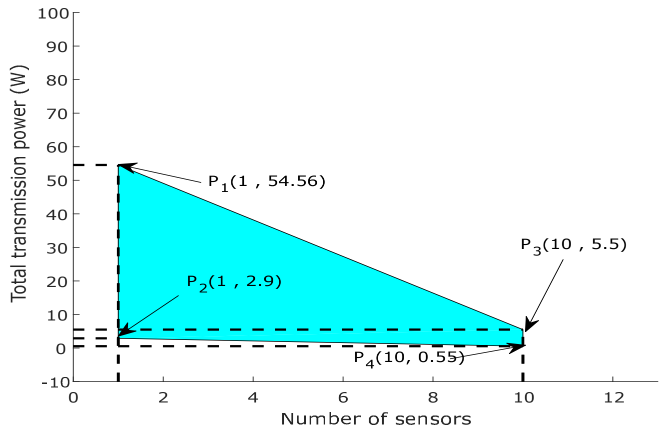

Figure 5.5: Feasible region of total transmission power for 10 towers

of total transmission power at 10 number of sensors while p_3 and p_4 depict the maximum and minimum points respectively of total transmission power at 100 number of sensors. At points p_1 and p_3, total transmission power of sensors is $5.17W$ and $0.469W$ respectively. The region exhibits the linearly decreasing behavior because as the number of sensors increases, the distance between sensors decreases. However, due to short distance between each others, sensors consume less power for data transmission.

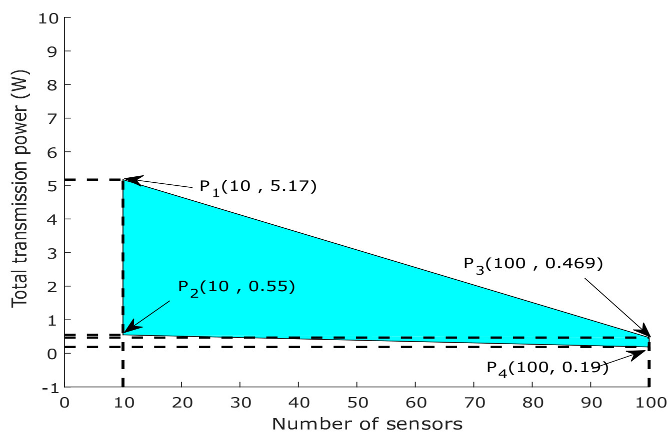

Figure 5.6: Feasible region of total transmission power for 100 towers

5.7 Feasible region of delay for 10 towers

Figure 5.7 shows the feasible region of delay for 10 number of towers and bounded by the points P_1(1,0.45), P_2(1,10), P_3(10,1.4) and P_4(10,10). Where p_1 and p_2 show the minimum and maximum points respectively of delay at 1 number of sensor while p_3 and p_4 depict the minimum and maximum points respectively of delay at 10 number of sensors. At points p_1 and p_3, delay of data transmission is $0.45ms$ and $1.41ms$ respectively. The region exhibits the slightly increasing behavior because as the number of sensors increases, monitoring data of sensors also increases. Thus, as sensor data increases, sensors take larger time for data transmission.

