LIMITATIONS OF IEEE 802.15.4 BASED WIRELESS MESH NETWORKS FOR WIRELESS LOCALIZATION

by

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ABSTRACT

LIMITATIONS OF IEEE 802.15.4 BASED WIRELESS

MESH NETWORKS FOR WIRELESS

LOCALIZATION

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It is highly desirable to create rapidly and inexpensively deployable mesh networks in certain scenarios. Consider the case of a large storage warehouse; workers are constantly moving in the area and not only do they need to send data periodically but their location needs to be tracked as well. Setting up such network can be accomplished with the IEEE 802.15.4 standard, but a mesh network must be created. There would need to be stationary 802.15.4 nodes that join together to form a backbone infrastructure. This backbone infrastructure (mesh network) would allow the workers, using mobile 802.15.4 nodes, to transmit their data from wherever they are as well as permitting the system to localize (find the location) the workers

within the warehouse. The backbone would then be responsible for relaying the data received from mobile nodes to destination nodes in areas outside their operating space.

This research work aims to shed more light on possible solutions and performance data of the previously described scenario. A model was created to show the behavior of a wireless mesh network built on the technology described in the IEEE 802.15.4 standard. Furthermore, models of mesh network routing and the application scenario have been devised in order to evaluate a proposed solution. We use our models to simulate a mesh network and client mobile nodes using the 802.15.4 standard in addition to existing wireless sensor data routing techniques to send data from mobile nodes to various data sinks. The findings will be presented and evaluation will be given as to how many client mobile nodes such network can accommodate.

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INTRODUCTION

1.1 Problem Description

In recent years, the research in the field of wireless sensor networks has begun to gain momentum. Scientists are using the networks to learn valuable information on a variety of topics. With this new emphasis in the networks, comes a need for wireless radios that can be used to transfer data without a need to consume large amounts of energy, which has motivated the establishment of the IEEE 802.15.4 standard. This standard defines the medium access and physical layers needed to create and transfer data within a low-rate personal area network. Thus, 802.15.4 has quickly become very prevalent in wireless sensor networks as it offers the means to rapidly build networks in an ad-hoc manner [2].

The 802.15.4 standard enables star-shaped and peer-to-peer communication topologies, allowing nodes to communicate with any node within their radio range [7]. This is very powerful as it can be extended to allow data to be routed between nodes without needing the nodes to be within a physical distance of each other. As all IEEE 802 standards, 802.15.4 defines only the physical and MAC layers, thus it does not describe how to create the large mesh networks as these networks need higher level concepts like smart data routing and network management.

It is highly desirable to create mesh networks in certain scenarios. Consider the case of a large storage warehouse. Workers are constantly walking the area and often need to send data to other locations in the warehouse. This can be accomplished with the 802.15.4 standard, but a mesh network must be created. There would need to be stationary 802.15.4 nodes that join together to form a backbone infrastructure. This backbone infrastructure would allow the workers, using mobile 802.15.4 nodes, to transmit their data from wherever they are as well as permitting the system to localize (find the location) of the workers within the warehouse. The backbone would then be responsible for relaying the data received from mobile nodes to destination nodes in areas outside their operating space.

This research work aims to shed more light on possible solutions and performance data of the previously described scenario. A model was created to show the behavior of a wireless mesh network built on the technology described in the IEEE 802.15.4 standard. Furthermore, models of mesh network routing and the application scenario have been devised in order to evaluate a proposed solution. We use our models to simulate a network using the 802.15.4 standard in addition to existing wireless sensor data routing techniques to send data from mobile nodes to various data sinks. The findings will be presented and described to show that the mesh networks can be created and are fairly reliable when routing data between various nodes in the network.

1.2 Outline Overview

This research work is organized in the following manner. In chapter 2, background information on the technologies used in the rest of this work will be provided. There will be a brief overview of wireless mesh network concepts, the IEEE 802.15.4 standard, and the data routing algorithm that was used in our models. In chapter 3, a description of the simulation models will be given. This will include a description of all the components that comprise the simulation. In chapter 4, scenarios used to test the wireless mesh network in the simulation will be described and presented. In chapter 5, the experiment results from the test scenarios will be presented and analyzed. Finally, chapter 6 will present conclusions and future work.

CHAPTER 2

BACKGROUND INFORMATION

In this chapter, background information on the concepts used in the simulation models is presented.

2.1 Wireless Mesh Networks

Wireless mesh networks (WMNs) have become a prominent research topic in the past years. WMNs are quasi-dynamic in nature, with nodes configuring and maintaining ad hoc networks between themselves. They can provide means for multi-hop communication between various nodes in the network.

2.1.1 Network Components

A WMN utilizes two types of network components, mesh routers and mesh clients. Mesh routers are used to create the backbone infrastructure of the network. Mesh clients can use that infrastructure to relay data. They each have different requirements and needs.

Mesh routers are nodes that have a minimal need for mobility and mostly remain in the same position. They connect with other mesh routers to create a network backbone that can be used to route data across the mesh. In addition to routing data, these nodes may have capabilities to communicate with different types of devices with the use of multiple radio interfaces.

Mesh clients on the other hand could be highly mobile. They communicate within the network by connecting directly with a mesh router in the backbone or by connecting with an access point that has a direct communication link with a mesh router [4]. The clients do not need to be as complex as mesh routers and often only have one type of interface to the network. Some examples of a typical mesh client could be cell phones, laptop computers, and wireless sensors.

2.1.2 Network Architectures

Although there is much ongoing research in WMNs, the architectures of the networks can generally be classified into the three architectures; infrastructure WMNs, client WMNs, and hybrid WMNs [4]. Infrastructure WMNs utilize mesh routers and clients, with all communication being done between routers and clients. Client WMNs utilize only mesh clients. Hybrid WMNs utilize both mesh routers and clients and allow communication between routers and clients, as well as between clients.

Infrastructure WMNs are built by using mesh routers to create network backbone [4]. The mesh routers form the network backbone by joining themselves together with wireless links. Each router will have a gateway or bridge to allow for various other wireless technology devices to join the network. Mesh clients that contain an interface with the same wireless technology as the mesh router can connect to that router directly. Mesh clients with different types of wireless technologies for their interface must connect to an access point for that technology that has a direct link to a mesh router [4].

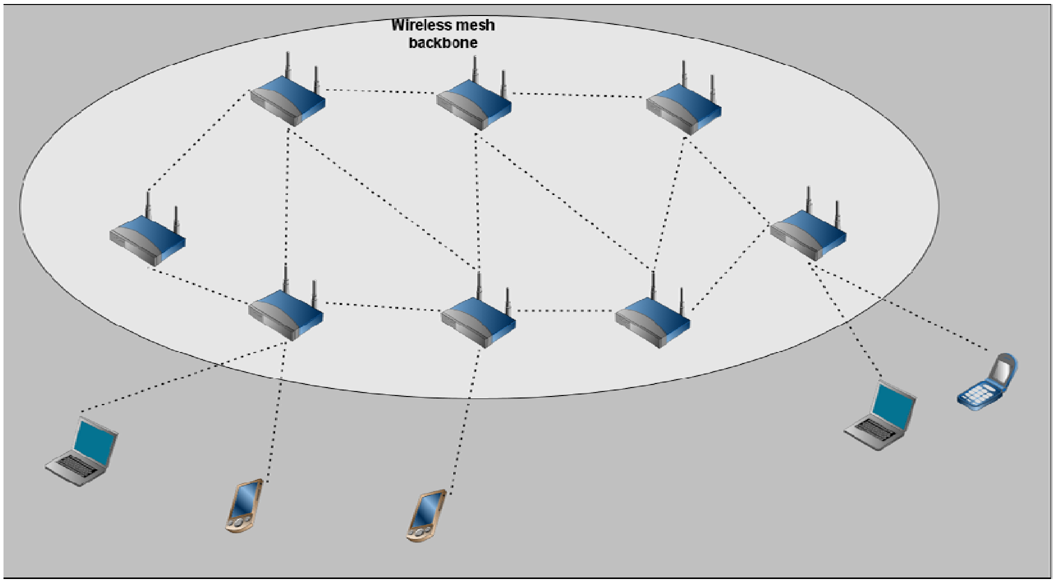

Figure 2.1 Example of an infrastructure WMN

Client WMNs are created with only mesh clients. The clients join together to form an ad hoc network as the clients move within the network area. This network is strictly peer-to-peer with all clients able to communicate directly with other clients [5].

The hybrid WMN architecture combines the infrastructure and client WMNs. These networks provide the capability to provide peer-to-peer communication between mesh clients, but still provide the power to route communication data across the network with mesh routers [4].

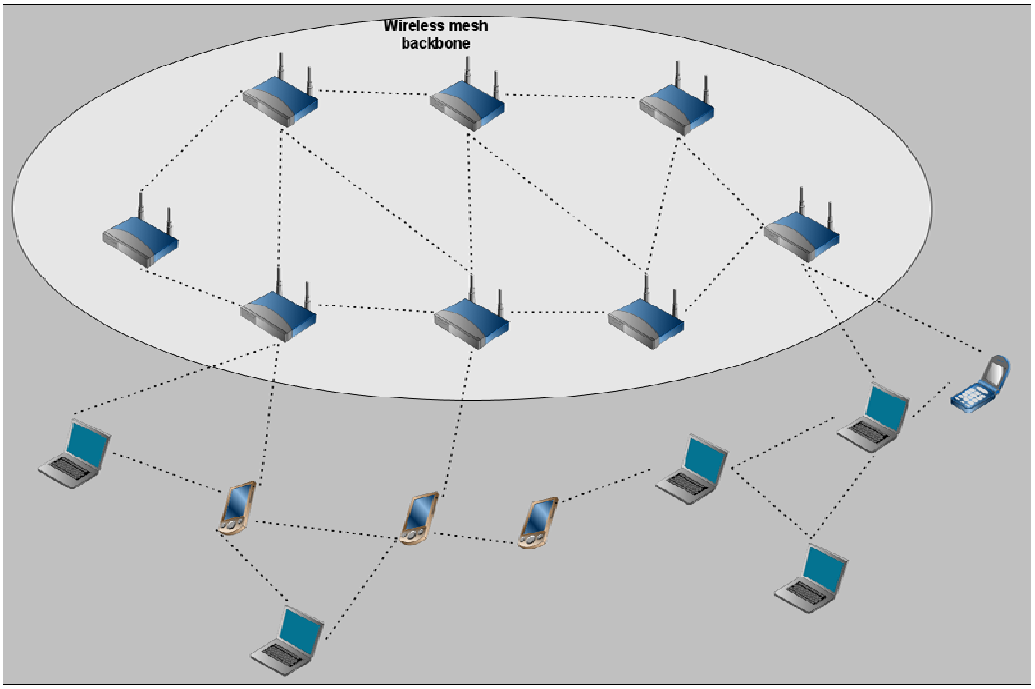

Figure 2.2 Example of a hybrid WMN

2.2 IEEE 802.15.4

The IEEE 802.15.4 standard was created to provide the ability to create low rate wireless personal area networks (LR-WPAN) for devices with low power needs [7]. It specifically details the available low-level network topologies, as well as the MAC and physical layers that all devices must use to comply with the standard.

2.2.1. Device Types

In [2] two types of devices are detailed, full function devices (FFD) and reduced function devices (RFD). The biggest difference between FFDs and RFDs is on their ability to behave as a coordinator. A coordinator is a device that serves as the manager of the personal area network and assigns all network addresses. FFDs can act as coordinators and can communicate with both types of devices. RFDs cannot act as coordinators and can only have communication with coordinator devices. RFDs are usually small devices that do not need to send large amounts of information, such as a sensor or light switch. FFDs are usually devices that are attached to a dedicated means of power and need to send large amounts of data [2].

2.2.2. Network Topologies

The IEEE 802.15.4 standard provides two network topologies that may be used: star and peer-to-peer [1]. The star network topology is a centralized topology where all communication must be handled via the personal area network coordinator. In a peer-to-peer network topology each node can communicate with all other nodes in the network.

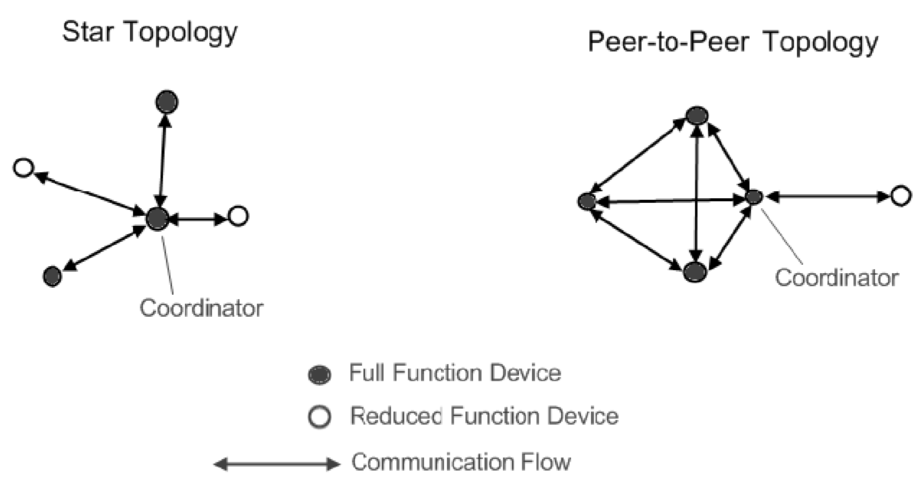

Figure 2.3 Star and Peer-to-Peer Topologies.

