M.Sc. Thesis in Computer Engineering, D, course, 30 points

Transmitter macrodiversity in WSAN and MANET

Energy consumption algorithms for wireless multihop networks

Arif Mahmud
Abstract

Three of the most important factors with regards to wireless multi-hop networks, namely reachability, energy consumption and network stability are considered in our transmitter macrodiversity supported broadcasting routing algorithms. Broadcasting applications are not only used to send routing table, queries, programming logic, any specific request etc. to all the nodes from access point but are also capable of playing a vital role in wireless TV distributions and visual sensor networks. All the algorithms are simulated in the MATLAB environment in which the nodes are random and are battery driven on a multi-hop randomized topology. Four new single frequency network (SFN) based algorithms (SFN-A, SFN-B, SFN-C and SFN-D) are formed in order to work over multi-hopping and where three of the algorithms SFN-A, SFN-B and SFN-D bear more or less the same amount of reachability. These three algorithms are able to reach more than 90% of reachability in only Tx power -8dBm whereas non-SFN requires -4dBm and SFN-C requires -2dBm and, in addition can achieve a maximum of 29 percentage points more reachability than the non-SFN algorithm. However, the best algorithm SFN-D consumes a maximum of 58.76% less energy than the SFN-A and a maximum of 14.28% less energy than the SFN-B. The SFN-D algorithm achieves a maximum 3.43 dB diversity gain together with the maximum 37.33% energy consumption gain in comparison to the non-SFN algorithm.

Keywords: Diversity gain, energy consumption, multihopping, reachability, transmitter macrodiversity.
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Terminology

Acronyms and abbreviations

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<td>Access point</td>
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<tr>
<td>BS</td>
<td>Base station</td>
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<tr>
<td>DSFN</td>
<td>Dynamic Single frequency network</td>
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<tr>
<td>FDM</td>
<td>Frequency division multiplexing</td>
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<td>FFT</td>
<td>Fast Fourier transforms</td>
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<td>IMANET</td>
<td>Internet based mobile adhoc network</td>
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<td>InVANETs</td>
<td>Intelligent vehicular ad hoc networks</td>
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<td>MSC</td>
<td>Mobile switching centre</td>
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<td>OFDM</td>
<td>Orthogonal frequency division multiplexing</td>
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<td>SFN</td>
<td>Single frequency network</td>
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<tr>
<td>SNR</td>
<td>Signal to noise ratio</td>
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<tr>
<td>VANET</td>
<td>Vehicular adhoc network</td>
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<tr>
<td>WLAN</td>
<td>Wireless local area network</td>
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<td>WSAN</td>
<td>Wireless sensor-actuator network</td>
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### Mathematical notation

<table>
<thead>
<tr>
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<tr>
<td>$P_{Rx}$</td>
<td>Receiver power required from transmitter</td>
</tr>
<tr>
<td>$P_{Tx}$</td>
<td>Transmitter power level</td>
</tr>
<tr>
<td>$Rx$</td>
<td>Receiver power</td>
</tr>
<tr>
<td>$Tx$</td>
<td>Transmitter power</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Propagation constant</td>
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1 Introduction

In the current era, the management and maintenance of these unstructured devices with regards to the undetermined and uncertain number of wireless nodes and their establishment in harsh areas has provided huge challenges for scientists. By definition it can be said that a wireless multi-hop network is the gathering of wireless nodes which are capable of setting up a temporary network dynamically without any established infrastructure. The network is dynamically self structured and self constructed and the nodes, themselves, within the network have the ability to establish and maintain mesh connectivity automatically. In this thesis work a wireless sensor-actuator network and a mobile ad hoc network are considered as being two important categories of wireless multi-hop network based on the applications.

Sensing devices are basically organized with a data processing unit and communicational abilities and whose the duty is to measure the specific constraints from the surroundings and to convert those parameters into electrical signals. These kinds of devices can significantly raise the effectiveness of both military and general functions including battle field inspection, safety, failure management and in some other areas where usual and normal attempts have proved to be very expensive and uncertain. Unstructured sensors also have the capabilities to observe a large amount of environmental conditions such as sound, pressure, temperature, motion etc. The architecture of a sensor network is based on a combination of actuators, sensor nodes and a base station. These sensor nodes consume resources such as a small bandwidth, communication range, memory, processing power and capability. It has now become very important to measure the energy consumption of these sensor nodes since they are battery driven and there is no continuous power supply attached to them. The processing of signals and communication activities are felt to be the two main areas of energy consumption with regards to these devices.
A mobile ad hoc network can be said to be an independent set of mobile nodes which are capable of communicating over relatively low bandwidth wireless links. As the name implies, it is a decentralized network in which the mobile nodes are capable of performing a variety of network functions including topology discovery, initialization, routing, messages transfer etc. This thesis can provide a significant role in relation to a mobile ad hoc network. It also has a role in relation to the power consumption for a network which is assumed to be unstructured and where the nodes are sited randomly and are battery driven. It is also useful from a reachability point of view even for those nodes which may have a continuous power supply.

This thesis also has the advantages over multi-hopping. Some of the nodes are very important in multi-hopping particularly for the case in which two or more nodes are dependent on it for data transfer. Thus, it is important that the node does not lose too much energy during each data transmission, thus causing the possibility that the node will die more quickly than other nodes due to a lack of battery power which may cause the network to collapse. The algorithm which will be created and simulated in this case will be based on transmitter macrodiversity but priority will be given to multi-hopping due to its low energy utilization. These algorithms have the ability to cause the network to remain alive for a long time even if some of the nodes are no longer useful. When a node dies, either some other node takes over the responsibility or an SFN will be formed in order to transfer data. In this manner, it is possible for SFN algorithms to be capable of solving one of key problems associated with multi-hopping.
On the other hand, broadcasting is a method in which messages are sent to all the members of the network and it is very energy efficient in comparison with uni-casting. In addition, it is a most common and useful idea to introduce this method into a wireless multi-hop network. This thesis has chosen an OFDM based transmission to reduce fading and inter symbol interference and it basically works using a broadcasting method. The algorithm has a number of applications in which the access point may send a routing table, queries, programming logic, any specific request etc. to all the nodes even those which are in a state of outage. Multi-hopping can be applied to a sensor network or access point which may send TV program guides to all the TV sets in a wireless TV distribution. It can be seen that, in this case, all applications are possible and are only energy efficient when using a broadcasting method.

Unstructured and unattended devices contain very little amounts of energy and are unable to send data over a long distance. However, the ability to increase the area of network coverage is one of the most vital factors for scientists to achieve. Transmitter macrodiversity is a term that can be introduced where all the transmitters are transmitting the same signal simultaneously and at the same frequency. This single frequency network is a new idea in a wireless multi-hop network but can raise the strength of signal and a better coverage area can be achieved as a result. The ultimate target will be to build some algorithms and to analyse them in relation to both their energy utilization and outage probability. These algorithms will work for a single frequency network and will attempt to save more battery life in comparison to a typical non-SFN algorithm while achieving better reachability.

1.1 Background and problem motivation

Unattended, unstructured and battery driven nodes are the most vital concern in wireless multi-hop networks due to their application in several fields. Many factors can affect their performance and scientists are concerned with both energy efficiency and in increasing node reachability. The aim is to merge these two factors in order to keep these nodes alive for a long time and to achieve a better network gain.
1.2 Overall aim

Two most important factors related to wireless multi-hop networks are energy consumption and reachability of nodes since the network is unstructured, random and the nodes are battery driven. The goal of this thesis is to save the battery power and energy while reducing the outage probability of the nodes.

1.3 Concrete and verifiable goals

As stated previously, some energy efficient algorithms will be generated based on transmitter macrodiversity and these algorithms will be simulated over multi-hopping. The energy utilization and reachability of the nodes of the network will be calculated and a comparison among those energy efficient algorithms including typical non-SFN algorithm will be made. Then the best SFN algorithm will be chosen based on high reachability and low energy consumption. An attempt will be made to increase the energy requirement of the non-SFN algorithm in order to provide a higher reachability which may be equal to the reachability of the best SFN algorithm. Then the energy utilization of these two algorithms will be measured and an attempt will be made to determine the gain associated with the SFN based algorithm.
1.4 Outline
The total project work will be divided into six chapters. These are as follows.

Chapter 1 will provide a brief introduction to the work together with the concrete problem specifications. Chapter 2 will explain all the ideas behind the work together with a literature evaluation and background information. Chapter 3 will describe the methodology behind the work and an explanation of the mathematical formulae. Chapter 4 will explain the algorithms in detail in addition to explanations, comparison, pseudo codes and JSPs associated with it. Chapter 5 will explain the results of the simulations. Chapter 6 will present the conclusion of work and suggestions for future work.