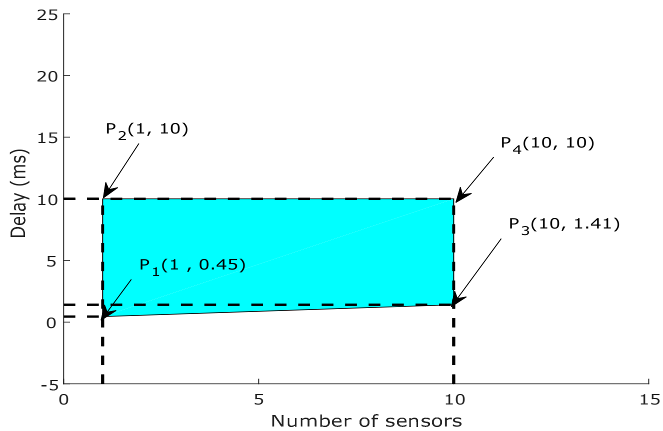

Figure 5.7: Feasible region of delay for 10 towers

5.8 Feasible region of delay for 100 towers

Figure 5.8 exhibits the feasible region of delay for 100 number of towers and bounded by the points P_1(10,1.2), P_2(10,10), P_3(100,10) and P_4(100,13.55). Where p_1 and p_2 show the minimum and maximum points respectively of delay at 10 number of sensors while p_3 and p_4 depict the minimum and maximum points respectively of delay at 100 number of sensors. At points p_1 and p_3, delay of data transmission is 1.2ms and 10ms respectively. The region exhibits the slightly increasing behavior because as the number of sensors increases, monitoring data of sensors also increases. Thus, as sensor data increases, sensors take larger time for data transmission.

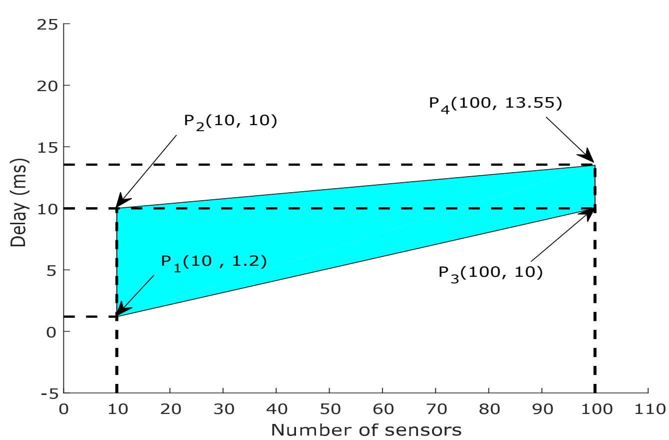

Figure 5.8: Feasible region of delay for 100 towers

Chapter 6

Simulation and Discussions

In this section, the performance of three stage hybrid monitoring network is described in detail. We consider total number of node is 100 and these nodes are installed on each towers. All towers are available in linear alignment having equal distance between each other. We also assume that data generation rate of sensors is $4kBytes$ and the reporting time is $4s$. ZigBee wireless protocol is considered for tower to tower communication and it supports data rate up to $31.25kBytes/s$. For direct wireless link, $3G$ and GSM are used as a wide area network and both these support data rate up to $48kBytes$ and $8kBytes$ respectively. MATLAB tool is used to solve the formulation.

6.1 Performance parameters definitions

There are two performance parameters maximum time delay and total power consumption. The maximum time delay involves three major factor, (1) when sensors sense data and send it to relay node on top of the tower, (2) when sensed data reaches from particular tower to substation and (3) from substation to control center. The total power consumption is divided into two main parts. The first part involves the power consumption of all the sensors for interpole relaying and the second part considers as power consumption of direct cellular link.

We also evaluate several parameters such as total transmission power, normalized transmission efficiency, SINR and delay for the modified scenario by assuming the variable distance between each tower and ignoring the groups that contain cellular technology.

6.2 Performance parameters discussions

Figure 6.1a depicts the maximum time delay at varying number of direct cellular groups. And, scrutinizes the affect of both $3G$ and GSM technologies on maximum time delay. When there are only two cellular groups then obviously, there will be more number of nodes exists in those groups. As the number of nodes increases the data in relaying between those groups increases and thus takes maximum time to reach CC. From the figure, it can clearly deduce that GSM technology shows significant larger time delay than that of $3G$ because data rate of GSM is lower than that of $3G$.

On the other side, GSM demonstrates privilege in terms of energy consumption. Figure 6.2a illustrates the total energy consumption versus maximum time delay. From Figure 6.2a for the same time delay, total energy spents by GSM technology is much smaller than $3G$ technology. When number of cellular groups increases, the data in relaying decreases but total energy consumption due to more cellular links is moderate, however, both total energy consumption and time delay decrease. Furthermore, if we incorporate too many cellular groups, the high-energy consumption of cellular groups starts to dominate the total energy. Result clearly depicts the trade-off between maximum time delay and total energy consumption.

Figure 6.3a shows the total transmission power on y-axis while total number of sensors on x-axis. We compare the results for both $P1$ and $P2$. It is shown that $P2$ has same amount of power allocation compared with $P1$. In Figure 6.4a, normalized transmission efficiency of sensors is compared for both $P1$ and $P2$. Result shows the same behavior as both indicate the increasing transmission efficiency of sensors. It can be seen vividly that transmission efficiency increases as link approaches closer to the substation.

