Propagation Analysis in Large-Scale Cooperative Multi-hop Ad Hoc Networks

By

Hemant Kumar

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Supervisor

Dr. Syed Ali Hassan

Department of Electrical Engineering

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Approval

It is certified that the contents and form of the thesis entitled "**Propagation Analysis in Large-Scale Cooperative Multi-hop Ad Hoc Networks** " submitted by **Hemant Kumar** have been found satisfactory for the requirement of the degree.

Advisor: **Dr. Syed Ali Hassan**

Signature: ________________

Date: ________________

Committee Member 1: **Dr. Sajid Saleem**

Signature: ____________________

Date: ____________________

Committee Member 2: **Dr. Fahd Ahmed Khan**

Signature: ____________________

Date: ____________________

Committee Member 3: **Dr. Rizwan Ahmad**

Signature: ____________________

Date: ____________________

Abstract

This dissertation involves the study of propagation analysis of a cooperative multi-hop opportunistic large array (OLA) network, where nodes are deployed in a strip-shaped manner. The network comprises the source and destination nodes separated by a significant distance. In addition, the network involves the random deployment of number of relay nodes which help in the transmission of source message to be received by the destination via multi-hop cooperation strategy. Initially, the performance of the overall network is gauged by the transmission of a single packet in basic OLA network. Moreover, to obtain energy efficiency of the OLA network, OLA threshold (OLA-T) protocol is used while maintaining quality of service (QOS). Furthermore, the propagation analysis of the multiple packets in multi-hop OLA network is performed in which interference plays a key role. This dissertation summarizes and compares the performance of various network topologies in terms of success probability and energy-efficiency using basic OLA and OLA-T protocol. The performance metrics used to evaluate the performance of multiple packets in multi-hop OLA network involves the outage probability and average number of hops to reach the destination at various network parameters.

Dedication

I dedicate this thesis to my grandfather **Mr. Nandlal Narsani**, father **Nawal Kishore Narsani** and my mother **Kamni Bai** for their endless prayers, love and encouragement.

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics which has been acknowledged.

Author Name: **Hemant Kumar**

Signature: ________________

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Chapter 1

Introduction

Wireless Sensor Network (WSN) is a wireless network consisting of spatially distributed autonomous devices using sensors to monitor physical or environmental conditions. WSN have gained interest in the context of Internet-of-Things (IoT) in 5G networks [1–5]. These ad hoc networks generally involve Machine-to-Machine (M2M) communication without the involvement of human beings and operate without any existing infrastructure and are de centralized [6–8].

1.1 Wireless Sensor Networks

1.1.1 Applications

WSN devices or sensors are tiny in size and therefore have small batteries into it, therefore, their coverage range is between 1 meter to 100s of meters depends on the the type of device and its corresponding application. For example, in wireless Body Area Network (BAN), sensor's coverage range is limited to $1-2$ meters, whereas, there is a $10s$ of meters of signal's range of wireless Personal Area Network (PAN). The typical examples of wireless BAN and PAN are Fitbit and Bluetooth devices respectively. The wireless PAN is a short range, low power consumption and high data rates network. The popular wireless PAN systems are based on infrared, Bluetooth, ultra-wideband and zigbee etc. The applications of wireless PAN are TV-remote, wireless headphones, wireless peripheral devices etc. Wireless BAN network connects everything you carry on you and with you, that is on your body. The potential applications of wireless BAN are fitness monitoring and wearable audio etc. The applications of WSN networks are shown in the Fig. 1.1.

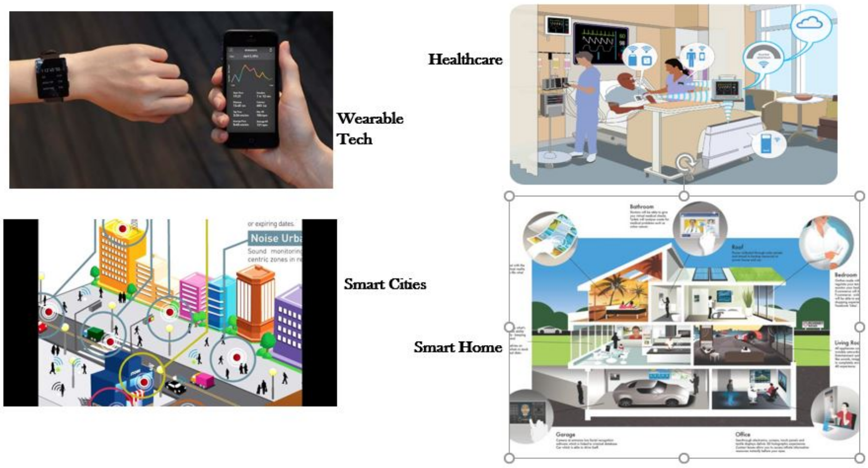


Figure 1.1: Applications of Wireless Sensor Networks.

The wireless communication systems and networks may be designed according to these few requirements, (i) data rate (ii) coverage area (iii) capacity in terms of number of devices or users (iv) mobility (v) power consumption (vi) use of spectrum (vii) direction of transmission and (viii) quality-o-service (QOS) etc.

1.1.2 Problem in WSN Networks

The WSN sensors are small devices, and thus have small coverage range, therefore they are unable to transmit their information to far-off destination sensor nodes, This is a huge problem in WSN networks and this problem is called *reach-back problem* [9]. There are so many applications of WSN networks such as bridge-alarm notification, in which sensor nodes are deployed in a row. When a desired sensor node wants to communicate with its desired far-off receiver node, but due to the large distance and huge path loss they are unable to communicate directly. In WSN, the message is usually transmitted in all direction among the other sensor nodes using medium access control (MAC) protocol, such as ad hoc on-demand distance vector (AODV) protocol, which causes overhead, low throughput and high latency in the network [10]. Moreover, wireless networks are under the influence wireless channel/medium in which multi-path fading plays a vital role [11–13], which creates difficulty in reliable communication.

The reliability in such large scale ad hoc networks can be achieved by many ways. One way is to increase transmit power. But due to small battery in sensor node, it is not possible that a node can send its information to its desired destination node which may be few kilometers away from its desired source node. Another way is to direct the position of sensor's antenna towards its desired receiver node. But since in some applications, sensors are deployed randomly and in other applications sensors change their positions such as in vehicular-to-vehicular communications. Due to these reasons it is not feasible to direct the antenna towards its desired receiver node to increase reliability.

Another way to achieve a reliable and the practical communication between these sensor nodes is cooperative communications which is also known as cooperative transmission (CT), which says that, all the sensor nodes between the source node and the destination node starts passing their information and work as relay nodes [10].

1.2 Cooperative Transmissions and its Protocols

Cooperative Communication (CT) is a prominent way of transmission in WSN, IoT, M2M and D2D networks. It is used for reliable communication between sensor devices. When two sensors are far away that their direct communication is not possible due to large distance and path loss, then all other nodes placed between these two nodes will act as relay nodes. These relay nodes take the source's message and pass it to other relay node one by one until it is received by its desired receiver sensor [14]. There is an immense improvement in the WSN's performance using this vastly used physical layer technology. The improvement in the performance of such wireless multi-hop ad hoc networks is in success rate and outage probability, latency, reliability and in throughput (bit error rates). It also provides a significant gain in terms of capacity and robustness [15], [16]. Such large-scale multi-hop cooperative ad hoc networks have gained a lot of importance in the areas of robotics, 5G cellular networks, computer networking, and mobile computing etc.

It can be seen in the Fig. 1.2 that a blue circle is a source node and wants to send its message packet signal to the red node which is the destination node. But there is a large distance between them and have huge path loss because of distance and wireless channel impairments. Therefore, it is not possible for a message of the source node to directly reach at the destination node. Due to these reasons, a node between the source and destination nodes shown with the green circle act as relay node, which receives source's message and pass this message to the destination node. As one can see that a single message took two hops to travel from the source node to the destination node. A message can take more hops in cooperative transmission if the source node and destination node are separated by larger distance.

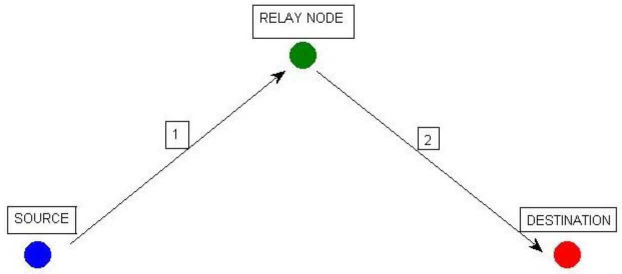


Figure 1.2: The concept of cooperative communication.

However, there is one problem in cooperative transmission, and that is any link between the source node and the destination node can be broken due to wireless channel impairments such as noise, multi-path fading and large distance between two relay nodes etc. This is because, only one relay node is allowed to receive source's message at one time and pass that message information to the other relay node in each hop. Due to this reason, a source node have to retransmit its message again and again until the message is received by the receiver node successfully.

To resolve the problem occurs due to cooperative transmission, a protocol of cooperative transmission is now vitally used in WSN's applications for reliable communication. The protocol is called Opportunistic Large Array (OLA). In Opportunistic Large Array, the source's message travels from one layer of radio nodes to another layer [17]. By using OLA, the complexity of the system increases as the avalenche of the incoming signals produces a stronger signal at the destination but at the same time, the system vulnerability becomes much lower. The OLA can easily be implemented on any network or system and a huge amount of work has been done in the past 15 years on OLA networks by considering different network topologies [18–20]. Nowadays, WSN and IoT networks require reliability there are myriad of applications which requires network scalability, and the OLA is the one which fulfills these two requirements.

For reliable communication in the large-scale cooperative multi-hop adhoc networks, OLA protocol is widely used. There are many versions of OLA and each version performs better in terms of one or two network parameters. In this thesis work, we are using two OLA protocols, Basic OLA and OLA-Threshold (OLA-T), which are briefly discussed as under.

1.2.1 Basic OLA

In a basic Opportunistic Large Array (OLA) protocol [21], the source node broadcasts the signal in the network. The sensor nodes that decode the source signal become part of first OLA or level or hop. The sensor nodes of the first OLA/level retransmit the source signal immediately after receiving the message signal without coordinating or exchanging any overhead with the other sensor nodes or devices. The sensor nodes that decode the message/information/packet signal sent by the nodes of first OLA/level declare themselves as the members of the second OLA level (or hop). This procedure continues until the message receives at the destination or is received by corresponding receiver node, where different combining techniques in order to achieve diversity, such as maximum combining ratio (MRC), equal gain combining ratio (ERC), etc., can be applied to get spatial diversity. Because of this diversity gain at the destination, the message signal can reach far distances without draining the entire source power.

The basic OLA also called OLA protocol unlike cooperative transmission says that not only one sensor node between the source node and the destination node receives the message, but all the nodes of the network receive the message of source. But only those nodes can be the relay nodes, who is able to decode the message accurately. In basic OLA, when a source node broadcasts the message signal with some specific transmit power, the nodes in the vicinity of the source node try to decode it. OLA protocol uses decode-and-forward cooperative communication technique in decoding the message. The nodes that receive the message signal compares their specific received power with a value of decoding threshold. Those nodes which receives message signal and has received power greater than or equal to the value of decoding threshold are called decode-and-forward (DF) nodes of this level. Now these all DF nodes will immediately broadcasts the message. In this case a source can also receive the message, but it will not retransmit it again, this is one of the algorithms of OLA, which says that any DF node or a node that transmits a message earlier at any time can also receives the message in these large-scale cooperative multi-hop ad-hoc networks but they will not retransmit it again to avoid the transmission loops. Now after broadcasting the message signal in the forward direction, all nodes that receive the message signal will receive multiple copies of the same message. At these nodes, diversity combining technique is used, which in our case is Maximum Ratio Combining (MRC) technique. In MRC, we are using post-detection diversity combining. That is the power received from multiple DF nodes of the same message signal at any node in the next hop first adds and then compares this accumulated received power with the decoding threshold. In this manner, diversity gain is achieved at each level in the next hop. Because of this spatial diversity, each next level of the network will have more nodes than its current level. Since each level will have more and more node in each next level, therefore, there is a less probability of all links of these nodes to get broken. Hence the reliability in such large-scale cooperative multi-hop ad-hoc networks is increased. For the same reason, these large-scale cooperative multi-hop ad-hoc networks can be scalable. Since more nodes in each level are permitted to take participate in the cooperation, a message can reach in a fast manner to the destination node compared to the basic cooperative transmission technique in which only one relay node can receive and pass the message signal in the next time slot.

In the transmission technique of OLA, nodes of each level receives the message signal information from the prior level nodes and transmit that message immediately in the next time slot without knowing their physical location and without any coordinating or sharing information of their current locations. The message travel through hop to hop until it is received by its corresponding destination node or is broad casted to the entire network in large-scale multi-hop cooperative network.

1.2.2 OLA Threshold (OLA-T)

The network can be made energy efficient when a few nodes of any level participate in forward transmission instead of all Decode-and-forward (DF) nodes of that level. However, it should be noticed that due to limited participation, the diversity gain at a receiving node becomes small, which affects the quality of service (QoS). It is network's users requirement what type of service he wants. If a user's requirement is a reliable network, then more DF nodes of a level are allowed to retransmit the message packet signal. If a user's focus is on energy and not on reliability in the network, then few DF nodes in each level are required to retransmit the message information signal.

