Density Adaptive Sleep Scheduling in Wireless Sensor Networks

Fengju An

Master of Science Thesis

Wireless and Mobile Communications Group

Department of Telecommunications

Faculty of Electrical Engineering, Mathematics and Computer Science

Delft University of Technology

TU Delft
Delft
University of
Technology

Density Adaptive Sleep Scheduling in Wireless Sensor Networks

Master of Science Thesis

For the degree of Master of Science in
Wireless and Mobile Communications Group (WMC)
at Department of Telecommunications
at Delft University of Technology

Fengju An

27.06.2013

Faculty of Electrical Engineering, Mathematics and Computer Science
Delft University of Technology
Delft, The Netherlands

Delft University of Technology
Department of
Telecommunications

The undersigned hereby certify that they have read and recommend to the Faculty of Electrical Engineering, Mathematics and Computer Science for acceptance a thesis entitled

Density Adaptive Sleep Scheduling in Wireless Sensor Networks

by

Fengju An

in partial fulfillment of the requirements for the degree of

Master of Science.

Dated: 27.06.2013

Supervisors:

dr.ir.Ertan Onur (Assistant Professor, TU Delft)

Prof. dr. K.G. Langendoen (Professor, TU Delft)

Readers:

Prof. dr. B.J.Kooij (Professor, TU Delft)

Ir. Y. Hu

Abstract

Broadcasting by flooding is one of the most fundamental services for both wired and wireless networks. This also includes several sensor network applications that use broadcasting to spread information from one sensor node to the other sensor nodes in the entire sensor network. These wireless sensor networks have certain characteristics such as limited power and battery driven. However the simple flooding mechanism causes lots of duplicated packets and consumes a lot of resources. In view of these constraints, the broadcasting service should reduce redundant transmissions such that energy conservation is obtained since the devices within a wireless sensor network have limited battery power. Since it is not necessary for each sensor node to be active all the time a more sophisticated method might be introduced to flood an entire network and the other side is more efficient. In this work, an asynchronous sleep scheduling is proposed by an adapted duty cycle for each sensor where the duty cycle is based on the RSS based density estimation for each sensor node. By using the proposed duty cycle the reachability is compared with that of the fixed duty cycle and the adapted duty cycle by using neighborhood discovery density estimation model. The results show that the reachability of the network with an adapted duty cycle in combination with RSS based density estimation is two times more than that of the neighborhood density estimation in a $100m$ x $100m$ WSN of 200 sensor nodes. Further the results show the reachability is as good as in the case of the 90% fixed duty cycle but is more energy efficient.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I am really thankful that God brought me here and choose me for Him purpose and Economy. By His mercy and grace I did both my bachelor degree Electrical Engineering in Dutch which is my third language and Master Electrical Engineering Track Telecommunications in TU Delft, the Netherlands. This thesis is the final part of my study in TU Delft.

For this thesis work I would like to express my gratitude for the assistance from my supervisors Dr. Ertan Onur and Prof. Dr. K.G.Langendoen. Thanks for their supporting and guiding me on the right path during this research and writing of this thesis. I would like to convey my thanks to Y. Hu as well.

I would also like to thank Prof. Dr. K.G.Langendoen and Prof. Dr. B.J.Kooij for their agreement to be the committee members and read my thesis. Special thanks to my parents in china, thanks for their sacrifice, encouragement and supporting all the way. It is really hard to describe it in words.

I am also thankful that God also prepared a good husband for me who is not only always supporting me in everything, but also always encouraging me and unceasingly loving me.

Finally I would also like to thank all the brothers and sisters in the Lord. Thanks for all their shepherding, prayers and petition.

Delft, The Netherlands Fengju An
27.06.2013

Chapter 1

Introduction

A wireless sensor network (WSN) consists of a large number of tiny and inexpensive devices, mostly sensors, which send their data wireless within a network. In general the tasks that these devices perform are the following: on board data processing, communication between sensors, sensing capabilities and actuation applicabilities but these are not all mandatory present within a WSN. These devices communicate with each other to share their data obtained from measurements taken by the device or to redirect their data to a central collection point. The advantages of these kind of networks is that the communication between the devices is performed wireless and there is no need for any additional network infrastructure. Hence these kind of networks are very flexible which makes them interesting to use in certain scenarios.
However WSN's have some slight disadvantages which can be characterized as the following properties: limited processing power, limited memory, low power, low rate, limited range and the devices within a WSN are mostly battery driven. Since the devices in WSN are often small devices the computational power of these devices is generally small since there is not much room to allow the presence of a large amount of hardware. Furthermore since the devices are wireless they need to obtain their energy from a battery which in the end needs to be recharged or replaced. If the battery of a device is depleted and not replaced it ceases to function within the WSN. If the number of devices with no battery power reaches a certain threshold the WSN might collapse. Despite these disadvantages WSNs are widely used in various kinds of applications such as military surveillance, health and environmental monitoring. [2].

1-1 Problem definition

Sensor nodes in a WSN have a limited amount of energy and if all the sensor nodes would be active all the time the whole network may collapse in a short time. This is due to the high energy consumption of the sensor nodes. However it is not necessary for all the sensor nodes to be active all the time, they only need to become active when there is a need to transmit and /or receive data. Therefore, sleep scheduling can prolong the lifetime of a WSN significantly. Sleep scheduling works by activation sensor nodes when there is a need to transmit/receive data the remainder of the time the sensor node sleeps. Sleep scheduling belongs to the category of power management protocols which is one of the main energy conservation techniques used for WSNs.

One of the most used sleep scheduling patterns is the scheduled rendezvous protocol which belongs to the category of synchronous protocols. The main advantage of this protocol is that when a sensor node is awake it is guaranteed that all its neighboring sensor nodes are awake as well. In this way the scheduled rendezvous protocol allows to broadcast messages very efficiently to all the neighboring sensor nodes. The disadvantage of this protocol is that it is a synchronized protocol which requires that all the sensor nodes need to have their internal clocks synchronized, this requires an extra exchange of additional information. The synchronization of the internal clock of the sensor nodes causes more communication overhead and more energy consumption.

To avoid the problems described above for synchronous protocols an asynchronous protocol can be used. One of the advantages of an asynchronous protocol is that a sensor node can wake up whenever it wants to communicate with its neighbors. In contrast with the scheduled rendezvous protocol, it is not possible to broadcast a message to all neighbors, though each sensor node is able to contact any of its neighboring sensor nodes in a finite amount of time. In an asynchronous protocol it is improbable that all neighboring nodes are simultaneously active unlike in the scheduled rendezvous protocol, so sensor nodes need to wake up more frequently in order to reach their respective neighbors.

Asynchronous sleep scheduling is more suitable for a WSN since it requires no knowledge of the network, it can be done locally without any additional communication overhead and it makes sensor nodes wake up independently. But the most important benefit is that it solves the clock synchronization problem. Hence there is a lot research ongoing about asynchronous protocols [8, 9, 27].

In this work an analysis is made for asynchronous protocols for WSNs and an analysis is made under which circumstances the reachability is maximized. It is assumed that before a source node wants to transmit a packet, a preamble of a certain length is sent. Only when the preamble overlaps with the active period of a sensor node the source node shall start transmitting the packet. Several factors may influence on how many neighbors are reached in this case such as what is the best ratio between active time of sensor compared to the time of one period, this is also known as the duty cycle, the node density within a WSN, the maximum transmission range and the preamble length. These factors should all be taken into account in order to obtain maximum energy conversation in combination with a maximum network coverage which is the desired situation for a WSN. Of course this also depends on the size of the area where the sensors deployed and the sensor density within an area however the characteristics of the area in which the sensor nodes are deployed is not easy to change. The goal in this report is to adapt the duty cycle based on the node density and a given preamble length so that maximum reachability is attained. In this way a simple and asynchronous sleep scheduling is implemented for a WSN.

1-2 Motivation

The density in this report is defined as the average number of sensor nodes per a certain amount of area and this sensor node density can influence the performance of a WSN significantly. According to [10] it is possible that in a WSN the energy consumption of sensor nodes may vary unevenly. It was shown in [10] about 30% of the sensor nodes consume 95% of their battery power while about 60% of sensor nodes only consume 10%-20% of their battery power. Therefore, it is necessary to make adaptations to the network protocols in order to adapt to the density. Because the density can influence the performance of a WSN it is of interest how to estimate this density. There are different approaches that have been studied using density control techniques for WSNs and also for ad hoc networks.

The use of density control techniques means that nodes in the network are scheduled to sleep and wake up in order to save energy and where the density of the network is used to select the time between a sleep and a awake period [10]. In a sparse network the active period needs to be longer in order to achieve the same reachability and for a dense network the active periods can be shorter for the same reachability.

Previous work done using density control techniques is proposed in [15] where an optimized routing protocol is introduced. The optimized routing protocol in [15] combines an energy efficient routing algorithm with the shortest distance routing algorithm to reduce the energy consumption and to optimize the distance between source and destination. In [14] an adaptive control of duty cycle mechanism by using the node density is proposed. This approach allows a sensor node to operate at a lower duty cycle, by leveraging the presence of its neighbors. This mechanism shows that the adaptive duty cycle based on density can reduce the energy consumption and extend the network lifetime. In a network with a higher sensor node density the network lifetime is longer when an adaptive duty cycle based on the sensor density is enabled. When these measured density are not implemented the network lifetime cannot be extended by increasing the node density.

In [11] a routing mechanism is proposed by taking into account the node density to select a power conservation route and keeping energy consumed evenly among the WSNs in order to extend the network lifetime. In [11] the sensor nodes are unevenly distributed, namely one part of the WSN has a high sensor node density area and the other part has a low sensor node density area. In [12] a cluster allocation algorithm is proposed based on the node density to preserve a high coverage ratio to prolong the network lifetime. It assumes that the WSN stops its operation if the coverage ratio goes below 80%, and the number of rounds in [12] is defined as the lifetime of the WSN. Then in [12] the node density near the base station was increased without increasing the total number of sensor nodes, since the sensor nodes close to the base station consume more energy. It also finds a better density proportion for usage in the deployment stage to extend the WSN lifetime. These above mentioned papers show certain ways so that the sensor nodes consume their energy evenly and more efficiently by combining with the density control of the network.

In summary, by using density control techniques the energy consumption can be reduced and the network lifetime can be extended. For a WSN with a local high sensor

node density the duty cycle can be lowered for sensor nodes in that specific area. Since all the sensor nodes do not be active for all time, only certain sensor nodes need to be active for a given period of time based on the proposed protocol. Hence there is larger chance to reach at least a few neighboring sensor nodes for the same duty cycle. By using sleep scheduling in combination with density control the network traffic can be reduced, and the routing job can also be facilitated [10]. Thus adaptive sleep scheduling based on the network density increases the lifetime of WSNs.
As described in the previous section, an asynchronous protocol is simple to implement and that is why density adaptive sleep scheduling with asynchronous protocol is implemented in this work.

1-3 Methodology

The methodology followed in this report is first to develop a solid understanding of the energy consumption in WSN's and the factors that influence the reachability of the network. This is done in chapter 2 where the theoretical background of the reachability and the energy consumption in a WSN is explained. After introducing the background of WSNs an analytical model is derived based on the analysis made from the previous background chapter. In this model the MAC layer and the physical transmitting properties are ignored and only the discovery of the neighboring nodes in combination with the the duty cycle and sensor density is considered. Further it shall also be tested what factors can improve the reachability in a WSN and at the same time reduce the energy consumption. Factors such as the introduction of a preamble and the use of an adaptive duty cycle where each sensor chooses an duty cycle based on the sensor density in its neighborhood. After this model is derived this model shall be validated under different circumstances with the use of matlab simulations and a conclusion based on these simulation results is made.