Figure 6.5a analyze the SINR for both $P1$ and $P2$, it is deduced that both increase linearly with regard of SINR. Because as amount of data on each sensor increases, sensor requires much more power to transmit it, thus, higher transmission power leads to higher SINR. In Figure 6.6a, delay for both $P1$ and $P2$ is discussed, result shows that as link gets closer to the substation aggregated data of the sensors increases and thus delay increases linearly among sensors.

6.3 Performance trade-off

As shown in Figure 6.1a, there is a tradeoff between maximum time delay versus number of cellular groups. As the number of cellular groups increases, less time delay achieves. But after a certain point, any further improvement in number of cellular groups will leave marginal affect on reducing maximum time delay.

It is clearly concluded from Figure 6.2a that as the number of cellular groups increases, the energy consumption of cellular groups starts to dominate the total power consumption while the maximum time delay reduces significantly. Thus, result explicitly depicts the tradeoff between maximum time delay and total energy consumption.

6.4 Scalability Analysis

Scalability is defined as a characteristic of a network, system and function that explicates its potential to cop and fulfil the task under expanding workload condition.

In first scenario, we considered two performance parameters. First parameter is delay and the second parameter is energy consumption. We measure the performance of scenario by varying the number of nodes ranging from 100 to 1000 nodes with the increment of 100 nodes in each sub scenarios. In modify scenario, we considered four performance parameters. First parameter is delay, second parameter is transmission power, third parameter is SINR and fourth one is transmission efficiency. We measure the performance of scenario by varying the number of nodes ranging from 10 to 100 nodes with increment of 20 nodes in each sub scenarios.

Figure 6.1b depicts the maximum time delay versus number of towers. ZigBee is used for interpole relaying while $3G$ and GSM networks are used for direct wireless link. From the figure, expanding the number of towers increases the maximum delay time. For the same number of towers, GSM network shows a significant larger delay than that of $3G$. It is just because data rate of GSM is much smaller than $3G$. On the other side, GSM network shows significant advantage in terms

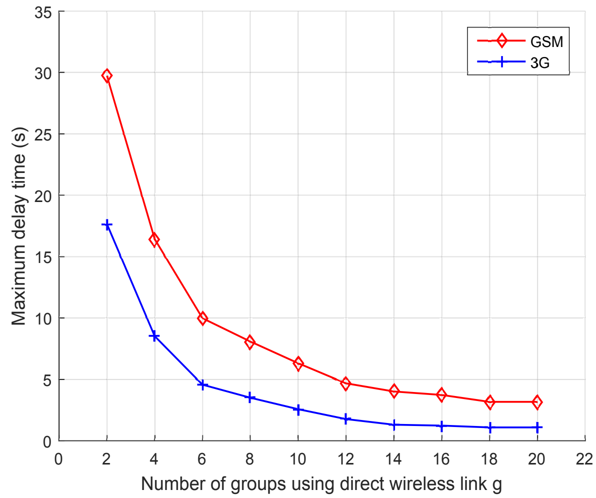

Figure 6.1a: Maximum time delay versus number of groups using direct wireless link

of total energy consumption because smaller data rate of the network covers only fewer number of towers and thus GSM network consumes less energy to transmit the whole data. Total energy consumption versus maximum time delay is depicted in Figure 6.2b.

Figure 6.3b shows the relationship between number of towers and total transmission power. As the number of sensors increases, the distance between sensors decreases. However, due to short distance between each others, sensors consume less power for data transmission. In Figure 6.4b, normalized transmission efficiency of sensors versus number of towers is depicted. Result shows the increasingly linear behavior of transmission. It can be seen vividly that transmission efficiency increases as link approaches closer to the substation. Figure 6.5b depicts the SINR versus number of towers. When number of towers is increased, data size also increases and sensor requires higher power to transmit its data and higher transmission power leads to higher SINR. Figure 6.6b illustrates the dependency of delay on number of towers. As the number of towers increases, monitoring data of towers also increases. Thus, as monitoring data increases, sensors take larger time for data transmission.