In this manner, the nodes of any level are sub-divided into two subsets, Active nodes and Idle nodes. Idle nodes are those nodes which are not allowed to retransmit the message in any level because they are at a greater distance from the nodes of the next level and therefore there contribution in making the next level nodes is minimum because of the huge path loss. Active nodes, on the other hand are the nodes of a level in OLA-T networks, which are near to the next level nodes and therefore their contribution in making the next level nodes is maximum because of the smaller distance between them and the nodes of the next level, thus they are allowed to retransmit the message. Both active and idle nodes in a level are DF nodes of that level.

1.3 Network Topologies used in OLA Networks

The Opportunistic Large Array (OLA) protocol can be used in all type of network topologies in large-scale cooperative multi-hop ad-hoc networks. The few are briefly described as following.

1.3.1 One-dimensional Strip-shaped Networks

In a one-dimensional network, sensor nodes are placed in a row in adjacent manner. Each level contains equal predefined number of sensor nodes in it. The distance between each sensor nodes in a level and between the levels is constant. Level boundaries are deterministic as well. A source node at the start of this strip-shaped network when broadcasts its packet, then the nodes of first level will receive it and compare their received power with some decoding threshold. When the nodes of the first level received the message with received power greater than or equal to the decoding threshold, then these sensor nodes of the first level are called decode-and forward nodes of $level-1$. Now these decode-and-forward nodes of $level-1$ immediately retransmit the source's message in the next time slot without any coordination with the next level nodes. In this manner, nodes of $level-2$ receive that message with their respective received power and then compares their composite received power with the decoding threshold. Lets say, if there are more than one DF nodes in the $level - 1$, then the chances of $level - 2$ nodes in decoding increases because of the diversity gain. The process of packet transmission continues, until the packet reaches at the particular receiver sensor node or broad casted into the entire network. The popular application of this type of one-dimensional topology is bridge-alarm, where number of sensor nodes are placed on a bridge to notify the fault alarms.

1.3.2 Two-dimensional Strip-shaped Networks

The two-dimensional strip-shaped network defines the deployment of sensor nodes in an area, where these sensor nodes are placed in some length and width. These Length and width defines the area of the network. Furthermore, this two-dimensional network is subdivided in the levels having some length, L and width, W. Each level contains equal predefined number of sensor nodes in it. For example, when $L = 3$ and $W = 2$, then there are total 6 nodes placed in a level, 3 in horizontal axis and 2 in vertical axis. The distance between each sensor node in a level and between the levels is constant. The level boundaries are also predefined and is constant for all the levels. When a source node at the start of this strip-shaped network broadcasts its message information signal with some transmit power, then the nodes of first level will receive it with their respective received powers and then compare their respective received power with some decoding threshold. When any node of the first level received message with the received power greater than or equal to the decoding threshold, then this sensor node is called decode-and forward (DF) node of $level - 1$. In these 2D networks, the possibility of the nodes to decode the message signal accurately is high because there are more nodes in each level and they are placed in two-dimensional in OLA network. Now these decode-and-forward nodes of $level - 1$ immediately retransmit the source's message in the next time slot without any coordination with the next level nodes. In this manner, nodes of $level - 2$ receive that message signal and compares their composite received with the decoding threshold. Lets say, if there are more than one DF nodes in the $level - 1$, then the chances of $level - 2$ nodes in decoding increases because of the diversity gain. This process of packet transmission continues, until the message information signal reaches at the particular receiver sensor node or broad casted into the entire network. The typical example of these type of two-dimensional topologies are in smart-grid stations.

1.3.3 Two-dimensional Random Node Locations Strip-shaped Networks

In this topology, the sensor nodes are uniformly deployed in two dimensional strip-shaped network having some length and width. There is no any-thing deterministic in this type of network topology. The sensors nodes have random node locations in an area of some length and width of the network. There is not any level boundary in such network topology. The distance between all sensor nodes in an area of this network topology is also not deterministic or same. Each level may or may not have the same number of nodes and it totally depends on wireless channel, transmit power, decoding threshold, path loss exponent, node density (number of nodes in unit area) etc.

When a sensor node which is placed at the start of this network transmits the message signal, and all the other deployed nodes in the network receive the message signal. Few will receive with minute received power that is negligible. Those nodes which are near to the source node will receive the message signal with greater received power. The received power at any node depends upon the distance between the nodes, path loss exponent and Rayleigh flat fading. Those nodes that receive the message signal and having received power greater than or equal to the decoding threshold will become the part of $level - 1$ and now these nodes will immediately retransmit the message signal in the forward direction and $level - 2$ is formed with diversity gain achieved. The process continues until the message is reached at the destination node or broad casted by the entire network. The typical example of these type of network topologies are smart-homes, smart-institutions and shopping-malls etc.

1.4 Packets Transmission in OLA Networks

In this thesis work, we examined the performance of various basic OLA networks in the manner of single and multiple packets transmission using different wireless network parameters. First, we chose single packet transmission in OLA network and analyzed its affects on the various networks. Afterwards, we insert multiple packets one by one to examine the performance of the network with the presence of interference in the OLA networks. In this thesis, we worked on two-dimensional random node locations OLA network.

1.4.1 Single Packet Transmission

When a source inserts a packet in random node location deployment in OLA network, the packet travels through multiple levels and ultimately reached at the destination node. In single packet transmission, a source node will not insert a new packet until either the current packet reaches at the destination or is lost in any intermediate level. The two wireless impairments affect the communication of single packet transmission, noise and multi-path fading.

1.4.2 Multiple Packets Transmission

The multiple packets transmission in OLA networks defines that there are more than one packets travel from the source node to the destination node simultaneously. There is a parameter called packet insertion rate, PIR, which defines that a new packet is inserted in a network after waiting few time slots. For instance, when $PIR = 1$, a new packets is inserted in a network after waiting one time slots and when $PIR = 2$, a new packet is inserted after waiting two time slots. There are now three wireless impairments affect in the OLA transmission, noise, multi-path fading and interference.

1.5 Thesis Motivation

The motivation of this thesis is to examine the performance of large-scale cooperative OLA networks where sensor nodes are deployed in a random manner. The performance is calculated in terms of latency, success and outage probability, energy-efficiency and reliability in different wireless communication scenarios. The network's analysis is also carried out in simultaneous packet transmissions in ad-hoc mobile networks to increase the throughput of the network while maintaining the success probability of the entire network.

1.6 Thesis Contribution

The thesis work presents the following main contributions:

- We study the performance of large-scale cooperative OLA networks, where the sensor nodes are deployed in two dimension strip-shaped network having an area of specific length and width. The location of sensor nodes is random in our scenario.

- The performance of networks at first is examined using basic OLA protocols in terms of success rate, latency and reliability. Afterwards the energy efficiency of several networks is also studied using OLA-T protocol. In both of these cases, only single packet transmission in the networks is considered.

- We then focus our attention using multiple packets transmission using basic OLA and have examined the effects of multiple packets on the cooperative networks. The throughput increased when we insert multiple packets while affecting the success rate because the of interference.

1.7 Thesis Organization

The organization of the thesis is presented as follows. Chapter 2 highlights the literature review of the important concepts proposed in this thesis for providing a flow for the readers. In chapter 3, we study the performance analysis of basic OLA networks and examine the performance of OLA-T networks. In Chapter 4, we investigate the affects of interference in multiple flows OLA networks and calculates its performance in terms of various network parameters. Chapter 5 discusses the results found in chapter 3 and 4. Finally, chapter 6 presents the conclusions and proposes the future work in cooperative OLA networks.

Chapter 2

Literature Review

Wireless and ad hoc sensor networks have gained popularity in the past decade owing to a multitude of benefits they offer such as low cost, easy deployment, and energy-efficient operations [22–28]. A basic purpose of deploying a sensor network is to gather information from a specific environment and to use this information to build a smart system. The basic idea behind this information exchange is the use of cooperative communication in wireless sensor networks. In literature different strategies for cooperative transmission have been proposed [29–33]

Cooperative communication is a physical layer approach that provides cooperative gains to the destination with an advantage of signal-to-noise (SNR) ratio of 10 to 20 dB [34–36]. Due to these advantages, the system reliability increases with an extra amount of decrease in transmit powers of the source node as compared to the single node scenario.

In [37], the one dimensional network is considered with two different types of node deployments. For the first case, the nodes are placed equidistant from each other while in the second case, the nodes are co-located with each other. The analytical model here shows the better performance for the co-located scenario. The authors in [38] have studied a strip-shaped linear network with the help of quasi-stationary Markov chain. In [39], the work done in [38] is extended and the effect of composite shadowing has been introduced in the system model.

A two-dimensional (2D) network is considered in [40], in which the authors have extended the work done in [39] and placed two nodes in a single level. The probability of the message to reach the maximum hop distance is determined for the different values of signal-to-noise (SNR) ratio. In [41], a network with random node deployment i.e., the nodes in this network are placed randomly using a Bernoulli distribution, is considered. The network coverage is analyzed by considering a discrete time Markov chain model, with Rayleigh faded channel. The results are compared with a regular node deployment scenario.

In [42], a cooperative multi-hop strip network is studied by considering a fixed boundary between the nodes level. The nodes in each level are assumed constant but the placement of each node is randomized. The coverage probability is determined at the destination node by considering the Weibull distribution for the distance. The authors in [43] have evaluated the timing synchronization errors by considering a multiple input multiple output (MIMO) system, where cooperation among the nodes is employed by implementing decode and forward (DF) protocol.

A linear strip-shaped network is considered in [44], where the nodes deployment is considered with the help of a Poisson point process (PPP). The probability distribution function (pdf) of the received energy at a particular node is derived, which helps in finding the outage of the nodes transmissions. The network performance in the context of success probability of one hop is investigated in the presence of Rayleigh fading channels.

In [45], a two dimensional (2D) network is studied in order to investigate the intra-flow interference which happens due to the movement of multiple packets in the network. The system model is studied using discrete time Markov chain and the results are derived considering various network parameters. However, the results reveal that the intra-flow interference greatly depends on the SNR. Therefore, the network performance can be optimized by using the higher values of SNR and with improved array gain.

In [46], the authors have considered the two 2D networks such that the information sent by the each source node is totally independent to each other. The destination in this case is a single node located at a very far distance. The concept of network coding is implemented here for merging the two sources information into one. This information then travels with the help of cooperative communication to a far away destination. The model is studied using a quasi-stationary Markov chain in the NLOS channel. The network performance is analyzed by using a state distribution at each node in terms of outage probability for varying values of SNR.

In [47], the authors introduced the concept of limiting the node participation for conserving the energy during transmission in a 1D and 2D finite node density networks. However, nodes distribution is deterministic. In [48], the authors analyzed the performance of random node locations with finite node density in a strip-shaped network where nodes are uniformly distributed.

Moreover, the algorithm for conserving energy was also proposed in terms of the fraction energy saved in quantified.

In [49], the authors introduced multiple packets transmission in one dimensional strip-shaped network to analyze the performance of 1D network with the presence of interference. The nodes in each level are considered constant. The distance between the nodes in the level and between the level is also considered constant. The authors calculated the outage probability and hop distance using several network parameters.

In [50], the authors examine the performance of multi-flow large scale opportunistic OLA networks in two dimensional strip-shaped network. The nodes in each level are constant and the distance between the nodes of a level or between the level is also considered constant. The performance of such networks is examined in which multiple packets travel through various levels to the destination. The performance is analyzed in terms of various network parameters with the presence of interference in two dimensional network.

In this thesis, we study the propagation characteristics in an OLA network where the nodes are deployed in such a manner that they follow a uniform distribution over a certain area. The distance between the nodes is also a random process. The number of nodes in each level as well as the boundaries of the levels are kept random. The transmission model is similar to typical OLA, where the transmission of the message signal from a source node to a far-off destination node forms uneven levels or hops in terms of sizes and with random number of DF nodes in each hop. The coverage probability is analyzed for a variety of node densities, powers and decoding threshold values. The study provides an in depth performance analysis of OLA broadcasts in finite density scenarios and transmission characteristics with respect to various network parameters. A study of network longevity is further carried out in a way in which few nodes are deliberately limited to take participate in transmission to conserve significant amount of energy. Afterwards, we insert multiple packets in strip-shaped networks to carry out the performance of networks with the presence of interference.

Chapter 3

Propagation Characteristics of OLA and OLA-T Networks

The chapter considers the propagation characteristics of opportunistic large array networks. First we will elaborate the propagation characteristics of the basic OLA networks with single packet transmission, and then we will examine performance of networks in terms of energy efficiency using OLA-T protocol.

The sensor nodes are deployed in a uniform distribution, where node locations is random. We take strip-shaped network with the area of large length and small width. The sensor nodes are arranged in a manner that their position is random in that particular strip-shaped area. The source node is considered the first node in the left most of the strip-shaped network and the destination node is the node which is farthest away from the source node.