1.5 Contributions
As stated previously, the ultimate target is to save the battery life of the nodes and to increase the lifetime of the multi-hop network. In order to achieve the goal, some new, simple, energy saving algorithms will be created and those algorithms will be analyzed based on their outage probability and energy consumption. Reachability and energy utilization are the two new ideas which will be implemented in this case to work with transmitter macrodiversity over multi-hopping and broadcasting technology.
2 Theory

Chapter 2 will describe in details all the factors and ideas related to the thesis work. This chapter will explain two important networks, namely the wireless sensor-actuator network and the mobile ad-hoc network which these algorithms are aimed at. Following this, some factors related to these networks such as energy consumption, OFDM, fading, multihopping will be illustrated. Finally, transmitter macrodiversity will be explained with its application in relation to the area of a sensor-actuator network, cellular network and a mobile ad-hoc network.

2.1 Wireless sensor-actuator network

The expectations of the sensor-actuator node subscribers have escalated together with the ever expanding science and technology. New challenges are being met by the scientists in relation to bringing the advanced and latest features together with improvements to the current network infrastructures in order to meet the demands of the users. The sensor-actuator network is not one of the newest technologies which are based on a combination of sensor nodes, base stations and actuators in their architecture and their communication medium is basically broadcasting. Sensor-actuator nodes can maintain a secure communication instead of having limited capabilities such as energy, bandwidth, communication range etc. even in harsh environments where human involvement is truly impossible. See figure 1.
Based on the topology or the position of the nodes the sensor-actuator network will be divided into two parts, namely the unstructured and the structured. Based on the energy supply, both the unstructured and structured networks are divided into another two parts namely the battery driven and continuous power supplies. One unusual phenomenon can occur here, in which unstructured nodes have a continuous power supply. Theoretically, this is possible, but practically it cannot exist and the target nodes are unstructured and battery driven.

Sensor-actuator nodes basically communicate with each other in radio frequency through broadcasting. Three types of communications can be maintained for three different purposes. Firstly, sensor-actuator nodes can send data to the base station in order to read an event. Secondly, the base station can transmit a definite request to a definite node after a given time gap. Lastly, the base station can broadcast to all the nodes available in the coverage area to announce forwarding table, programming logic, update queries etc. The unstructured and unattended sensor-actuator nodes can be said to be intelligent devices but are unable to perform all the heavy duties due to certain limitations, including inadequate amount of memory, energy, communication bandwidth, computing power and communication distances.
2.1.1 **Sensor-actuator node architecture**
A sensor-actuator network can contain a huge amount of sensors and actuators with one or more base stations or access points or high potential data storage and a processing centre that can act as a gateway to other networks. These base station or access points can have adequate amounts of memory, energy, communication bandwidth, computing power and communication distance in comparison to sensor-actuator nodes and can be referred to as a sink.

Berkeley mica mote is taken here as an example for a sensor node which can be few cubic inches in size. The features of a sensor node are given below

- **Processor**: The sensor node contains 8 bit, 4 MHz Atmel AT-MEGA103 processor with 128 KB cache memory.
- **Operating system**: Sensor node contains TinyOS operating system.
- **Memory**: The memory is divided into 2 parts, RAM and flash memory. RAM can contain 4 KB of data and flash memory can contain 512 KB of data.
- **Energy consumption**: The life time of a sensor node is based on two AA batteries that can provide 2850 mAh (approx). Energy consumption of a sensor depends on transmitting, receiving and sleeping mode. Transmit requires a maximum of 12 mA, receiving a maximum of 4.8 mA and sleeping a maximum of 51 A.
- **Bandwidth**: Sensor nodes can communicate with each other with a maximum of 40 Kbps bandwidth with 916 MHz radio frequency.
- **Coverage distance**: It can communicate within a distance of a few dozen metres.

A sensor node can contain many components based on its purposes but can be classified into 5 parts which are fundamental such as sensing element, analog to digital conveter (ADC), processor (CPU), energy component and communication component. See figure 2.
Sensing element: This component is responsible for capturing any event from real world phenomena.

Analog to digital converter (ADC): The captured event is analog and the ADC converts them into digital and sends them to the CPU.

Processor (CPU): CPU processes the digital data and converts it into human readable format.

Energy component: It is basically the source of energy i.e. battery. All the components collect energy from it.

Communication component: This part is responsible for communicating with the user.

The actuator node makes its decision based on the sensed reading by the sensor node and its actions are performed accordingly over an actuation device. An actuator node is only a sensor node based on its architecture but with an enhanced amount of energy, processing power, transmission rate and communication distance. Actuator nodes are not required to be deployed in huge amounts in target places in comparison with the amount of sensor nodes due to their better capabilities. See figure 3.
Decision unit: This block accepts the input from sensor data and creates output as a command.

DAC: Generated command from the controller is basically analog data and DAC converts them into digital and sends them to an actuation unit.

Actuation unit: This block is responsible for converting the command function into action.

Sensors and actuators perform as a team and can also be integrated into a device. A simple example of an integrated sensor-actuator node is a robot which can sense values and can perform accordingly.
2.1.2 Sensor-actuator node applications

The most important function of these sensor-actuator nodes is to alert people in time after the capture of events and thus save them from any potential disasters. The application of the unstructured sensor-actuator nodes is increasing day by day due to their small size, low cost, easy placement procedure etc. Some examples in which sensors- actuators can be utilized efficiently are provided below.

1. Environment observation: Unstructured sensor-actuator nodes can be set in harsh and rough places in order to observe the changes in nature. They can monitor many events such as the discovering and tracking of wildfires, the forecasting of earthquake, observation of pollution, studies on habits, greenhouse monitoring etc.

2. Home and office application: These sensors-actuators can be set with several electrical appliances and can make our day to day life easier and better. They can be useful in home and office security, automation etc.

3. Health application: These sensor-actuator nodes can be embedded into several pieces of medical equipment, a patient’s body and are capable of assisting doctors and nurses in increasing their performances. These nodes can be very helpful in monitoring human psychology, the presence of doctors, nurses, administrators, patients, visitors etc and in relation to the presence of legal and illegal drugs etc.

4. Military applications: Since these sensor-actuator nodes are capable of working in rough and tough places, these are able to assist in defense activities. They have many military functions including the scrutinizing of friendly and enemy power, ammunition and utensils, maintaining a close watch on the theatre of war, an inspection of opposing forces, providing combat damage evaluations, the presence of biological, chemical and nuclear equipments.
5. Traffic monitor: Sensor-actuator nodes have the ability to play a significant role in traffic world and are able to assist drivers, passengers, traffic police and others to perform their jobs. They have the ability to display performances in relation to traffic controlling, vehicle monitoring, speed measuring, weight calculations etc.

6. Agricultural application: The utilization of sensor-actuator nodes in agricultural sector is increasing day by day. These are very helpful in irrigation computerization, water utilization monitoring, water pump and tank level checking, plant growth observation, presence of insects etc [3], [4], [5].

2.2 Mobile adhoc network

Mobile ad hoc network (MANET) is also known as mobile mesh network which is a self-configured network with mobile nodes connected via radio signals. All the nodes connected in MANET can change their position and can link to other nodes dynamically. Each node behaves as a router for next nodes. MANET does not require any preset infrastructure with a base station in order to control and operate it. In this case, all the devices are independent and can make decisions which indicate that there is no master-slave relationship.

Due to the dynamic nature of the devices, algorithms utilized in MANET are very complicated in comparison with traditional routing algorithms. The function of these sophisticated algorithms is to maintain low bandwidth and overhead with better route convergence. Mobile ad hoc networks support both homogeneous and heterogeneous networks. A homogeneous network contains the same type of devices in a network whereas a heterogeneous one contains different kinds of devices.
Mobile ad hoc networks can be classified into two types namely vehicular ad hoc networks (VANETs) and internet based mobile ad hoc networks (iMANET). Vehicular ad hoc networks (VANETs) are utilized for communications in relation to vehicles and roadside equipment. Intelligent devices can be included with VANETs and this can convert them into intelligent vehicular ad hoc networks (InVANETs). InVANETs are capable of determining accidents, collisions between vehicles, illegal driving etc. A sophisticated routing algorithm is required for internet based mobile ad-hoc networks (iMANET) which is capable of connecting between mobile nodes and internet-gateway nodes [6], [7]. See figure 4.

![Figure 4: A typical example of MANET [8]](image)

### 2.3 Orthogonal frequency division multiplexing

OFDM can be said to be the grouping of multiplexing and modulation and in which multiplexing means to share the bandwidth among different and distinct sub carriers and modulations indicate the binding of data and a carrier signal. OFDM can be divided into 16 to 256 sub carriers. These have the ability to share bandwidth and all the sub carriers can be modulated individually since they are orthogonal to each other. It can also be stated that the multicarrier FDM also has the same data which is divided equally in all sub carriers and all the sub carriers then follow the typical modulation scheme in order to transfer data. Some of the important features of OFDM are given below

- Data transfer rate is 6Mbps to 48Mbps
- It supports 4 different types of modulations such as QPSK, 16QAM, BPSK and 64QAM.
• It is based on a typical concatenated coding system.
• It supports different FFT sizes including 48 which is used for data, 4 is used for pilot and 64 is used along with 52 sub carriers and in which the FFT period is 3.2 μsec and the symbol time is 4 μsec.
• Allocated frequency is 20 MHz which is divided in all 64 subcarriers with an equal frequency of 0.3125 MHz.