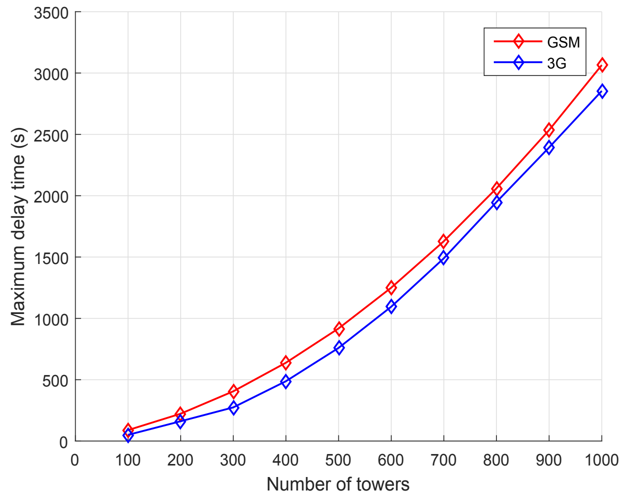

Figure 6.1b: Maximum time delay versus number of towers

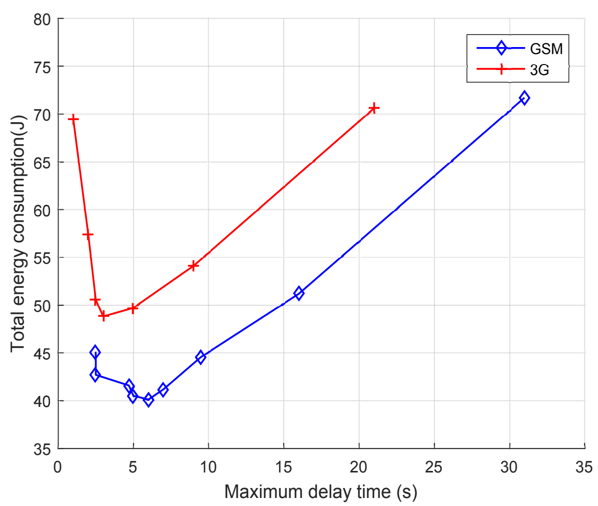

Figure 6.2a: Total energy consumption versus maximum time delay

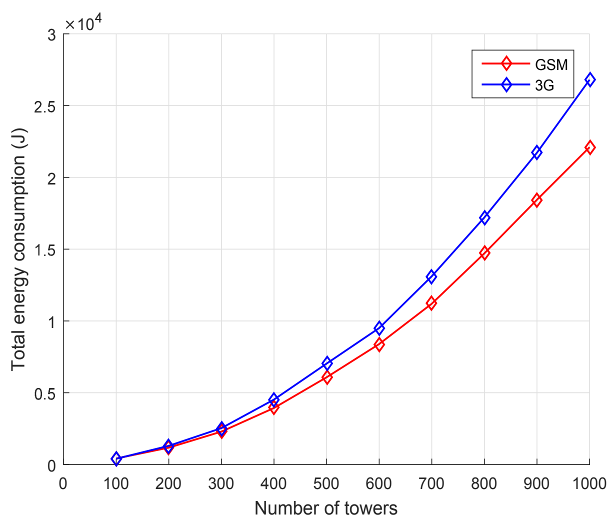

Figure 6.2b: Total energy consumption versus number of towers

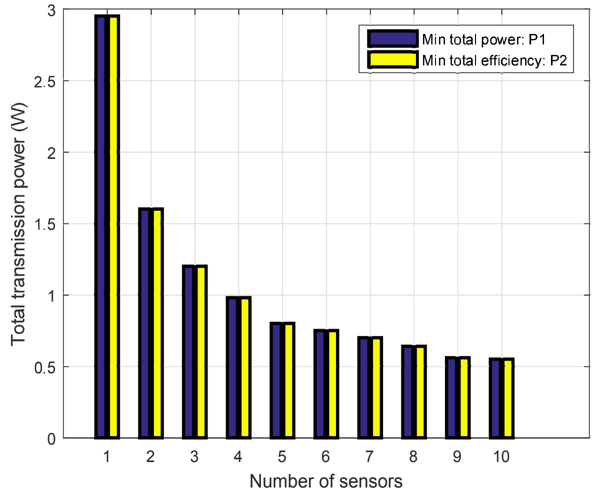

Figure 6.3a: Total transmission power versus number of sensors

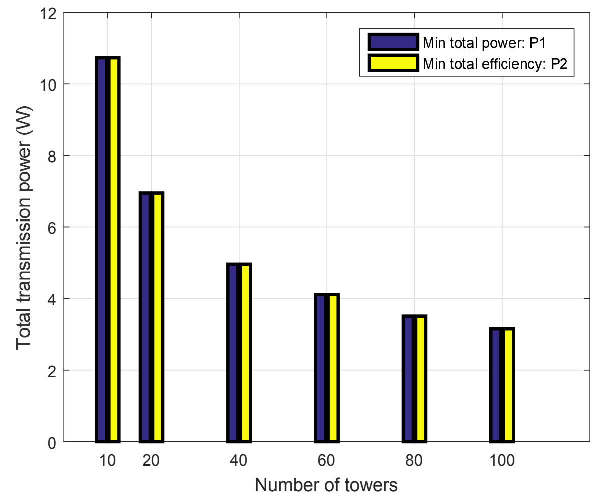

Figure 6.3b: Total transmission power versus number of towers

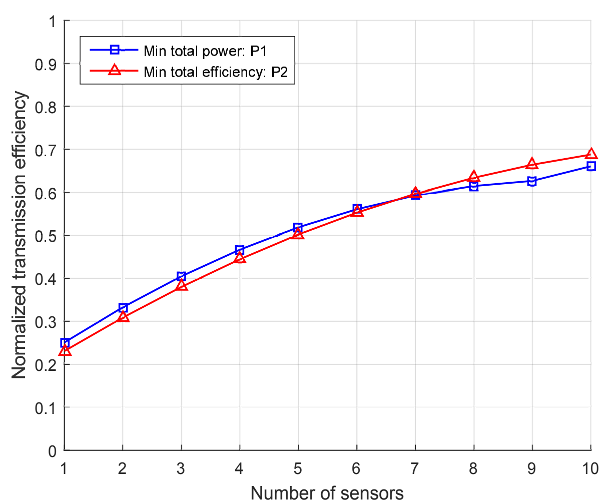

Figure 6.4a: Normalized transmission efficiency of each sensor

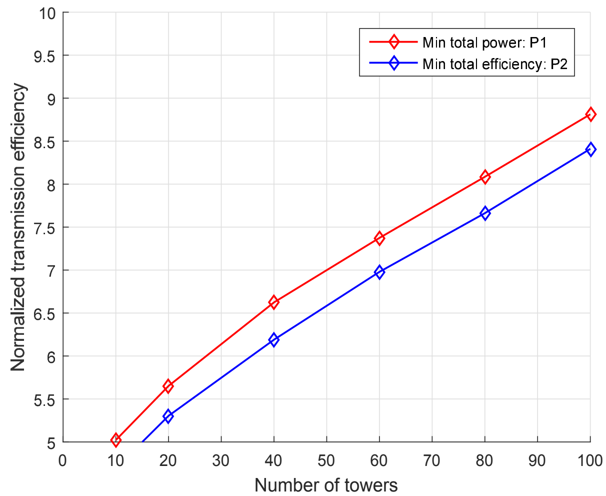

Figure 6.4b: Normalized transmission efficiency versus number of towers