In this work the proposed methodology can be summarized as following:

- Theoretical background of the reachability and the energy consumption in a WSN
- Derivation of an analytical modeling
- Validations using matlab simulation
- Conclusion

1-4 Contribution of thesis project

In this work the length of the duty cycle depends on the density estimation in WSNs, each sensor node estimates its density individually and based on the estimated value the duty cycle is adapted for each sensor node. Because it was seen that for different situations a adapted duty cycle performs better. This work provides an analysis of the optimal duty cycle in asynchronous networks under different circumstances. The effect of different lengths of preambles on each sensor node is determined and the duty cycle is based on the density estimation. This work also shows that the energy consumption of an adapted duty cycle is less than that of the fixed duty cycle. Comparing this proposed adapted duty cycle to the adapted duty cycle in combination with using the neighborhood discovery density estimation it is also shown that there is better reachability in this proposed model than the other model.

1-5 Outline of the work

- In chapter 2 the background is given about the sensors, WSNs, power management, data transmission and broadcasting.
- Chapter 3 contains the analytical modeling, matlab simulations and validation of the proposed method.
- After the validation of chapter 3, density estimation is discussed in chapter 4, based on the estimated density the duty cycle is adapted individually and the performance analysis by using density control is evaluated.
- Finally in chapter 5 the work is concluded and the future recommendations are made.

Chapter 2

Background

2-1 Sensors

A sensor is a device that used to measure a physical quantity and convert it into an electronic signal which can be observed by an observer or measured by an instrument [1]. It is also a device that produces a measurable response to a change in some physical condition such as temperature or to a chemical condition such as concentration [28].A possible application for sensors is to use them in wireless networks where the sensors sense, processes this data and communicate the measured values to one another. Sensor networks may consists of different types of sensors such as seismic, thermal, visual, infrared, acoustic and radar [13]. It is also possible that sensors transmit their measured values wirelessly to one or several sinks [2]. Unfortunately a sensor is limited in power, computational capacities and memory [4]. This is because sensor nodes in wireless networks are wireless and henceforth rely on battery power. The current situation is that sensor nodes in wireless networks carry limited amount of battery power. The current technology for batteries has not yet reached the stage that sensor nodes can operate for a long time without recharging or energy harvesting. Hence one of the most important limitations of sensor nodes is power consumption. When a sensor node has drained out of its battery, it directly affects network usefulness because it may break the entire network.

2-2 Wireless Sensor Networks

Wireless sensor networks (WSN) consist of a large number of small, battery-powered, inexpensive and wireless sensors which send their data wirelessly. More specifically, a WSN consists of spatially distributed autonomous sensors to monitor physical or environmental conditions, such as temperature, sound, pressure, etc [3]. Typically, data packets are generated by each node and are sent to a Base Station (BS) or a sink.

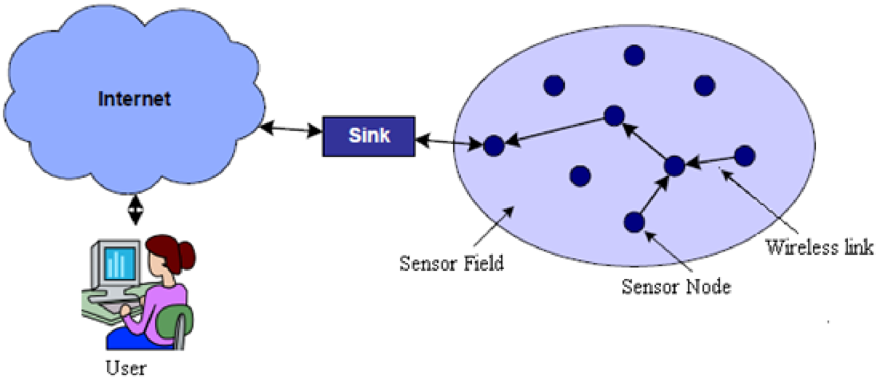

Figure 2-1: Basic architecture of a Wireless Sensor network

Here the data is aggregated and forwarded to the user. In Figure 2-1 it shows the basic architecture of a WSN using sensors to monitor the physical conditions. From the above a WSN has peculiarities such as limited processing power, limited memory, low power, low rate, limited range radio and battery driven.

2-2-1 Applications

WSNs are widely used in various kinds of applications, such as military surveillance applications, health applications, and environmental applications. For example, in military applications WSNs can be an integral part of military command, control, communications, computing, intelligence, surveillance, reconnaissance and targeting systems, can be used for target detection, to monitor forces and equipment, to detect nuclear, biological or chemical attacks and for the surveillance of battlefields. Another example is using WSN for health applications, which are providing interfaces for the disabled, integrated patient monitoring, diagnostics and hospital drugs administration. WSN are also used in environmental monitoring where WSN can be used for tracking the movements of the small animals, detecting forest fires, flood detection and environmental monitoring in marine and soil environments. One of the applications is the use of WSN in homes such as home automation [2]. In recent years WSNs are widely used in more fields such as wireless factory, smart(intelligent) buildings and implantable medical sensors which are used for medical applications [28].

2-2-2 Issues

An important limitation for WSNs is that sensor nodes carry a limited amount of batteries and hence have a limited amount of energy. In a WSN it is possible that the sensor nodes are deployed in large numbers over a wide area and it can be difficult to replace or recharge the batteries of all the sensors. A sensor node may be impossible to reach physically, for example in environmental monitoring where sensor nodes are attached to animals or lowered on the ocean floor, or it is economically too expensive,the operation of changing the battery may cost more than the entire sensor node. Therefore the lifetime of a WSN is dependent on the battery power of the sensor nodes. If a certain percentage of the sensor nodes in a WSN die because they have no more power the whole network may collapse. However, for many applications it is desirable that a WSN has a long network lifetime. In order to prolong the network lifetime of a WSN there are two possible directions, the first one is energy conservation which is the current focus of a lot of research groups in WSN. Energy conservation makes sure that the lifetime of the network is maximized. The second option is energy harvesting or recharging the batteries, this approach becomes more a research topic recently and got more attention. In a WSN, the communication of sensor nodes consumes more energy than the data processing of the received information. Hence the primary focus in energy conservation is that communication between sensor nodes needs to be minimized. Additionally, all the sensor nodes in a WSN do not necessarily need to sense continually hence turning off some sensor nodes or having a alternative sleeping schedule for a certain percentage of the sensor nodes does not necessarily affect the network as long as there are enough functioning sensor nodes with enough energy to sense and communicate.

2-3 The Power Management Protocol for WSNs

The power management protocol for WSNs is one of the main energy conservation techniques available for a WSN. The power management protocol can be classified into two categories depending on the location of the power saving within the network layering. Each category of these power management protocols is best suited for a certain type of network topology .The two power management protocols are independent sleep-/wakeup protocols running at the network or application layer and integrated with the MAC protocol itself. Based on the specific sleep scheduling, the MAC protocol then optimizes the medium access functions which are used for power management. Independent sleep/wakeup protocols can be used in combination with any MAC protocol in order to reduce the energy consumption. Within these kind of sleep/wakeup protocols a classification can be made into three main categories: on-demand, scheduled rendezvous and asynchronous protocols [21]. Each of these specific sleep/wakeup protocols has advantages and disadvantages. In the following section these three sleep/wakeup protocols are presented with their respective disadvantages and advantages.

2-3-1 The On-demand Protocol

First of the power management protocol that is introduced is the on-demand protocol. This protocol is based on the idea that a sensor node should be in the sleep mode or off when there is no data packet to transmit and/or receive. As soon as there is a data packet that needs to be transmitted and/or received the sensor node shall become active. In this way sensor nodes alternate between active and sleep periods depending on network activity. The consequence is that the energy consumption is minimized since sensor do not waste energy by unnecessary transmissions and unnecessary sensing. But the main disadvantage of this protocol is that it is difficult to inform the sleeping sensor nodes if another sensor node wants to communicate with them.

In order to combat this disadvantage the use of multiple radios is required. This requires two channels to work corporately, namely a data channel and a wakeup channel, the former one is used for normal data communication and the other one is for awaking neighboring sensor nodes when needed. [24, 25] implemented the on-demand wakeup schemes in combination with two different channels, one for normal data communication and the second channel for awaking neighboring sensor nodes when needed.In [5] the energy quality of on demand sleep /wakeup protocol is presented with the purpose of providing high performance energy efficient local monitoring for WSNs.

Therefore, although the approaches mentioned above can be optimal both latency and energy efficiency [24, 25], they are not very practical due to the additional cost of the second radio.

2-3-2 The Scheduled Rendezvous Protocol

The second power management protocol is called scheduled rendezvous protocol which belongs to the synchronous protocols since it requires all neighboring sensor nodes to wake up at the same time. In Figure 2-2 the sleep scheduling of sensor nodes using a scheduled rendezvous protocol is shown. In this approach sensor nodes wake up according to a wakeup schedule and remain active for a short time interval to communicate with their neighbors. After the transmission of the data the senor nodes will go to sleep until the next rendezvous time. The main advantage of this protocol is that it is guaranteed that if a sensor node is awake that all its neighboring sensor nodes are awake as well. It is very convenient for data aggregation and allows sending broadcast messages to all neighbors.

The disadvantage is that this protocol is a synchronized protocol which requires all the neighboring nodes exchange the synchronization information so that their clocks are synchronized. Because a synchronous protocol in a WSN aims at equalizing the local times for all the sensor nodes in that WSN. Some of the applications require time synchronization for all sensor nodes at all time and this is the most energy consuming protocol. It is expensive and in some cases it is difficult to achieve in a WSN. Some other applications require only time synchronization of few sensor nodes at a time. In [6] three time synchronization algorithms are presented and compared, the three time synchronization algorithms are the following: Reference Broadcast Synchronization(RBS), Timing-Sync Protocol for Sensor Networks(TPSN) and Tree-based Synchronization Algorithms. In terms of accuracy, the RBS and TPSN algorithm perform very well and their accuracy is in order of few micro seconds. In TPSN the need for sending and receiving extra packets makes it less energy efficient than the RBS algorithm. The Tree-based Synchronization Algorithms are flexible and based on the given precision,complexity might be high or low. The root node plays a main role in this type of algorithms.

In order to reduce the energy consumption the sensor-MAC(S-MAC) algorithm [7] has been proposed. It is a fully synchronized protocol specifically designed for WSNs. In this case, all the sensor nodes within the network cope with idle listening by repeatedly putting nodes in active and sleep periods. The sensor nodes are synchronized to a common wakeup scheme with a slotted structure. At the beginning of a slot the

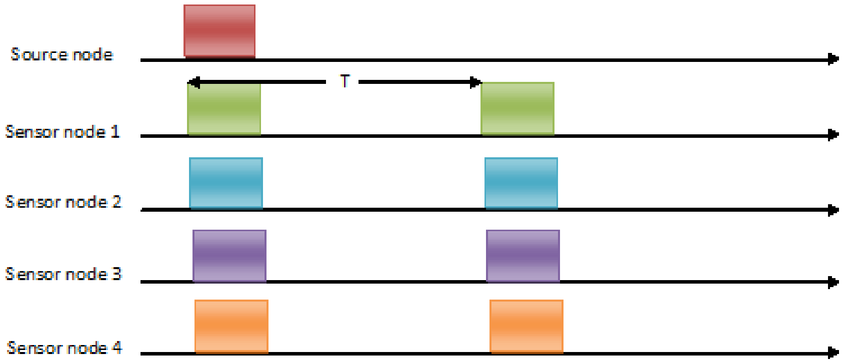

Figure 2-2: The Sleep Scheduling for a Synchronous Protocol

synchronized packets are regularly broadcasted, the neighboring nodes can adjust their clocks to the latest synchronized packet. By applying this method the relative clock drifts are corrected.The result shows that this protocol achieves low duty cycle operation of each node by periodic sleeping and reduces energy consumption caused by idle listening.

There also exists some drawbacks for this protocol such as it is difficult to determine an optimal size of active periods and it must be based on idle listening and collisions. For example, if the active periods are too short they increase contention and thus collision rates even if the idle listening period was reduced. On the other side if the active periods become too long the contention is reduce but the idle listening period was increased.