The star topology is created by the personal area network coordinator, which is the first full feature device (FFD) node to initialize and send out a network beacon.

FFD and reduced feature device (RFD) nodes existing in the operating space of the coordinator will join the star network upon receiving the network beacon. From that point forward, communication can only exist between a device and the coordinator in one of the following modes:

- Device to coordinator
- Coordinator to device

The peer-to-peer topology consists of mainly FFDs that all exist in the same logical operating space. The first FFD to initialize is designated the personal area network coordinator, which assigns addresses to all other devices. The FFDs can directly communicate with all other devices within the operating space, without the need to route communication through the network coordinator. The RFDs in the network can only connect to and communicate with the personal area coordinator. This is the basic topology that provides a relatively straight forward way to create higher level network topologies such as a mesh network.

2.2.3. MAC Layer

The MAC layer in 802.15.4 devices are responsible for associating with coordinator devices and handling the communication between all devices. This is handled in two different manners, depending on how the network devices are enabled for the use of network beacons. In network beacon enabled networks, the beacon is the driving force in building the network and determining the communication between devices. In non-enabled network beacon networks, the beacon only plays a role in building the networks.

The network beacon is a MAC frame that is used to synchronize communication between nodes. The beacon information is located within the MAC payload, and is surrounded by a MAC header and a frame check sequence. The beacon information describes how the superframe, the structure used for beacon-enabled communication between devices, will be organized. It also contains network addressing information.

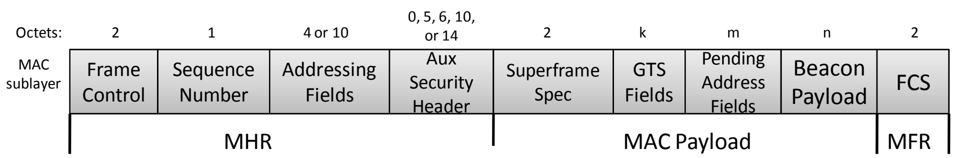

Figure 2.4 Beacon frame structure

2.2.3.1 Network Association

Network association is handled similarly by both beacon enabled and non-beacon enabled networks. Unassociated devices generate an association request and transmit it to a coordinator in the network it wishes to join. Upon receiving a request, the coordinator sends an acknowledgement which forces the unassociated device into a waiting mode (waiting to receive the response to the association request for a preset amount of time). The coordinator takes the association request and generates an association response, which will include the network address for the new device, and sends it to the unassociated device. The unassociated device sends an acknowledgement to the coordinator upon receiving the association response and then notifies any higher layers of the new network association. The coordinator now updates the status of the new device as being part of the network.

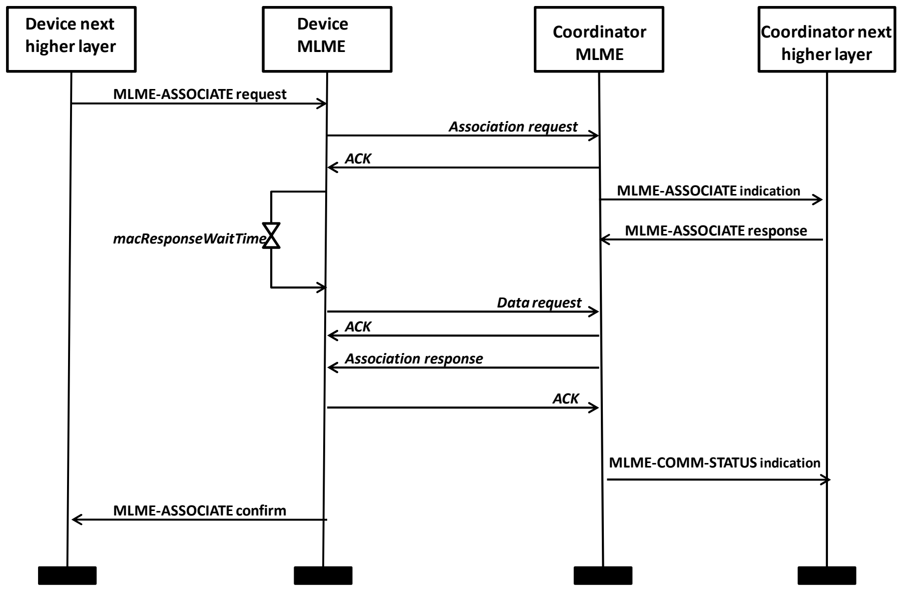

Figure 2.5 Network association sequence

2.2.3.2 Sending Messages in Beacon Enabled Networks

Beacon enabled networks, by their nature; tend to be of a star topology, meaning that all message communication must take place between a device and its network coordinator [7]. To handle this communication, 802.15.4 defines the use of a superframe structure. The superframe is divided into 16 equal time slots, and is started and ended by network beacons sent by the network coordinator. If a device wishes to send data during this superframe (contention access period), it must attempt to access one of the slots using the slotted CSMA-CA algorithm. Additionally, a network coordinator can use a portion of the superframe to offer guaranteed time slots. In this case, the contention access period is shortened and the guaranteed time slots will immediately follow in what is considered the contention free period.

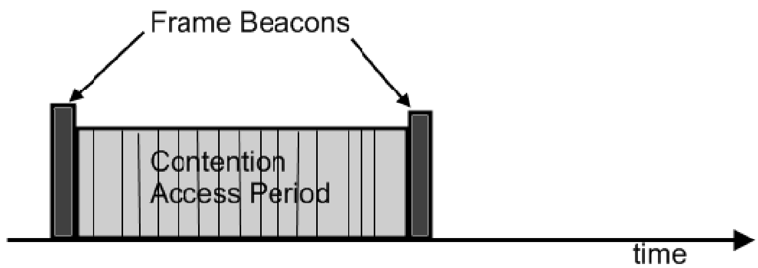

Figure 2.6 Superframe with no GTS

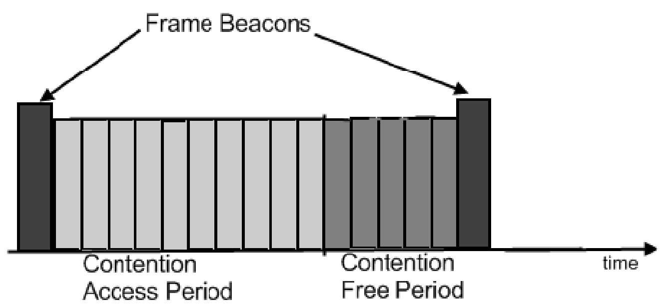

Figure 2.7 Superframe with GTS

If the coordinator has data for a particular device, the coordinator will add data to the beacon payload that will notify the device that it has data pending. The device that is to receive the data will select a slot to attempt to send a data request to the coordinator. If the coordinator receives the request and can send the data at that time, it will reply with an acknowledgement and then begin to send the data. If the receiving device successfully receives the data, it replies to the coordinator with an acknowledgement. If at any point, the data being sent is not acknowledged the receiving device will select another slot in the contention period if possible, or attempt to try again upon receiving the data notification in the next beginning network beacon.

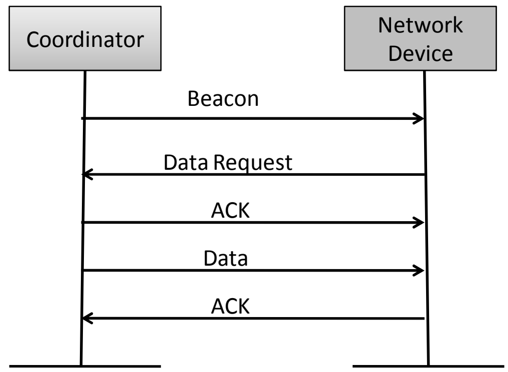

Figure 2.8 Coordinator to device communication in a beacon enabled network

If a device has data to send to the coordinator it will wait to receive a network beacon from the coordinator to signal that the coordinator is available for communication. The device will select a slot in the contention period and attempt to send the data frame to the coordinator at that time. If requested, the coordinator will send an acknowledgement to the device if the data was received successfully; otherwise the device will notify its upper layer that the data was sent. If the device had requested acknowledgement and did not receive it, it would attempt to send the data again in another time slot just as it had in the coordinator to device communication.

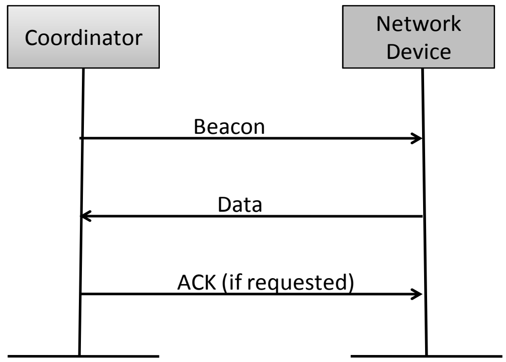

Figure 2.9 Device to coordinator communication in a beacon enabled network

2.2.3.3 Sending Messages in Non-Enabled Beacon Networks

Devices in non-enabled beacon networks tend to be connected in a peer-to-peer topology, so all devices can communicate with all of the other devices in their personal operating space [7]. This makes the need to wait for a network beacon irrelevant and the access to the bandwidth CSMA based. To send data, the devices will access the wireless medium using the un-slotted CSMA-CA algorithm. When a device has data to send it will choose a random number of preset waiting periods to attempt to send the data to the receiving device. This method is much simpler than using the network beacons to synchronize communication, but it may also increase the occurrence of wireless packet collisions.

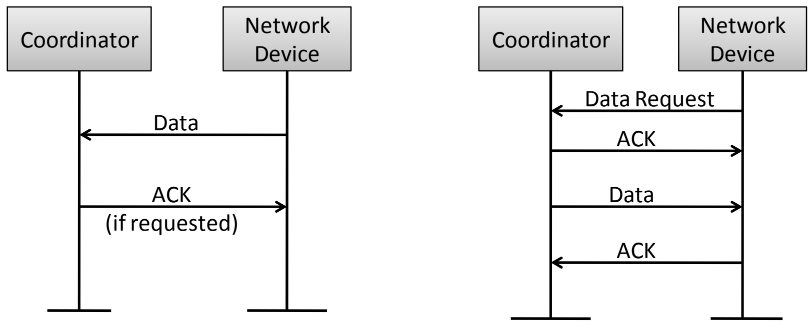

Figure 2.10 Communication in non-beacon enabled networks

2.2.3.4 CSMA-CA

The MAC uses CSMA-CA to handle access to the radio channels. When the layer receives data to be sent, it will randomly choose a later time to attempt to send data. In slotted CSMA-CA, this delay is selected by randomly selecting a slot in the contention access period to use for transmission. In un-slotted CSMA-CA, this delay is selected by randomly selecting a number of preset time periods to wait. After such wait period, the layer detects if the channel is busy. If the channel is not busy (there is no energy detected), the layer will begin to transmit the data onto the radio channel. If the channel is busy, the MAC will check the radio channel at a later time period or contention slot and attempt to send the data again. If the MAC cannot access the channel after a set number of attempts, the data transmission will be reported as a failure.

2.2.4. Physical Layer

The physical layer (PHY) in the 802.15.4 is responsible for enabling and disabling the wireless radio and determining the status of the wireless channel for CSMA-CA. The layer can operate the wireless radio on different channels at various frequencies to get different transmission rates and in some cases different transmission powers influencing the transmission range.

Table 2.1 802.15.4 Frequencies and Transmission Rates

Frequency Range	**Transmission Rate**
868.0 – 868.6 MHz	20 kb/s
902.0 – 928.0 MHz	40 kb/s
2.4 – 2.4835 GHz	250 kb/s

2.3 Minimum Cost Forwarding

The IEEE 802.15.4 standard does not specify a network layer for devices, nor does it define how to use the peer-to-peer topology to form higher layer topologies. This requires the use of a network layer protocol. The protocol must be able to handle the creation of a multi-hop network and be able to route data between nodes. The use of minimum cost forwarding will satisfy both of these requirements.

Minimum cost forwarding is a simple routing protocol that can be used in a sensor network for forwarding data from a source node to a designated sink node [21]. It allows all nodes to send data to the sink along the minimum cost path. For this to be possible, all nodes must have valid link costs based on the same criteria. From that point, the nodes must be able to differentiate between its connected links to determine which link should be chosen when routing data towards a sink.

2.3.1. Cost Field Establishment

The cost field must be established with a meaningful value. The value must be unique enough that it will allow for a true path determination [21]. Simply setting each link cost as a default value will not allow the network to be traversed in an efficient way. The initial starting node, usually a sink node, will be set with its initial link costs and will then send the cost values to its neighbors. Its neighbors will receive the link costs values and add them their link costs and forward these new values, which represent their costs to the initial node, to their neighbors, who in turn do the same. Eventually all nodes will have a link cost to reach the initial node. This process will be repeated with each node that is intended to receive data from all other nodes so that upon completion each node will have built a table storing each sink node with a total path link cost associated with it.