OFDM can provide many advantages compared to some other multiplexing techniques in addition to some problems. OFDM can easily keep pace with harsh channel setting with larger spectral effectiveness and lower synchronization errors without any complicated equalizations. It does not in favour inter symbol noise, co-channel noise in narrow band and fading factors due to multi-path propagation. It is very effective in dealing with transmitter macrodiversity and no filtering is required in order to tune a sub channel in comparison to the typical FDM. On the other hand, it is in favour of a Doppler shift and frequency synchronization. It can suffer from poor efficiency due to the larger peak to average power ratio (PAPR) and guard interval [9].

Orthogonal FDM (OFDM) is a spread spectrum system which allocates the signal over a huge amount of carriers which are sited apart on specific frequencies. This distribution of signal generates the orthogonality feature among the subcarriers. A brief idea concerning the OFDM functionalities from the block diagram in figure 5 is given below.
It can be assumed that there are n subcarriers to transmit in serial sequence. The serial-to-parallel (S/P) block converts the serial data into parallel OFDM symbols. The inverse fast-Fourier transform (IFFT) generates n number of parallel sub channels at a time domain which is larger than a single carrier system by a factor of n. Then these n sub channels are converted into a serial sequence by a parallel to serial (P/S) block. The cyclic prefix (CP) block is introduced to maintain orthogonality and to reduce interference among the subcarriers and neighbouring OFDM symbols respectively. The follow-on symbol is then amplified and transmitted over the channels.

At the receiver part a completely opposite phenomenon occurs. At the beginning, the inserted cyclic prefix (CP) by the transmitter is removed and signals are converted into parallel by an S/P block. Then a fast Fourier transform (FFT), (P/S) and detection block are utilized to equalize, regain and detect the actual transmitted symbol [11], [12].
2.4 Energy consumption

In a broad sense, energy consumption means the expenditure of energy. From the electrical engineering point of view energy consumption regularly indicates the amount of electrical energy provided to run the electrical devices. It is often calculated in joules. This is a unit employed and means the energy reduction capability of an electrical appliance. It is known that, energy = power*time, where power is measured in watts, energy in joules and time in seconds. But if time is taken as a constant, power becomes equal to energy.

Energy utilization is the most important task of the sensor-actuator nodes. If these sensor-actuator nodes want to live for a long time, energy utilization should be reduced as much as possible. A crucial characteristic of the network is its life duration which depends on the exploitation of the energy source. Since it is known that unstructured sensors-actuators are battery driven, their energy is greatly limited. This is why hardware, protocols, applications have to be aware of this fact and that the energy consumption has to be optimized. Generally, the networks are established in rough environments where manpower placement is very difficult. If the sensors-actuators utilize their entire battery life then the entire network will collapse.

Sensor-actuator nodes basically spend energy in transmitting and receiving data and very little in sleeping mode. It spends energy when an event occurs or during periodic sampling. There are some energy efficient Mac layer protocols namely SPIN, LEACH etc.
2.5 Fading

Fading means the distortion of a signal which is modulated with a carrier and is experienced on reliable transmission media. The fading channel means the transmission channel which is experienced with fading. In a wireless transmission system the fading occurs because of multi-path transmission and it is also known as multi-path fading. Multi-path is used simply as a term to explain the several paths of radio waves that can be pursued between receiver and transmitter. This transmission path includes the earth wave, refraction from the ionosphere, re-radiation from the ionosphere layers, reflected by the earth’s surface etc.

Multi-path fading can be reduced by methods known as frequency diversity and space diversity. In space diversity, two or more than the amount of receiving antennas are placed with some distances among them. Fading is not observed simultaneously in all antennas. Two receivers and two transmitters are utilized at frequency diversity and in which it is possible for each pair to be tuned to a different level of frequency. It maintains the same type of information intact even though it is propagated simultaneously on both frequencies [13].

Rayleigh fading can be defined as a statistical representation of the consequence of the transmission scenario of a radio signal and can be utilized in wireless devices. It is assumed by means of a Rayleigh fading representation that the signal magnitude which passes through a transmission media (also called a communications channel) can diverge randomly based on a Rayleigh distribution. Rayleigh fading can be taken as a logical model for both the ionosphere and the troposphere signal transmissions together with the effect of a largely constructed metropolitan location over radio signals. Rayleigh fading can generally be applied while there is no central transmission through the line of sight between the receiver and the transmitter [14].
Rician fading can be stated as being a random radio propagation model irregularly generated by partial deletion of a signal by the radio signal itself. The signal can reach the receiver end following the two distinctive paths and after that it is possible for one of the paths to be increased or decreased in size. Rician fading can occur when the strength of one of the paths becomes stronger than other paths. Rician fading basically occurs in either the line of sight or direct path signal and received signal amplitudes of all the signals become Rayleighy distributed [15].

2.6 Multi-hopping

By definition, multi-hopping is a phenomenon when two or more hops or nodes are engaged in order to carry a signal from the source to its destination. In this case, the base station is not sufficient to transmit data to a destination and it is rather the case that intermediate nodes are utilized to carry the signal. As the name implies multiple hops or nodes are employed to form a network and each node acts as a router for the next node. A larger coverage area can be accomplished compared to that for a single hop network in which the base station merely broadcasts the signal to all the nodes. From an application viewpoint, multi-hopping can be divided into two parts, namely a mobile ad-hoc network and a multi-hop cellular network.

![Figure 6: An example of multi-hopping](image)
In figure 6, there are 5 nodes in a network which have formed a mesh network. Since it is an ad hoc network, there is no typical base station. For example, node A is connected to nodes B, C and D but not to E. If A wants to send any data to B, C or D, it can send it directly. But if A wants to send any data to E, it cannot send it directly but has to go via C. It is known that wireless multi-hopping supports several standards such as IEEE 802.11 a, IEEE 802.11 b, IEEE 802.11 g, personal area networks (PAN), Bluetooth, HIPERLAN/2 and wireless local area networks (WLAN) [15].

### 2.7 Transmitter macrodiversity

Transmitter macrodiversity is a phenomenon which is not a new term in cellular and sensor networks and is found to be very useful nowadays. From the definition point of view, transmitter macrodiversity is a term used when a number of transmitters are utilized to transmit the same data at the same time. The gaps among the transmitting antennas are retained more than the signal wavelength. Since all the transmitters deal with the same signal at the same time, the signal strength will increase and as a result the coverage area of the signal will also increase. On the other hand, it is very useful in reducing the signal interference and fading. See figure 7.

![Transmitter macrodiversity](image)

**Figure 7: Application area of transmitter macrodiversity**
The macrodiversity term can be classified based on its application in different areas. Single frequency network (SFN) is used only in sensor network whereas soft handoff, hard handoff and dynamic single frequency network (DSFN) are the most common terms used in a cellular network. In a sensor network all the nodes are basically transceivers but they cannot transmit and receive at the same time. On the other hand, base stations and access point are responsible for transmitting data since transmitting antennas are associated with them in a cellular network.

Diversity gain is the most important term used in macrodiversity which is basically calculated to explain macrodiversity. Diversity gain is the enhancement of the signal-to-noise ratio because of various diversity systems. It can also determine the amount of transmitting energy that can be reduced without lowering the performance after the introduction of a diversity method.
2.7.1 Single frequency network

Single frequency network (SFN) is one of the sub divisions in the transmitter macrodiversity category applicable to a sensor network. In SFN all the transmitters transmit the same signal or the same data at the same frequency and at the same time. The goal of SFNs is the effective employment of a radio signal spectrum and it is capable of broadcasting a larger number of television and radio programmes than a typical multi-frequency network (MFN) transmission [16], [17]. See figure 8.

![Figure 8: An example of single frequency network [18]](image)

In this case 9 transmitters are visible in a network. Each of the transmitters is within range of either one or more transmitters. As a result it is possible for one transmitter to send data to any of the other transmitters through multi-hopping.
2.7.2 Dynamic single frequency network

Dynamic Single Frequency Networks (DSFN) is merely another form of SFN in which the SFN grouping can be changed dynamically based on received criteria. Otherwise it is the case that everything remains the same such as several transmitters transmitting the same signal at the same frequency but during different time slots. The idea of DSFN is based on dynamic changes of SFN grouping over time. As stated previously, DSFN is one of the transmitter macrodiversity methods used in OFDM supported cellular networks and the goal of DSFN is to attain effective utilization of spectra in uni-cast and multi-cast communication [19], [20].