A contention-based MAC protocol for WSNs, the so called T-MAC algorithm is proposed in this paper [26]. The T-MAC algorithm uses an adaptive duty cycle by dynamically ending an activation event interval when there is no activation event for a given time. Although in this method nodes often go to sleep too early, this reduces the amount of energy consumption on idle listening and maintains a reasonable throughput.

2-3-3 The Asynchronous Protocol

The last algorithm that can be used is the asynchronous protocol. The basic idea is that each node is allowed to wake up independently of the others by guaranteeing that neighboring sensor nodes always have overlapped active periods of time within a specified number of cycles. Figure 2-3 shows the sleep scheduling of an asynchronous protocol. According to this figure only sensor node 1 and sensor node 3 can receive the transmitted packet. Since the active period of the sensor nodes partially overlap with the active period of the source node.

One of the advantage of this protocol is that a sensor node can wake up at anytime when it wants to communicate with its neighboring sensor nodes. Therefore, in asynchronous

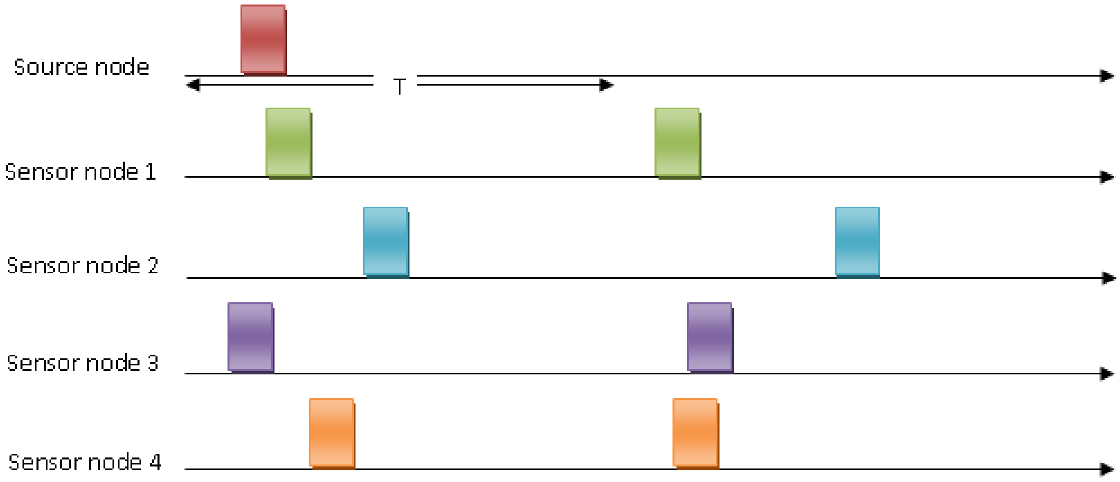

Figure 2-3: The Sleep Scheduling for an Asynchronous Protocol

protocols there is no need to exchange extra synchronization information unlike in the synchronous protocols so that the energy efficiency is improved. In contrast with the scheduled rendezvous protocol, it is not possible to broadcast a message to all neighboring sensor nodes in one period of time. Though each sensor node is able to contact any of its neighboring sensor nodes in a finite amount of time, it almost never happens that all neighbors are simultaneously active. In contrast to scheduled rendezvous protocols, sensor nodes need to wake up more frequently.

The asynchronous scheme B-MAC [8] has been proposed to reduce the energy consumption within a WSN. In this approach a long preamble is used before the data packet to reduce the duty cycle and minimize idle listening. It shifts the cost of coping with idle listening from the receiver to the transmitter. This paper also compared the B-MAC algorithm with the S-MAC algorithm mentioned above. The conclusion was that the B-MAC algorithm performed much better than the S-MAC algorithm in packet delivery rates, throughput, latency, and energy consumption [8].

In order to reduce the end-to-end latency with an energy efficient data transmission [27] proposed an Asynchronous Wakeup Schedule(AWS) in WSNs. Each node was assigned a particular color and maintains a forwarding table which contains the color information of the neighboring nodes. The result shows that the end-to end latency was reduced by using the forwarding table which helps to find out the neighboring node that becomes active sooner.

In [9] two advanced MAC protocols in WSNs are proposed, namely the Adaptive Duty Cycling Synchronous MAC (AD-MAC) and the Asynchronous-MAC(AS-MAC) for a synchronous and a asynchronous approach, respectively. AD-MAC improves the energy efficiency by using Preoccupancy Request to Send technique which can avoid overhearing and diminish the long delay. AS-MAC also reduces the energy consumption caused by idle listening and overhearing by using a preload message which contains the address of the receiver and the remaining time until data transmission is finished.

2-4 Data Transmission

Data transmission is an important topic of WSNs, as the distance between each sensor nodes is different; the energy consumed by each sensor node is different. When the distance between a sensor node and the base station is large the data transmission from sensor node to base stations consumes more energy than in the case when the distance is small. Hence the distance between sensor nodes among another and the distance from sensor nodes to the base station impacts the lifetime of the WSNs. Data transmissions can be classified into two categories, namely direct transmissions and indirect transmissions [22]. Figure 2-4(a) shows a data transmission from source to destination directly without any intermediate nodes, however, in Figure 2-4(b) data packet was transmitted from source to destination via the intermediate nodes, the distance d_i can either be equal to each other or different from each other.

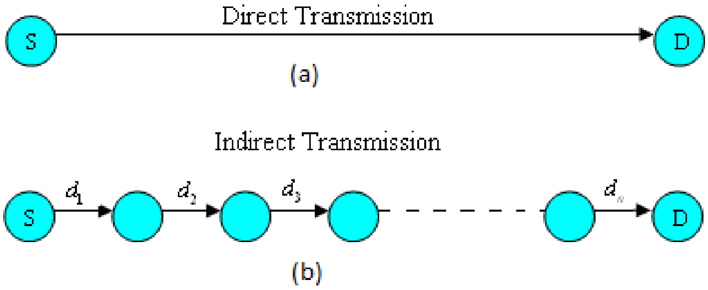

Figure 2-4: Data Transmission

2-4-1 Direct Transmission

In a direct data transmission, each sensor node collects and transmits the data to the base station directly, there do not exist any intermediate nodes for transmission, the path which from sensor node to the BS can also be called single-hop path. The advantage of direct transmissions is that the data rate is higher and the implementation is easier. WNS using these kind of transmissions are suitable for local scale applications. In large scale applications, especially if the sensor node is far away from the BS, the battery power can drain quickly due to the long distance which needs to be covered for the data transmission. Another disadvantage is that the data may not be sent to the BS because the sensor node is too far away.

2-4-2 Indirect Transmission

Indirect transmission means that sensor nodes send their collected data to intermediate nodes also called relay nodes that are in the proximity of themselves. This relay node will then forward the aggregated data to the BS, the path from the sensor node to the BS is also called multi-hop path. The advantage of this kind of transmission is that the high energy consumption problem in long distance transmission has been solved. The drawback is that the sensor nodes closest to the BS may consume more energy to forwarding data for other nodes, thus it will also impact the lifetime of WSNs. The indirect transmission is more energy efficient than the direct transmission only when the distance from source to destination is longer so that it cannot be reached with the direct transmitting power [23].

2-5 Broadcasting

In both wired and wireless networks broadcasting is one of the most fundamental services in order to reach every node in a network. More specifically broadcasting is the principle that one sensor nodes want to transmit data to every other sensor nodes. Since broadcasting ensures a maximum number of delivered packets among the entire network. Broadcasting works that if a sensor node wants to transmit data it will broadcast the data to all its neighboring nodes. The sensor nodes that received the packet from the source node shall further rebroadcast the packet to their respective neighboring sensor nodes which the source node could not reach. In this way in a short time the entire network is reached. Although broadcasting has many advantages such as it is simple to implement, fast and robust, it also has some disadvantages. The disadvantages are lots of contention, collision, duplicated packets and it is not energy efficient. Especially this last disadvantage is important for a WSN since in a WSN each sensor node carries limited amount of energy.

When the source node transmits its packets to its neighboring nodes in a synchronous WSN, then all the neighboring sensor nodes receive these packets due to the synchronized active periods. This is the best case, the source node waits until all other neighboring sensor nodes to be active and then broadcasts the packet as shown in Figure 2-5, after one period of time the entire network with each of the sensor node is reached and hence maximum reachability. In this way the waste of energy is also lim-

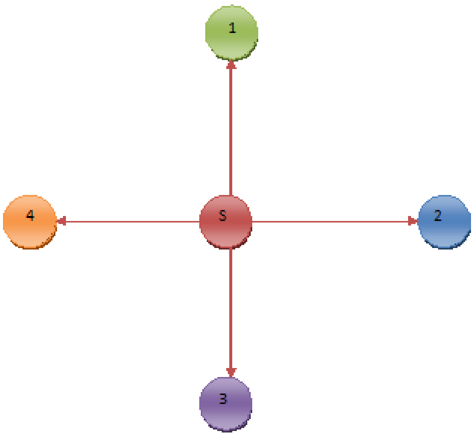

Figure 2-5: Synchronous broadcasting

ited. However most WNS are asynchronous and the sensor nodes do not have the same sleep scheduling as the synchronous protocol and the wakeup period of one sensor node does necessarily overlap with the source node, then the waiting time becomes infinite. The worst case is that all the sensor nodes have a different sleep scheduling as shown in Figure 2-6, in this figure if there is overlap between the source node and just one sensor node it will lead to broadcast 4 times to the number of 4 sensor nodes . Since this requires much more energy consumption then in the synchronized WSN. In asynchronous WSN it is important that the active periods of each node overlaps each other in the case of a broadcast. However, large active periods also means a high energy consumption. Hence there is a tradeoff for duty cycle and the attained reachability in a broadcast and the energy consumption otherwise. In this work an attempt is made to find an optimal way of choosing the duty cycle so that the energy consumption is minimized but the network reachability is optimized.

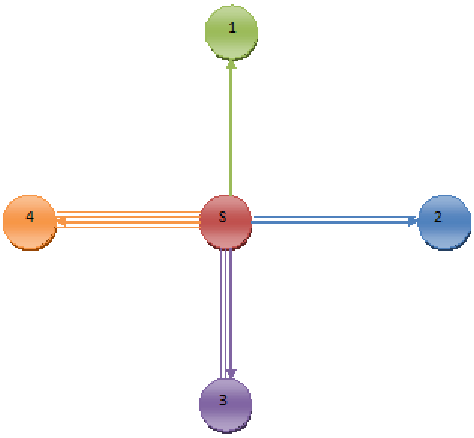

Figure 2-6: Asynchronous broadcasting

There are various approaches for broadcasting in WSNs that have been explored, broadcasting techniques can be classified into four categories: simple flooding, probability-based, area-based and neighbor knowledge-based scheme [31].

2-5-1 Flooding

Flooding is a technique to update the topology databases for each node. It is one of the fundamental broadcasting mechanisms in both wired and wireless networks. In simple flooding each incoming packet is sent out on every outgoing link or interface except for the interface it entered [29]. Figure 2-7 shows the structure of the simple flooding. The source node broadcasts packet to every node, they can all receiver the packet, afterwards each node broadcasts the packet to the neighboring nodes except the source node. This process generates lots of duplicated packets repeatedly and it does not stop by itself unless some measures are used to limit the number of the duplicates such as Time To Live(TTL) and sequence number techniques. Simple flooding consumes most of the network resources and may also cause too high overhead.

Due to the high cost of flooding in WSNs, energy conservation is achieved by selecting parents with the highest link quality in a flooding tree based design. Unlike this traditional selection, [19] proposed correlated flooding that nodes with high correlation are assigned to a common sender and a single acknowledge message is used for receiving the broadcasting packets. The result shows that the energy consumption can be reduced by letting higher correlation nodes receive packets simultaneously.