Figure 2.11 shows an example of the cost field calculation for a network. The node A in the figure is the sink node and sends its cost to its neighboring nodes, B and C. These nodes store the cost to the sink and the next hop node, which in this case is the sink node. The nodes B and C now calculate the costs to route data to node A through them. These new costs are sent to the neighboring node D. Node D receives both costs and stores the node with the minimum cost as the next hop node, which is node C. Node D would now send its routing cost to its neighboring nodes as the process would continue until all nodes had a cost and next hop node stored for the sink node, node A.

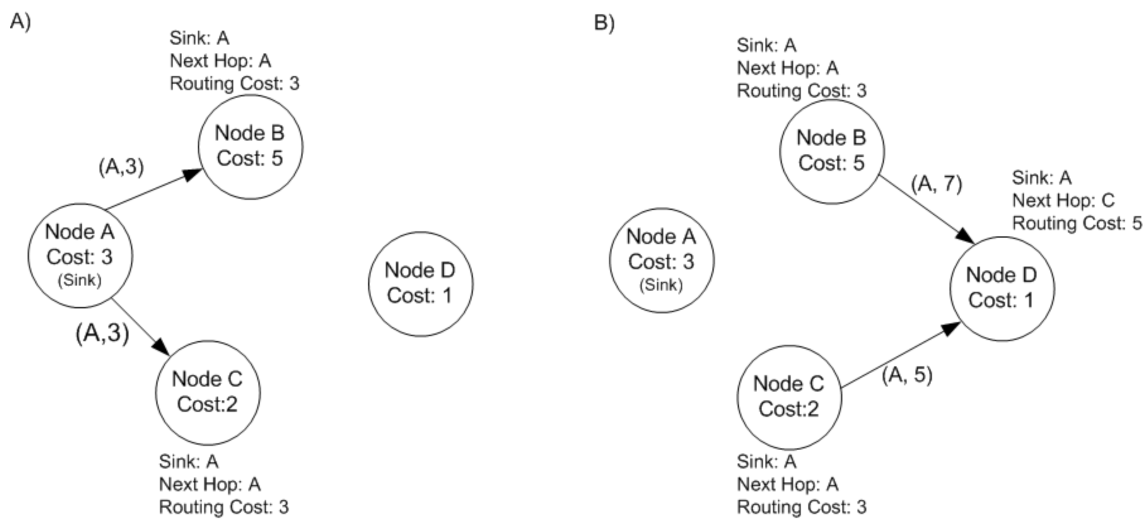

Figure 2.11 Cost calculation and routing table creation.

2.3.2. Cost Field Use in Routing Decisions

With each node having access to a link cost associated with each sink node, the nodes can determine which next-hop node to select when routing data. For example, if a node x receives a data that is addressed to node z as its final destination, node x will first search its link cost table for an entry for node z. If such entry exists in the table, node x retrieves the link cost values associated with it and chooses the next hop node with the lowest value. The next hop node receives the data and does the equivalent. This continues until the data is received by node z. Following this method, allows the routing of the data to be handled in a distributed manner utilizing the greedy nature of the algorithm [21].

The routing decision process is shown in figure 2.12. Node A sends a packet to node B that is addressed to the sink node Z. Node B has two next hop entries for the sink node. Node B will compare the costs for the two entries and choose the next hop node with the minimum cost. In this case, node B selects node C and routes the packet to the node. Node C would perform the same process as would all next hop nodes on the path to the sink.

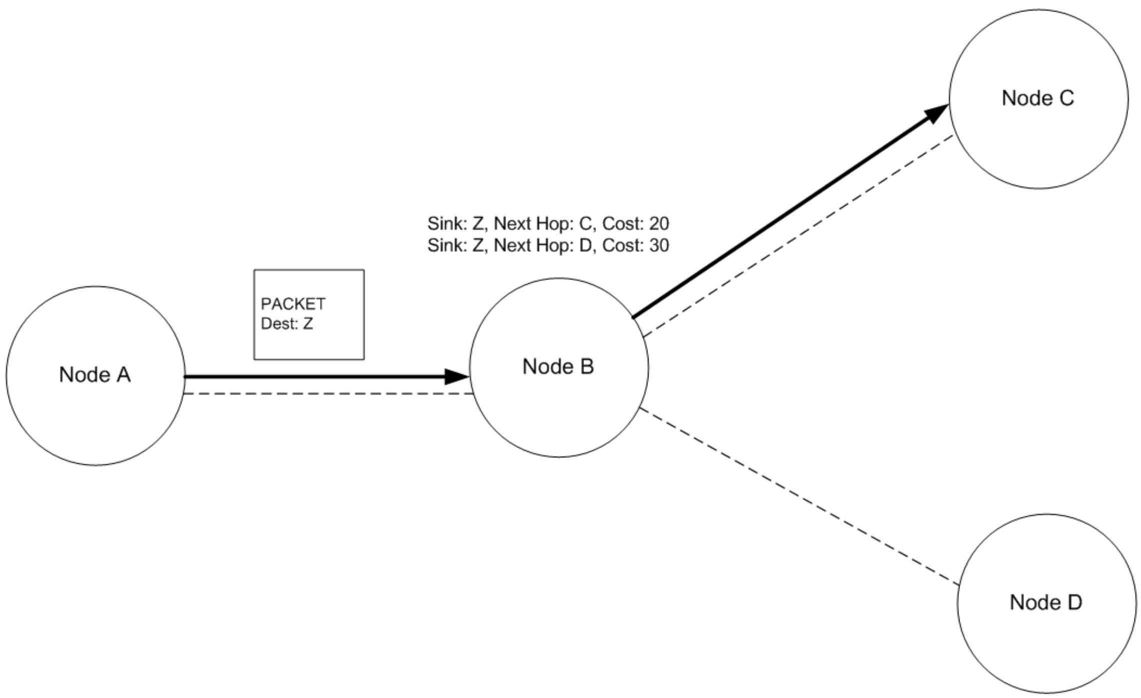

Figure 2.12 Routing decision example

CHAPTER 3

SIMULATION MODEL OVERVIEW

A custom written, object oriented (C++) discrete event simulation [12] tool is used to model a location tracking system using IEEE 802.15.4. At its heart, our simulation effort consists of a simulation engine and numerous simulation events. Events are created and set to execute at a certain time *t*. These events are input into the simulation engine which in turn sorts the current group of events to ensure they execute in chronological order. This allows the system behavior to be modeled in such a way that it can be studied to gather lifelike performance data.

Models of each of the above described layers were created for a discrete event simulation, thus models are organized into layers. A simulation engine was created to receive and execute simulation events from each of the models. This in turn allowed for performance data to be collected on a simulated 802.15.4 mesh network. These models will now be further described.

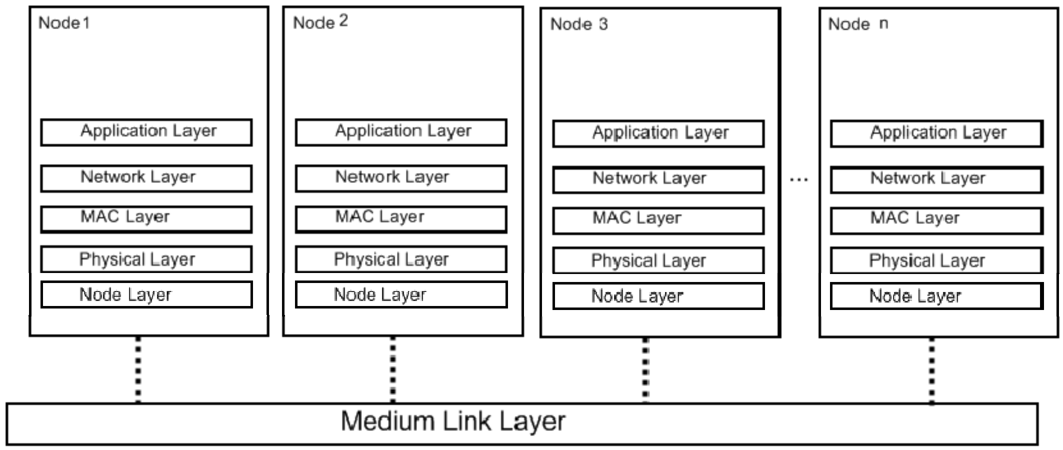

Figure 3.1 Layers in node models

3.1 Model Components

3.1.1 Medium Link Model

In this model, the medium link is used to model a wireless link between nodes. It is responsible for the relaying of packets between nodes. The link will propagate all packets transmitted by a node to all other nodes within a radius of *r* meters at a configured link transmission speed. Upon transmission, the link also checks for packet collisions when multiple nodes are transmitting packets within overlapping transmission radii.

This model has the following key events:

- Start of a packet transmission
- End of a packet transmission

3.1.2 Node Layer Model

The node layer model is responsible for storing the location of a node within a defined area. The location of the node is set at the commencement of the simulation. Nodes that are used in the backbone mesh infrastructure maintain a static location. Mobile nodes however traverse the defined area throughout the simulation duration. The node layer model handles all updates to the location of mobile nodes using the random waypoint mobility model described in [15]. In this model, nodes move for a random duration with a random velocity vector, then changing their direction and speed again based on the same random distributions.

3.1.3 Physical Layer Model

The physical layer model is used to control the use of the wireless radio. It must enable and disable the radio when instructed to do so by a higher layer. It provides the ability to do carrier sensing for CSMA-CA. It must also use the wireless radio to transmit packets onto the medium link and store the current transmission status.

This model has the following key events:

- Enable radio
- Disable radio
- Do carrier sensing
- Transmit packets onto the medium link

3.1.4 MAC Layer Model

The MAC layer model has the main responsibility of controlling access to the medium link when nodes have data to transmit. The model must first create the

802.15.4 network by having the first node to initialize assign itself as the network coordinator. This coordinator will periodically send network beacons which will allow all other nodes to associate themselves with the network and receive a network address. Now all nodes can begin to access the medium link by using un-slotted CSMA-CA.

This model has the following key events:

- Initialize the MAC layer (assign network coordinator)
- Broadcast network beacon
- Associate with the network
- Send data with CSMA-CA

3.1.5 Network Layer Model

The network layer model will create the wireless mesh network and route data between nodes by using minimum cost forwarding. Upon layer initialization, a node that operates as a data sink will broadcast an advertisement (ADV) message to neighboring nodes that contains its current location. Nodes receiving the ADV message use the sink location to calculate their next hop cost to the sink. These nodes now broadcast ADV messages that contain their minimum next hop cost and to reach the sink node to their neighboring nodes. This continues until all nodes have a minimum next hop cost and node for each sink node in the network. Upon receiving a packet of data from a higher layer, the network layer will use the sink destination to determine the next hop node to send the packet along the minimum cost path.

When network layers in mobile nodes receive a data packet from a higher layer, they must exhibit a slightly different behavior. The mobile nodes do not have the ability to store a next hop node for paths to a sink node. These nodes must create ad hoc paths to the sink by routing its data packets to the nearest static node. This is done by broadcasting what is known as a HELLO message in ad hoc on-demand vector routing [18]. A static node receiving this message will respond to the HELLO message if it can handle the request. At this point, the mobile node will route its data packet to the responding static node.

This model has the following key events:

- Broadcast ADV message
- Broadcast HELLO message
- Respond to HELLO message
- Route data to next hop

3.1.6 Application Layer Model

The application layer model is used to generate data for mobile nodes that needs to be localized in the mesh network. The data is generated at uniformly random intervals and is addressed to be sent to a randomly selected sink node within the network. The layer in sink nodes will handle the receipt of the localized data.

This model has the following key events:

- Generate data packet to send to a sink node
- Receive data packet in a sink node

3.2 Model Behavior

The simulation model utilizes each layer to mirror the activities in an actual wireless mesh network consisting of 802.15.4 devices. The layers are stacked on top of each other to form what we refer to as a node.

The model begins by uniformly placing N static nodes in a rectangular area. A subset of these N nodes will be marked as data sinks. These data sink nodes will initialize and initiate the formation of the mesh backbone for the infrastructure WMN. It is at this point that a variable number of mobile nodes are randomly placed in the rectangular area. These nodes will traverse the area and periodically generate data to be sent to a randomly chosen data sink in another part of the area.