In figure 9, it can be seen that there are 2 transmitters TX1, TX2, five receivers RX1, RX2, RX3, RX4, RX5 and 2 timeslots Timeslot 1, Timeslot 2. Here, the base stations are centrally monitored, harmonized and all the transmitters and receivers are allocated with the same channel of frequency. Two transmitters TX1, TX2 are responsible for sending data to all the receivers. TX1 and TX2 transmit different data in Timeslot 1 and the same data in Timeslot 2.
In Timeslot 1, TX1 will be able to send data only to RX1 and TX2 only to RX2 which fall inside the coverage area of TX1 and TX2 as shown by the inner circle in the figure. Here it can be seen that the remainder of the transmitters such as RX3, RX4 and RX5 are in outage state and data cannot be sent to them as the co-channel noise is too large outside those inner circles.

In Timeslot 2, TX1 and TX2 will form an SFN since both transmitters fulfilled the requirements of the SFN; sending the same information, at the same frequency and at the same time slot. As a result their coverage area will increase since the signal strength will increase and they will form a sophisticated shape. It can be seen from figure 9, that the SFN can reach receivers RX1, RX2, RX3, and RX4 but not RX5 since still the co-channel noise is still too large for the SFN to recover and RX5 will be in outage state.

2.7.3 Soft handoff

Soft handoff is known as soft handover and it is utilized basically in a CDMA based cellular network. It is capable of making an overlap of the coverage area of the base stations and, as a result, a mobile station can always remain within range of the base stations. A mobile station always maintains a connection with at least two base stations and never becomes disconnected from a base station before creating another connection. A soft handover is based on a technology which is able to rapidly switch and establish connections with the base stations and it is expensive and complicated in comparison to the hard hand over. The soft handover is very helpful for video conferencing since it can reduce fading, interference and latency of signal. This connection is more or less permanent and is also reliable since there is hardly any fear of call termination [22].

In this case it can be seen that when a mobile user (MSC) is switching from one cell (coverage area of a transmitter) to another, it can be assumed that the user is engaged in a conversation. The MSC will decide, under which cell it will reside based on many criteria one of which would be the signal strength. See figure 10.
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Now the user is within cell1 and within a few moments will be within cell2. The MSC is responsible for checking the signal strength at all times and it will take the decision afterwards. In the first figure the user is moving from cell1 to cell2. The user is simultaneously connected to two base stations and will remain connected to cell1 before becoming connected to another cell. It is also known as ‘make before break’ communication which is thought to be reliable for communication. See figure 11.

Figure 10: An example of soft handover [23]

Figure 11: An example of soft handover [23]
2.7.4 Hard handoff

A hard handoff is known as a hard handover and it is utilized basically in FDMA and TDMA based cellular networks. A mobile station always maintains a connection with at least one base station and disconnects from the base station after creating another connection. A hard handover is based on a technology which is able to quickly break off before establishing connections with the base stations and it is less expensive and complicated in comparison to a soft handover. A hard handoff is very useful in WiMAX, VoIP, and broadband internet which can tolerate delay and unreliability. Here it can be seen that a mobile user (MSC) is switching from one cell (coverage area of a transmitter) to another and it can be assumed that the user is engaged in a conversation. The MSC will decide, under which cell it will reside, based on many criteria including the signal strength. Now the user is within cell1 and within a few moments will be within cell2. The MSC is responsible for checking the signal strength at all times and it will then make a decision [24].

![Figure 12: An example of hard handover](image)

In figure 12, the user is moving from BS1 to BS2 and the user is only connected to BS1 but not BS2. When the user falls within cell BS2, it becomes disconnected from BS1 and becomes connected to BS2. This type of handoff is known as make before break and is known to be unreliable. See figure 13.

![Figure 13: An example of hard handover](image)
2.7.5 Wireless TV distribution

Wireless TV distribution can play a great role for a home theatre system, video streaming, video conferencing, etc and this is also known as wireless audio video distribution. People often have several TV sets, computers and loud speakers running simultaneously and this involves a great deal of cabling. However, home should not be the same as an office and cabling should be avoided. Audio and video signal should be transmitted by some defined wireless schemes. At present, musicians use many sophisticated musical instruments for both indoor and outdoor activities and this usually involves significant cabling and the need for a continuous power supply since these musical instruments are portable. This is the reason why they prefer to avoid these problems and use wireless ones which are battery driven.

Audio video distribution means the distribution of the standard quality of audio video signal to all destinations within a mobile ad hoc network. It also indicates the distribution of non-licensed radio frequency signals. The process includes three general functions involving gathering, amplifying and distributing and the broadcasting method is generally used in this case. Transmitter macrodiversity can be applied to both wired and wireless devices to increase the coverage area but it will only be effective for wireless and battery driven instruments from a power consumption point of view.

The idea of wireless TV distribution has been a hot topic for many years but it has not proved to be as successful as expected. Previously an infrared signal (IR) was used to transmit a signal whereas radio frequencies from 900 MHz to 2.4 GHz did provide some better results. An infrared signal bears line of sight properties and its communication range is small. These infrared signals also run the risk of interference from other instruments played using similar radio frequencies.
At present, instruments based on 802.11b, 802.11g etc standard are the ones generally preferred and these standards also support the mobile ad-hoc network (MANET). These standards have the ability to provide a number of better solutions and also a better quality audio-video signal. However, the communication range still remains as a problem. Scientists are attempting to increase the transmission range by means of an amplifier or some other extending device, but this is lowering the quality of signals. Since one or more computers are included in a mobile ad-hoc network with TV sets, loudspeakers, mp3 players, etc, the signal quality and strength can be easily measured and compared. Thus, it can be stated that transmitter macrodiversity over a mobile ad-hoc network can be very effective in providing better network coverage and lower energy utilizations. See figure 14.

Figure 14: An example of wireless TV distribution [26]
Chapter 3 will describe the methodologies behind the work together with an explanation regarding all the mathematical formulae. This chapter will explain the SFN formation procedure, different actual SFN appearance and size with a wave propagation model. SFN, non-SFN range and SFN based SNR with examples will be calculated. This chapter will also describe the packet transmission procedure with its related energy consumption formula.

3.1 SFN formation procedure

It can be assumed that all the nodes are transceivers. However, as they work under a shared channel, it is not possible to establish a duplex channel in which it is possible for the nodes to behave simultaneously as both a transmitter and receiver. It is known that in a multi-hop network all the nodes have the ability to act as a route for other nodes. However, it is not possible to reach those nodes which fall outside the coverage area of the source or adjacent nodes. In this case, an attempt will be made to form SFNs under a multi-hop network in which increased network coverage can be formed and thus it will be possible to reach those nodes which were in a state of outage from the source node or other nodes.

The following provides a simple explanation of an SFN group creation in which the source node was assumed to start the network but in which the SFN creation algorithm is not followed exactly.
In figure 15, it can be seen that there are 6 nodes in a network and they are situated randomly. It can be assumed that N1 will initiate the network which can be assumed as being an access point and it will attempt to reach all the nodes situated in the network.

In figure 16, N1 can reach directly to N2 via broadcasting. Multihopping is formed among the four nodes N2, N3 and N4. As a result N1 can send messages to N2, N3 and N4 but is unable to reach N5 and N6. N5 and N6 still remain in a state of outage even after multi-hopping. See figure 17
It can be assumed that the 4 nodes N1, N2, N3 and N4 will behave as transmitters and the other two nodes N5 and N6 as receivers. In figure 17 the maximum coverage area for each transmitter is shown by circles. The aim of the transmitters is to reach the two receivers through SFN by means of multi-hopping.
In figure 18, all the four transmitters connected through multi-hopping are transmitting the same data, at the same frequency and at the same time and the result is the formation of an SFN. The SFN is shown in the white area bearing a sophisticated kind of shape. Due to this SFN, RX5 can be achieved within the coverage area. However, RX6 still remains outside the coverage area and it can be stated that RX6 is in a state of outage.

3.2 Wave propagation model

The goal is to measure the distance between the transmitter and receiver based on a wave propagation model formula in which several factors are taken into account which will be explained at a later stage. As stated previously all the nodes are basically transceivers but have the ability to act as either a transmitter or receiver but not simultaneously. The communication media between them is not duplex and they basically use a shared transmission medium.

It can be assumed that there are two groups of sensor nodes, one behaving as the transmitter and the other as the receiver. Suppose that $N$ number of elements of the transmitter and $M$ number of elements of receiver exist. The transmitters are $Tx1$, $Tx2$, $Tx3$, $Tx4$...$TxN$ and the receivers are $Rx1$, $Rx2$, $Rx3$, $Rx4$...$RxM$. Another 2 variables can be taken as $i$ and $j$ which can represent any transmitter and receiver from 1 to $N$ and 1 to $M$ respectively.

The formula is given below for a specific transmitter $i$ and receiver $j$:

$$P_{i,j} = \frac{P_i * F_{i,j} * G_{i,j}}{d_{i,j}^\alpha}$$

$$= \frac{P_i * C}{d_{i,j}^\alpha} \text{ here, } C = F_{i,j} * G_{i,j}$$

$$= \frac{1}{d_{i,j}^\alpha} \text{ here, } P_i * C = 1$$
Here,  
\( P_{i,j} \) represents the power received by the receiver \( j \) which is generated by transmitter \( i \).  
\( P_i \) represents the power generated by transmitter \( i \). It is often taken as fixed and here assumed to be 1.