In the basic OLA single packet transmission, a source transmits a single packet in a network and will not transmit the next packet until the current packet either reaches at the destination node or lost in an intermediate hop (or level) in the network. In this chapter, we describe the working of various OLA networks and each network perform differently by varying the network parameters. The performance of each network is precisely analyzed in terms of success and outage rate, latency, reliability and energy efficiency. The network parameters of these large-scale opportunistic OLA networks are path loss exponent, decoding threshold, node density and transmit power etc.

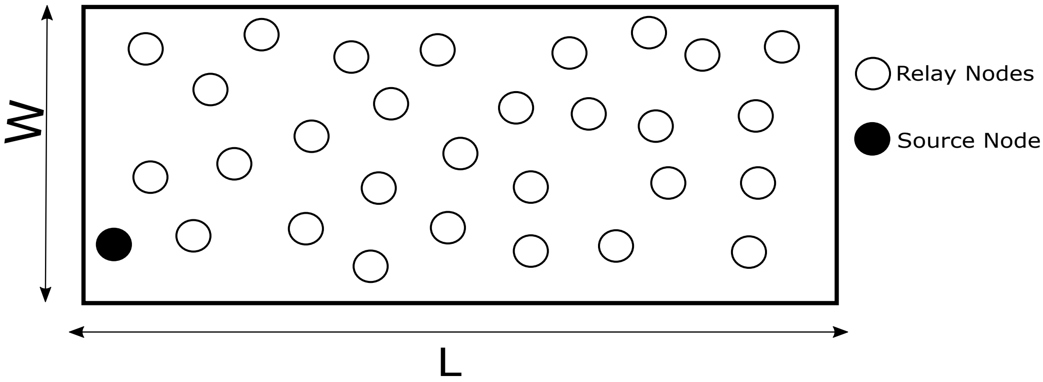


Figure 3.1: Random deployment of nodes in a 2D strip-shaped network.

3.1 Basic OLA

In this section, we describe network arrangement and assumptions used for modeling cooperative multi-hop OLA network. First we will elaborate the propagation model of basic OLA using single packet transmission and then we will analyze the performance of those networks in terms of various network parameters.

3.1.1 System Model

Consider a strip-shaped network shown in the Fig 3.1, where L is the length and W is the width of the strip-shaped network. There are some sensor nodes deployed in this strip-shaped network. The nodes are arranged in uniform distribution and the distance between the nodes is the uniform random variable. The black filled node at the start of the strip-shaped network is considered as a source node and the hollow nodes are the relay nodes. The destination node is one of the nodes at the end of this striped-shaped network which is considered the farthest away from the source node.

The source node broadcasts its message signal information and the message is received by all other relay nodes in the vicinity and each node tries to decode the message. A node can successfully decode the message depending on transmit power, wireless channel impairments, decoding threshold and node density. The nodes that successfully decode the message are called decode-and-forward (DF) nodes and these DF nodes become members of first level (or hop). The DF nodes will broadcast the message received from source to the nodes ahead in the next time slot cooperatively and level-2 is formed. Note that the nodes in level-2 combine signals from the previous level nodes, thereby obtaining a diversity gain. This action of retransmissions continues and subsequent levels are formed until the message signal is disseminated over the entire network or reached at a particular destination node. A node can successfully decode the signal, transmitted by a group of nodes in the previous level, if the accumulated received power is greater than the decoding threshold. The power received at each node of any level is a random variable (RV), and depends upon channel impairments such as path loss and multi-path fading.

It can be seen in the Fig 3.2 that a hop is formed opportunistically during the entire transmission process and there are no fixed boundaries between the nodes of two levels. The levels or hops are denoted by $k-1$, k, $k+1$ and so on. A node of any level can be a member of many levels in different sessions of cooperative transmission because of random boundaries, channel characteristics and geometry. The irregular boundaries of levels shown in the Fig 3.2 and these are the imaginary boundaries and can vary because of random channel characteristics and random locations of node. Nodes of a level can be a part of many levels in various iterations of cooperative communications because of random node deployments. Due to random sensor nodes deployment, there are random level boundaries in each session or iteration. The channel characteristics is also considered random because of random locations of node.

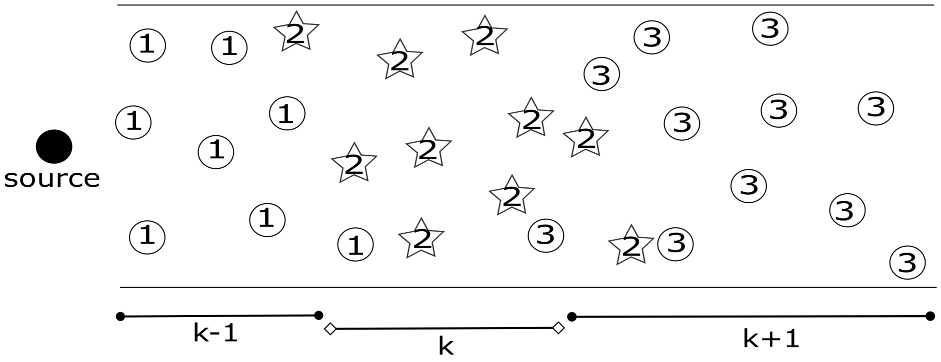


Figure 3.2: The propagation of transmission from source to different nodes in different levels.

Nodes of a level shown in the Fig 3.2 can be part of that level in the next iterations depend on the position of the node. When the nodes are located around the center of a level, the tendency of the nodes to be the member of that level increases. When nodes are present near the irregular imaginary boundary of two levels, its tendency decreases dramatically. The main parameter in controlling such behavior of the nodes is path loss. Nodes located around the center of the level has lower chances to become part of the adjacent level because of the higher path loss as compared to the nodes located near the boundary of a level. The chances of a node that it transmits in level k is different for every other node of the level as shown in the Fig 3.2. For example star-node located in the level $k-1$ is a member of level k but it can be member of level $k-1$ in the next iteration. likewise circle-node located in level k is a member of $k-1$ but it can be member of level k in the next iteration. In a general manner, each level or hop contains a random number of nodes in each session or iteration. Due to this reason, there are random number of hops required to deliver a message to a destination node or to a given distance and this depends upon network parameters such as transmit power, decoding threshold path loss exponent and node density. A node can successfully decode a message if its received signal-to-noise ration (SNR), after post-detection combining is greater than or equal to some value of decoding threshold and then these nodes are called decode-and-forward (DF) node of that particular level.

Fig 3.3 shows the formation of a virtual multiple input single-output (MISO) scenario by which reliability is achieved because of spatial diversity. The circle nodes in the Fig 3.3 are the decode-and-forward nodes of level k and now are ready to retransmit the message packet which is received from the previous level. All these decode-and-forward nodes of level k have the same message received from the nodes of prior level. When these nodes broadcast a message packet, each node have its own channel gain shown by h_i. This is because of the random nodes deployment. Due to the random node locations, when a same message packet is received by a node of next level from all the decode-and-forward nodes of the current level, it is less probable that all channels h are effected by fading and noise. A message is received by several forward nodes (not shown in the figure), the received power from all DF nodes is first added at that node and then the accumulated power at the node is compared with the decoding threshold. This is called post-detection diversity combining technique. In our scenario we are using Maximum-ratio-combining (MRC) diversity combining with post-detection. When the composite power at the node is greater than or equal to the value of decoding threshold, then that node becomes the member of level $k+1$ and called DF node of this level. Because of the diversity gain at each level, the OLA is the reliable transmission protocol of multi-hop cooperative ad hoc networks.

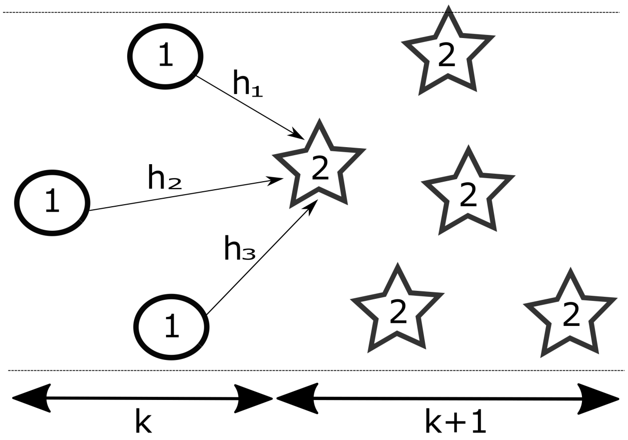


Figure 3.3: Node of next level receives multiple copies of a same message signal from the nodes of previous level forms a MISO scenario.

In basic OLA, let Φ_k denotes a set, which contains the DF nodes at a level k, then the power received at a jth node of level $k+1$ is given as

$$P_{r_j}(k+1) = P_t \sum_{i \epsilon \Phi_k} \frac{h_{ij}}{d_{ij}^{\alpha}}, \tag{3.1}$$

where P_t is the transmit power of a node, h_{ij} denotes the effects of Rayleigh flat fading modeled with unit mean exponential RV, d is the Euclidean distance between node i of level k and node j of level $k+1$ and α represents the path loss exponent where its range varies between 2-4. The outage probability of the node j is calculated as

$$P_o = \mathbb{P}\{P_{r_j}(k+1) < \tau\}, \tag{3.2}$$

where τ is the decoding threshold.

3.1.2 Simulation Model of Basic OLA Networks

The simulation model of random node location deployment is shown in the Fig 3.4. The network is considered a square network having the same length and width of 100 meters. The node density, which is the number of nodes per unit area is 100. The transmit power is considered same for all the deployed sensor nodes. The decoding threshold is constant for all nodes of a levels or hops in the network. The network deployment is constant for each session or iteration. For a particular network to analyze its performance, path loss exponent is also considered constant for all sessions.

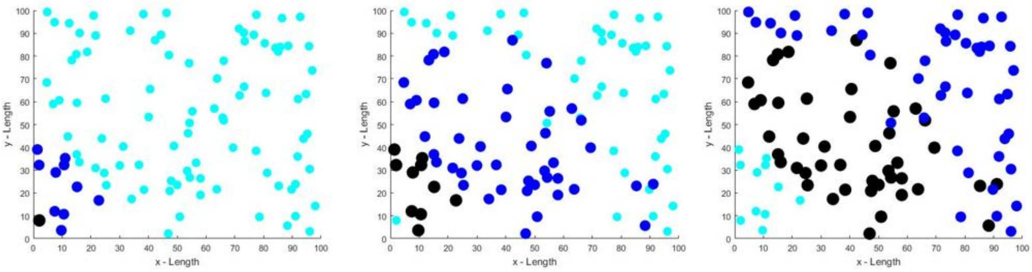


Figure 3.4: The simulation model of basic OLA with single packet transmission.

It can be seen in the Fig 3.4, that a black node at the start of this network is the source node, which broadcasts its message packet signal with some specific transmit power. The relay nodes that receive the message signal try to decode it by comparing the received power with some decoding thresholds. Nodes that receive the message signal with the received power greater than or equal to the decoding threshold are called the decode and forward nodes of level-1 and are shown by dark blue nodes. Now these DF nodes of level-1 will immediately broadcast the message packet signal received from the source node in the next time slot without prior coordination to any node. When these DF nodes of level-1 broadcast the packet signal, the signal will also be received by the source node and by the DF nodes of this level. The source node and these DF nodes will ignore the message. This is the algorithm of OLA protocol that a node that received and broad casted the message signal, will ignore the same message packet if it is received again in such large scale cooperative multi hop OLA networks. The power of message packet received by any forward node transmitted by several DF nodes of level-1 is first added at that node. There are several transmitters transmitting the same message of source node shown by black nodes in second snap shot of Fig 3.4. The received powers are added at any forward node and then that accumulated received power is compared with the same decoding threshold. In this manner, level-2 is formed which has more DF nodes comparing to level-1 because of diversity gain.

Due to the diversity gain at each level in the transmission of opportunistic large array (OLA) network, the reliability of OLA network is outstanding. The level-2 nodes will broadcast the same source's message received from level-1 nodes and hence level-3 is formed. This process continues until the source's message is received by a particular destination node or is disseminated to the entire large scale cooperative ad hoc network. The received power denoted by P_r in the network shown in Fig 3.4 is calculated by $P_t \sum_{i \epsilon \Phi_k} \frac{h_{ij}}{d_{ij}^{\alpha}}$, where P_t is the transmit power of a node, h_{ij} denotes the effects of Rayleigh flat fading modeled with unit mean exponential RV, d is the Euclidean distance between node i of level k and node j of level $k+1$ and α represents the path loss exponent.

3.1.3 Effects of Network Parameters

In the Fig 3.4, a destination node is the node which is farthest away from the source node. It can be seen in the figure that a source's message takes three hops to reach at the destination node in a single iteration. It may happen that a message can take fewer or more hops to reach at the destination node. The number of hops a message take from the source node to the destination node depends on several network parameters, such as transmit power, decoding threshold, value of path loss exponent, distance between nodes, Rayleigh flat fading and node density.