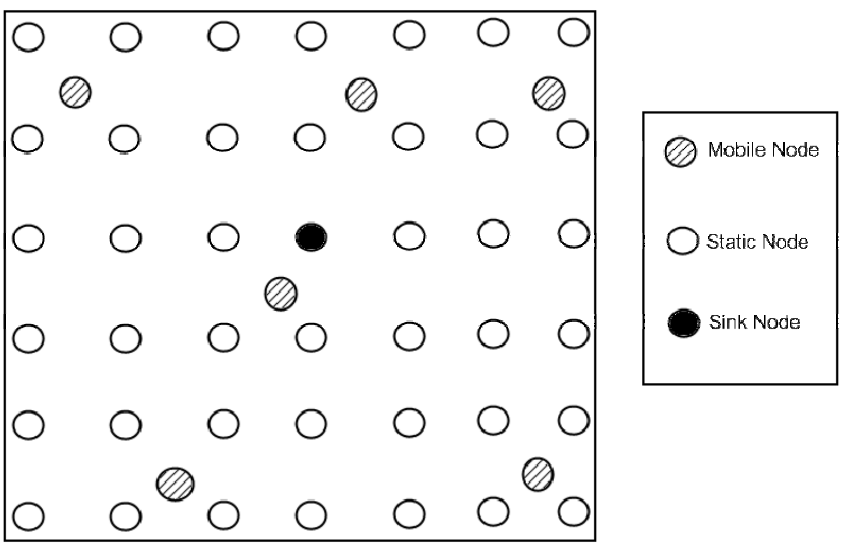

Figure 3.2 Sample layout of nodes in the rectangular area.

Examples of how the layers interact with one another in the model are shown below in the form of sequence diagrams. Figure 3.3 shows the behavior for node associating itself with the 802.15.4 network coordinator. Figure 3.4 displays the behavior for a static node that is participating in the creation of the backbone in the wireless mesh network. Figure 3.5 displays the behavior for a mobile node sending a packet to the mesh backbone to be routed to a sink node. Finally, Figure 3.6 displays the behavior of a static node receiving a packet from another static node that is to be routed to a data sink.

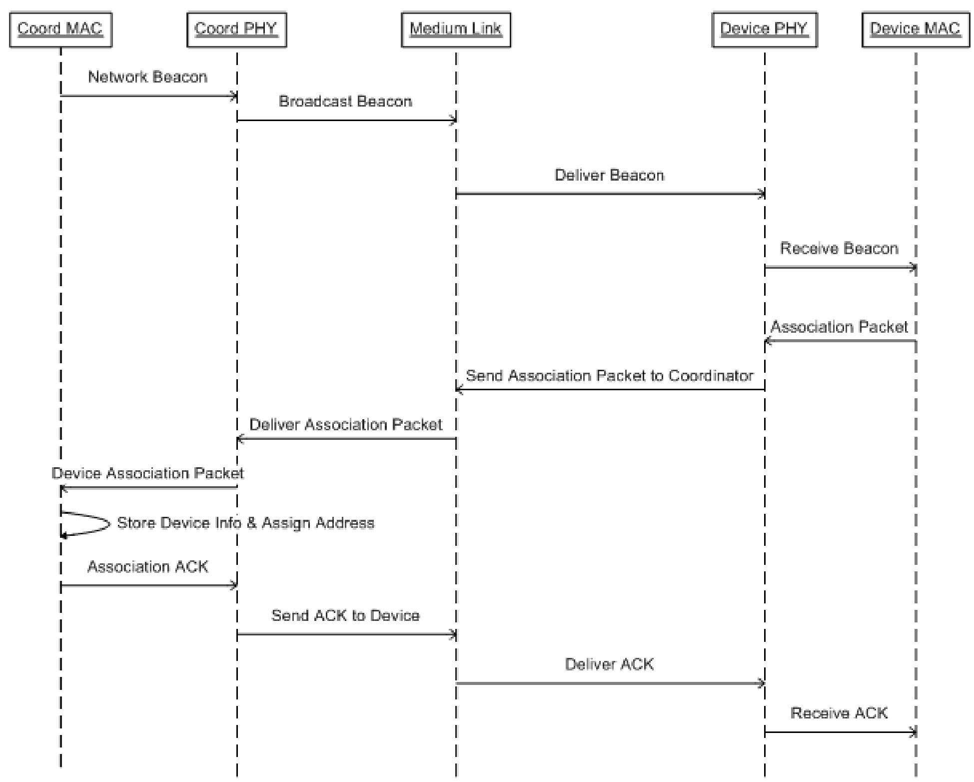

Figure 3.3 Model sequences for MAC device association.

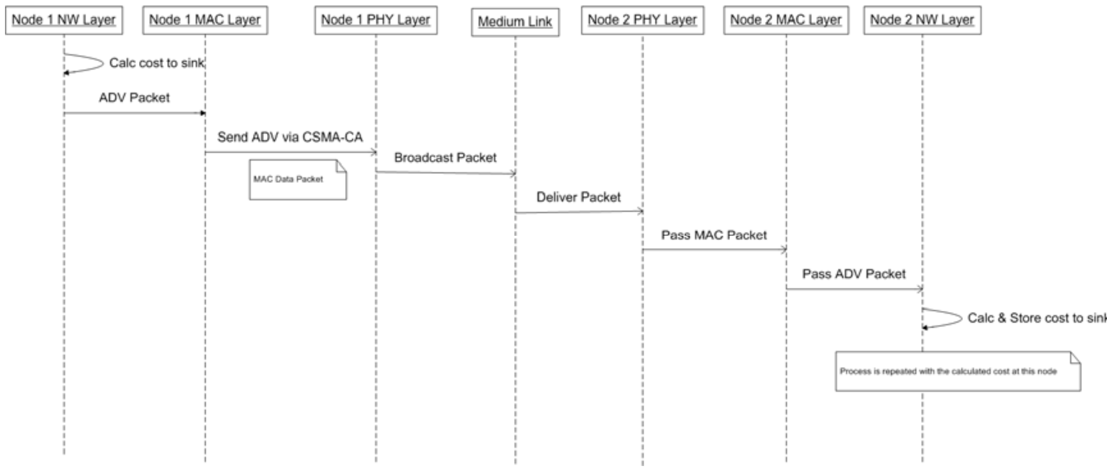

Figure 3.4 Model sequences for mesh backbone creation.

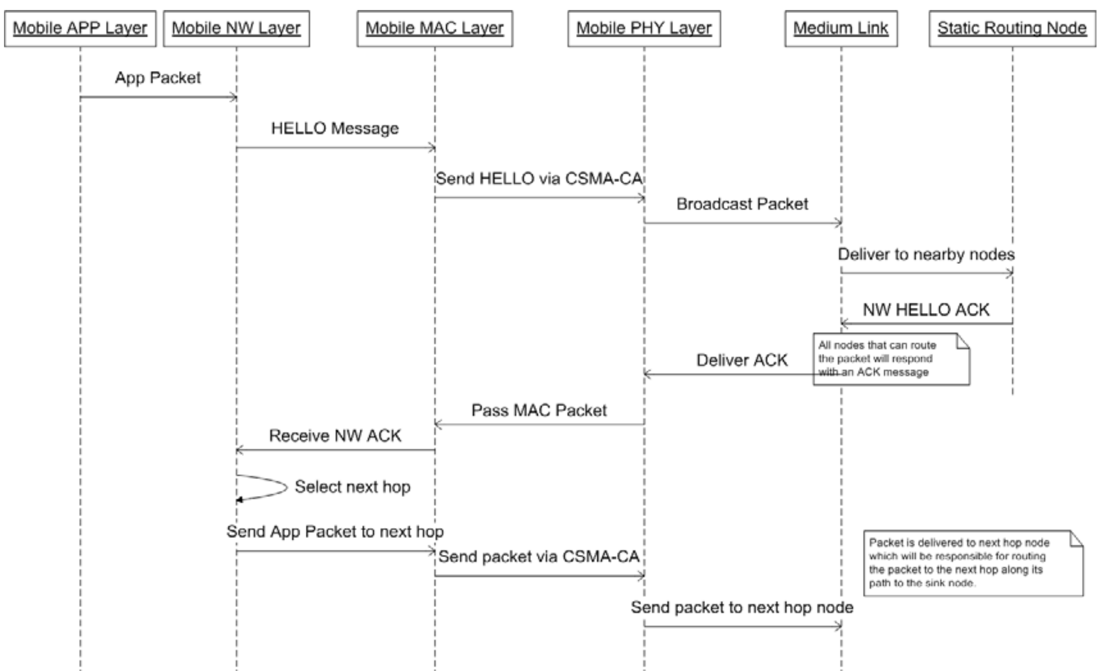

Figure 3.5 Model sequences for a mobile node sending a packet.

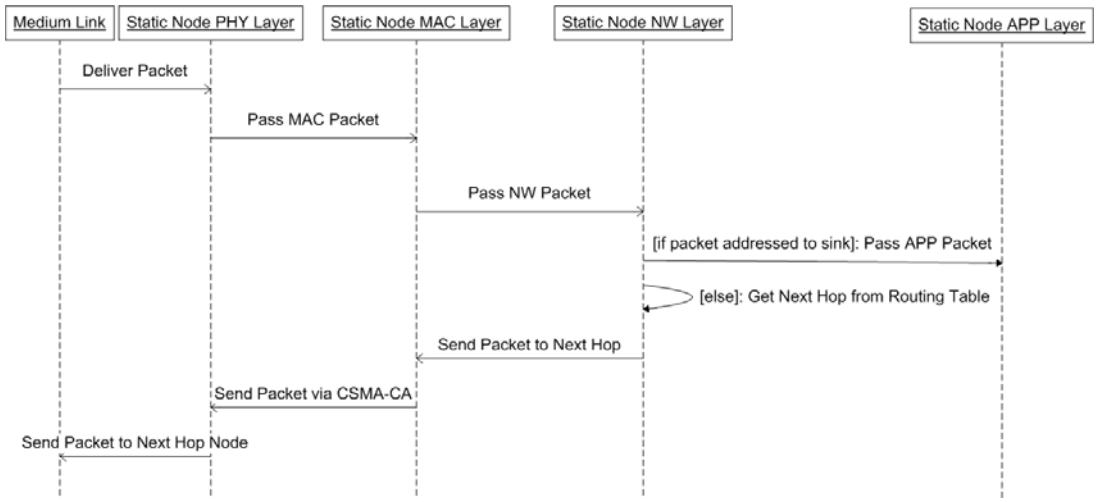

Figure 3.6 Model sequences for a static node routing data to its next hop.

CHAPTER 4

EXPERIMENT SETUP

Building a wireless mesh network with 802.15.4 nodes creates the ability for mobile 802.15.4 nodes to be localized within the network. The mobile nodes can send data to a sink node in another are without a wireless link for direct communication. This allows the network as a whole to achieve similar goals as those for other ad hoc wireless networks that aim to send data to a designated sink node. However, when using a mesh network the locations and number of sink nodes must be chosen with extra care. If the sink nodes are placed in an area that will require most data packets to travel long paths and possibly introduce unnecessary network complications. If the incorrect amount of sink nodes are used similar problems may occur.

Due to the effects the decisions on the sink node population number and their location can have on network performance, the possible scenarios with various sink node configurations should be studied. In this chapter we define a set of scenarios that are aimed to simulate possible selections for sink node configurations. The scenarios will be executed so that performance data on the networks can be extracted and analyzed. The scenario results will be presented in the next chapter.

4.1 Scenario-1: Single Sink Node Placed at a Corner

In this scenario we model the use of a single sink node placed on a corner of the rectangular network area. This will require that all mobile nodes send their data packets to a single destination. By locating the sink node on a corner of the network area, there will be instances where a mobile node might have its data routed along the diagonal of the area. This routing path would represent the longest straight-line path a data packet would have to travel to reach the sink node.

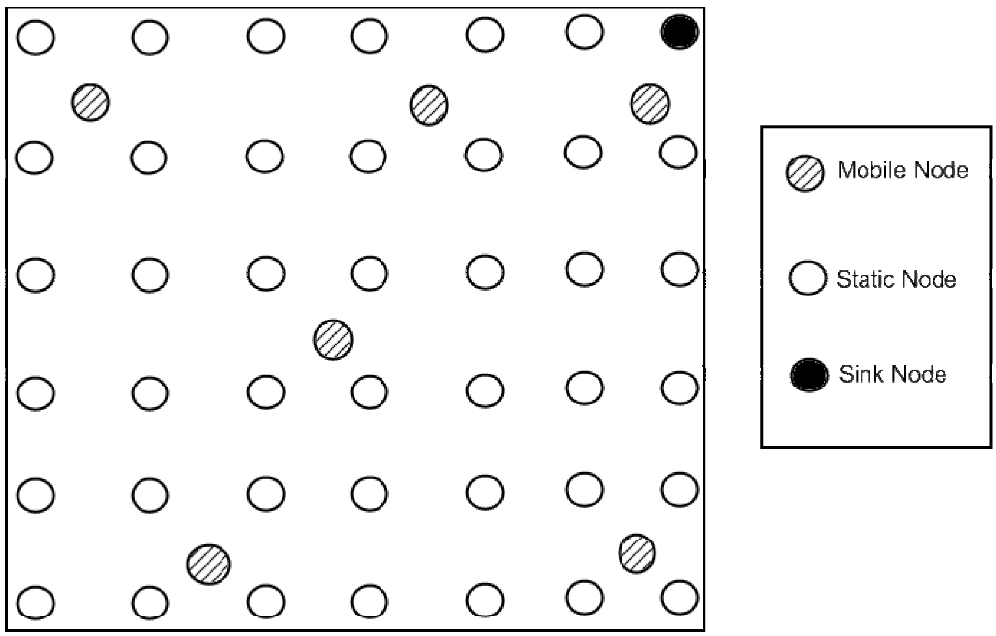

Figure 4.1 Sink node placed at a corner

<u>4.2 Scenario-2: Single Sink Node Placed at the Center Point</u>

In this scenario we model the use of a single node placed near the center point of the rectangular network area. This will still require that all mobile nodes send their data packets to a single destination. However, by locating the sink node in the center of the area it creates a situation where the maximum straight-line path to the sink node is 50% less costly than the path used in the previous scenario.