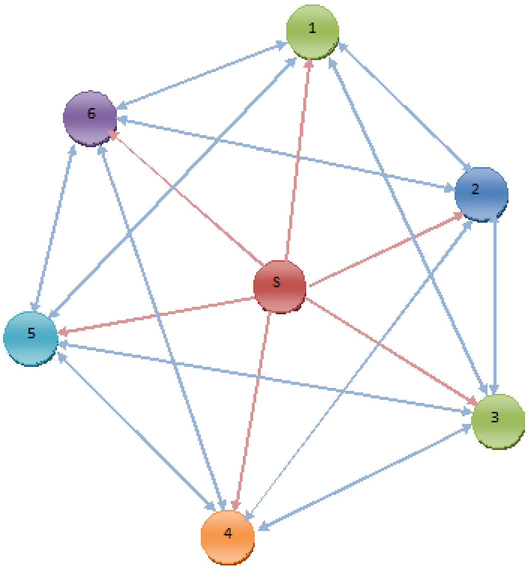

Figure 2-7: Flooding

2-5-2 Gossiping

Gossiping is a probabilistic broadcast method that tries to improve the flooding algorithm [34]. This approach works in the following way: the nodes in the network have a pre-specified probability $P_{gossip} \leqslant 1$ which is needed in order to broadcast packets. With the probability of 1- P_{gossip}, the received packet is discarded [34]. In order to achieve the desired application requirements and minimize the overhead, a probability P_{gossip} is chosen. There are no synchronization requirements for gossiping. Although gossiping is a simple solution and it is capable to achieve better reliability and load balancing, choosing the correct probability is a difficult problem. However, when the probability is chosen correctly, the broadcast message is received with a very high probability among the entire network. Thus, a correctly chosen P_{gossip} may extend the network lifetime [35].

2-5-3 Duty Cycle Awareness

Various approaches have been studied for reducing unnecessary power consumption in WSNs. One of these approaches is to let sensor nodes use a low duty cycle, such as in B-MAC, in order to prolong the network lifetime.

An asynchronous duty cycle broadcasting (ADB) [30] has been proposed, it is a new protocol for efficient multihop broadcast in WSNs using a asynchronous duty cycle. Unlike the traditional multihop broadcast, this protocol is integrated with the MAC layer in order to use the information which is only available at this layer. As this is an asynchronous protocol each sensor node has a individual sleep scheduling. This method optimizes the broadcast transmission from a node to its each neighbor individually. The final result shows that the energy consumption was reduced.

Paper [14] proposed a duty cycle function for a node based on the number of its neighbors that are closer to the sink. As the number of its neighbors increases, the duty cycle decreases.

2-5-4 Preamble Awareness

Before a transmitter sends a data packet a preamble of certain length is sent before the data packet. In WSNs with high sensor node density a small preamble will be sent before the data transmission. This preamble is received by a number of neighboring sensor nodes which are present within the transmission range of a sensor node. The neighboring sensor nodes that received the data packet will rebroadcast the packet in the next period of time and will still use the same preamble length. If the preamble is large, the transmission cost at the transmitter increases. Figure2-8 shows that a preamble before the data packet is sent by the source node where only sensor node1 and sensor node 3 can receive the transmitted packet in this scenario.

Figure 2-9 shows that flooding with preamble of the transmitter and duty cycle of the receiver technique in the network. In this figure it can be seen that the source node transmits packets to node 1 and node 3 because the preamble of the source node overlaps the duty cycle of node 1 and node 3. After node 1 and node 3 receive the packet, they will broadcast the packet to their neighboring node which is node 6 and node 2. Finally node 6 reaches node 4 and node 5. In this technique there is no duplicated packets.

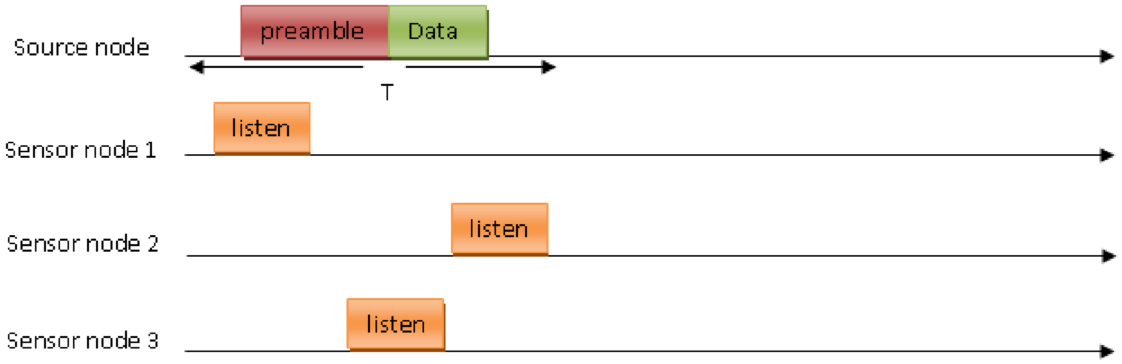

Figure 2-8: Data packet transmission with preamble

To overcome some of the disadvantages of B-MAC, X-MAC [16], DPS-MAC [17], and [18] have been proposed. In [16–18], a short preamble was proposed to replace the long preamble in B-MAC. Since a small preamble is thought to be enough in or-

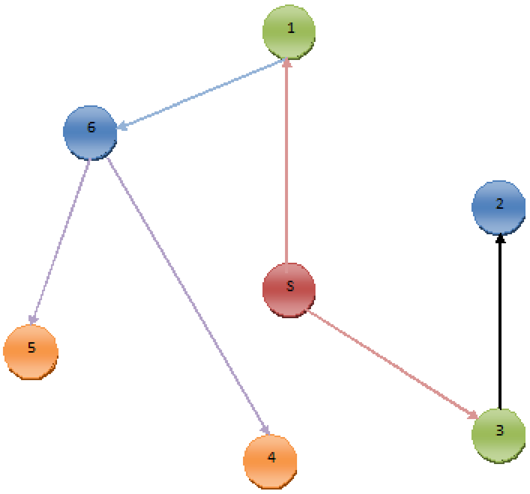

Figure 2-9: Flooding with preamble technique

der to achieve sufficient reachability and throughput in dense WSNs and it can save the energy required to broadcast a packet. [18] proposed a variable preamble length-based broadcasting scheme for WSNs and compared with an existing probability-based scheme. The result shows that in a dense network, broadcasting a packet with a small preamble is sufficient, but in a sparse network a large preamble is needed.

Chapter 3

Modeling the Reachability within a WSN

In WSNs, broadcasting is an important and fundamental service to spread information from one sensor node to the other sensor nodes in the whole WSN. For example, such information can include updates, alarms, packets broadcasting, etc. Flooding is the basic and a simple broadcasting mechanisms for both wired and wireless networks. However, the simple flooding algorithm causes duplicated packets and uses a large amount of resources, which consume avoidable energy from the sensor nodes. Especially in the limited battery driven WSN. In contrast, probabilistic flooding protocols avoid the problems described above and are a simple, energy efficient, alternative to flooding.

In this chapter the protocol design is firstly explained followed by the derivation of the analytical modeling for the adaptive duty cycle. Also the effects of the preamble length and the length of the duty cycle on the reachability are studied .This is done by using large scale matlab simulations. From these simulations results, the reachability for the different preamble lengths and duty cycles is plotted versus the time. From these simulation results it can be concluded that the sensor node density has an effect on the needed duty cycle for reaching the same reachability. Subsequently the local reachability is also plotted versus time for different duty cycles. After this section the effects of the preamble length on the attainable reachability is also studied by using matlab simulations and the reachability is also plotted versus time. Finally the adaptive duty cycle algorithm is validated and the results with the adaptive duty cycle shall be evaluated.

3-1 The Protocol Design

The general idea for the sleep/wakeup protocol is that each sensor node chooses a starting time between 0 and T_{period} randomly and each node follows its own wakeup schedule for the subsequent periods. For convenience lets assume that T_{period} is equal to 1. The duty cycle is defined as the percentage of time a node is active compared the time for one period T_{period}. The ratio between the preamble length P over one period of time T_{period} is denoted as p, since T_{period} is assumed equal to 1, therefore p is equal to P in this work. The preamble length in this work is expressed as "preamble p" due to the T_{period} equal to 1.

The reachability is defined as the number of the received packets by the sensor nodes N_r over the total number of sensor nodes N within the area. Thus the reachability is can be written as R $=N_r/N$. The number of the received packets can be attained both directly via the source node and indirectly via the retransmitting of other sensor nodes in the area.

As described in Chapter 2, not only the duty cycle awareness affects the attainable reachability but also the preamble plays an important role. If there is no preamble but sensors only have an active period it is assumed that the active period t_{on} of the source node has the same length of active period as the other sensor nodes in the area. When there is overlap between the active period of the source node and the active period of one of the receiving sensor nodes, then the number of the received packets is incremented. Nodes that sensor nodes that are already visited are ignored.

The second case is that the transmitting node inserts a preamble before transmitting, the fixed preamble length is used by the source node before the data is sent. The receiving sensor nodes still have their active periods equal to the duty cycle of the receiving nodes and when the preamble of the source node overlaps with the duty cycle of one the receiving sensor nodes the number of the received packets is updated with 1. As in the previous case sensor nodes that are already visited are ignored. When the sensor nodes receive the packets, the sensor nodes can rebroadcast the packets, hence some of the sensor nodes shall receive the packet from the source indirectly.

3-2 Duty Cycle Adaptation

It is assumed that each sensor node has $N_s - 1$ neighboring sensor nodes within its maximum transmission range of a total of N_s sensor nodes that are present within the WSN. The duty cycle of the sensor node shall be denoted as d. It is also assumed that the preamble length p is shorter than the time duration of one period which as earlier mentioned is assumed to have value of one second. Since every sensor node has to become active within a cycle there is always an active period for each sensor node in one round. The total number of sensor nodes that can receive the packet and are reached with a certain preamble p and a duty cycle d is denoted as n.

The probability of reaching n nodes is represented with the random variable X which follows the binomial distribution with parameters N and Pr. Where Pr is denoted as the probability that the preamble and the duty cycle overlap with each other is $p + d$ when $p + d$<1, the probability that the preamble and the duty cycle overlap with each other is 1 when $p + d \geqslant 1$. This is given by the following probability mass function:

$$f(n; N, p+d) = \Pr(X = n) = \binom{N}{n}(p+d)^n(1-p-d)^{N-n}, \tag{3-1}$$

With the expected value of X equal to

$$E[X] = N_s \cdot min(p+d, 1), \tag{3-2}$$

From (3-2) it can be written as

$$n \approx N_s \cdot min(p+d, 1), \tag{3-3}$$

Where N_s is the total number of sensor nodes within the transmission range, so it can be written as:

$$N_s = \hat{\lambda} \cdot \pi \cdot R^2, \tag{3-4}$$

where $\hat{\lambda}$ is the estimated sensor node density. Put (3-4) into (3-3), the number of the expected sensor nodes which can successfully received the packet

$$n = \hat{\lambda} \cdot \pi \cdot R^2 \cdot min(p+d, 1), \tag{3-5}$$

Therefore, the duty cycle d can be expressed as

$$d = \frac{n - \hat{\lambda} \cdot \pi \cdot R^2 \cdot p}{\hat{\lambda} \cdot \pi \cdot R^2}, (p+d < 1). \tag{3-6}$$

3-3 The effect of node density on duty cycle adaptation for a high reachability

As the design method was described above, when the active period of a certain sensor t_{on} overlaps with the active period of the source node and the senor node is within a certain maximum transmission range R_c of the source node, then the number of the received packets N_r is incremented from the source directly and when the sensor nodes receive the packets, the packets can be rebroadcasted by the sensor nodes, hence some of the sensor nodes can receive the packet from the source indirectly. Nodes which have already broadcast the same packet, discard the packet upon successive receptions. It is assumed that the source node has the same length of active interval as that of all the sensor nodes in this scenario.
In this scenario the following assumptions are also made:

- In a 100m x 100m field, a wireless sensor network is present with the number of sensor nodes N= 50, N = 100, N= 200 and N = 300 which are uniformly distributed.
- Each sensor node with a asynchronous sleep/wake scheduling wakes up for a active period of length t_{on} and enter into the sleep mode of length t_s , the scheduling of the sleep and awake periods of each sensor node is independent.