\( d_{i,j} \) represents the distance between transmitter \( i \) and the receiver \( j \).

\( F_{i,j} \) represents the fading effect between transmitter \( i \) and the receiver \( j \). It is taken as being a constant and is assumed to be 1. It depends on several factors such as antenna gains, antenna heights, and carrier frequency. The value of \( F_{i,j} \) should be less than 1 according to real world phenomena.

\( G_{i,j} \) represents the gain between the transmitter \( i \) and receiver \( j \). It depends on the shadow effect. It is taken as being a constant and is assumed to be 1. The value of \( G_{i,j} \) should be less than 1 according to real world phenomena.

Here \( \alpha \) represents the propagation constant. The value of \( \alpha \) is taken to be 4. The value of \( \alpha \) can be 2, 3 or 4.

\( C \) represents the constant. Since \( C \) is the multiplication of \( F_{i,j} \) and \( G_{i,j} \). The value of \( C \) should be very much less than 1 though it is taken as 1.

### 3.3 Non-SFN range calculations

The basic formula can be derived to discover the network coverage area of a transmitter without SFN when several factors are defined. There are five factors found to be used here but only the distance and required receiver power will be taken into account while the remaining factors were taken as being constants.

\[
P_{Rx} = \frac{P_{Tx} \times C}{d^\alpha}
\]

Here,

\( P_{Rx} \) represents the receiver power required from the transmitter.

\( P_{Tx} \) represents the transmitter power level which is assumed to be 1 here.
C represents the constant which is assumed to be 1.

d represents the distance between the transmitter and the receiver.

\( \alpha \) represents the propagation constant which can be 2, 3 or 4 but in this case is assumed to be 4.

Since \( P_{Ts} \) and \( C \) are assumed to be 1,

\[
P_{Rs} = \frac{1}{d^\alpha}
\]

(3.3)

Here two varying constants \( P_{Rs} \) and \( d \) are found and these are inversely proportional. If the receiver power increases, the distance becomes less between the transmitter and the receiver. It means that the transmitter is close to the receiver when the transmitted power is constant. Inversely, if the receiver power decreases, the distance increases between the transmitter and the receiver which indicates that the transmitter is situated far from the receiver and where the transmitted power is assumed to be constant.

### 3.4 SFN based SNR

In a single frequency network all the transmitters send the same signal at the same frequency and at the same time. SFN is able to increase the coverage area of a network and thus some nodes which reside outside the range of the other nodes can be included within the area of coverage. It is possible to calculate the signal to noise ratio in an SFN based network. Thus, the signal to noise ratio (SNR) at receiver \( j \) and averaged over all OFDM subcarriers can be calculated according to the formula given below

\[
SNR = \frac{\sum P_{i,j}}{\sum Q_{i,j} + N_j}
\]

(3.4)

Here,

\( i \) and \( j \) represent any particular transmitter and receiver respectively.

\( P_{i,j} \) represents the power received by receiver \( j \) which is generated by transmitter \( i \) and when both the transmitters and receivers are inside the SFN.
$Q_{i,j}$ represents the power received by receiver $j$ which is generated by transmitter $i$ but the transmitters are outside the SFN and the receivers are inside the SFN.

$N$ represents the external noise.

![Figure 19: SFN based signal to noise ratio](image)

In figure 19, there are 8 nodes in a network, 5 behaving as transmitters and 3 as receivers. The transmitters are TX1, TX2, TX3, TX4 and TX5 and the receivers are RX1, RX2 and RX3. An SFN group can be formed with transmitters TX1, TX2 and TX3 together with receiver RX1. On the other hand, the remainder of the transmitters and receivers, namely TX4, TX5, RX2 and RX3 are outside of the SFN group. It can be assumed that all the transmitters, inside and outside of SFN, are sending signals to the receiver RX1. The power received by receiver RX1, which is generated by transmitters TX1, TX2 and TX3 can be expressed by $P_{i,j}$, $P_{i+1,j+1}$ and $P_{i+2,j+2}$ and these transmitters are within the SFN. Similarly, the power received by receiver RX1 which is generated by transmitters TX4 and TX5 can be expressed as $Q_{i,j}$ and $Q_{i+1,j+1}$ respectively which are outside of SFN. Thus, the signal to noise ratio (SNR) at receiver RX1 can be calculated by the given formula.
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3 Methodology

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\[ SNR = \frac{P_{i,j} + P_{r+1,j+1} + P_{r+2,j+2}}{Q_{i,j} + Q_{r+1,j+1} + N} \]  

(3.5)

3.5 SFN based SNR calculations

Figure 20: SFN based signal to noise ratio calculation

In figure 20, \( P_{1,3} \) represents the power received by RX3 which is generated by TX1. It is taken as 1 mW. The distance between the transmitter TX1 and the receiver RX3 is assumed as 1m.

\[ P_{1,3} = \frac{1}{d^\alpha} \]
\[ = \frac{1}{1^4} \]
\[ = 1 \text{ mW} \]

\( P_{2,3} \) represents the power received by RX3 which is generated by TX2. It is taken as 1/16 mW. The distance between the transmitter TX2 and the receiver RX3 is assumed as being 2m.

\[ P_{2,3} = \frac{1}{d^\alpha} \]
\[ = \frac{1}{2^4} \]
\[ = \frac{1}{16} \text{ mW} \]
$P_{4,3}$ represents the power received by RX3 which is generated by TX4. It is taken as $0.1 \, mW$ (It is taken as an example since the distance between transmitter TX4 and receiver RX3 is not defined).

$N$ represents the noise which is taken as $0.2 \, mW$ (as for example).

\[
SNR = \frac{P_{4,3} + P_{2,3}}{N_{1,3} + N} = \frac{1 + \frac{1}{16}}{0.1 + 0.2} = 3.54 \, \text{times}
\]

\[
\text{Signal strength of the SFN} = 10 \log_{10} SNR = 10 \log_{10} 3.54 = 5.49 \, \text{unit}
\]

As for example SNR is often taken as $5 \, dB$ which is $3.16$ times.

\[
SNR_{db} = 10 \log_{10} SNR
\]

Let, $SNR_{db} = B = 10 \log_{10} SNR$

\[
\Rightarrow \quad SNR = 10^{B/10}
\]

If $B = 5 \, dB$, $SNR = 10^{5/10} = 3.16 \, \text{times}$.

On the other hand, if the noise value is known, the signal strength can be calculated since SNR value is defined. For example, SNR is taken as $5 \, dB$ and the noise value is assumed to be $30 \, W$.

From the previous formula, $SNR = 10^{5/10} = 3.16 \, \text{times}$.

\[
SNR = S/N
\]

\[
\Rightarrow 3.16 = S/30
\]

\[
S = 94.8 \, W \approx 95 \, W
\]

Here, $S$ represents the signal strength and $N$ represents the noise value.

Similarly, the noise value can be calculated if the signal strength and SNR value are known but this is not important.
3.6 Energy consumption for packet transmission

In this case the energy consumption required to detect the nodes will be calculated for a broadcasting scenario.

\[ \text{No. Of packets} = 1 + \text{no. of connected nodes} + (2 \times \text{no. of forwarding nodes}), \quad (3.6) \]

Here, the connected node represents the nodes which are within the base station coverage area. Forwarding represents the nodes which forward the information apart from the access point and connected nodes. See figure 21.

![Figure 21: Random nodes with no. of hops](image)

At the 1st step, there are no connecting nodes and forwarding nodes. At the 2nd step, there are 3 connected nodes but no forwarding nodes. From the 3rd step to the 5th step, only the number of forwarding nodes will increase.

1st step: Energy utilization = 1 Energy unit
At N1: 1+C0+F0 = 1+0+0=1 Energy unit
2nd step: Energy utilization = 3 Energy unit
At N7: ROUTE> N1, N7
At N4: ROUTE> N1, N4
At N8: ROUTE> N1, N8

3rd step: Energy utilization = 8 Energy unit
At N2: ROUTE> N1, N7, N2
At N3: ROUTE> N1, N4, N3
At N6: ROUTE> N1, N4, N6
At N11: ROUTE> N1, N8, N11

4th step: Energy utilization = 10 Energy unit
At N9: ROUTE> N1, N7, N2, N9
At N15: ROUTE> N1, N4, N3, N15
At N13: ROUTE> N1, N4, N6, N13
At N10: ROUTE> N1, N8, N11, N10
At N5: ROUTE> N1, N8, N11, N5

5th step: Energy utilization = 4 Energy unit
At N14: ROUTE> N1, N7, N2, N9, N14
At N12: ROUTE> N1, N8, N11, N5, N12

From figure 21 it can be seen that N1 is included in the 1st step, N7, N4 and N8 are in the 2nd step, N2, N3, N6 and N11 are in the 3rd step, N9, N15, N13, N10 and N5 are in the 4th step and N14 and N12 are in the 5th step. Here N16 is in a state of outage since no node can reach it. The 1st step requires 1, the 2nd step requires 3, the 3rd step requires 8, the 4th step requires 10 and the 5th step requires 2 energy unit. It can be seen that a maximum of 26 (1st step + 2nd step + 3rd step + 4th step + 5th step) energy units are required to reach all the nodes with the exception of N16.