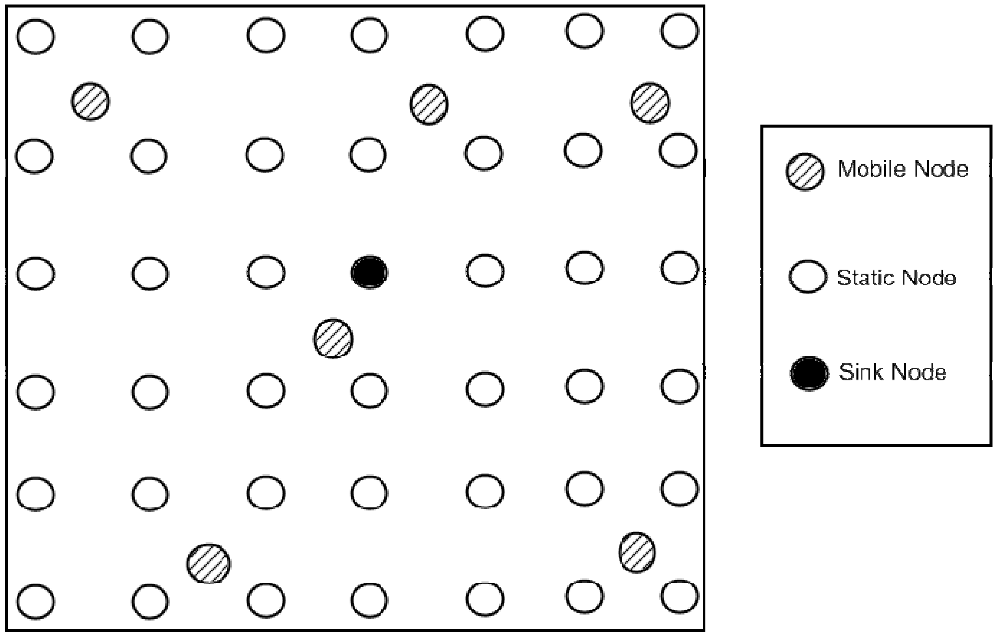

Figure 4.2 Sink node placed at center

4.3 Scenario-3: Multiple Sink Nodes Placed at the Corners

In this scenario we model the use of multiple sink nodes, with each node placed on a corner of the rectangular network area. This allows the mobile nodes to select a data packet destination from the multiple sink nodes present in the area. This provides a more ideal network solution, but there will remain some instances where the mobile nodes would still have to send data packets along the diagonal paths as in the first scenario. This will test how the mesh network reacts to having to simultaneously route data from the mobile nodes to sink nodes in completely separate portions of the coverage area.

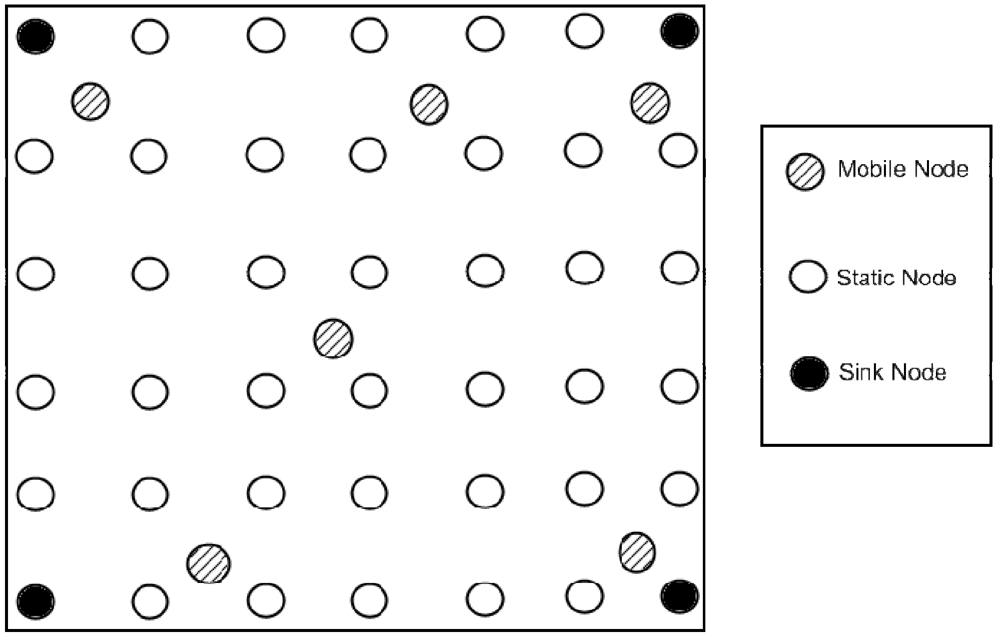

Figure 4.3 Sink nodes placed at corners

4.4 Scenario-4: Multiple Sink Nodes Placed Around the Center Point

In this scenario we model the use of multiple sink nodes placed around the center point of the rectangular area. This still allows the mobile nodes to select from multiple sink nodes, but also eliminates the possibility of a mobile node having data routed along the entire diagonal path. With all sink nodes placed in the center of the area, all mobile nodes should have their data packets routed towards the center of the network regardless of their location. This will test how the network handles the scenario where a majority of the data generated must be routed to a certain area of the network as all data will be sent to the center of the network.

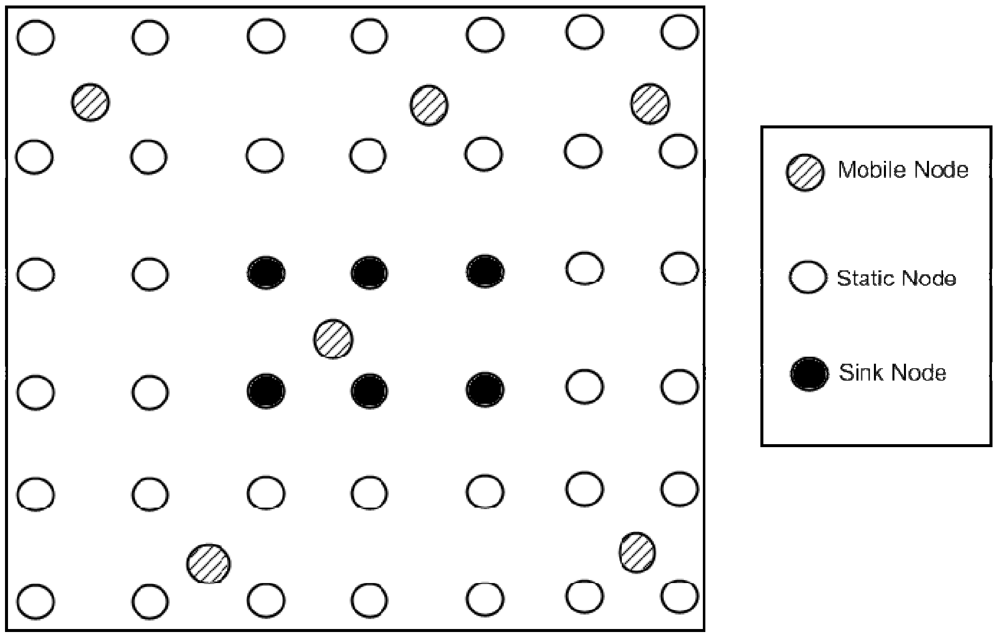

Figure 4.4 Sink nodes placed around center point

CHAPTER 5

EXPERIMENT RESULTS

In this chapter we present findings and results from the executions of the scenarios presented in the previous chapter. Each scenario was executed with a variable number of mobile node populations and mobile node packet arrival rates. Each mobile node in the scenario networks generates data packets of a uniformly distributed size of 250 ± 10 bits at a rate based on the designated packet arrival rate. These networks are used to extract performance data on the following: total network load, average packet delay, network throughput, and network goodput. Each experiment was performed to show a 95% confidence that the results are within a 5% relative to the mean error.

5.1 Single Sink Scenarios (Scenarios 1 and 2)

The single sink node scenarios were intended to show how the location of a single sink node would change the performance behavior of the mesh network. The scenarios place the sink node on a corner of the area (Scenario 1) and at the center of the area (Scenario 2).

5.1.1 Scenario 1 Results

In Figure 5.1, we show the effect that the packet arrival rate of each mobile node and the mobile node population size has on network load. As the packet arrival rate increases, the network load percentage increases. As the population of mobile nodes increases, the total network loads increase accordingly. This is to be expected as increasing the number of mobile nodes present in the network by increases the packet arrival rate for the entire network by n times, where n represents the mobile node population.

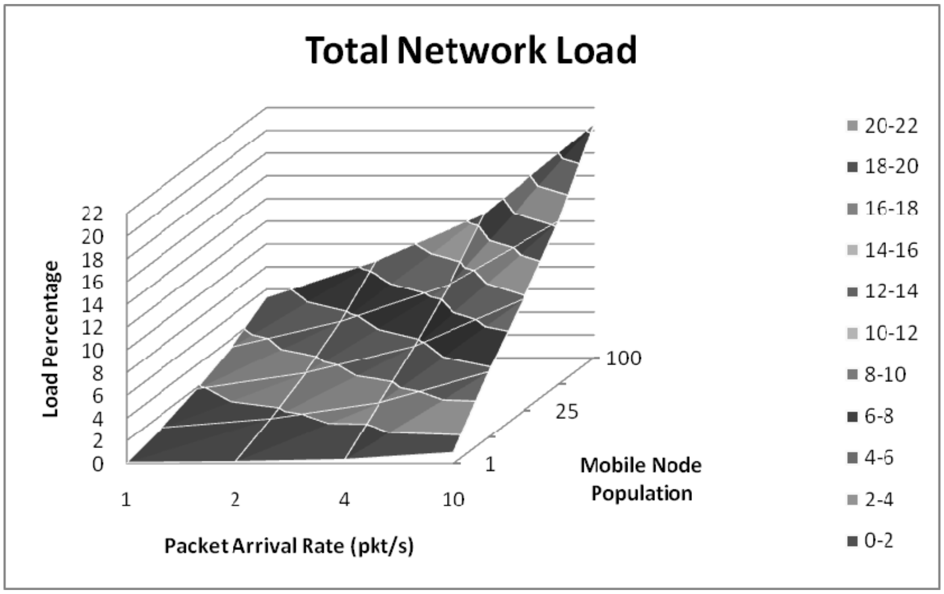

Figure 5.1 Total network loads for a network with a single sink node placed on the corner of its coverage area.

In Figure 5.2, we show the average end-to-end packet delay for packets sent from a mobile node to a sink node. As the packet arrival rate per mobile node increases, the amount of delay for a packet routed to the sink destination increases exponentially.

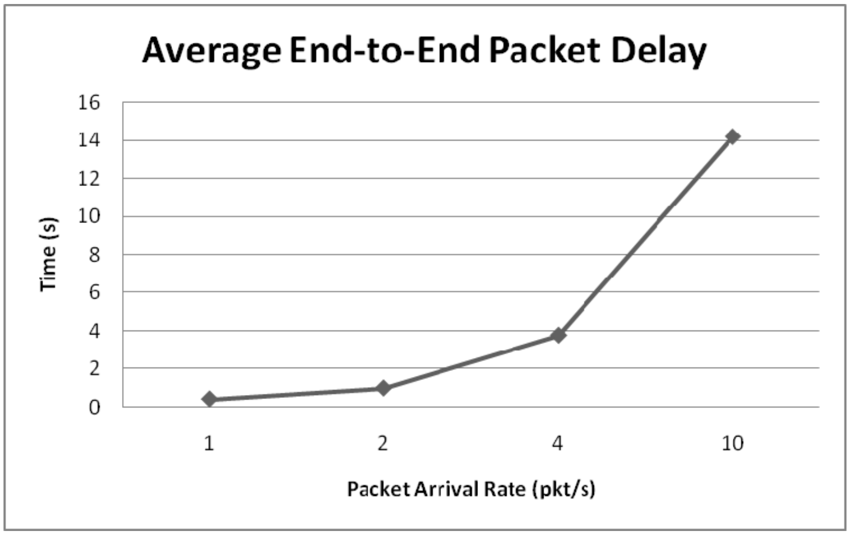

Figure 5.2 Average end-to-end packet delays due to packet arrival rate

Figure 5.3 shows the network throughput and goodput as the packet arrival rate of each mobile node increases. Network throughput is considered the bit rate at which data from any layer is successfully transmitted and received in the network. Network goodput is considered the rate at which the sink nodes receive the meaningful location data from mobile nodes in its application layer. The figure shows that though the network throughput uses approximately 25% of the symbol rate for the network, the goodput remains below 5%. The network throughput also greatly increases as the packet arrival rate increases; however the network goodput only increases in a linear manner.