- Each sensor has a omnidirectional antenna which can transmit within transmission range R_c.
- The sensor nodes are stationary.
- No collisions occur.
- A number of 100 simulations are done when for each simulation new starting times to wake up are generated randomly.

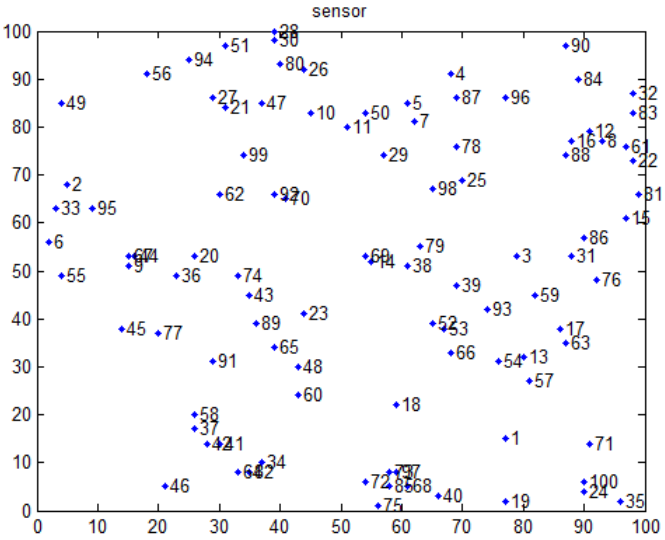

Figure 3-1: Distribution of 100 sensor nodes within an area

Figure 3-1 shows 100 sensor nodes are uniformly distributed in a field of 100m x 100m. In the case of sensors that send at a frequency of 900MHz in a wireless sensor network a typical transmission range of 5.5 to 70m can be attained. When the same receiver operates at 900MHz and are elevated above the ground for 3 to 6 m, the transmission range varies from 50 to 75m [32]. In this example a maximum transmission range R_c= 35m has been chosen.

Figure 3-2 shows the average reachability of 50 sensor nodes and for each sensor node with the maximum transmission range $R_c = 35$m. The chosen duty cycles are equal to 0.1, 0.2, 0.3, 0.5 and 1 and the reachability is plotted versus the time. In this scenario the sensor node density is written in the following equation. W and L are the width and length of the field separately.

$$\lambda = \frac{N}{W \cdot L} = \frac{50}{100 \cdot 100} = 0.005 nodes/m^2 \tag{3-7}$$

From this figure it can be seen that with a low duty cycle, such as 0.1 , the reachability increases slowly and can maximal reach 24% for this scenario. On the contrary with a duty cycle is equal to 1 the reachability can reach 100% after 4 seconds. This shows that the reachability of sensor nodes depends on the used duty cycle. From Figure 3-2, it can be seen that when the duty cycle is above 50% of period of time the reachability

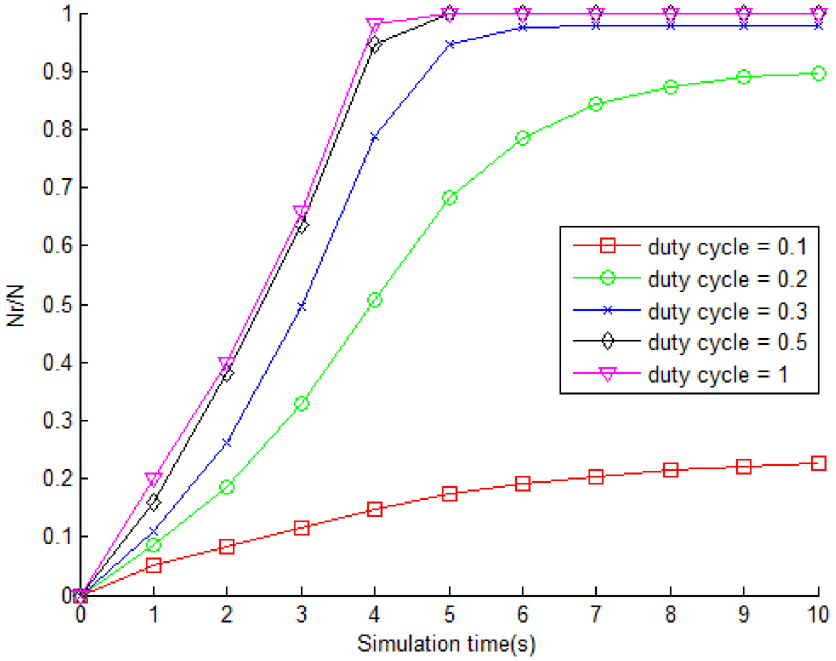

Figure 3-2: The average reachability of 50 sensor node

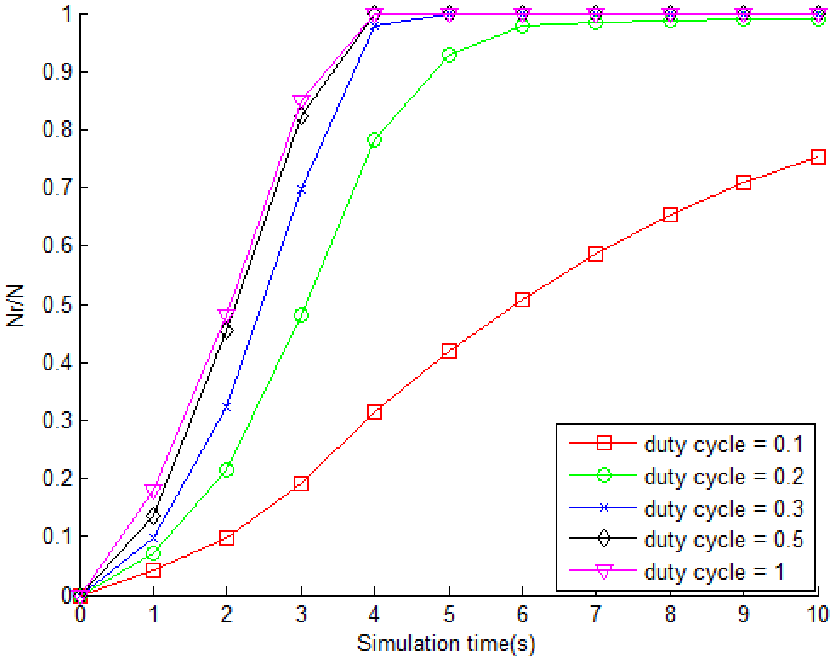

Figure 3-3: The average reachability of 100 sensor nodes

almost overlaps with the reachability if the used duty cycle is 70%, 80%, 90% and 100%. The reachability is all above 97.5% at T= 4 seconds, this also shows that the sensor nodes in the WSNs are not necessarily always active all the time.

Figure 3-2, with a sensor node density of $\lambda = 0.01$ $nodes/m^2$ ($N = 100$ sensor nodes are uniformly distributed in the field of 100m x 100m) , shows the reachability of the sensor nodes with different duty cycles which are the same as the earlier scenario. In this figure when the duty cycle is larger than 50%, the reachability increases very fast and reaches the maximum value of 100% when T=4 seconds. Compared to Figure 3-2 it can be concluded that with a higher sensor node density the reachability can be attained 100% within a shorter time and with a lower duty cycle.

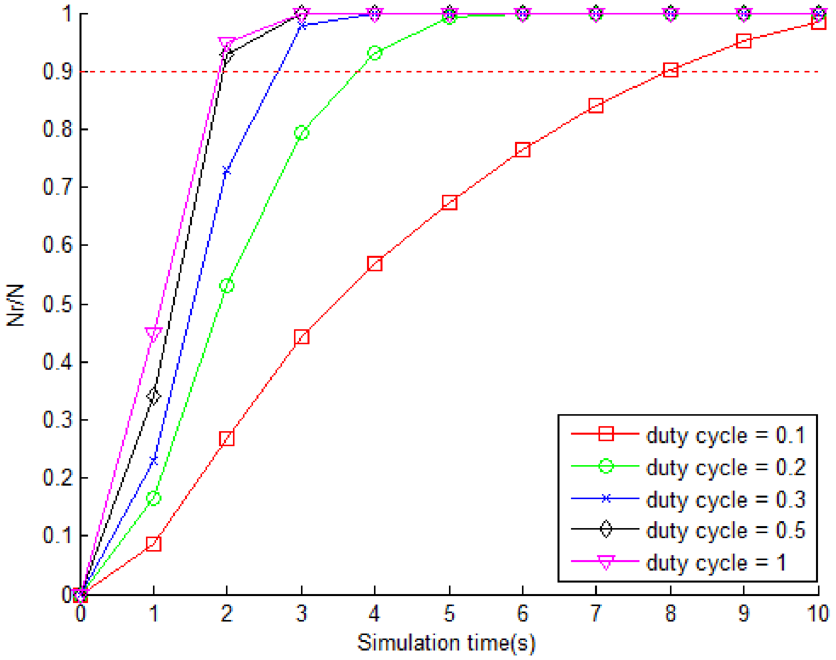

Figure 3-4: The average reachability of 200 sensor nodes

In Figure3-7 the reachability of the sensor nodes for different duty cycles, which are the same as in the earlier scenario, is show with a sensor node density of λ=0.02$nodes/m^2$ (N = 200 sensor nodes that are uniformly distributed in a field of 100m x 100m). In this figure it can be seen that when the duty cycle equals to 10% at T=4s, the reachability is already 56%. When the duty cycle is larger than 20% the reachability increases very fast and reaches the maximum value of 94%. The reachability is almost the same if a duty cycle is chosen from 50% up to100% , this produces almost the same results. For the same WSN the needed time in order to obtain a reachability of 90% in combination with a duty cycle of 10% is 8 seconds. If the duty cycle is changed to 20% then the time to obtain the same reachability is less than 4 seconds, however for duty cycles equal to 50% to 100% the time to obtain the same reachability is less than 2 seconds. Comparing Figure 3-4 to Figure 3-2 it can be again concluded that with a higher sensor node density the reachability that can be attained is closer to 100% and within a shorter time for a lower duty cycle. It was shown in Figure 3-4 that with a the duty cycle equal to 40% the reachability reaches 100% at T = 4 s.

Figure 3-5 shows with the sensor node density of λ=0.03 $nodes/m^2$ (N = 300 sensor nodes are uniformly distributed in the field of 100m x 100m), the reachability of the

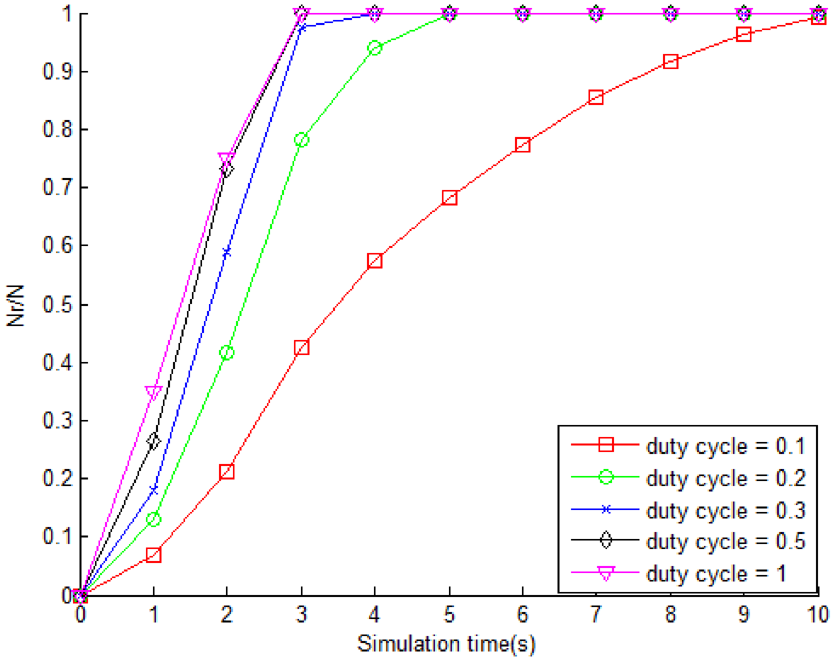

Figure 3-5: The average reachability of 300 sensor nodes

sensor nodes with different duty cycles which are the same as in the earlier scenario. Figure 3-5 with the node density of 0.03 $nodes/m^2$ show even better results as the node density equals to 0.02 $nodes/m^2$.