For example, if N1 wants to detect N10, it has to traverse the 1st step, 2nd, 3rd and 4th steps and the energy spent will equal 1+3+8+10=22 energy units.

If uni-casting is considered, it is necessary to apply a different formula.
For example, N1 is the source and N4 is the destination.
The formula given for, transmission energy consumption= (1+ no. of forwarding nodes) 

\[ (3.7) \]
The formula given for, total energy consumption = 2* transmission energy
= 2(1+ no. of forwarding nodes) 

(3.8)

Here the forwarding nodes are N7, N2 and N9
So, transmission energy consumption=1+3=4 energy unit and total energy consumption= 2*4=8 energy unit

Since this thesis work is based on a broadcasting scenario and the energy required for packet transmission, the formula is given below

Energy consumption (unit) = (No. Of packets *Size of a packet)*25*10^{-9} joules, (3.9)
No. Of packets = 1+no. of connected nodes + (2* no. of forwarding nodes) (3.10)
Here, Size of a packet = 1024bit and both the transmission and reception of 1 packet requires 25 nJ.

Again, Energy consumption for data forwarding (per node and bit) = 20nj/bit
+ (PTx (watt))/9.3*10^{-5})*10 nj/bit (3.11)
4 Design

Chapter 4 will explain the entire five algorithms non-SFN, SFN-A, SFN-B, SFN-C and SFN-D in detail. The explanation will be followed by the pseudo codes and the JSPs associated with them.

4.1 A non-SFN algorithm

In figure 22, a network can be considered with 9 nodes, N1 to N8, including an access point where AP and N8 can be assumed as being the source and destination respectively. It can be assumed that this network will not allow any SFN formation which indicates that this network will only allow multi-hopping. In this case N1 and N2 are the connected nodes. AP is able to reach N1 and N2 since they are within the coverage area of AP. N1 is able to reach N3 and N2 is able to reach N4 through multi-hopping. N3 is also able to reach N5 through multi-hopping. Here N6 to N8 are in a state of outage since multi-hopping can not reach those nodes.
4.1.1 Pseudo code of Non-SFN algorithm

1. Until all nodes are visited
   a. Locate the access point connected nodes.
   b. If any node is located, insert its position to the list.

2. Until all connected nodes are visited
   a. Until each node from the connected nodes list is compared with rest other nodes
      i. At the beginning all the nodes are assumed as the neighbour of connected nodes. Pick a node from
         connected node list and verify the range to locate its neighbour.
      ii. If any node is located within the range, insert it to connected node’s list.
      iii. Not to go on verifying and comparing the next node.

JSP of Non-SFN algorithm is as follows. See figure 23.
Non SFN Algorithm

Stop_flag=0

* Until Stop_flag=1

Within coverage area?

Yes

Continue

No

Set Stop_flag=1

* Until Stop_flag=1

Until no new connections are added

* For each node

New Connection?

Yes

Continue

No

Set Stop_flag=1

For each node

Figure 23: JSP of Non-SFN algorithm
4.2 SFN-A algorithm

In figure 24, a network can be considered with 9 nodes, N1 to N8 including an access point and where AP and N8 can be assumed as being the source and destination respectively. It can be assumed that this network will allow SFN-2 which indicates two nearby nodes will form the SFN. N1 and N2 are connected nodes in this case. AP is able to reach N1 and N2 since they are within the coverage area of AP. N1 is able to reach N3 and N2 is able to reach N4 through multi-hopping. Here N5 to N8 are in a state of outage. Then N3 and N4 will form an SFN and will be able to reach N5, N5 and N4 will form an SFN to reach N6, N6 and N5 will form an SFN to reach N7 and finally, N6 and N7 will form an SFN to reach N8. Here it can be seen that N6, N7 and N8 are not too far from N5 and N5 can easily reach N8 through multi-hopping. Since this algorithm does not allow multi-hopping after SFN, SFN-2 has to be applied. Thus, some wastage of energy is associated with this algorithm.

4.2.1 Pseudo code of SFN-A algorithm

1. Try direct connection of nodes with access point (one hop)
2. Try multi-hopping, over and over again
   Until no new connections are added
3. Try SFN size 2, 3... Max SFN size, over and over again
   Stop when no new node is added
JSP of SFN-A algorithm is as follows. See figure 25.

![SFN-A Algorithm Diagram]

**Figure 25: JSP of SFN-A algorithm**
4.3 SFN-B algorithm

In figure 26, a network can be considered with 9 nodes, N1 to N8 including an access point and where AP and N8 can be assumed as being the source and destination respectively. It can be assumed that this network will allow SFN-2 which indicates two nearby nodes will form the SFN. N1 and N2 are the connected nodes in this case. AP is able to reach N1 and N2 since they are within the coverage area of AP. N1 is able to reach N3 and N2 is able to reach N4 through multi-hopping. Here N5 to N8 are in a state of outage. Then N3 and N4 will form an SFN and may reach to N7. N7 can easily reach N5, N6 and N8 through multi-hopping. Thus, this algorithm can save energy since some nodes can be reduced and multi-hopping is allowed to be applied even after the SFN.
4.3.1 Pseudo code of SFN-B algorithm

1. Try direct connection of nodes with access point (one hop)
2. Second hop:
   For each node:
   Try multihopping, if not possible
   Try SFN size 2, 3... Max SFN size
3. Third hop
   For each node:
   Try multihopping, if not possible
   Try SFN size 2, 3... Max SFN size
4. Fourth hop
   Same as previous hop
   Etc.
   Stop when no new connections are added

JSP of SFN-B algorithm is as follows. See figure 27.
Figure 27: JSP of SFN-B algorithm
4.4 SFN-C algorithm

In figure 28, a network can be considered with 9 nodes, N1 to N8 including an access point and where AP and N8 can be assumed as being the source and destination respectively. It can be assumed that this network will allow a flexible SFN size which indicates that any number of nearby nodes will form the SFN. Here N1 and N2 are the connected nodes. AP is able to reach N1 and N2 since they are within the coverage area of AP. N1 is able to reach N3 and N2 is able to reach N4 through multi-hopping. Here N5 to N8 are in a state of outage. Then N3, N4 and N5 will form SFN-3 and may reach N6. N6 can easily reach N7 through multi-hopping. Finally, N6 and N7 can form the SFN-2 to reach N8.
4.4.1 Pseudo code of SFN-C algorithm

1. Try direct connection of nodes with access point (one hop)
2. Second hop:
   - For each node:
     - Try multihopping, if not possible
     - Try Max SFN size...
     - SFN size 1, 2

3. Third hop:
   - For each node:
     - Try multihopping, if not possible
     - Try Max SFN size...
     - SFN size 1, 2

4. Fourth hop:
   - Same as previous hop

Etc.

JSP of SFN-C algorithm is as follows. See figure 29.
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Figure 29: JSP of SFN-C algorithm
4.5 SFN-D algorithm

In figure 30, a network can be considered with 9 nodes, N1 to N8 including an access point and where AP and N8 can be assumed as being the source and destination respectively. It can be assumed that this network will allow SFN-2 which indicates that two nearby nodes will form the SFN. Here N1 and N2 are the connected nodes. AP is able to reach N1 and N2 since they are within the coverage area of AP. N1 is able to reach N3 and N2 is able to reach N4 through multi-hopping. N3 is able to reach N5 and N5 is able to reach N6 through multi-hopping. N5 and N6 will form the SFN-2 to reach N7. Finally, N7 can reach N8 through multi-hopping.
4.5.1 **Pseudo code of SFN-D algorithm**

1. Try direct connection of nodes with access point (one hop)
2. Try multihopping, over and over again
   Until no new connections are added
3. Try SFN size 2
   If new connection: Go to step2
4. Try SFN size 3
   If new connection: Go to step2
5. Same as previous
   Etc.
   Stop when Max SFN size is reached

JSP of SFN-D algorithm is as follows. See figure 31.
SFN-D Algorithm

Stop_flag=0

Until Stop_flag=1

For each node

SFN size=1

Stop_flag=0

Until no new connections are added

Within coverage area?

Continue Set Stop_flag=1

SFN size=1

Continue

Set Stop_flag=1

For each node

New connection?

SFNsize=SFNsize+1

Add new node?

Continue

Break

Figure 31: JSP of SFN-D algorithm
4.6 Comparison of five algorithms

The goal of this non-SFN algorithm is not to use any SFN formation and to attempt to reach the nodes only by means of multi-hopping. This algorithm is concerned with energy utilization but the reachability was not considered. As a result the reachability is very low and the outage probability is very high. This algorithm is based on two steps in which the connected nodes of the access point are determined at the first step and multi-hopping is employed to increase the coverage area at the final step.