When a node transmits a message packet with high transmit power, more forward nodes when receive this message signal will have received power greater than or equal to the decoding threshold. In this way, when these nodes retransmit the message in the forward direction to form the next level nodes with the same transmit power, next level will have more nodes than the current level. In this manner, it may happen that a message can reach to the destination in the only two hops. Likewise, when a node transmits the message with less power, few nodes can be able to decode it and thus it may happen that a message takes more than ten hops to reach at the destination in this particular network shown in Fig 3.4. It may further happen that when a node transmits the message with low power, the nodes at any intermediate hop may not decode the message, this is called outage. Outage is defined as when a destination node do not receive the message or is unable to decode the message. Outage occurs when power received at any node of an intermediate hop or a level is less than the decoding threshold. Outage event occurs when a message is either not decoded by any node of any intermediate level (or hop) or is not decoded by a destination node. The outage probability of the node j is calculated by $P_o = \mathbb{P}\{P_{r_j}(k+1) < \tau\}$, where τ is the decoding threshold.

The value of decoding threshold plays a vital role in the number of hops counts and success and outage rate in the OLA networks. When the value of decoding threshold is small, then the received power at any node meets the decoding threshold easily and thus more nodes in a level become the member of the level. In this way, a message reaches in fewer hops to the destination node, because in each subsequent hop (or level) more nodes will become the member of that particular level because of diversity gain.

The path loss exponent defines the characteristic of wireless environment. The value of path loss exponents varies between 2 to 4. When the value of path loss exponent is 2, which means that the wireless environment is fair. As value of path loss exponent increases, the wireless channel or environment gets worse. This wireless parameter plays a critical role in wireless communications and networks. When we consider the minimum value of path loss exponent, that is 2, then more nodes in each level become the member of that level. Thus a message takes fewer nodes to reach at the destination node. As value of path loss increases, a message takes more and more hops to reach at the destination and the success rate also decreases because of less diversity gain.

The node density defines the number of nodes per unit area. As node density increases, which means more nodes will be present in that particular area. Thus the distance between the nodes decreases. When the distance between the node decreases, more nodes come close to each other. Therefore, when nodes of a level transmit a message, there are greater chances of more nodes that decode the message in the next hop or level. Thus, by increasing the node density, lesser hops are required by a message to reach at the destination. Due to this reason, node density plays an important role in large scale cooperative OLA networks.

3.2 OLA Threshold (OLA-T)

Opportunistic Large Array threshold (OLA-T) is a version of basic OLA protocol for energy efficiency in the large scale cooperative multi-hop ad hoc networks. The wireless ad hoc network can be made energy efficient when a few nodes of any level participate in forward transmission instead of all decode-and-forward nodes of that level. However, it should be noticed that due to limited participation, the diversity gain at a receiving node becomes small, which affects the quality of service (QoS). It is network user's requirement what type of service he wants. If a user's requirement is a reliable network, then more decode-and-forward nodes of a level are allowed to retransmit the message information signal. If a user's focus is on energy and not on reliability in the network, then few decode-and-forward nodes in each level are required to retransmit the message information signal.

3.2.1 System Model

In OLA-T, the nodes of any level are sub-divided into two subsets, Active nodes and Idle nodes. Idle nodes are those nodes which are not allowed to retransmit the message packet in any level because they are at a greater distance from the nodes of the next level and therefore there contribution in making the next level nodes is minimum because of the huge path loss. Active nodes, on the other hand are the nodes of a level in OLA-T protocol, which are near to the next level nodes and therefore their contribution in making the next level nodes is maximum because of the smaller distance between them and the nodes of the next level, thus they are allowed to retransmit the message. Both active and idle nodes in a level are decode-and-forward nodes of a level. It may or may not happen that the number of active and idle nodes in a level becomes equal. The size of active nodes are chosen on the basis of percentage participation, which tells the percentage of total DF nodes in a level that are allowed to become the active node and retransmit the packet in forward direction.

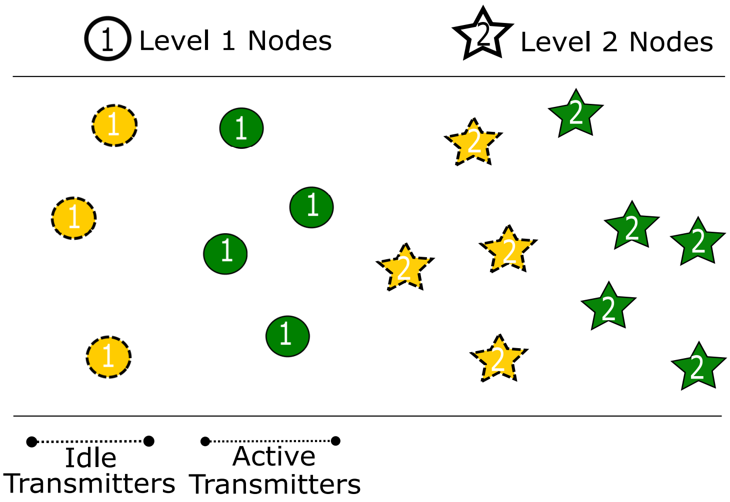


Figure 3.5: System model of OLA-T, The DF nodes in a level are divided into two subsets.

As you can see in the Fig 3.5 that the circle nodes are the nodes of the level-1 and star nodes belong to the level-2 nodes. Furthermore, circle nodes are subdivided into idle and active transmitters by yellow and green colors respectively. The yellow circle DF nodes of the level-1 are at a greater distance from the nodes of the level-2, thus when these yellow nodes retransmit the message signal information, then due to larger distance, there will be huge path loss. Due to this large path loss, their signal will attenuate with the distance and the received power at the nodes of the level-2 will be very small that their contribution in diversity combining will be minimum or might not be effective. Because of this reason, these DF nodes of a level are not allowed in transmission to conserve the energy of the OLA network. The number of nodes are allowed in each level depends upon the requirement of the user or the network administrator. In our case, we divide DF nodes on the basis of percentage of all DF nodes of any level. For instance, in a level, if 50 nodes decode the message successfully, and 10% of the DF nodes are allowed to take part in the transmission, then only 5 DF nodes of that level will be active nodes and the other 45 DF nodes become idle and will not take part in transmission. Likewise, if 2 nodes decode the message in a level and 20% of DF nodes are allowed for transmission, then at least one of these two nodes will be active and the selection of the active node is based on distance between it and the next level nodes. The size of two subsets can be made dependent upon the quality of service (QOS) and other network parameters.

The size of idle and active nodes may or may not be same and depends on the percentage participation. When the percentage participation value is small, for instance 10%, then the size of active node compare to the idle nodes become small. To maintain the quality of service in terms of success rate, the transmit power for the active nodes has to be high to successfully transmit the packets to the destination node. In this cases, the active sensor node will have to consume its maximum power to maintain the quality of service. However, the overall performance of network in terms of energy, or the consumption of the total power consumed from source node to the destination node is minimum compare to the basic OLA protocol.

3.2.2 Simulation Model of OLA-T Networks

The simulation model of the random node location using OLA-T protocol is shown in the Fig 3.6. The network is taken the square network having the same length and width of 100 meters. The node density, which is the number of nodes per unit area is 100. The transmit power is considered same for all deployed sensor nodes. The decoding threshold is constant for all nodes of levels or hops in the network. The network deployment is constant for each session or iteration. For a particular network to analyze its performance, path loss exponent is also considered constant for all sessions.

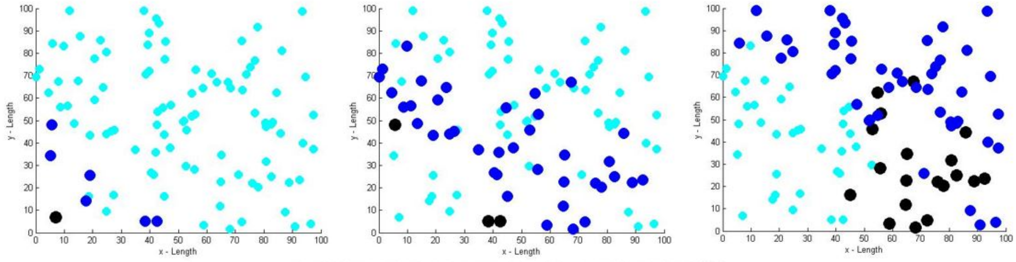


Figure 3.6: The simulation model of OLA-T.

It can be seen in the Fig 3.6, that a black node at the start of this network is a source node, which broadcasts its message packet signal with some specific transmit power. The relay nodes that receive the message signal try to decode it by comparing the received power with some decoding threshold. Nodes that receive the message packet with the received power greater than decoding threshold are shown by dark blue nodes and they are now called the DF nodes of level-1. One can see in first snap shot of the figure, that in the first level, there are six DF nodes shown by dark blue circles. Now unlike basic OLA protocol, not all these six DF nodes transmit in OLA-T. In OLA-T these DF nodes will be sub-divided into the idle and active nodes. In this example, we took 50% participation of nodes. which means, out of six DF nodes, only three will become the active nodes and the other three will be the idle nodes of this level. The question arises, which nodes should be selected in these type of networks where the locations of node is uniformly distributed. The answer is, those nodes will be chosen as a active nodes, which are either far away from the source node(s) or near to the next level nodes.

As one can see in the second snap shot of the Fig 3.6, that the out of six DF nodes of level-1, only three nodes become the active nodes and broadcast the message packet of the source node in the next time slot. These active nodes are shown by the black nodes in the second snap shot of the Fig 3.6. One can notice that these active transmitters can be chosen on the basis of the distance between them and the next level nodes. The process of packet transmission will continue with the percentage participation of 50% in each level until the data reaches at the destination node or spread out to the entire network.

3.2.3 Energy-efficiency using OLA-T Networks

The performance of a network using OLA-T protocol in terms of energy efficiency is noticeable. In Fig 3.6, since the the number of DF nodes in each level are now become half because of 50% participation compare to the basic OLA protocol, the energy of the network is also conserved about 50%. However, in OLA-T networks, number of hops taken by a message to travel from the source node to the destination node becomes large because of less diversity gain at each hop or level. For the same reason, the success rate also decreases in OLA-T networks. There are few network parameters which can compensate the network's performance in OLA-T networks, such as transmit power, node density and decoding threshold. To maintain the success probability of OLA-T protocol in large scale cooperative OLA networks, one has to analyze the performance of the networks by changing the value of these parameters to examine the opportunistic value of the parameters.

The transmit power, decoding threshold, node densities, path loss exponent, and Rayleigh flat fading plays the vital in large scale cooperative multi hop ad hoc networks. The transmit power, decoding threshold and node density are changeable network parameters. These network parameters are adjusted according to the network's requirement. When the nodes transmit with high transmit power, a message take fewer hops to reach at the destination with hight success rate in OLA-T networks. Likewise, when node density is chosen high, then more nodes in each level becomes the part of that level, and thus again few hops are required by a message to reach at the destination with high success rate. However, the performance of networks in terms of reliability and success rate in OLA-T networks will always be minimum compared to the basic OLA in which all the DF nodes of a level retransmit the message packet. For this reason, to maintain the same quality of service in basic OLA and OLA-T, less node density and less transmit power can be used in basic OLA compared to the OLA-T protocol. But the energy is conserved using OLA-T protocol because of less number of DF nodes in each level.

Chapter 4

Intra-Flow Interference in Basic OLA Network Subject to Multiple Packets

In this chapter, we will study the performance of basic OLA network in which multiple packets travel simultaneously in the network.

4.1 OLA with Multiple Flows.

In this section, we will explain the basic OLA network with multiple packets transmission and the effects of transmission of multiple packets on the network. The working of multiple packets transmission in basic OLA network is similar as that of single packet transmission in OLA networks. The fundamental difference is that in OLA network with single packet transmission, a new packet is not allowed for the transmission until either the current packet either reaches at the destination or is lost in any intermediate hop (or level). However, in multiple packets transmission, a new packet is allowed after some time slots.

The performance of network is precisely analyzed in terms of success and outage rate, latency and reliability. The network parameters of these large-scale cooperative OLA networks are path loss exponent, decoding threshold, node density, transmit power, interference and signal-to-noise-interference ratio (SINR).

4.1.1 System Model

The basic system model of a basic OLA network with multiple packets transmission is shown in the Fig 4.1. The sensor nodes are deployed in uniform distribution where node locations is random. We take strip-shaped network with the area of some length and width. The sensor nodes are arranged in a manner that their positions is random in that particular strip-shaped area. The source node is the first node in the left most of the strip-shaped network and destination node is the node which is farthest node from the source node. The source node will insert multiple packets one by one and the working for each packet is same in the entire network.

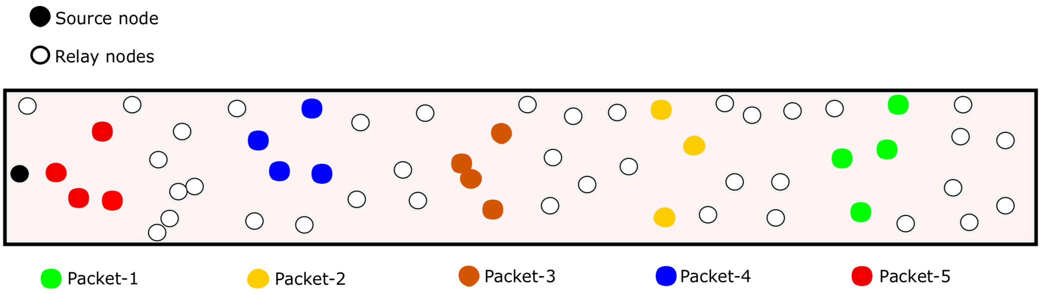


Figure 4.1: The multiple packets transmission in strip-shaped OLA networks.