Figure 3-6 shows for different network densities the reachability versus the duty cycle at T= 2 seconds. In this figure the network density changes from 0.005 $nodes/m^2$ (N=50) to 0.03 $nodes/m^2$ (N=300). In a sparse network that network density equals to 0.005 $nodes/m^2$ (N=50), the maximum reachability is less than 60% for a duty cycle equal to 1. With a network density of 0.01 $nodes/m^2$ (N=100) in combination with a duty cycle equal to 50% the maximum reachability that is obtained is around 60%. When the sensor node density changes to 0.02 $nodes/m^2$ (N=200) then a 30% duty cycle is enough and in a dense network with a density of 0.03 $nodes/m^2$ (N=300) the maximum reachability reaches 98%. From this figure it can be concluded that the duty cycle needs to be adapted to the node density present in a WSN. A smart choice for the duty cycle based on the sensor node density can save a large amount of energy

In a WSN a sensor node that has a low duty cycle has a much more longer lifetime than a sensor with a high duty cycle. For operation in a WSN a low duty cycle means sensor nodes do not need to be active for a long time hence this conserves the energy consumption of the sensor nodes within a WSN. However if the sensor nodes density is too low, in other words the number of sensor nodes is small then the reachability does not include the entire WSN. This phenomenon depicts the necessity that the duty cycle has to be adapted to the network density. If the network density increases then the reachability also increases. For the same amount of reachability a higher sensor nodes density a lower duty cycle can be used and with a lower sensor nodes density a higher duty cycle needs to be used.

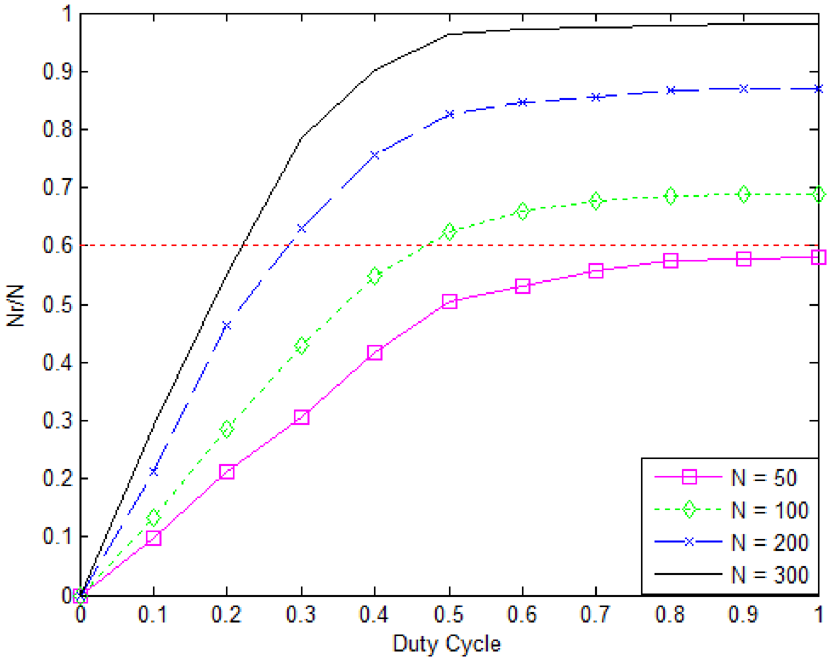

Figure 3-6: The reachability for various node densities and for different duty cycles at T = 2 seconds.

3-4 The number of reached neighbors

The number of reached neighbors is defined as the number of nodes that received the broadcast packet from the source node within one cycle. The number of reached neighbors of the simulation for the first period is listed in this section. Here the active period of the source node has the same length of the active times of the receiving sensor nodes. With the source node positioned in the center of the field, the percetage of the number of the reached neighbors over the total number of the neighbors are listed in table 3-1. The total number of the deployed sensor nodes equals to 50 in this case and the maximum attainable number of sensor nodes within the transmission range for this scenario is 22 sensor nodes.

Table 3-2 lists ratio of the number of reached neighbors over the total number of neighbors that within the transmission range and from a total of 100 sensor nodes deployed in the field. Table 3-3 lists the percentage of the the number of reached neighbors over the total number of neighbors that within the transmission range and from a total of 200 sensor nodes deployed in the field.

Table 3-1, Table 3-2 and Table 3-3 show that with an increases of the duty cycle the number of the reached neighbors also increases within the transmission range. Figure 3-7 shows the number of reached neighbors versus the duty cycle for different network densities. From the results it can be seen that with a denser network the number of reached neighbors is larger and for the same number of reached neighbors only needs a lower duty cycle. For example, the desired number of reached neighbors should be 20

duty cycle	percentage of the number of reached neighbors over the total number of neighbors
10%	18%
20%	36%
30%	50%
40%	63%
50%	72%
60%	81%
70%	86%
80%	95%
90%	100%
100%	100%

Table 3-1: The ratio of the number of reached neighbors over the total number of neighbors for a WSN with 50 sensor nodes

duty cycle	percentage of the number of reached neighbors over the total number of neighbors
10%	20%
20%	34%
30%	51%
40%	62%
50%	75%
60%	82%
70%	88%
80%	94%
90%	100%
100%	100%

Table 3-2: The ratio of the number of reached neighbors over the total number of neighbors for a WSN with 100 sensor nodes

duty cycle	percentage of the number of reached neighbors over the total number of neighbors
10%	19%
20%	35%
30%	51%
40%	61%
50%	75%
60%	81%
70%	89%
80%	95%
90%	100%
100%	100%

Table 3-3: The ratio of the number of reached neighbors over the total number of neighbors for a WSN with 200 sensor nodes

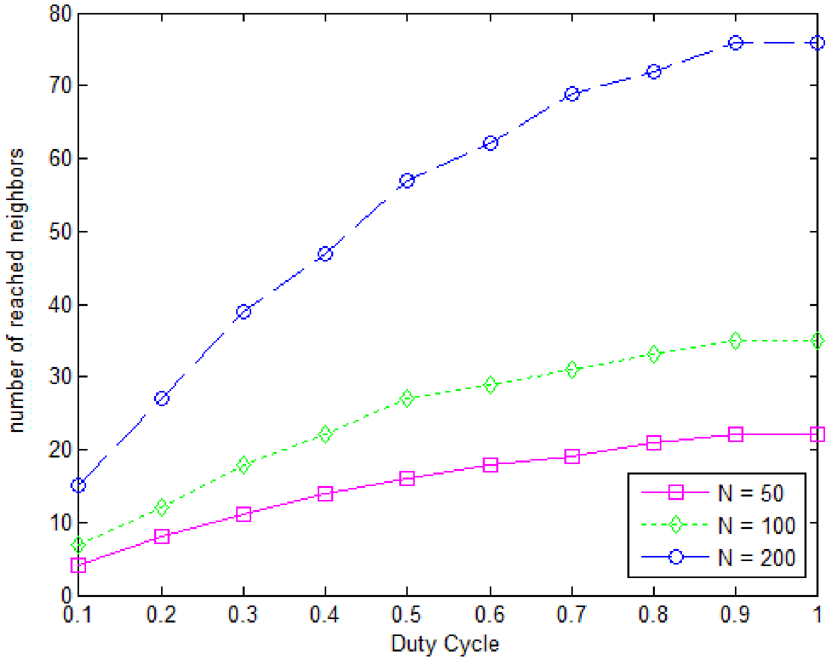

Figure 3-7: The number of the reached neighbors for different sensor nodes density

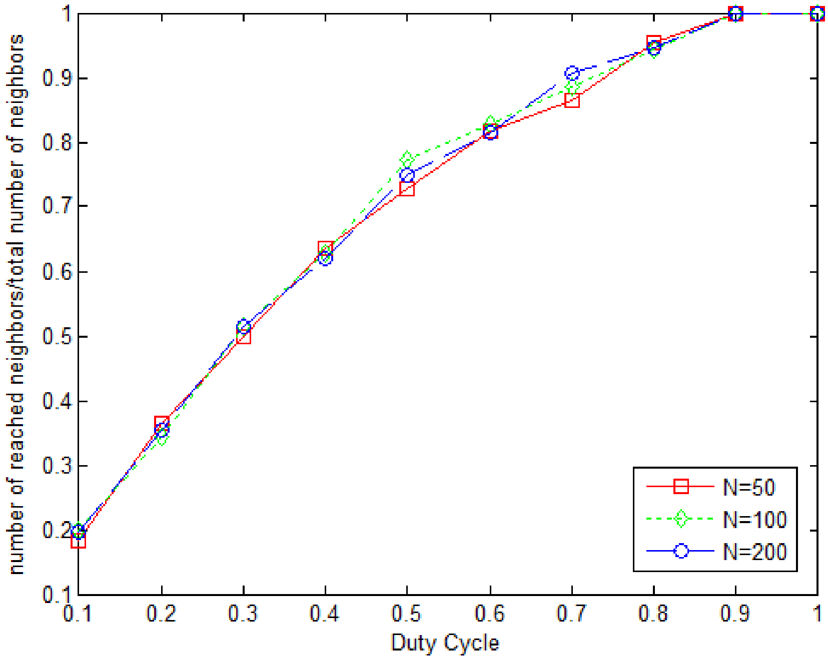

Figure 3-8: Percentage of the number of the reached neighbors over the total number of neighbors for different sensor nodes density

then in a sparse network with a density equal to 0.005 $nodes/m^2$ (N=50) the sensor nodes need a 80% duty cycle to reach this number. However in a dense network with a node density equal to 0.02 $nodes/m^2$ (N=200) then a duty cycle less than 20% is enough to reach 20 nodes. This again shows that the duty cycle needs to be adapted to the network density.

Figure 3-8 shows the percentage of the number of the reached neighbors over the total number of neighbors for different sensor nodes density, it can be seen that the ratio versus different duty cycles overlaps for different node densities.

3-5 The effect of Preamble length on duty cycle

Preambles are an extra transmission period that come before the data transmission of a wireless signal, the length of the preamble can be varied and it depends on the density of the wireless network. Here it is denoted as $T_{preamble}$ and it should be smaller than one period of time interval T =1 second. Due to the simplicity and no requirements of synchronization a preamble is appealing to WSNs. Before a source node transmits a packet, firstly it sends a preamble with a certain length to find the neighboring nodes which are active Then the packet is sent and the received sensor nodes rebroadcast the packet to other sensor nodes.

In the following sessions different lengths of the preamble are applied for duty cycle equals to 10%, 20%, 30% and 50%. Since the experiment of the first section has been shown that a high duty cycle which is above 50% has almost the same reachability as the duty cycle equals to 1. A long preamble length costs more energy for a transmitter, thus the chosen preamble length of 0.05, 0.1, 0.2, 0.3 and 0.4 is taken since these are relatively short. The same number of nodes N = 50, N = 100 and N = 200 is used and they are uniformly distributed in a 100m x 100m field. The source node is sensor node 1 and is also randomly placed in the topology.