The aim of this SFN-A algorithm is only to reduce the outage probability and did not consider the energy utilization. This means that it will only increase the coverage area of the access point and will reach the nodes which are in a state of outage even after multi-hopping. This algorithm is divided into three steps in which the connected nodes of the access point are determined at the first step. Thus multi-hopping is employed to increase the coverage area and the SFN is deployed at the final stage to reduce the outage probability. In this case there is no overlap of steps which indicates that multi-hopping will not be used after SFN even if it is required. It can be stated that if there is a higher number of participating nodes to form the SFN, then this will provide a better gain but with an increased wastage of energy.

The remaining three algorithms will allow an overlap of steps and it is possible to employ multi-hopping even after the SFN formation and this may reduce the energy utilization of the entire network. The aim of these algorithms is to firstly reduce the outage probability and then to reduce the number of hops. Thus, these algorithms will reduce the outage probability using lower energy utilization. These algorithms can be said to be the modification of the previous two algorithms because they have considered the energy consumption. These algorithms will also increase the coverage area of the access point and will reach the nodes which are in a state of outage even after multi-hopping.
Unlike the previous two algorithms, the SFN-B algorithm is divided into hops rather than steps. At the first hop the access point connected nodes are determined. From the 2nd hop to the final hop multi-hopping and SFN formation will run in parallel. The iteration will cease when no new node is discovered. At first, multi-hopping will be employed and then SFN size2 to Max SFN size will be utilized in the 2nd hop when multi-hopping fails to discover a new connection. All the other hops will follow the same iteration until no new nodes are discovered.

SFN-C algorithm is very similar to the SFN-B algorithm with one difference. At the 2nd hop multi-hopping will be employed at first and then Max SFN size to SFN size2 will be utilized if the multi-hopping fails to find a new connection and all the other hops will follow the same iteration until no new nodes are discovered.

These two algorithms, SFN-B and SFN-C have, by some means, given the same priority to the SFN formation and multi-hopping although it is still the case that multi-hopping will be employed as the first option. In any hop, multi-hopping attempts to connect nearby nodes and the SFN attempts to connect far distant nodes. Thus, multi-hopping will not be applied to connect to those particular nodes. It may sometimes be the case that it could be sufficient to use multi-hopping to connect a far distant node after a number of hops but this will not occur as the SFN will have already reached there. These two algorithms may be very effective in uni-casting but not so much in a broadcasting scenario from an energy consumption point of view.
Unlike the two previous algorithms, SFN-B and SFN-C, the SFN-D algorithm will be based on steps rather than hops. This algorithm is divided into several steps and the nodes connected to the access point are determined at the first step. Then multi-hopping is employed to increase the coverage area and SFN is deployed to reduce the outage probability. This algorithm has given more priority to multi-hopping in comparison to the SFN formation. In this case multi-hopping will be employed at first and the SFN formation will not be employed until and unless it is required to reach distant nodes. Unlike the previous two algorithms, this SFN-B algorithm allows multi-hopping in order to reach distant node even though it is possible for the SFN formation to reach that node. SFN will be employed when multi-hopping fails to reach any node and then multi-hopping will then be employed further in order to continue. This overlapping of steps will continue until Max SFN size fails to detect any nodes.
5 Results

The experiments were based on three factors, reachability, energy consumption and network stability. Reachability means the number of nodes that can be reached within a network and it can be said as being the opposite of a state of outage. Suppose that there are 100 nodes of which 90 can be reached then, the reachability is 90% and the state of outage is 10%. The energy consumption indicates the utilization of energy and the aim of the algorithms developed in this case was to reduce energy utilization. Network stability involves the time that the network can continue after one or more nodes have die. It is known that if any important node dies in multi-hopping then the network may collapse. However, the algorithms developed here have the ability to choose different routes or form an SFN if one or more nodes die. As a result the network remains stable.

The experiments have been based on three steps. As shown previously, four new SFN algorithms were developed namely SFN-A, SFN-B, SFN-C and SFN-D. At the first step all the five algorithms (including a non-SFN algorithm) were measured and compared based on their reachability and energy consumption. The best SFN algorithm would then be chosen. At the second step the best SFN algorithm and a non-SFN algorithm were then compared based on the same reachability in order to calculate the diversity gain and energy reduction. At the final step a specific scenario was taken in order to show and explain the efficiency of the best SFN algorithm in terms of network stability.

These experiments were based on three variables, transmission power, and topology size and node density. The transmission power ranges from -20 dBm to -2 dBm with a difference of -2 dBm. The topology size varied from 60*60 to 300*300 and the node density was either 0.01 or 0.02 nodes/m². The ideal transmission power was assumed to be -10.3 dBm when the topology size was 100*100m² for 100 nodes and the node density was 0.01 node/m². See figure 32.
All five algorithms non-SFN, SFN-A, SFN-B, SFN-C and SFN-D were checked and verified based on their reachability. The transmission power varied from -20 dBm to -2 dBm along the X-axis with reachability from 0% to 100% along the Y-axis.

It can be seen that all five algorithms are more or less equal at -20 and -2dBm. This indicates that if the transmitter power is reduced to less than -20 dBm reachability will be 0% for all the algorithms and if the Tx power is increased to above -2 dBm, the reachability of all the algorithms will be 100%. Thus, these five algorithms behaved in a satisfactory manner within this Tx range.

Figure 32: Node reachability of five algorithms as function of transmission power
Based on the definition that the best algorithm will reach the highest reachability for the lowest Tx power, three algorithms SFN-A, SFN-B and SFN-D have achieved a 97% reachability in -6 dBm whereas the non-SFN required -2 dBm and SFN-C required more than -2dBm to achieve an equal amount of reachability. Algorithms SFN-A, SFN-B and SFN-D are more or less equal from a reachability point of view. From figure 32, it can be seen that at a certain Tx power (-10dBm) algorithm SFN-A achieved a reachability of 74.92%, SFN-B 73.88% and SFN-D 73.44%. See figure 33.

The requirement now is to determine the best of these 3 algorithms which has been based on the energy consumption where the X-axis represents the Tx power in dBm and the Y-axis represents the energy consumption in Joules. All the three algorithms appear to be more or less equal at lower and higher Tx power (below -20 and above -2dBm respectively) but vary greatly within this range. SFN-D always consumes less energy than the SFN-A and SFN-B. For example, at a specific Tx power (-10 dBm) SFN-A requires 0.0097 Joules, SFN-B requires 0.0046 Joules and SFN-D requires 0.0040 Joules and thus the, SFN-D can be said to be the best of these five algorithms from reachability and energy consumption viewpoint.
Figure 34: Diversity gain of SFN-D algorithm

Figure 34 shows the diversity gain achieved by the SFN-D algorithm. It is a comparison of the SFN-D and a non-SFN algorithm based on reachability where the X-axis shows the Tx power in dBm and the Y-axis shows the reachability. It can be seen in this case that at lower Tx power (below -20dBm) and higher Tx power (above 0dBm) both the algorithms have the same reachability (0% and 100% respectively) and both algorithms behave in a satisfactory manner within this range. In this case in order to achieve a 97% reachability the SFN-D algorithm requires -6dBm and the non-SFN algorithm requires -2.84dBm thus the diversity gain is 3.16 dB. The above graph shows that the diversity gain achieved involves a minimum of 2.26 dB and a maximum 3.43 dB. On the other hand, it can be seen that at a certain Tx power (such as -12dBm) the SFN-D algorithm can achieve 57% reachability whereas the non-SFN can only achieve 27% reachability. Thus it is possible to achieve a reachability gain of 30 percentage points.
Figure 35 shows the energy consumption gain achieved by the SFN-D algorithm. It is a comparison of the SFN-D and the non-SFN algorithm based on the energy consumption where the X-axis shows the reachability (%) and the Y-axis shows the energy consumption in nJ. In this case, it can be seen that in order to achieve a 97% reachability the SFN-D algorithm requires 60nJ and the non-SFN algorithm needs 87nJ; thus the energy consumption gain is 31%. The above graph shows that a maximum 37.33% energy consumption gain can be achieved. On the other hand, it can be seen that at certain energy consumption (such as 32nJ) the SFN-D algorithm can achieve 73% reachability whereas the non-SFN can only achieve 48%. Thus, a reachability gain of 25 percentage points can be achieved. See figure 36.
Another variable topology size is now taken in order to determine the differences in diversity gain. From figure 36, it can be seen that the diversity gain is increasing as the topology sizes increase. At topology size 60, the diversity gain is 1.5 and becomes 3 dB at topology size 300. It is also expected that the diversity gain will continue to increase for higher topology sizes. As the network size increases so does the number of nodes however, this also increases the probability that the nodes will be sited at a distance. As a result the non-SFN algorithm requires more Tx power in order to achieve a particular amount of reachability. Thus, the SFN-D algorithm has a better diversity gain for larger network sizes.
From figure 37, it can be seen that the energy consumption gain also increases with an increase in topology size. At the topology size 60, the energy consumption gain is 10% and becomes 22.32% at a topology size of 300. It is also expected that the diversity gain will continue to increase for higher topology sizes as if the network size increases so does the number of nodes but this also increases the chances for the nodes to be sited at a greater . As a result the non-SFN algorithm requires more energy in order to achieve a particular amount of reachability. Thus, the SFN-D algorithm has a better energy consumption gain for larger network sizes.
In this case an attempt will be made to determine the efficiency of SFN-D algorithm based on the network stability and as analysis of a specific case will be used to prove the stability of that algorithm. It is known that some of the nodes are very important in multi-hopping for the case in which two or more are connected to that node. This node consumes more energy during each time of transmission and it may die more quickly than some other nodes. If this node dies, then the access node may loose connection with the nodes which were connected to that important node. As a result the reachability is greatly reduced and the network becomes unstable. However, the SFN-D algorithm is able to make new connections if an important node dies. This algorithm either chooses a different router through multi-hopping or forms an SFN in order to reach other nodes. Thus there is little effect on the reachability of the access node even if one or more important node dies and the network remains stable as before. This algorithm has solved one of the major problems of multi-hopping basically for those nodes which are random and battery driven.