Here are two networks parameters which needs to be defined; i) Packet Insertion Rate (PIR) and ii) tiers of interference, T. Packet insertion rate is defined as the rate per time slot at which the source node inserts a new packet in the network. The tiers of interference is defined as, that with different tiers, T, different number of levels interfere with the nodes of a level.

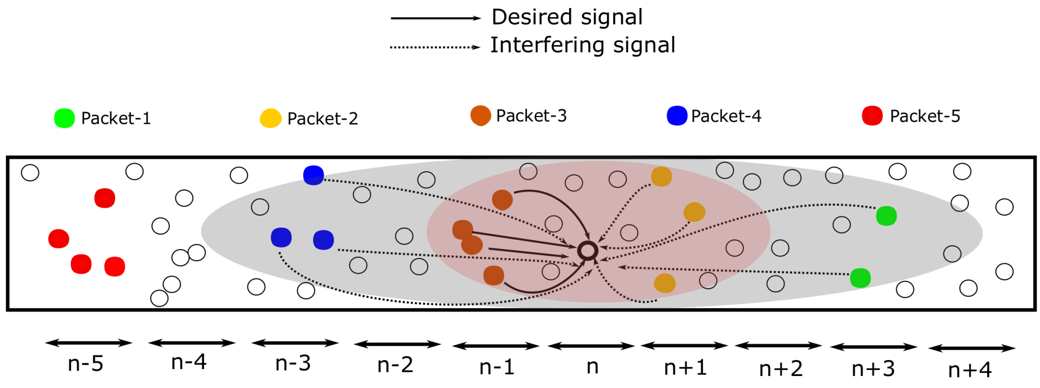
In Fig 4.1, a black node is the source node which inserts the packets for the transmission. A source node has transmitted first packet in the network shown by green circles and then transmitted the second, third, forth and fifth packets shown by yellow, brown, blue and red circles respectively. It can be seen that the source node inserts a new packet after waiting some time-slots, which is called Packet Insert Rate. Unlike, single packet transmission in basic OLA network, there are number of packets traveling through multiple hops to the destination at the same time.

Due to multiple transmissions in a network, there is another wireless network impairment called interference occurs in such networks. Interference occurs when unwanted signals disrupt wireless communication. Interference may prevent reception altogether, may cause only a temporary loss of a signal, or may affect the quality of the signal.

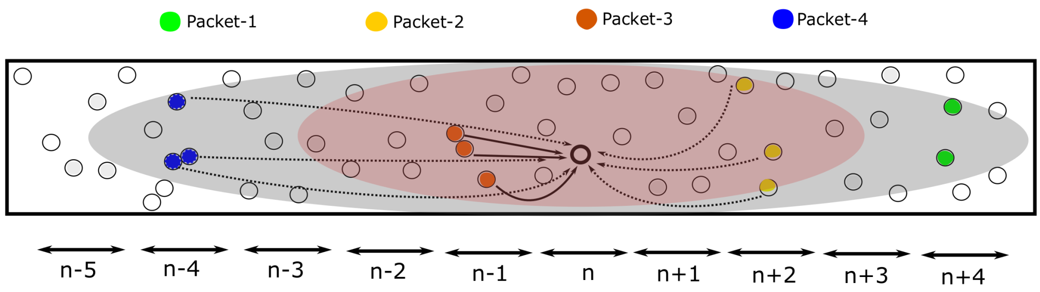
Fig 4.2 shows the two dimensional strip-shaped network with multiple packet transmission for PIR=1, 2 and for T = 1, 2. There are multiple packets transmitting at the same time in the network. As you can see in the Fig 4.2 (a) when PIR = 1, which implies a packet insertion rate after waiting one time slot. For instance, the DF nodes at level $n-1$ transmits a new packet to level n. Similarly, level $n+1$ transmits a former packet to level $n+2$, and so on. This is an example of fastest possible PIR. In Fig 4.2 (b), PIR = 2 implies that the source node inserts a new packet in the network after waiting two time slots between consecutive transmissions. When the node at level n receives the new packet from the DF nodes of level $n-1$. This packet is the desired packet for the node of level n and is shown by solid arrows. At the same time, when DF nodes of level $n+1$ transmits the former packet to the nodes of level $n+2$, the message packet is also received by the node of level n because of omni-directional antennas used in WSN networks. This is the unwanted signal or the interfering signal for the node of level n and is shown by dotted arrows.

A new packet from the nodes of level $n-1$ to the sensor nodes of the level n shown by solid arrows are the multiple desired signals, whereas, the dotted arrows shows the interfering or unwanted signals that occur because of multiple flows in the network.

The different number of levels interfere with the nodes of a level with different tiers, T. Fig 4.2 (a), for T = 1, the interfering signals or the unwanted signals affecting the node arrive only from the level $n+1$, where as for T = 2, level $n-3$ and level $n+3$ also contribute to the interference with the



(a) $PIR = 1$



(b) $PIR = 2$

Figure 4.2: Strip-shaped network for $PIR = 1 and 2$, pink ellipse denotes $tier - 1$ interference and gray ellipse denotes additional interfering signals from $tier - 2$.

PIR=1. The unwanted signals coming from the different levels are further away from the affected node when we increase the value of PIR as shown in the Fig 4.2 (b), where PIR = 2. Hence, the levels of interference differ with different combinations of PIR and T.

The node of any level can decode the message accurately when its received desired signal power and signal-to-interference-noise are greater or equal to decoding threshold, τ and SINR threshold, ϕ, respectively. The desired received power at a mth node of the level n denoted as $P_{r_m}(n)$ shown in the

Fig 4.2 and is given as

$$P_{r_m}(n) = P_t \sum_{k=1}^{K} \frac{h_{km}}{d_{km}^{\alpha}} \tag{4.1}$$

where P_t is the transmit power of a node, h_{km} denotes the effects of Rayleigh flat fading modeled with unit mean exponential RV, d_{km} is the Euclidean distance between node k in the previous level to the node m of the current level and α represents the path loss exponent.

The signal-to-interference-noise ratio (SINR), χ, which is the ratio of desired power and interfering power plus noise and is given as

$$\chi = \frac{\sum_{k=1}^{K} \frac{h_{km}}{d_{km}^{\alpha}}}{\sum_{i=1}^{I} \frac{h_{im}}{d_{im}^{\alpha}}}, \tag{4.2}$$

where K are the number of desired signal and I are the number of interfering signals. The interfering signals are also assumed as Rayleigh flat fading. The d_{km} represents the distance between the node of current level and the nodes of previous level, whereas, d_{im} denotes the distance between the node in the current level and the nodes of interfering levels.

4.1.2 Simulation Model of Multiple Flows OLA Networks

The simulation model of random node location deployment with multiple flows is shown in the Fig 4.3. The network is an strip-shaped network having the the length of 500 meters and width of 20 meters. The node density, which is the number of nodes per unit area is 300. The transmit power is considered same for all the deployed sensor nodes. The decoding threshold τ and SINR threshold ϕ are constant for all nodes of a levels or hops in the network. The network deployment is constant for each session or iteration. For a particular network to analyze its performance, path loss exponent is also considered constant for all sessions.

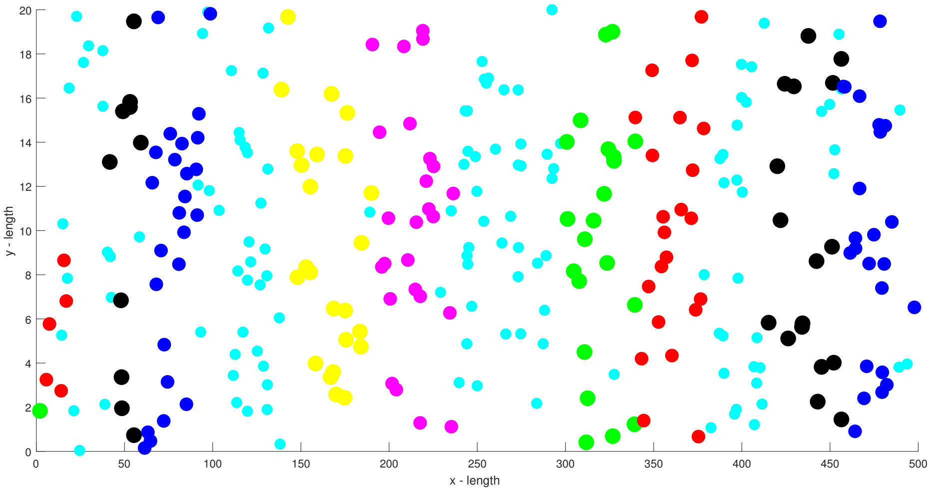


Figure 4.3: Simulation model of multiple flows for PIR = 2.

The Fig 4.3 shows multiple flows in the network. The source node is considered the left most node in the snap shot and the destination node is the farthest node from the node. It can be seen in the figure that source has transmitted first packet shown by blue-black nodes in the right most of the strip-shaped network. The blue nodes are the DF nodes of the next level, and the black nodes right before of these DF nodes are the transmitters of the prior level. The second packet is shown by red-green nodes, the third packet is shown by purple-yellow nodes ans so on. This network is for the PIR = 2, in which a source has to wait two time slots before inserting a new packet in the network.

When the source node transmits its first packet in the network shown by blue-black nodes, the packet travels from hop to hop like in a basic OLA with single packet transmission. The first packet when reaches at the forth level (or hop), a source inserts the second packet in the network. Because of the second packet's transmission in the network, the interference occur in the network.

When all these five packets flow in the network at the same time as shown in the Fig 4.3, the interference of one packet will affect the transmission on the other packet. We assume a band-limited system and that all the nodes use the same carrier frequency, thereby causing co-channel inter-ow interference. The first packet is affected by the other four subsequent packets. Likewise, the third packet is affected by first, second, forth and fifth packets. The middle packets are the one which are affected very much because the interference coming from the forward and backward levels.

4.1.3 Effects of Network Parameters in Multiple Flows

In addition to increasing and decreasing the transmit power, decoding threshold, path-loss exponent and node densities values in single packet transmission, there are three other network parameters which play vital role in multiflow OLA networks. These three network parameters are interference, packet insertion rate and tiers of interference and are described as under.

Interference is one of the prominent impairments in wireless communications. Since wireless communication is open medium for all, it is the important impairment which effects the channel of a user and affects the performance of overall network. Interference occurs when more than one user communicate in the vicinity with their specific power. When two nodes or users start transmit their message packets in the network, then the power of one user will mixed-up with the power of the other users and therefore the receiver will become confused in finding its desired data from its corresponding user.

Packet insertion rate is defined as how many slots a node has to wait before transmitting a new packet in the network. When a node start transmitting packets one by one, then the power of one packet will interfere severely with the power of next packet.

The tiers of interference defines that from how many levels in the network can contribute in the interference. When the value of this parameter is high, then more nodes of multiple levels will contribute in the interference. For the lower values of this parameter, few nodes will contribute for the interference in the network.

Chapter 5

Results and Discussions

This chapter presents the results for basic OLA with single packet transmission, OLA-threshold and basic OLA with multiple packets transmissions.

5.1 Results of Basic OLA networks with single packet transmissions

In this section, we discuss the performance of the network in terms of success probability, latency and energy efficiency. We consider a network having a length of 1500m and a width of 50m where 500 nodes are deployed uniformly in this area. The source node is one of these 500 nodes and is located at the start of the network. The destination node is considered as the farthest node from the source node in this strip-shaped network. The channel model includes Rayleigh fading and path loss.

Fig 5.1 shows the relationship between outage probability and transmit power for different values of path loss exponent, α. The outage event occurs when the destination is unable to receive the data. This may arise due to the fact that a running OLA dies down at an intermediate stage before the destination is reached. The transmit power of each node in the network remains the same for all nodes. It can be seen that at $\alpha = 2$, the outage probability of the network is least as expected. As the value of α increases, the performance of the system becomes worse. For example, when $\alpha = 2.5$, each node requires about 6dBm of transmit power to achieve an outage probability of 10%, which is 3dBm higher than that required at $\alpha = 2$ to get the same outage probability.