Figure 3-9 shows the reachability with a 100 sensor nodes with a 10% duty cycle and a variable preamble lengths of 0.05, 0.1, 0.2, 0.3 and 0.4 plotted versus time. When the preamble equal to 0.4 the reachability reaches 94%, which means 94 % of the sensor nodes in the whole network are reached. It shows that the maximum reachability with different preambles ranges from 55% to 94% at T=10 seconds.

As mentioned in Chapter 2 the source node broadcasts the packet to the neighboring sensor nodes and before the broadcast will send the preamble. If the preambles overlaps with an active sensor nodes then the sensor nodes can receive the packet from the source node. The sensor nodes that received the packet will rebroadcast the packet in the next cycle. Figure 3-10 shows the reachability with 100 sensor nodes for a 20% duty cycle and a various preamble length of 0.05, 0.1, 0.2, 0.3 and 0.4 plotted versus time. Comparing Figure 3-10 with Figure 3-9 it can be seen that with a higher duty cycle the reachability increases faster and reaches a higher maximum value which ranges from 56% to 100% at T= 7 seconds compared to a range of 55 % to 94 % in Figure 3-11.

Figure 3-11 shows the reachability with 100 sensor nodes for a 30% duty cycle and a various preamble length of 0.05, 0.1, 0.2, 0.3 and 0.4 plotted versus time. With the higher duty cycle of 30% the reachability increases much faster and the reachability ranges already from 56% to 100% at T= 4 seconds. Figure 3-12 shows the reachability with a 100 sensor nodes for a 50% duty cycle and various a preamble lengths of

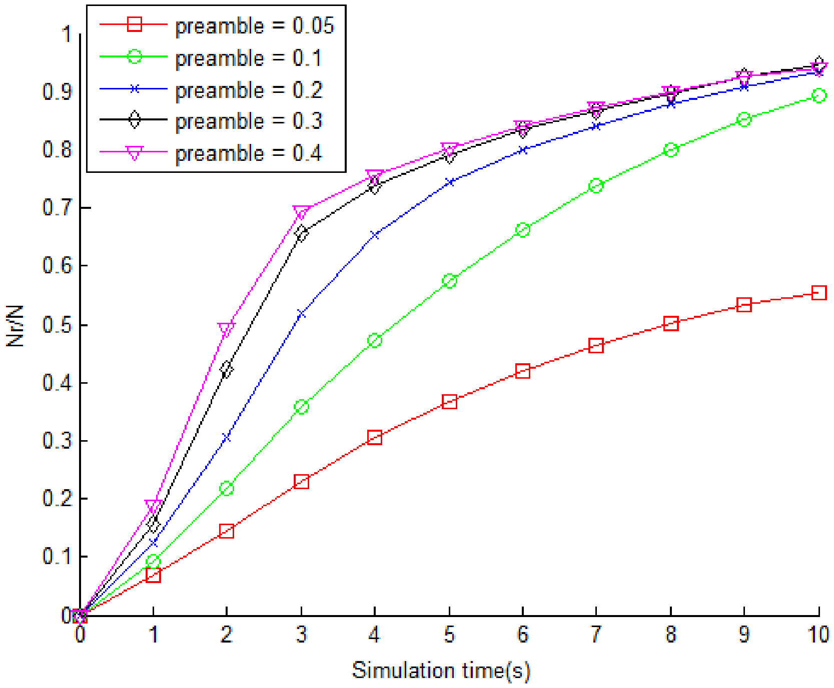

Figure 3-9: The average reachability of 100 sensor nodes with various preamble lengths where $d = 0.1$

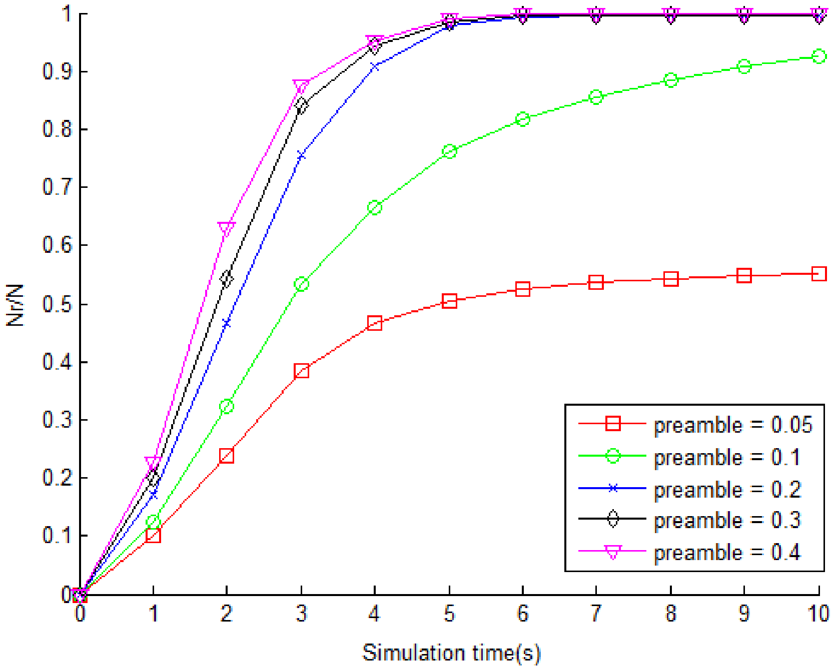

Figure 3-10: The average reachability of 100 sensor nodes with various preamble lengths where $d = 0.2$

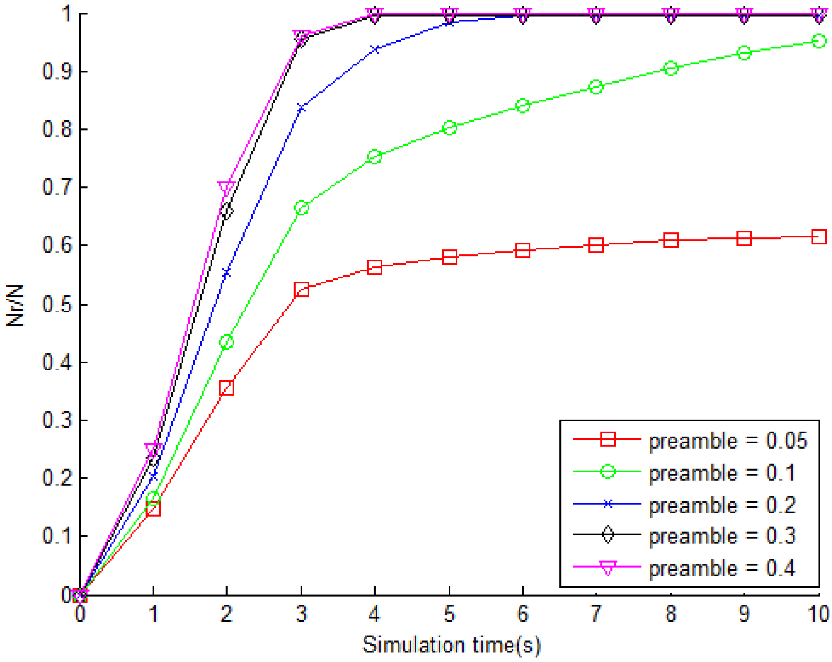

Figure 3-11: The average reachability of 100 sensor nodes with various preamble lengths where $d=$ 0.3

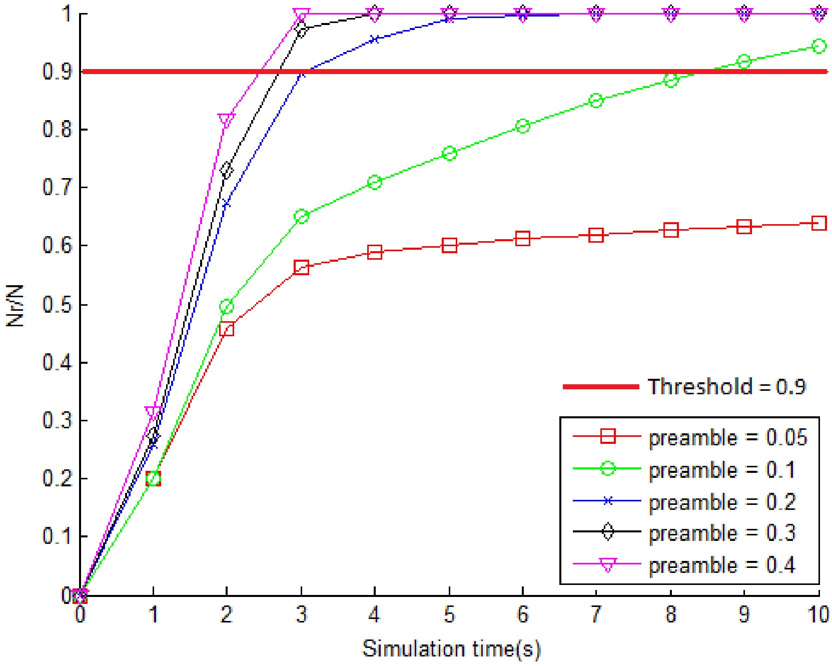

Figure 3-12: The average reachability of 100 sensor nodes with various preamble lengths where $d=$ 0.5

0.05, 0.1, 0.2, 0.3 and 0.4 plotted versus time. With a higher duty cycle of 50% the reachability is almost the same as in the situation for a 30 % duty cycle since for both duty cycles the reachability ranges from 58% to 100% at T= 4 seconds. In this figure it can be seen that with a preamble length of 0.05 the reachability can maximal reach 65% of the whole network. When the preamble length is increased to 0.1 it still needs more than 8 seconds to reach the threshold which is a reachability of 90% of the whole network. For the preamble lengths larger than 0.2 it only needs around 3 seconds to reach 90% of the whole network. From it is show that for a larger preamble the desired reachability can be reached within less time.

Comparing Figure 3-9 to Figure 3-12 it shows that by increasing the duty cycle from 10% to 50% under the same conditions the reachability increases. It can also be concluded that for the same duty cycle the increase of the length of a preamble has the effect of a larger reachability to a certain attainable maximum.It also be seen that with a 100 sensor nodes and a node density of $0.01 nodes/m^2$, the preamble length of 0.3 has almost the same effect as a preamble length larger than 0.4.

In Figure 3-9 a duty cycle of 0.1 and a preamble length of 0.4 was used opposed to the used duty cycle of 0.5 and preamble length of 0.2 in Figure 3-12. But in both cases the reachability reaches 94% . Thus the reachability can also reaches 94% with a duty cycle of 0.5 and a preamble of length 0.2 is used. This concludes that there is a energy trade off between the length of the preamble of a transmitter and the duty cycle of a receiver.

Figure 3-13 shows the reachability with 50 sensor nodes in combination with a 10%

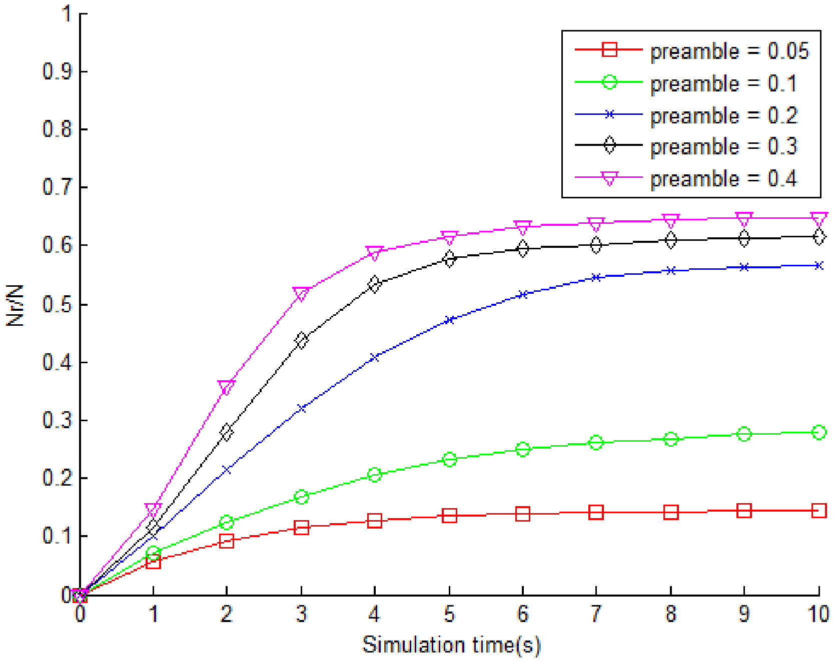

Figure 3-13: The average reachability of 50 sensor nodes with various preamble lengths where d= 0.1

duty cycle and a various preamble length of 0.05, 0.1, 0.2, 0.3 and 0.4 plotted versus time. The reachability only reaches a maximum of 65%, which means that only 65% of the whole network is visited when the preamble equals to 0.4. The minimum reachability is only 14% with the preamble equal to 0.05.