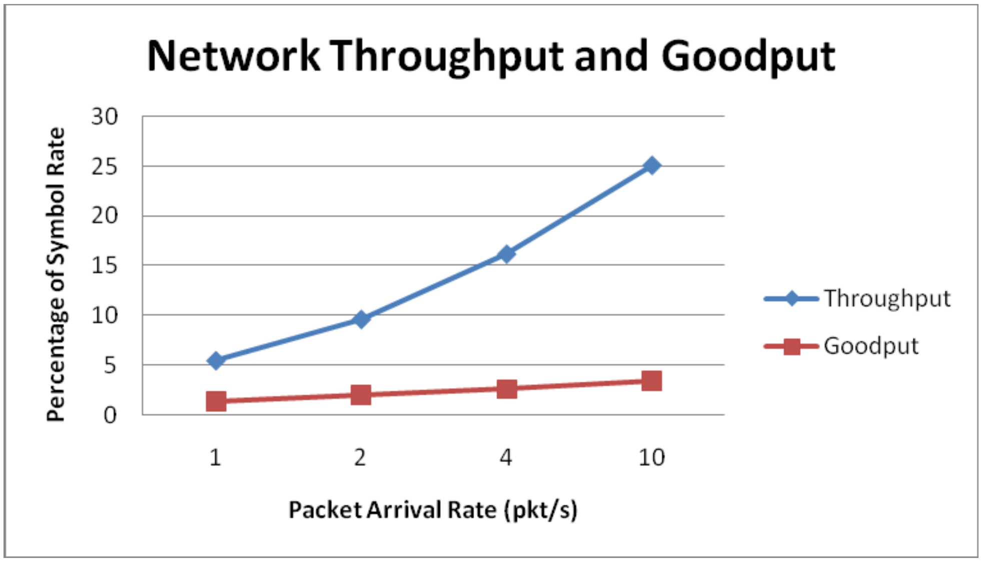

Figure 5.3 Network throughput and goodput due to packet arrival rate

In Figure 5.4 we see the effects on average packet delays due to the mobile node population. As the mobile node population approaches 25 nodes, the amount of delay is increasing. However, as the mobile node population approaches higher values the delay begins to decrease in value.

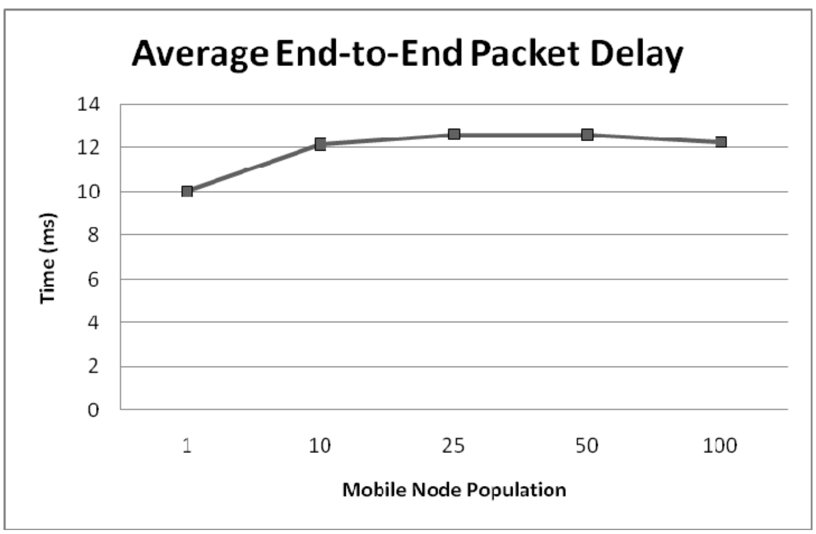

Figure 5.4 Average packet delays due to mobile node population for a network with a single sink node placed at its corner.

In Figure 5.5 we see the effects on network throughput and goodput due to the mobile node population. Both the network throughput and goodput values are increasing as the mobile node population increases. As the mobile node population reaches a value of 100 approximately 15% of the network throughput is used for goodput.

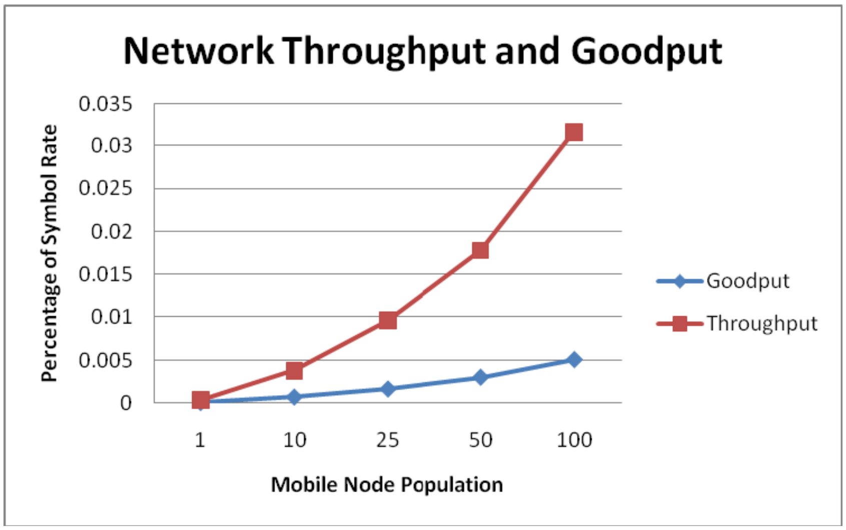

Figure 5.5 Network throughput and goodput due to mobile node population for a network with a single sink node placed at its corner.

5.1.2 Scenario 2 Results

In Figure 5.6 we see the effects on network load due to increases in the mobile node packet arrival rates and population. The network load increases as higher mobile node populations are reached. The load also increases as the packet arrival rates increase. The network will reach its higher levels of loads as both the mobile node packet arrival rates and mobile node populations reach higher levels.

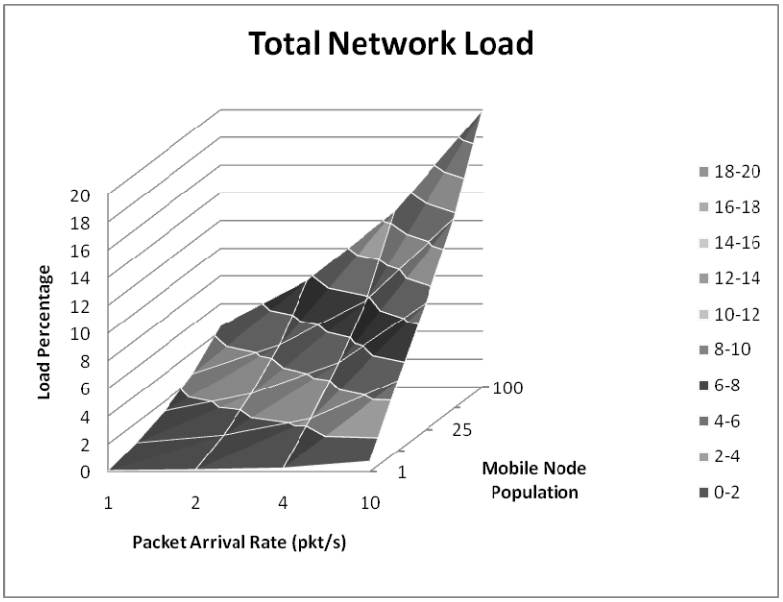

Figure 5.6 Total network loads for a network with a single sink node placed at its center.

In Figure 5.7 we see the end-to-end delay values for packets sent by mobile nodes as the packet arrival rate increases. The delay increases at a rapid rate as the arrival rates increase with an almost 400% increase in delay when increasing from 4 to 10 packets per second.

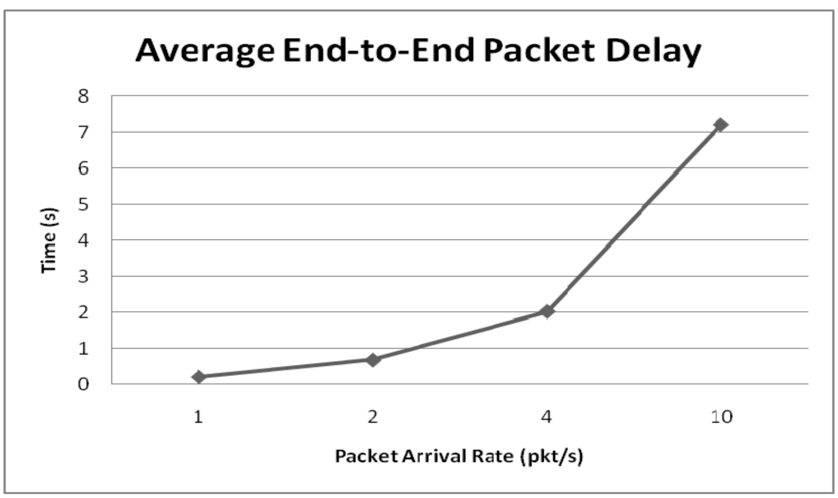

Figure 5.7 Average end-to-end packet delays due to packet arrival rate for a network with a single sink node placed at its center.

In Figure 5.8 the percentages of network throughput and goodput as the packet arrival rate increases is presented. The network throughput is at a level of approximately 24% of the network symbol rate, while the network goodput remains below 5%. The network throughput increases exponentially as the packet arrival rate increases. The network goodput increases only linearly as the packet arrival rate increases, but begins to level as the the arrival rate reaches a rate of 10 packets per second.

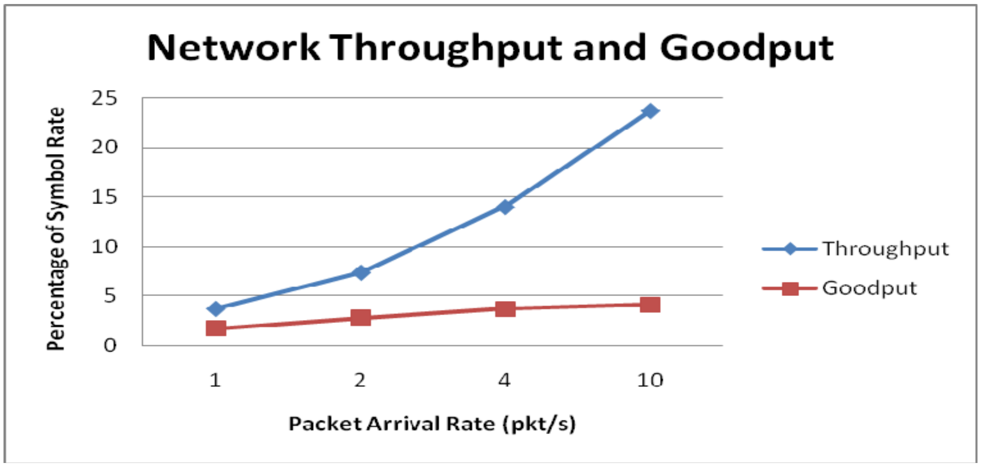

Figure 5.8 Network throughput and goodput for a network with a single sink node placed at its center.

In Figure 5.9 we see the end-to-end packet delays due to the mobile node population. As the mobile node population increases, the delay times steadily decrease. This inverse relationship is likely due to many mobile nodes sending data when they are in the immediate proximity of the sink.

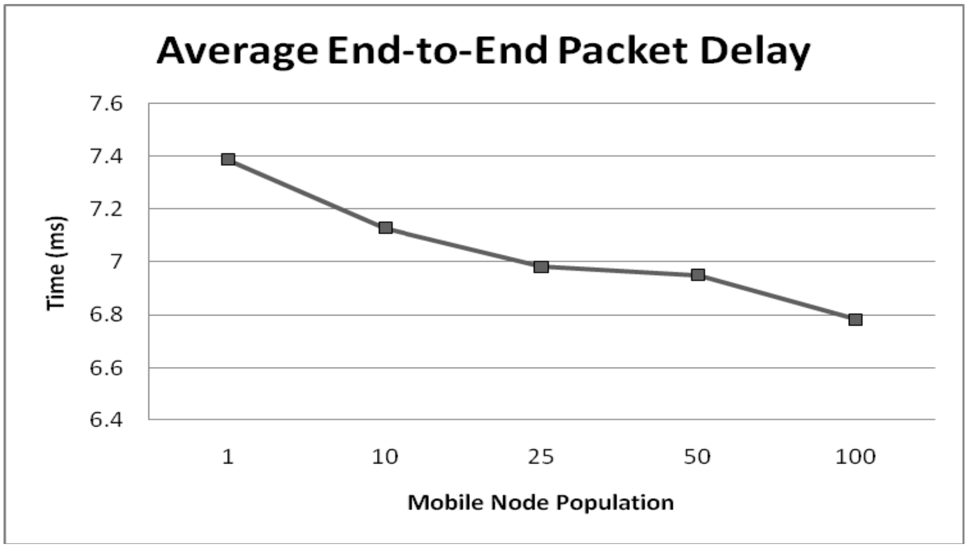

Figure 5.9 Average end-to-end packet delay due to mobile node population for a network with a single sink node placed at its center.