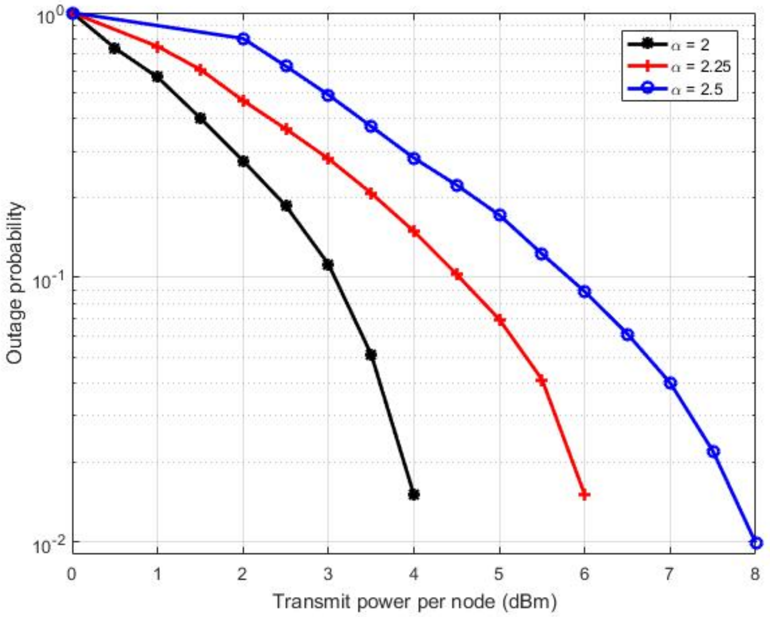


Figure 5.1: Outage probability against transmit power for three different values of α with node density = 500, decoding threshold = 0.5, L = 1500, W = 50.

In Fig 5.2, the average number of hops from the source node to the destination node is calculated at multiple transmit power of nodes for different values of α. It can be seen that less number of hops are required for the message to reach the destination node when path loss exponent is small. As seen in Fig. 6, about 15 hops on average is taken by the message to reach the destination node with outage probability of 10% for $\alpha = 2$, whereas 50 hops on average are required with $\alpha = 2.5$ to maintain the same outage probability. Hence path loss exponent plays a detrimental role in coverage of OLA multi-hop networks.

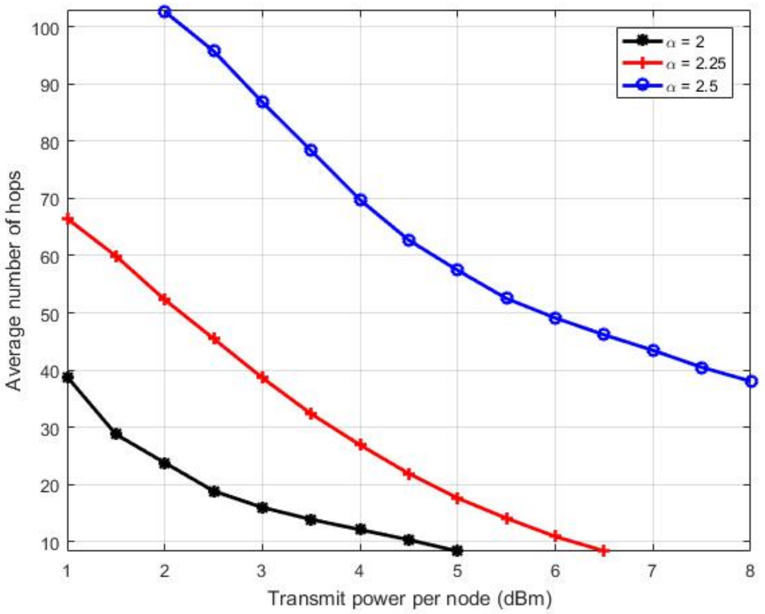


Figure 5.2: Average hops against transmit power for three different values of α with node density = 500, decoding threshold = 0.5, L = 1500, W = 50.

Fig 5.3 depicts the relationship between node density, success probability and average hops for different values of α. The figure shows that the success probability increases for all values of α when the node density increases while the average number of hops decreases. The reason is that as the number of nodes per unit area becomes large, diversity gain increases and therefore, the chances of node participating in a level and likelihood of decoding increases. As more nodes engage in retransmission, it is less probable that the message fails to reach the destination. For the same reason of SNR advantage, a message takes fewer hops from source to destination when the node density becomes large as shown in Fig. 7. It can be seen that for $\alpha = 2.5$ when the node density is 550, 100 hops on the average are required by a message to reach the destination with success probability of only 45%. However, if the node density is increased to 750, average hops becomes 90 with a success rate of around 90%.

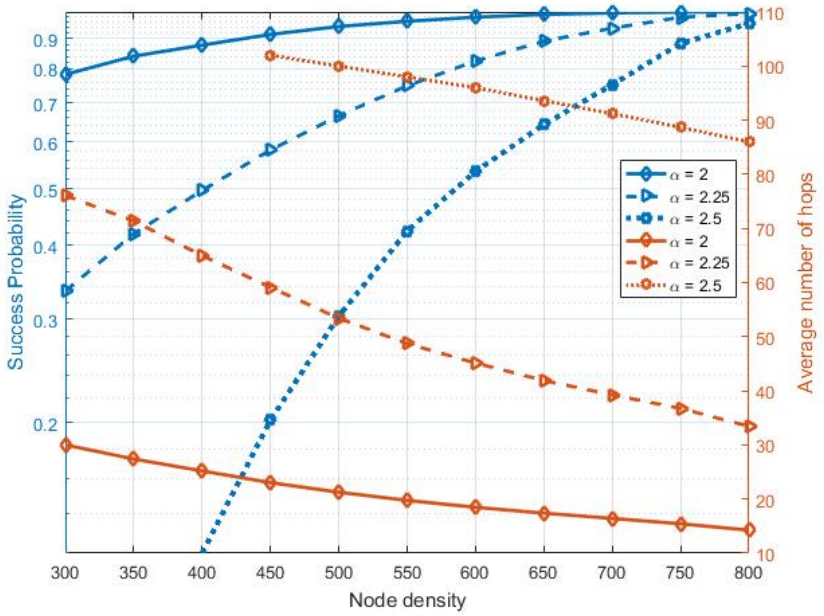


Figure 5.3: Success probability and Average hops against node density for three different values of α with transmit power per node = 2dBm, decoding threshold = 0.5 , L = 1500, W = 50.

Fig. 5.4 provides information of power against success probability and average hops for different node densities at $\alpha = 2$. As described in Fig. 5

that by increasing transmit power of nodes, the outage probability decreases, however it decreases rapidly when node density is high as shown in Fig. 8. For a node density of 500, the node are located near to each other as compared to a node density of 400, therefore, the success increases. For the same reason, a message reaches earlier at the destination when the node density is high. At 3.5dBm, for a node density of 400, on average 21 hops are required for a message to be received by destination node with success probability of about 94%, whereas about 18 hops on average are required when the node density is 500 with success probability of about 98%.

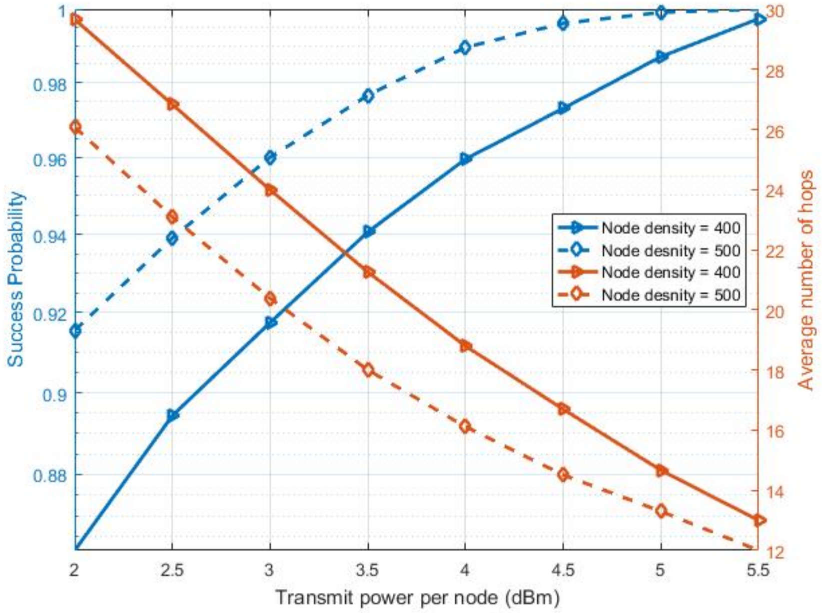


Figure 5.4: Success probability and average hops against transmit power for different node densities, L = 1500, W = 50.

Fig 5.5 provides information of decoding threshold and outage probability. We can see that by increasing decoding threshold, outage probability also increases. This is because at high threshold values, power received at node does not meet the value of the decoding threshold and therefore that node is not able to decode the message accurately. For this cause, fewer nodes meet the threshold and become DF nodes of a level and take part in transmission. Due to less sum of nodes retransmit the message from hop to hop, effective diversity gain is reduced and therefore probability of outage rises. Hence, a message takes more number of hops from the source node to destination node when decoding threshold increases as shown in Fig 5.6. Fig 5.6 depicts that, at 0.3dBm, on average 10 hops are required for a message to reach at destination with success probability of 95% when $\alpha = 2$. Whereas about 26 hops are needed for a message to reach at destination with success probability of 90% at $\alpha = 2.25$, and 57 hops are used with success probability of 84% at $\alpha = 2.5$.

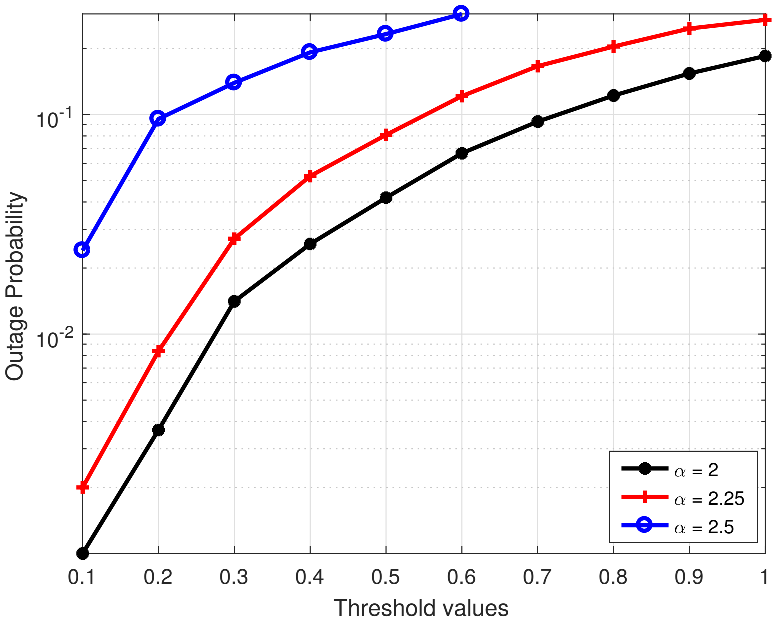


Figure 5.5: Outage probability against decoding threshold for three different values of α with node density = 500, transmit power per node = 3dBm, L = 1500, W = 50.

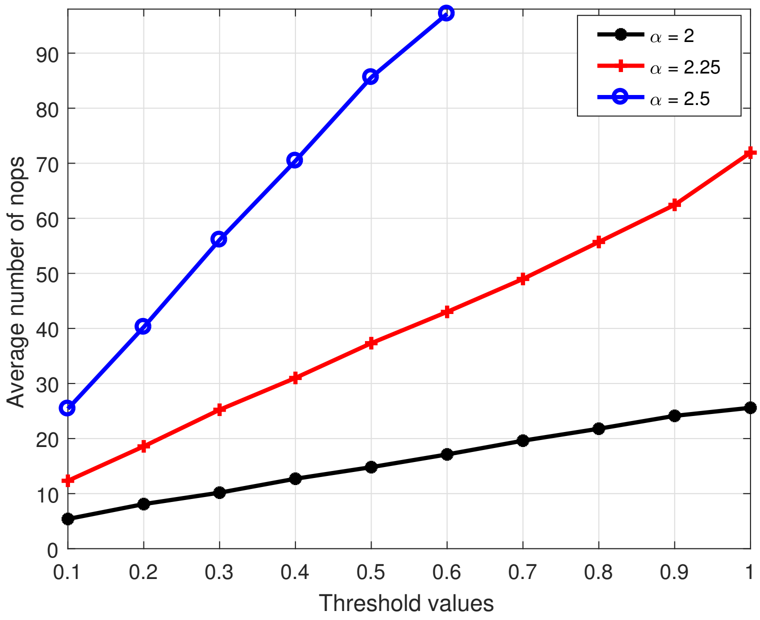


Figure 5.6: Average hops against decoding threshold for three different values of α with node density = 500, transmit power per node = 3dBm, L = 1500, W = 50.

Fig 5.7 shows the relation of decoding threshold and outage probability for different node densities. As demonstrated in Fig 5.5, when threshold increases, outage increases because receive power at nodes does not meet threshold. However, outage can be decreased by increasing node density. When number of nodes per unit area increases, more nodes are present near to one another. As the distance between nodes become smaller, path loss will be minimum, causing a node to receive a message with received power greater than decoding threshold, thus outage probability decreases as shown in the Fig 5.7. Furthermore, number of hops taken by a message to reach at destination node decreases with the increase of node density as shown in Fig 5.8. This is because, more nodes per level will participate and each subsequent level has higher number of nodes because of diversity gain. Thus fewer hops will be taken by a message to travel through. Fig 5.8 validates this point when at 0.5dBm for node density of 400, about 24 hops required for a message to reach at destination with the success probability of 90% whereas for node density of 500, a message travel through about 20 hops to reach at destination with success probability of 93%.