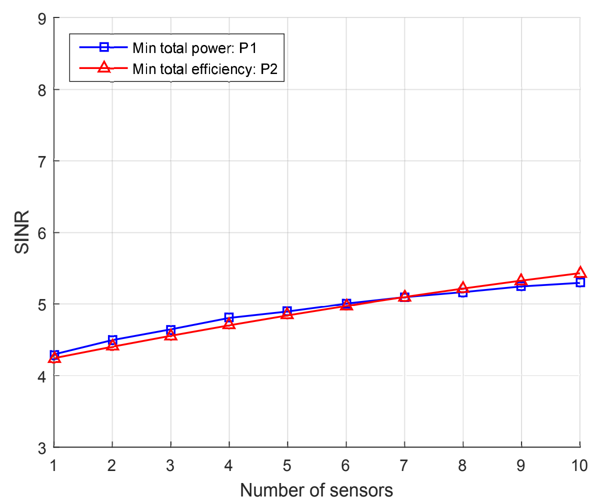

Figure 6.5a: Associated SINR of sensors

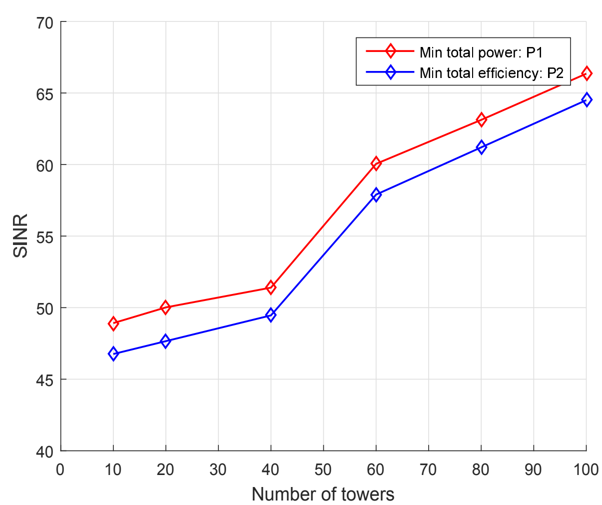

Figure 6.5b: Associated SINR versus number of towers

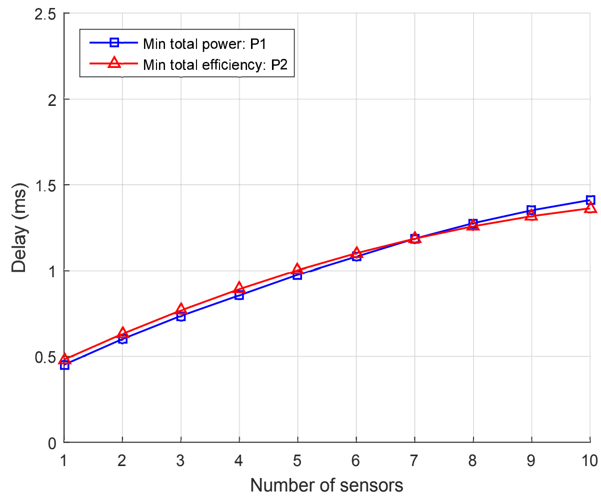

Figure 6.6a: Delay between sensors

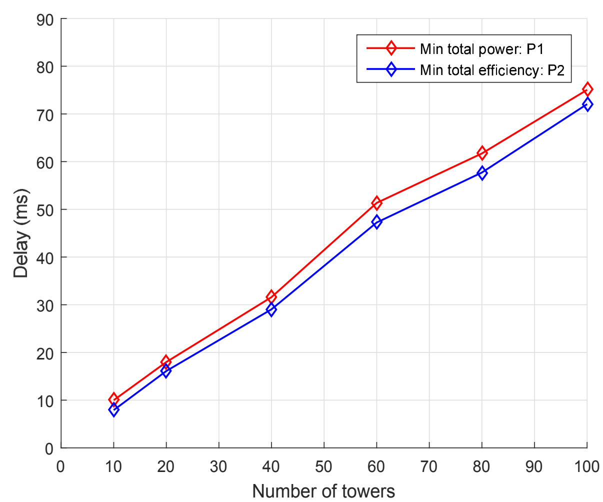

Figure 6.6b: Delay versus number of towers

Chapter 7

Conclusion

In this thesis, we proposed a three-stage hybrid monitoring model for real time status of the transmission lines and towers. We also developed a mathematical framework to understand the behaviour of direct links with the associated transmission delays. The proposed model appeared to be very significant in delivering information timely. Moreover, the trade-off between variation of the number of groups of towers and consequent transmission delays is also discussed. It is discovered that increasing the number of direct links decreases the time delay; however, too many direct links are not significant because it increases the energy consumption of the system overall. The power allocation scheme is proposed to minimize the total transmission power of sensors. For showing productiveness and legitimacy of our work, feasible regions are calculated and then are computed for optimal delay, energy consumption and transmission power. Through simulations, feasible regions are validated that delay and energy are reduced up to a considerable amount.

Chapter 8

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