In Figure 5.10 we see the network and throughput values due to the mobile node population. Both the network throughput and goodput increase as the mobile node increases. At the higher population values the goodput reaches a level that is approximately 20% of the network throughput.

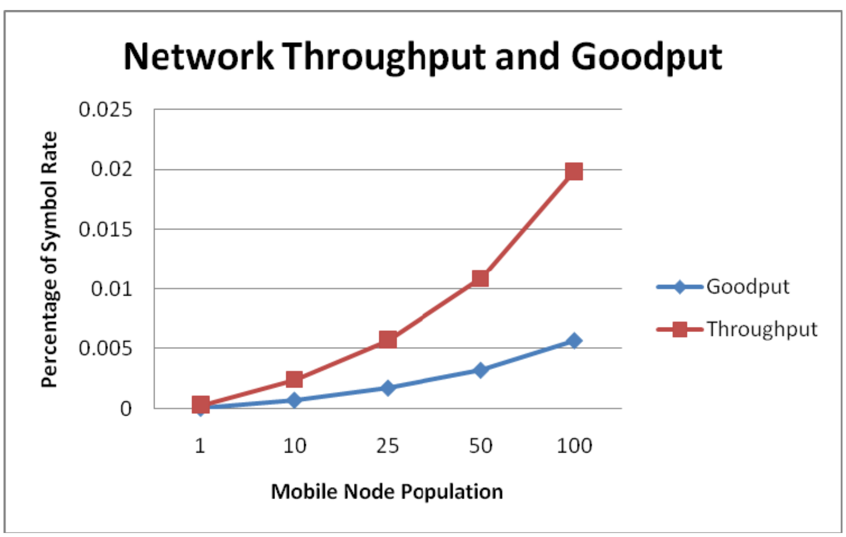

Figure 5.10 Network throughput and goodput due to mobile node population for a network with a single sink node placed at its center.

5.1.3 Discussion

The scenarios using single sinks slightly vary in overall network performance. The placement of the sink node only slightly provides a lesser network load when placing it at the center of the area. The main differences between the two scenarios lie in the packet delay and network throughput and goodput.

The end-to-end packet delay is vastly different for the two scenarios. The network placing its sink node on a corner has an end-to-end delay that is approximately double that of the network with a sink node at its center. This is to be expected as the path traveled to reach a corner is approximately double the distance needed to travel to the center of the area.

The throughput for both network scenarios both increase at a similar rate as the packet arrival rate increases. The difference between the two scenarios is that the network with a sink node in its corner is able to achieve a throughput that uses a higher percentage of the network symbol rate. The reason for this is that as the packet arrival rate increases more and more data is sent into the network. With only one sink node being used, all of this data will be sent to this one node. When the node is placed in the center, data is all sent to the center of the network from all directions. This creates a greater possibility of the hidden node problem where two nodes that cannot detect each other both send data to the same node. This would cause both packets to be lost to collisions. Placing the sink node on the corner does not remove the possibility of the hidden node problem, but it decreases it as the node can only receive data from the portion of its radius that overlaps the network area.

The network scenarios achieved similar results for network goodput as they did for throughput. The network placing the sink node on a corner achieved a level of goodput approximately 20% less than the network placing the sink node at its center. However, only the latter network had its goodput continue a rate of increase as the packet arrival rate increased. Placing the sink node in the center caused the goodput to begin to level as the packet arrival rate reached 10 packets per second.

Both scenarios can be successfully used, but they each are better suited for different types of networks. If the network will have many mobile nodes and receive data packets at a high rate, placing the sink node on a corner is a better solution. Though this scenario achieves a delay that is over two times longer than its counterpart, it provides a higher level of network throughput and a steadily increasing rate of goodput. However, if the network will have a smaller number of mobile nodes and receive data packets at a lower arrival rate, placing the sink node in the center of the network would be best. Data will be received at the sink node destinations in approximately half the amount of time than it would if located on a corner and the network will achieve a higher rate of goodput.

5.2 Multiple Sink Scenarios (Scenarios 3 and 4)

The multiple sink scenarios were intended to show the network performance behavior when distributing the sink node responsibilities across a number of nodes. In this case, the multiple sink nodes collectively do the work that a single sink node in the previous scenarios would do. The scenarios place the sink nodes on the corners of the area (Scenario 3) and around the center point of the area (Scenario 4). The mobile nodes will randomly select a sink node to receive its data based on a uniform distribution.

5.2.1 Scenario 3 Results

In Figure 5.11 we show that the network load steadily increases as the mobile node population and packet arrival rate reach higher levels. However, as the population approaches 100 nodes and the arrival rate approaches 10 packets per second, the network begins to increase to a level approximately 25% higher than what is observed at a population of 50 nodes.

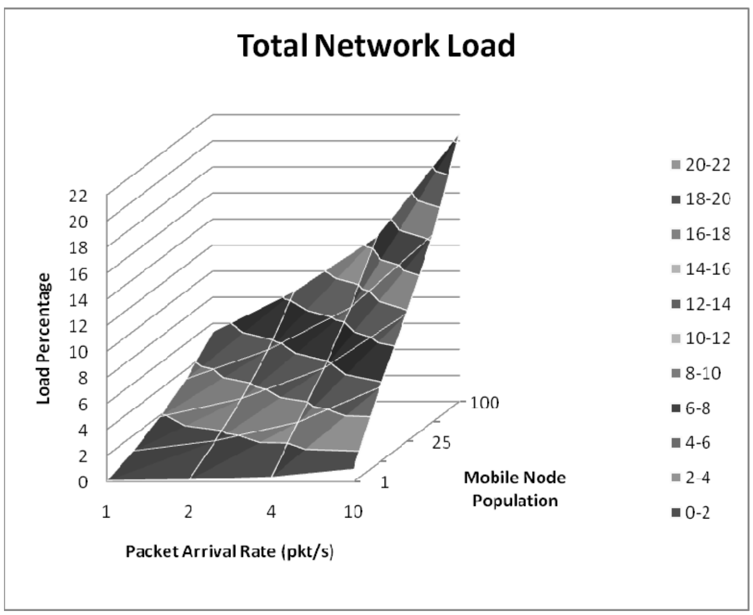

Figure 5.11 Total network load for a network with multiple sink nodes placed at the corners.

In Figure 5.12 the average delay for packets sent from a mobile node to a sink node on one of the corners is shown. The delay values increase as the packet arrival rate for each mobile node increases. The greatest increase is seen when increasing the packet arrival rate from 4 to 10 packets per second.

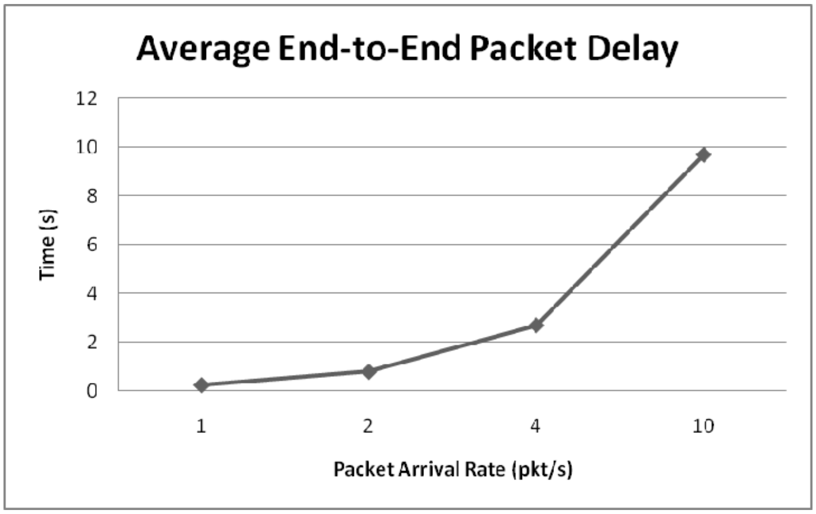

Figure 5.12 Average end-to-end packet delays for a network with multiple sink nodes placed at the corners.

Figure 5.13 displays the network throughput and goodput associated with the network in the scenario. The network throughput increases as the arrival rate increases. The goodput increases in an essentially linear manner as the packet arrival rate increases.

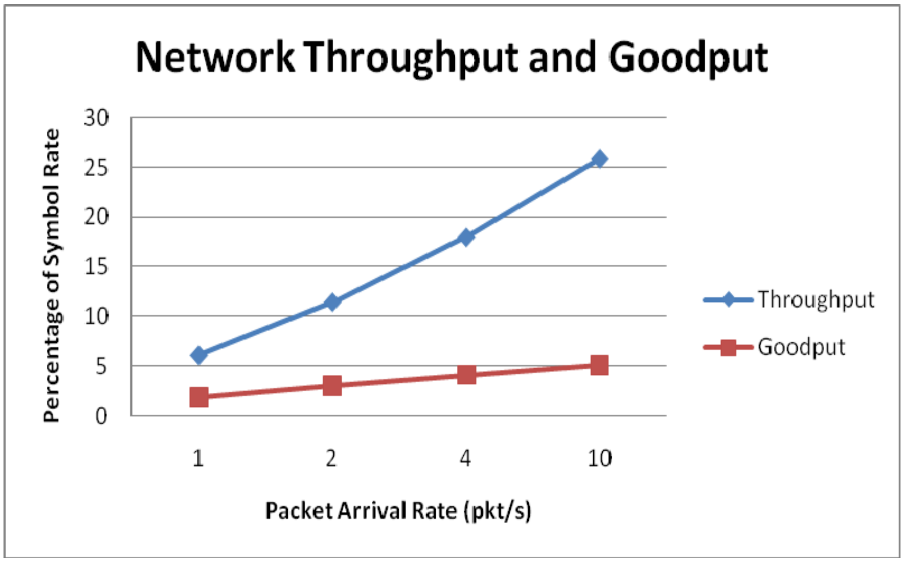

Figure 5.13 Network throughput and goodput for a network with multiple sink nodes placed at the corners.

In Figure 5.14 we see the average end-to-end packet delay due to the mobile node population. As the mobile node population increases the amount of delay steadily decreases. The amount of delay decreases approximately 5% when increasing the population from 1 node to 100 nodes.

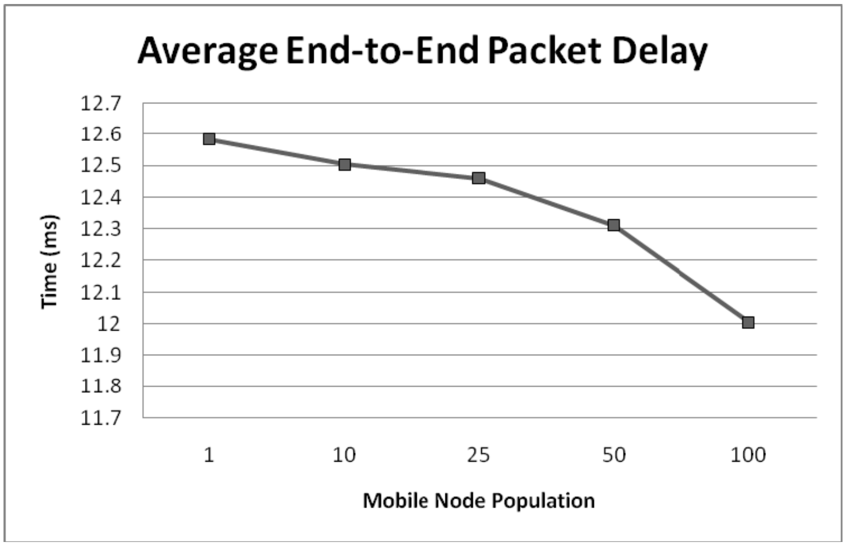

Figure 5.14 Average end-to-end delay due to mobile node population for a network with multiple sink nodes placed at the corners.

In Figure 5.15 we see the network throughput and goodput due to the mobile node population. As the mobile node population increases, both the network throughput and goodput values increase accordingly. At the higher mobile population values the network goodput approaches a value that is approximately 20% of the network throughput.

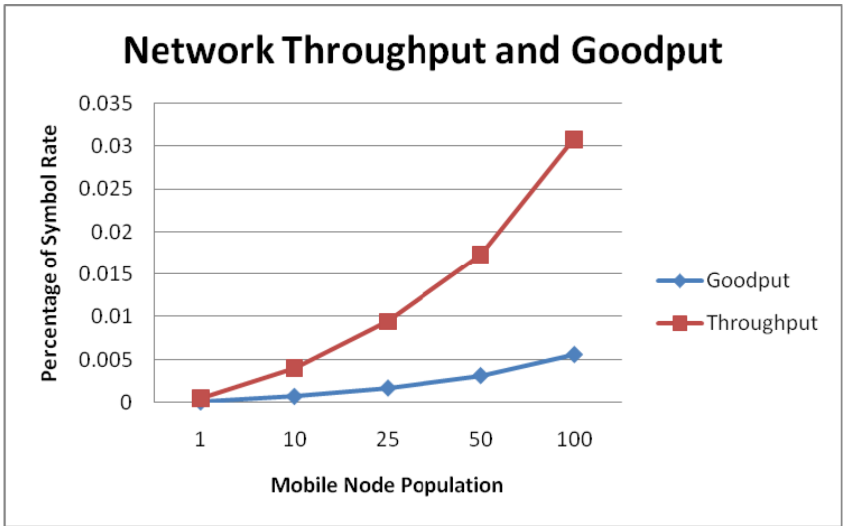

Figure 5.15 Network throughput and goodput due to mobile node population for a network with multiple sink nodes placed at the corners.