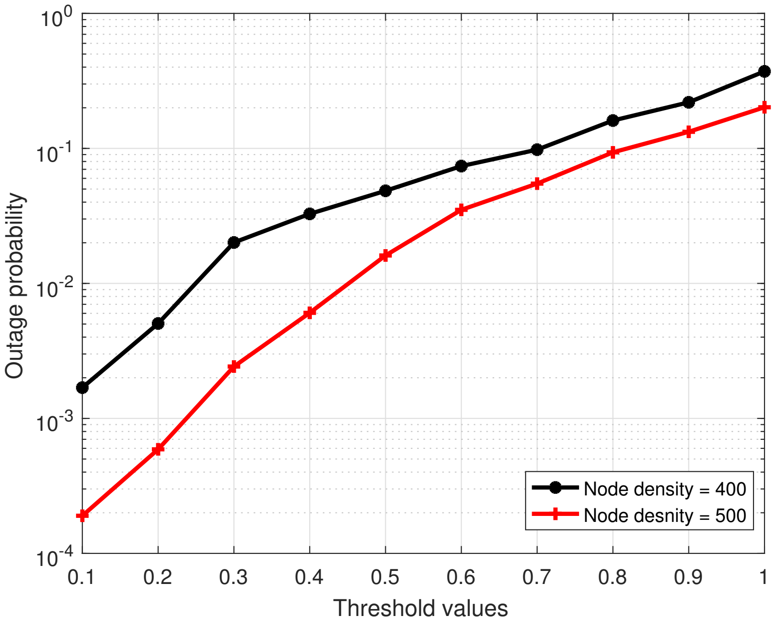


Figure 5.7: Outage probability against decoding threshold for different node densities with transmit power per node = 2dBm , L = 1500, W = 50.

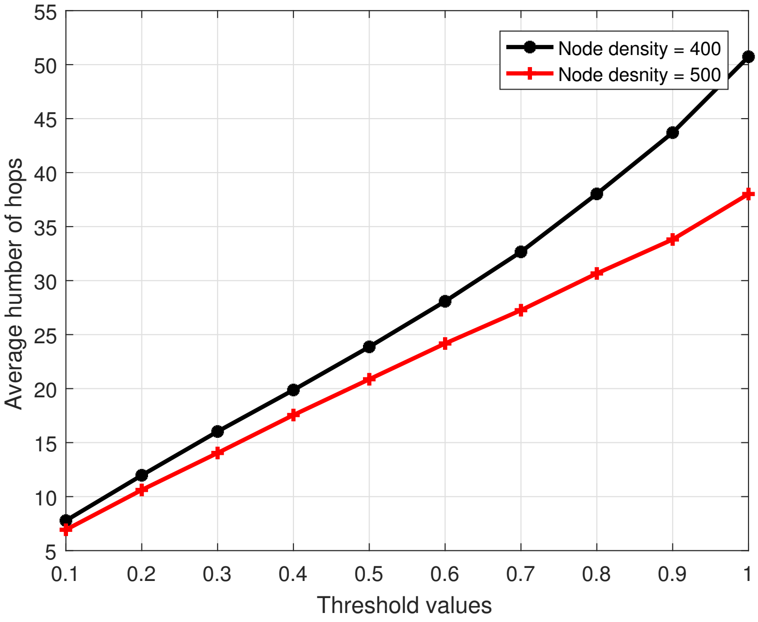


Figure 5.8: Average hops against decoding threshold for different node densities with transmit power per node = 2dBm , L = 1500, W = 50.

5.2 Results of OLA-T Networks

We now focus on the results of OLA-T network for which we demonstrate the result of energy efficiency. In Table I, the performance of three networks is summarized in terms of power per node. These networks are defined as X, Y and Z. The node density for each network is 100 and the decoding threshold is same for all topologies. The percentage participation from 10% - 90% shown in table defines the percentage of nodes allowed in each hop for retransmitting the received message. These nodes are called active nodes and the selection of these nodes is on the basis of path loss to the next level nodes. The nodes near the boundary of the next level are chosen as active nodes.

Table 5.1: The performance of OLA-T of three different networks

Dimension		**Percentage participation**									
		10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100/Basic OLA**
X= 300 x 50	**Ω**	**10.23/50.08**	**17.14 /63.75**	**28.43/83.26**	**38.22/83.96**	**44.92/83.96**	**56.83 /87.43**	**66.70 /88.47**	**73.78 /87.53**	**83.33/88.88**	**1**
	Power(dBm)	**4.10**	**3.15**	**2.35**	**1.90**	**1.80**	**1.55**	**1.50**	**1.50**	**1.48**	**1.48**
	Hops	**10.49**	**11.25**	**11.47**	**11.64**	**10.97**	**10.59**	**9.84**	**9.26**	**8.77**	**8.63**
Y= 200 x 50	**Ω**	**8.62 /45.83**	**15.79/62.05**	**25.95/73.36**	**35.36 /78.04**	**42.83/80.87**	**54.19/84.27**	**63.39/84.90**	**71.38/85.27**	**81.20/86.70**	**1**
	Power(dBm)	**2.80**	**2.20**	**1.60**	**1.20**	**1.10**	**1.0**	**0.90**	**0.90**	**0.90**	**0.90**
	Hops	**8.70**	**8.80**	**8.96**	**9.76**	**9.48**	**8.71**	**8.71**	**8.15**	**7.74**	**7.59**
Z= 200 x 100	**Ω**	**7.66/48.26**	**13.54 /56.59**	**20.59/59.51**	**28.62/65.09**	**34.29/65.05**	**44.40/69.93**	**52.21 /71.06**	**60.21/72.35**	**68.38/73.45**	**1**
	Power(dBm)	**7.20**	**5.00**	**3.50**	**3.00**	**2.85**	**2.75**	**2.75**	**2.70**	**2.70**	**2.70**
	Hops	**6.04**	**6.35**	**7.00**	**6.89**	**6.67**	**5.85**	**5.51**	**5.34**	**5.22**	**5.13**

The 100% shows the basic OLA in which all nodes that decode the message retransmit it. For each network with its corresponding percentage participation, different transmit power (in dBm) per node required for maintaining a success probability of 80% is also provided. Lastly, Ω denotes the ratio of total active nodes to total DF nodes from the source node to the destination. It can be seen that when the percentage participation value is minimum, more power per node is required to guarantee a success probability of atleast 80% at the destination. It can be further noticed that average number of hops approximately remains the same for different percentage participation. Because of this limitation in participation of nodes, there will be less effective diversity gain in each hop. As the percentage participation increases, diversity gain increases in each hop even at less power per node. It can be further noticed that when nodes are separated by larger distance between them, as in network Z, more power per nodes is needed to transmit the message to destination node.

Fig 5.9 describes the energy efficiency of the three networks shown in Table I at 50% percentage participation. For the network X, there are on average 44.92 active nodes which transmitted the message from hop to hop up to destination with equal transmission power of 1.80dBm while maintaining 80% success probability. Therefore, the total energy consumed from

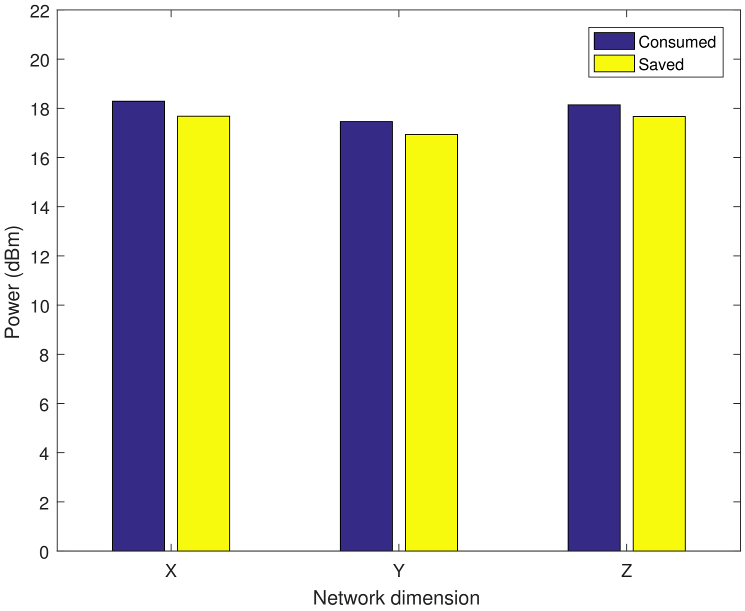


Figure 5.9: Fraction of energy saved and consumed at active nodes 50% for three different networks.

source to destination is 18.29dBm while saving 17.68dBm by limiting other nodes to participate. This implies that about 50% of energy is saved for this network compared to basic OLA. Likewise, energy consumed for networks Y and Z is 17.46dBm and 18.14dBm, respectively while conserving 16.94dBm and 17.67dBm, respectively as shown in Fig. 9. Comparing to basic OLA, where all DF nodes transmit the message, almost 50% of the energy is conserved. However, in basic OLA a node requires minimum transmit power to broadcasts its message, but on the same time, since all nodes in basic OLA take part in transmission, the power consumed from source to destination is much higher compare to OLA-T. Hence it can be observed that OLA-T provides energy efficient approach than basic OLA and can be used in various cooperative transmission-based applications.

5.3 Results of Multi-flow Interference in OLA Networks

In this section, we will discuss results of OLA networks with multiple packets transmission to examine the performance of the networks in the presence of interference.

Fig. 5.10 shows the relationship of SINR threshold and outage probability for different packet insertion rate and node densities. It can be seen in the figure that when the value of SINR threshold increases, the outage increases for all packet insertion rates and node densities. When the $PIR = 1$, which means a source inserts a packet in the network after waiting one time slot, therefore the interference of one packet over the other packets affects the performance of the network because of small path-loss. This is the severe possible affect of interference in mutli-flow OLA networks. As value of PIR increases, which means a source waits more time slots to insert the next packet. As one can see in the Fig. 5.10 that for $\phi = 0.1$, outage probability is about 64% for $PIR = 1$ when node density = 300. For the same node density, the outage is about 49% when $PIR = 3$ and $\phi = 0.1$. As the value of SINR threshold increases, outage also increases as one can see for SINR threshold 0.5, the outage probability for the node density 300 and PIR 1 and 3 is 79% and 65% respectively. For the lower density at the same transmit power for all values of SINR threshold, the difference between the outage results of different PIR is minimum. As node density increases as shown in the figure, the difference between the outage rates for different PIR values become maximum. For node density 500, at $\phi = 0.1$, the outage rate is 4%

and 1.6% when PIR is $1 and 3$ respectively. At $\phi = 0.5$ for the same node density, the outage rates are 38% and 10% when PIR is 1 and 3 respectively.

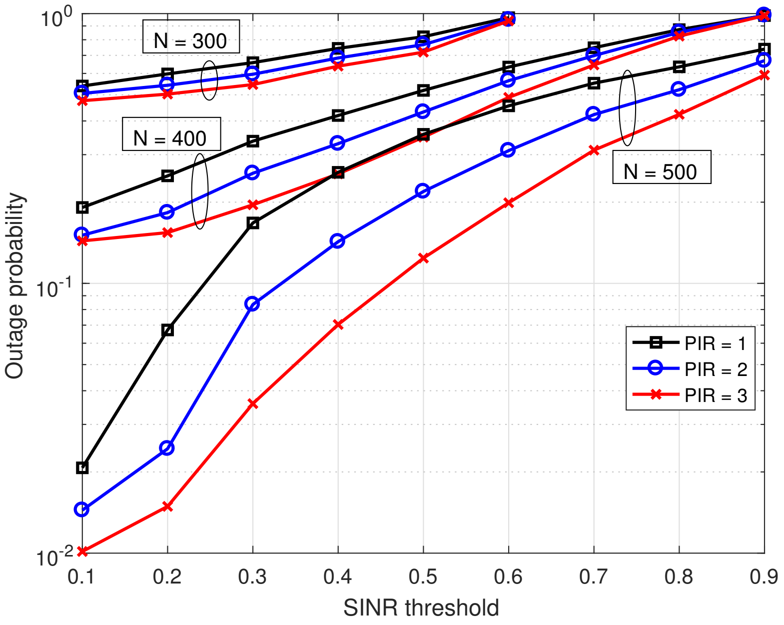


Figure 5.10: SINR threshold against outage probability for three different node densities and packet insertion rates.