As stated previously a particular case will be considered and some of the required factors must be predefined. The network size taken here is 100*100m$^2$, and the node density is $10^{-2}$/m$^2$, the Tx power is -10.3dBm, the propagation constant ($\alpha$) is assumed to be 4 and the range is 10m. The access point is sited in the middle and has a range of 20m and all other nodes are positioned randomly. Blue lines represent the direct connections between the access point and the nodes, the red lines represent the multi-hopping and the green line represents the SFN formation.
Transmitter macrodiversity in WSAN and MANET - Energy consumption algorithms for wireless multihop network

Arif Mahmud

5 Results

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Figure 38: Example of non-SFN algorithm

Figure 39: Example of SFN-D algorithm
In figures 38 and 39, the actual network reachability can be seen for the non-SFN and the SFN-D algorithms respectively and in which it is clearly apparent that the SFN-D algorithm achieves better reachability than the non-SFN algorithm.

The non-SFN achieves 60% whereas the SFN-D achieves 78% reachability. Thus, the SFN-D has increased the reachability by 18 percentage points. In figures 38 and 39, node 64 and 89 can be said to be the important nodes because a large number of nodes are dependent on them for data reception. In figure 40, when nodes 64 and 89 die, the access point looses its connection with those nodes. But in figure 41, it can be seen that SFNs are formed to transfer data when nodes 64 and 89 die. As a result the network does not loose too much reachability and the network remains stable with rest of the nodes. See figure 40 and 41.

Figure 40: Some nodes are dead in non-SFN algorithm
In figure 41, another two important nodes are going to be killed in SFN-D algorithm namely nodes 12 and 62 and where many nodes are dependent on them. However, it can be seen that two simple multi-hopping are formed for these two nodes and the access point can easily access those nodes even without SFN formation. See figure 42.
Figure 42: Some more nodes are dead in SFN-D algorithm
6 Discussion

In order to achieve the maximum reachability, four new SFN based algorithms (SFN-A, SFN-B, SFN-C and SFN-D) were formed to work over multi-hopping. Three of the algorithms SFN-A, SFN-B and SFN-D achieve more or less the same amount of reachability. These three algorithms were able to reach more than 90% of reachability at only Tx power -8dBm whereas the non-SFN requires -4dBm and SFN-C requires -2dBm. These three SFN based algorithm achieved a maximum 29 percentage points more reachability than the non-SFN algorithm and reached maximum 99.2% reachability at -2dBm. In order to determine the best SFN algorithm, SFN-A, SFN-B and SFN-D were compared based on their energy consumption in Joules. The results showed that the SFN-D algorithm always consumes less energy than any of these three algorithms. The SFN-D algorithm consumes a maximum of 58.76% less energy than the SFN-A and a maximum of 14.28% less energy than the SFN-B. Thus, the SFN-D was selected as the best SFN algorithm.

Three of the most important factors reachability, energy consumption and network stability were merged in this thesis work. It was also assumed that no fading effect occurred in this network. The SFN-D algorithm was able to generate some good results for all three factors and thus may be able to provide a contribution to the research and development of wireless multi-hop networks. However, additional work is required on the same algorithm in which the fading factor could be taken into account. The SNR value was fixed and taken as 4 dB as a simulation parameter. However, it is possible for this SNR value to vary in practical cases.

The ultimate target was to achieve a diversity gain and an energy consumption gain while retaining a high reachability. The SFN-D algorithm achieved a maximum 3.43 dB diversity gain together with a maximum 37.33% energy consumption gain. Basically the target area was a wireless multi-hop network where the nodes are random and are battery driven and a reduction of this high amount of energy can play an important role in extending the lifespan of the network.
The SFN-D algorithm achieved a diversity gain of 1.5dB and an energy consumption gain of 10.44% for 60\(^*\)60m\(^2\) and a diversity gain of 3dB and an energy consumption gain of 22.32% for 300\(^*\)300m\(^2\). It is expected that the algorithm will be able to produce far better results from a diversity gain and energy consumption gain viewpoint for larger networks and this was the aimed for an expected result. A broadcasting scenario was applied in this case and results were expected to be utilized in generic cases. In fact all the utilized factors are very close to real world scenarios and thus little difference in results should be expected when employed in a real situation.

It is not possible for the access node to reach all the nodes present in the network in the majority of cases and the Tx power has to be massively increased in order to achieve better reachability. This is the reason for employing multi-hopping as it requires little extra energy to increase the reachability. However, it is known that even after multihopping sufficient reachability may not be achieved and a significant number of nodes are sited in a state of outage. Thus transmitter macrodiversity is employed over multi-hopping in order to reduce the number of outage nodes and to increase the reachability.

The application area involved included wireless multi-hop network, broadcasting, reachability and energy consumption. The SFN-D algorithm is able to generate a satisfactory amount of reachability and also maintain a stable network but extra work is required in relation to energy consumption. On the other hand, multi-casting is much more energy efficient in comparison to broadcasting and it is unknown as to how effective this would be in relation to the SFN-D algorithm.

The assertion in this case is that transmitter macrodiversity should not be exploited unless and until the requirement is to increase the reachability and to maintain a more stable network. Greater priority has been given to multi-hopping over SFN formation in the SFN-D algorithm because the SFN formation requires more energy than multi-hopping. SFN formation is not very energy efficient and it would be wasteful of energy if the SFN is employed unnecessarily anywhere in the network.
6.1 Routing protocol
A protocol should be deployed which will work with transmitter macrodiversity in a multi-hop network. Some key factors must be determined such as syntax, semantics and time synchronization. Syntax determines the formation of data and semantics declares how that formation will be interpreted. Syntax will define the size of a packet together with the arrangement of data which may include sender address, receiver addresses, information data etc. Semantics will explain at what rate and how the optimal route will be chosen in order to reach the destination. Time synchronization will declare when to transmit, receive and go for sleeping mode.

6.2 Return channel algorithm
A back channel algorithm is required to be employed to work with transmitter macrodiversity to support the network event and make it reliable. When SFN is formed to forward data to a node, it becomes difficult for that node to send a reply acknowledgement even if any event is captured by that node. Back channel is also known as return channel or reverse channel and is utilized in a cellular network. It works basically in the opposite direction of forwarding and maintains a low speed and low data rate. It is not so important for a return channel algorithm to be present in the SFN-D algorithm since the work is based on a broadcasting scenario. The number of transmissions can be fixed to avoid back channel. For example, the same message can be sent at most twice if there is no acknowledgement.

6.3 Scheduling
Maintaining a time scheduling or adding a time slot on each hop could be a new idea to implement. If a time slot is added, the signal strength may increase and the practical result can be even better than the theoretical result. In theory a 2-SFN will be formed to reach a distant node but, practically, more SFNs can be created to reach other nodes. In theory the signal strength based on one 2-SFN may be calculated but, practically, other signal strengths of other SFNs will also be added which may produce some better reachability.
6.4 Multicasting algorithm

All the algorithms are based on a broadcasting scenario because the application that was in mind supported a broadcasting method. On the other hand, the fact is that multi-casting is better than broadcasting from an energy consumption point of view. From the application viewpoint, all the nodes are important but some different application scenarios can be thought about in which some of the nodes will be useful. It then becomes better to use multi-casting rather than broadcasting and a different multi-casting based algorithm is required to be created to be implemented with transmitter macrodiversity over multi-hopping.

6.5 Network stability

The SFN-D algorithm is able to choose different routes if any node dies. When a node collapses, either a different node will take the responsibility or an SFN will be formed to transfer data. However, it would be reasonable to determine the amount of energy spent by each node at any specific time. If any node starts losing too much energy due to multi-hopping, a different node may be chosen as a route and network stability can then be maintained. Here all the algorithms are based on a broadcasting scenario but network stability can be maintained with a uni-casting scenario.
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