5.2.2 Scenario 4 Results

Figure 5.16 presents the total network load for a network with the sink nodes placed around the center of the area. The level of load witnessed in the network increases at a rapidly accelerating rate as the packet arrival rate increases. The level of load begins to spike and increase at an almost linear rate as the mobile node population approaches 100 nodes.

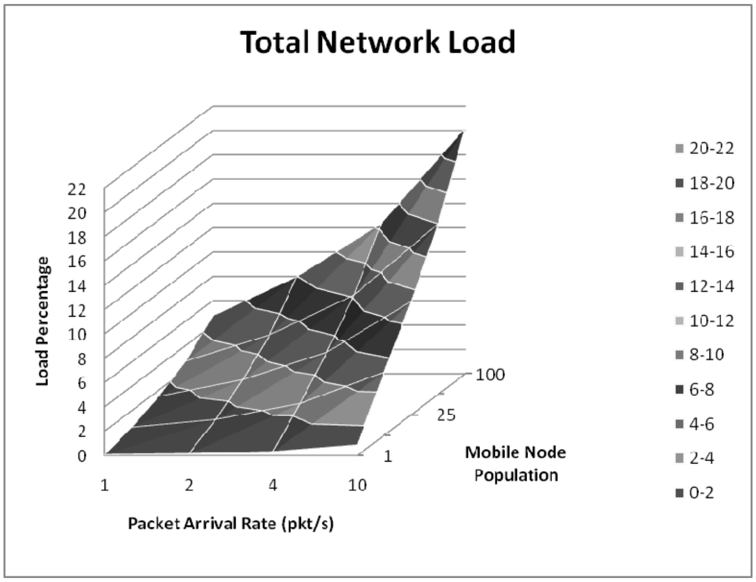

Figure 5.16 Total network load for a network with multiple sink nodes placed at its center.

In Figure 5.17 we see the average delays for packets sent from a mobile node to one of the sink node destinations. The delays increase as the packet arrival rates increase. As the arrival rate approaches 10 packets per second the delays reach a value that is almost 700% longer than the delays witnessed at a packet arrival rate of 1 packet per second.

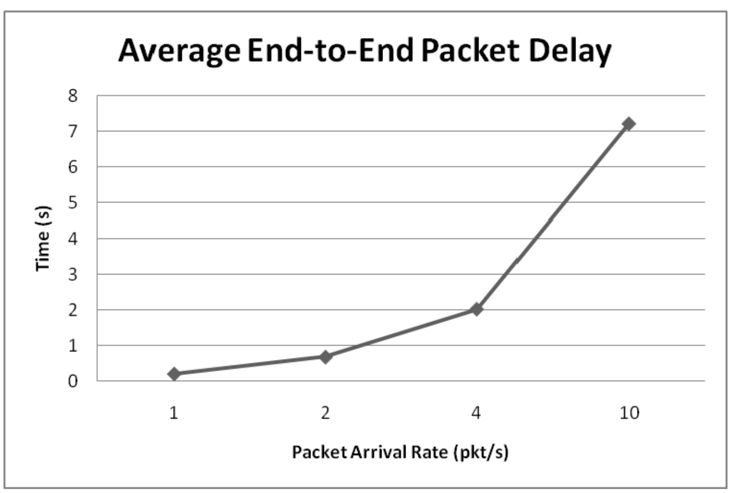

Figure 5.17 Average end-to-end delay for a network with multiple sink nodes placed at its center.

In Figure 5.18 the network throughput and goodput are presented. The throughput rapidly increases as the packet arrival rate increases. The network goodput initially increases in a linear manner as the packet arrival increases, but begins to decrease as the packet arrival rate approaches 10 packets per second.

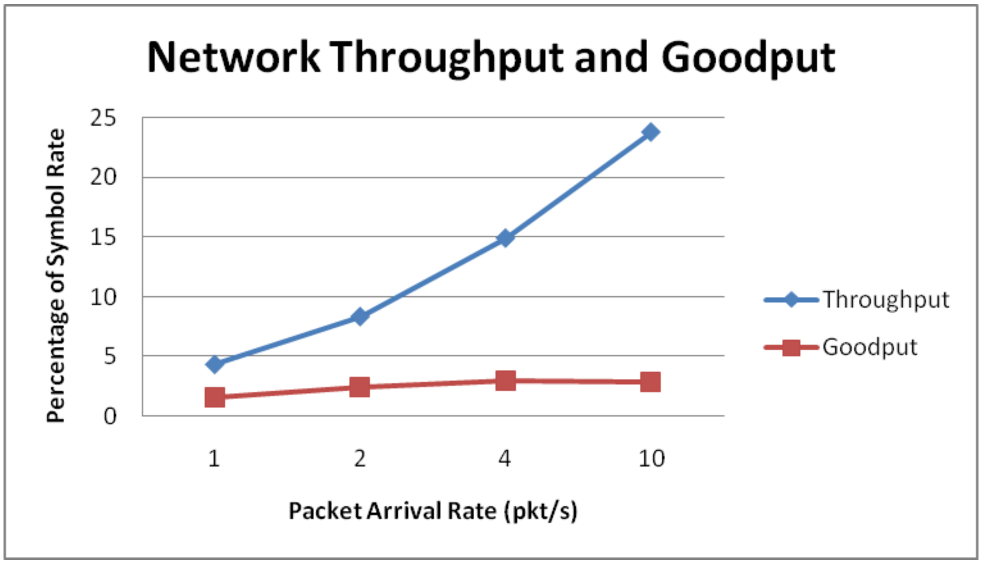

Figure 5.18 Network throughput and goodput for a network with multiple sink nodes placed at its center.

In Figure 5.19 we see the average end-to-end packet delay due to the mobile node population. As the mobile node population increases, the average packet delay decreases. As the mobile node population is increased from 1 node to 100 nodes the delay value decreases by approximately 8%.

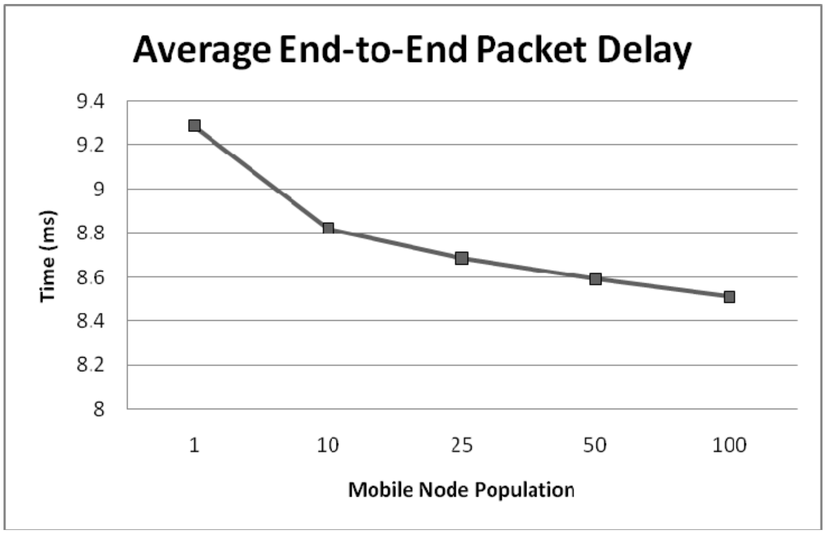

Figure 5.19 Average packet delay due to mobile node population for a network with multiple sink nodes placed at its center.

Figure 5.20 presents the network throughput and goodput due to the mobile node population. As the mobile node population increases, both the network throughput and goodput values increase. As the population reaches higher levels, the goodput reaches levels that are approximately 21% of the total network throughput.

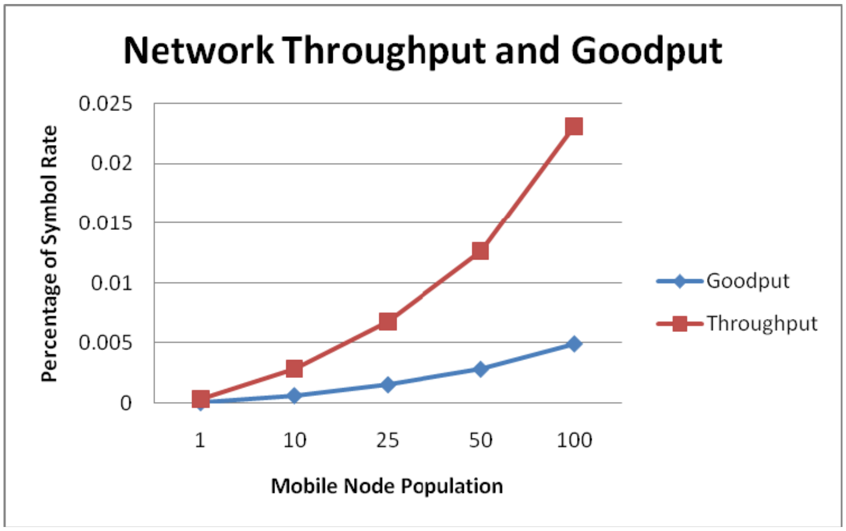

Figure 5.20 Network throughput and goodput due to mobile node population for a network with multiple sink nodes placed at its center.

5.2.3 Discussion

The scenarios using multiple sinks are fairly similar. Placing the sink nodes on the corners of the area or near the center of the area does not seem to have much effect on the network load. In either case, the load values increase as the population of mobile nodes and packet arrival rate increases. The differences between the two scenarios arise when viewing the packet delays and the network throughput and goodput.

The delays for both scenarios increase as the packet arrival rate increases. However, placing the sink nodes in the center of the network area provides a lower amount of delay than placing the nodes on the corners of the area. This is to be expected as it takes less routing hops to reach the center of the network when using the distance from a sink as the routing cost value no matter where the from the mobile node begins.

The throughput for both scenarios increases as the packet arrival rate increases. The network with sink nodes at its corners achieves a much higher level of throughput. The network with the sink nodes at its center has a throughput approximately 10% lower. This is due to all of the data packets sent by mobile nodes travelling towards the center of the network area, essentially causing network congestion which causes packet loss.

The two networks have greatly differing goodput values. The network with sink nodes placed on its corners has a goodput that increases as the packet arrival rate increases. However, the network with sink nodes placed at its center has a goodput that begins to decrease as the packet arrival rate approaches its higher rates. We infer that this is due to a large amount of the network load being focused in the center area, causing packets to be dropped before they reach the final destination node. The network with the sink nodes on the corners does not suffer from this problem as the packets entering the network will be equally routed to one of the corners, equally distributing the network load across the network.

Taking into account the various performance data presented, we infer that placing sink nodes on the corners of the network area when using multiple sinks will allow the network to achieve a higher level of network performance. Placing the sink nodes in the center of the area will create a situation where the center of the network will be bombarded with all of the packets generated for delivery.

CHAPTER 6

CONCLUSIONS & FUTURE WORK

The IEEE 802.15.4 standard was created to provide a viable option for building low rate wireless personal area networks. Much of the research on the standard has focused on the use of the star topology. The peer-to-peer topology provided by the standard can be used to build higher level network topologies, such as a wireless mesh network. We have researched the network given limitations for a wireless localization scenario with a wireless mesh network based on the 802.15.4 standard. The mesh could successfully deliver data across the backbone infrastructure with adequate network performance.

For future work, there are higher level layers that need to be researched, such as the application layer. The choice for the application layer must be made carefully due the unreliable nature of wireless medium. The Zigbee Alliance is currently working on higher level layers for the 802.15.4 standard and these could certainly be expanded upon [5].

Additionally, we believe that further research could be done on the use of the CSMA-CA algorithm in the MAC layer. Many other MAC protocols for wireless networks use the RTS-CTS handshake to cut down on the possibilities for collisions. Using a protocol more related to this behavior would most likely increase the levels of goodput achieved in 802.15.4 based networks and possibly reduce any unnecessary network load.

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William Wallace II was born in Fort Worth, Texas in January 1981. He received his Bachelors of Science in Computer Science and Engineering from the University of Texas Arlington in August 2003, graduating with Magna Cum Laude honors. During his undergraduate work, he worked in a project with other undergraduate students to design and build a computer-based baby monitoring device to assist parents in monitoring their newborn children.

He began his graduate study in the Computer Science and Engineering Department at the University of Texas at Arlington in May 2005 as a part time student, while he worked full time as a software engineer in industry. He focused much of his graduate study on network systems and software engineering. He received his Masters of Science in Computer Science and Engineering in December 2007.

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