The Fig. 5.11 presents the relation of node density and average time slots for different packet insertion rates and SINR threshold values. The time slots defined as the number of hops taken when the first packet inserted in the network to the last packet reached at the destination. The left bar graph represents the results for SINR threshold = 0.1 and the right bar graph shows the results for SINR threshold = 0.5. It can be seen in the figure that for any value of SINR threshold, average time slots increase when PIR value increases. This is because of a source node that has to wait more time slots to insert a new packet in the network. It can be seen in the left bar graph that for node density 300, there are on average 50 time slots are needed when

$PIR = 1$, and for large PIR value, lets say for $PIR = 3$, the average time slots become around 63. Likewise, for high node density, less time slots are required on average. As one can see in the left bar graph, on average 36 time slots are required for the node density 500 and $PIR = 1$, and when PIR value increases, 46 time slots are required for $PIR = 3$ for the same node density. In the right bar graph, the results are for higher SINR threshold value. As one can see in the right bar graph that by increasing the value of SINR threshold, more average time slots are required for all node densities at any value of PIR compared to the left bar graph.

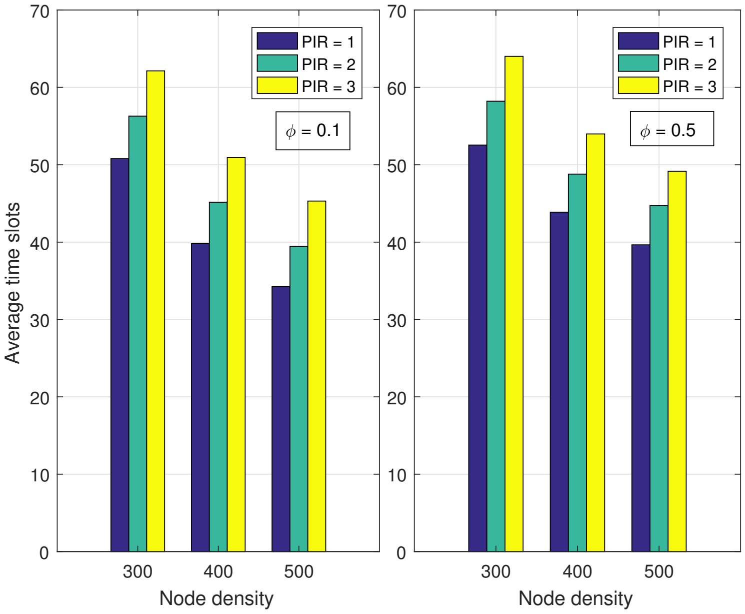


Figure 5.11: Average time slots against node density at $\phi = 0.1$ & 0.5 for three different node densities and packet insertion rates.

The Fig. 5.12 shows the relation of SINR threshold and outage probability for different network parameters. It can be seen that as the value of SINR threshold increases, the outage also increases for all node densities, packet insertion rate and path loss exponent values. When $\phi = 0.2$, the outage probability at $\alpha = 2.50$ is 42% when node density 400 and $PIR = 1$. This is the most severe performance of a network because of lower node density and higher value of path loss exponent. For higher node density such as 500, at $PIR = 1$ and $\alpha = 2.5$, performance of network becomes better to some extent as one can see that at SINR threshold 0.2, the outage is 11%. As the value of PIR increases, and the node density increases with small path-loss exponent, the performance of the network becomes better. It can be easily depicted from the figure that for $PIR = 2$, node density 500 and $\alpha = 2.25$, the performance of the network is best for all values of SINR threshold. This is because of lower affect of interference in each level. For the higher values of SINR, the performance of a network degrades for every packet insertion rate, path loss exponent and node density.

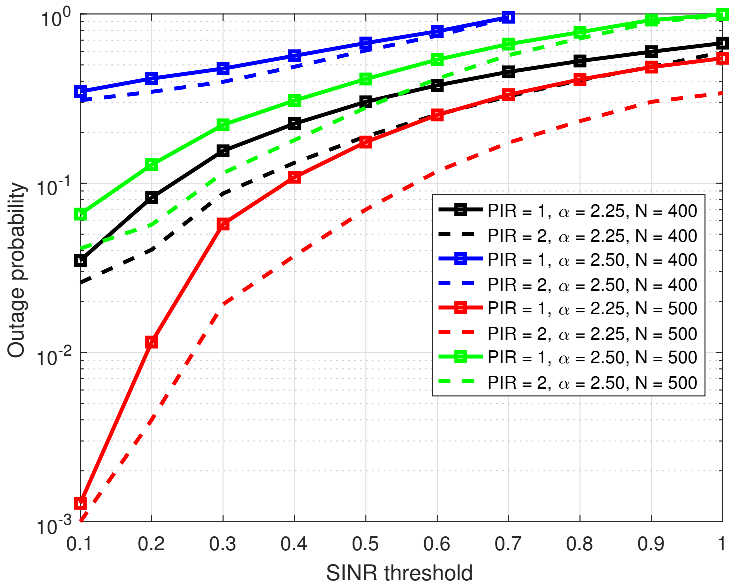


Figure 5.12: Outage probability against SINR threshold for different network parameters.

The Fig. 5.13 shows the performance of the networks in terms of average time slots and SINR threshold for various network parameters. It can be seen that for higher values of PIR, more time slots are required at each value of SINR threshold for all node densities and path-loss exponents. This is because, a source node has to wait more time slots for higher PIR values before inserting the new packet in the network. It can be further noticed that as the value of SINR threshold increases, more time slots are required for all values of packet insertion rate, path loss exponent and node densities. When the values of PIR and path loss exponent are minimum and node density is high, few time slots are required compared to the other as shown by the dark solid red line in the Fig. 5.13. For higher values of path-loss exponent and packet insertion rate, more and more time slots are required regardless of node densities. But for higher node density, lesser time slots are required to some extent compared to the lower node density. As one can see, at ϕ =0.5, $PIR = 2$ and $\alpha = 2.5$, on average 60 time slots are required when the node density is 500, whereas 70 time slots are required when the node density is 400. Hence node density, path-loss exponent and packet insertion rate play a vital role in multi-flows wireless ad hoc cooperative networks.

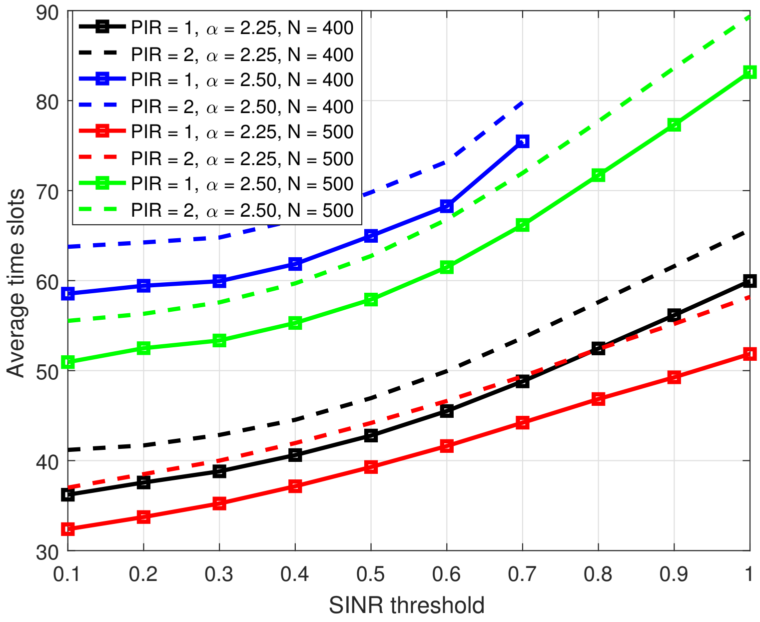


Figure 5.13: Average time slots against SINR threshold for different network parameters.

The Fig. 5.14 shows performance of a network for different values of tiers of interference and packet insertion rates in terms of outage probability against SINR threshold. The results are for the node density of 400. One can see that for all tiers of interference and packet insertion rates, the outage increases when the value of SINR threshold increases. The tiers of interference show that from how many levels or hops contribute in the interference in the performance of the network. When packet insertion rate is 1, the outage rate is high for both values of tiers as shown in the Fig. 5.14. For higher tiers of interference, the outage rate increase rapidly because more interfering nodes of multiple levels contribute in the performance of the system. At $\phi = 0.5$, the outage rate is 40% when $PIR = 1$ and tier of interference is 2. Compared to tier of interference 3, outage is 47% at $\phi = 0.5$ and $PIR = 1$. When the value of PIR is high lets say $PIR = 2$, the performance of the network becomes better as shown in the Fig. 5.14.

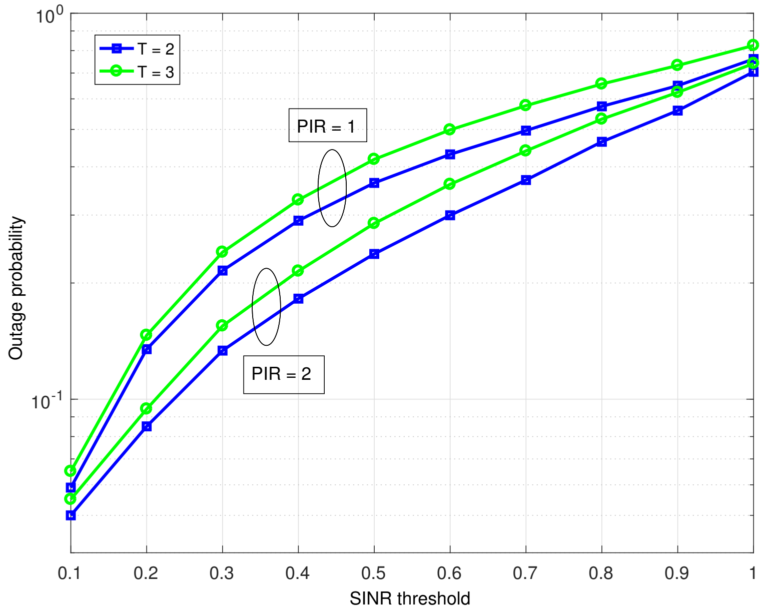


Figure 5.14: Outage probability against SINR threshold for different network parameters.

The Fig. 5.15 shows the performance of a network in terms of average hops for different tiers of interference and different values of packet insertion rates. One can see in the Fig. 5.15 that when the value of SINR threshold increases, average hops increases as well. It can be noticed that, for all values of SINR threshold for the value of tier of interference 3 and packet insertion rate 1, more hops are required by a message to reach at the destination compared to other network parameters. This is the severe performance of the network in terms of average hops when the value of PIR and tier of interference is large.

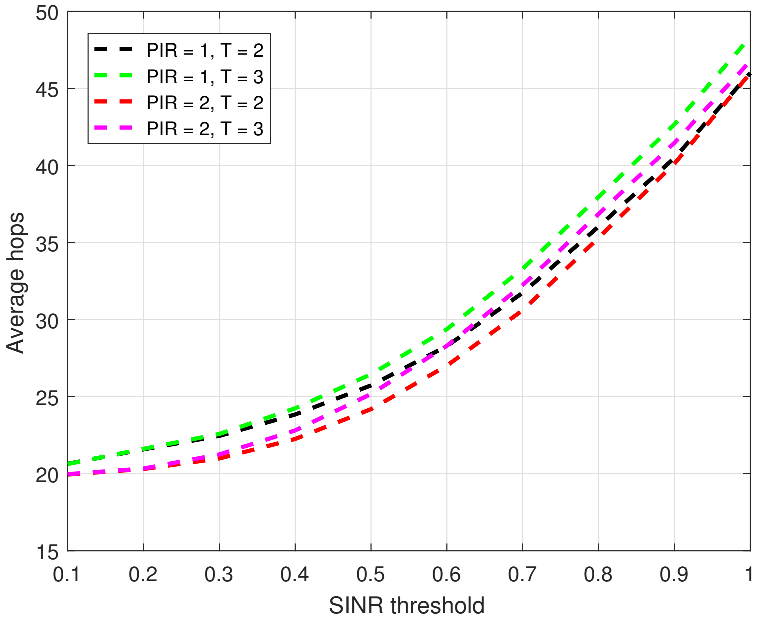


Figure 5.15: Average hops against SINR threshold for different network parameters.

Chapter 6

Conclusion & Future Works

In the thesis work, we analyzed the performance of a basic OLA network with single packet transmission from the source node to destination node in multiple iterations. The networks are considered real simulation models in which the nodes are deployed randomly in strip-shaped networks. The performance is carried out in terms of the success probability, the average hops(a message take from source to the destination) and the node density at different network parameters. We analyzed that the performance is totally dependent upon path-loss exponent, node density, transmit power and decoding threshold.

We then examined network performance in terms of energy efficiency using OLA-T protocol where we deliberately make some nodes idle to not to take participate in the transmission. We concluded that the energy efficiency of the network can be achieved by limiting few nodes to participate in forward transmission. However, higher transmit power per node is required in OLA-T network, to achieve a desired Quality of service.

We took our attention on multi-flow transmissions in half-duplex to analyze the affect on the basic OLA networks when several packets travel from the source node to the destination node in the network. In multiple packet transmission, two new network parameters, PIR and tiers of interference play vital role in the performance of cooperative OLA network. We concludes that for higher PIR, success rate improves but average hops and average time slots become high for all values of path-loss exponent and node densities. It can further be concluded that for higher value of tiers of interference, success rate decreases because more nodes of multiple levels contribute in the interference.

The future direction of this work would be to manage multiple sources that insert different packets simultaneously in the networks is the important direction of research.

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