Figure 3-14 and Figure 3-15 show the reachability with 50 sensor nodes for a 20% and 30% duty cycle with various preamble lengths plotted against time. In Figure 3-13 and Figure 3-15 the same network topology was used. In Figure 3-13 when the duty cycle is equal to 10% and a preamble length of 0.4 a reachability of 65% is achieved. In Figure 3-15 when the duty cycle equals to 30% and with a preamble length of 0.1 the reachability 65% is also obtained.

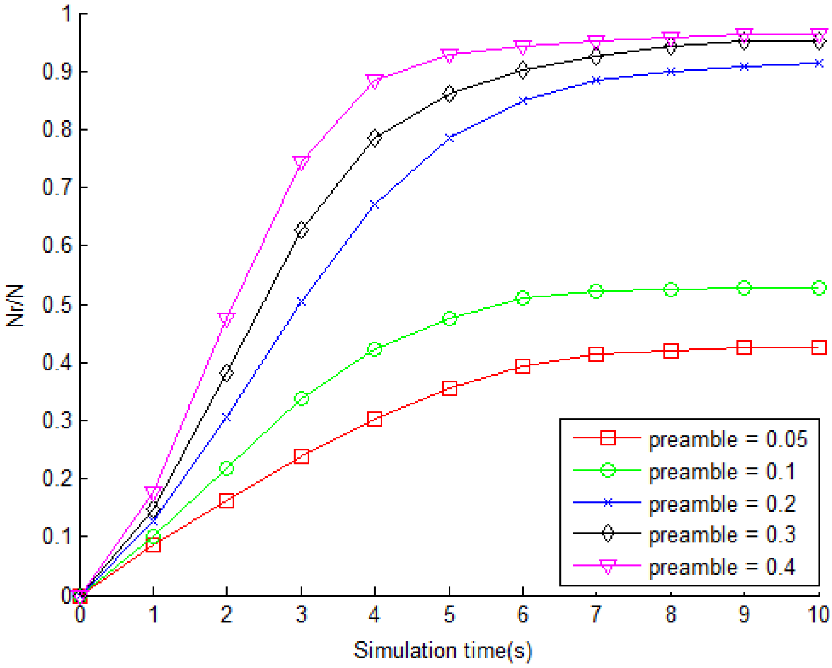

Figure 3-14: The average reachability of 50 sensor nodes with various preamble lengths where $d=$ 0.2

Figure 3-16 shows the reachability with 200 sensor nodes for a 20% duty cycle with various preamble lengths plotted versus time. From this figure it can be seen the reachability of the network is high with a longer preamble length. It can also be concluded that with a higher node density, the reachability with various preamble length also has higher reachability than compared to networks with a lower node density.

Figure 3-17 shows the necessary time in order to obtain a reachability of 80% of the whole network for two node densities with the duty cycle equal to 0.2 and where the preamble length ranges from 0.1 to 0.8. The time in order to reach 80% is plotted against different preamble lengths. The green line represents the sparse network with a node density equal to 0.01 $nodes/m^2$ and the blue line represents the dense network with a node density equal to 0.02 $nodes/m^2$. This shows that for the same amount of reachability, a dense network needs less time compared to the sparse network. It also shows that with the increase of the preamble length less time is needed to reach the desired reachability.

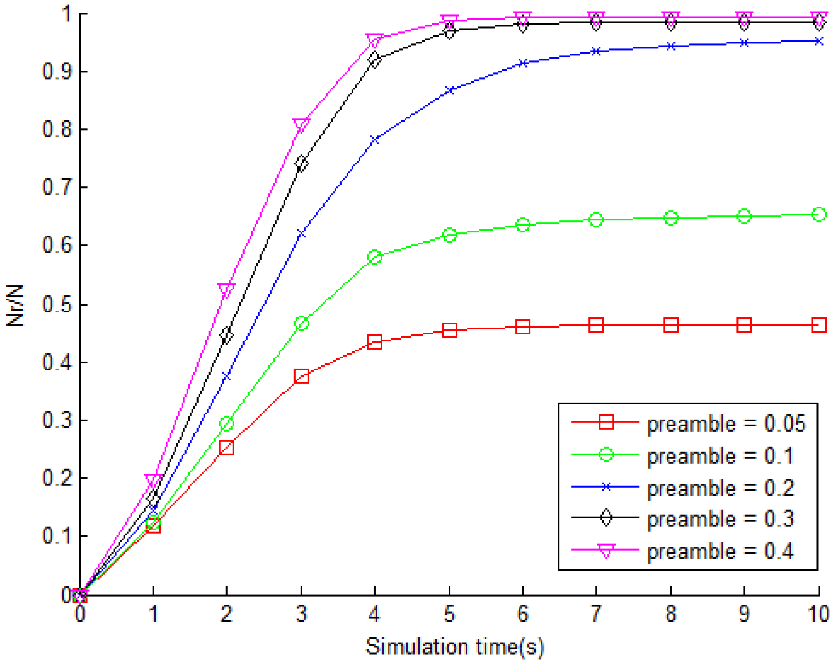

Figure 3-15: The average reachability of 50 sensor nodes with various preamble lengths where $d = 0.3$

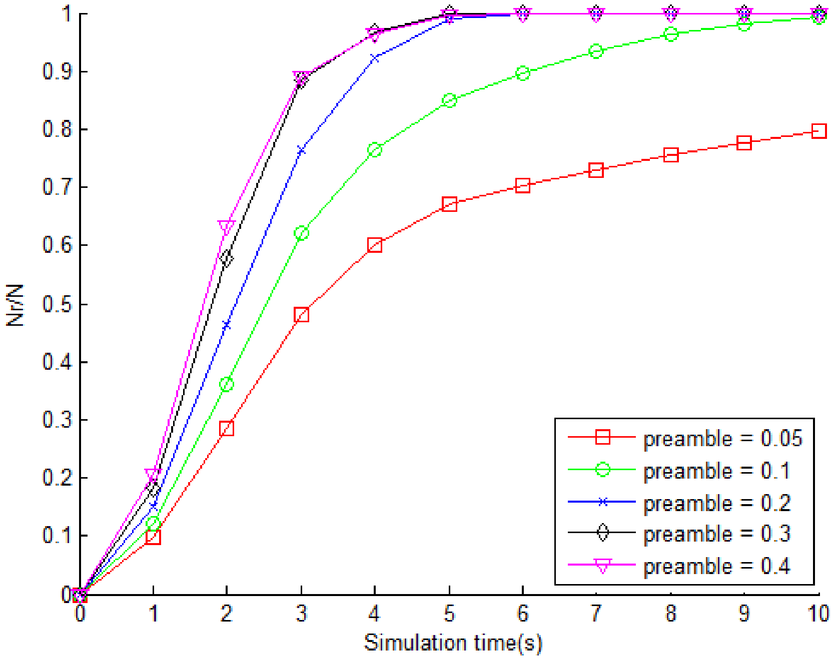

Figure 3-16: The average reachability of 200 sensor nodes with various preamble lengths where $d = 0.2$

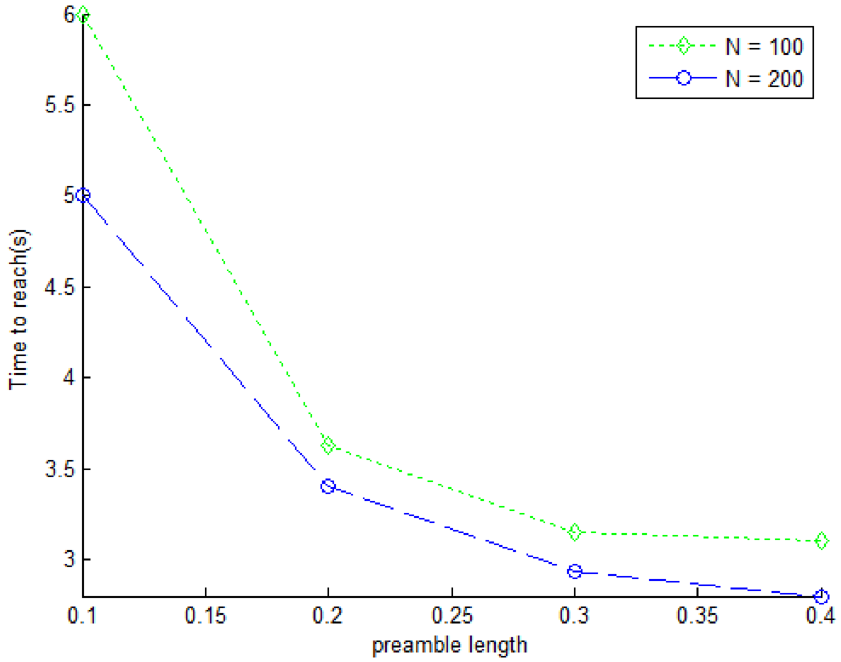

Figure 3-17: Maximal time to reach 80% of the network with various node density for the duty cycle equals to 0.2

In Figure 3-18 the necessary time to reach 80% of the whole network is shown for two

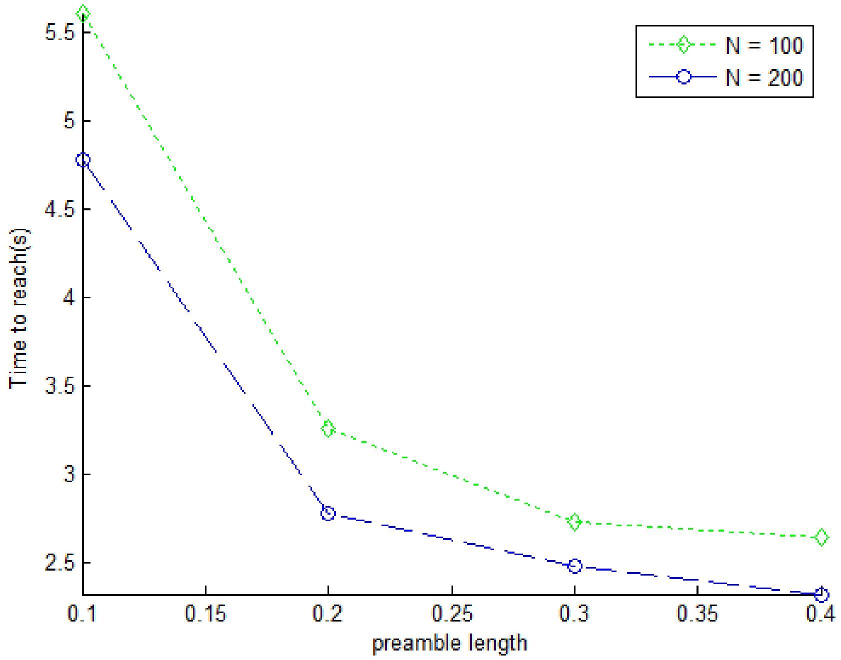

Figure 3-18: Maximal time to reach 80% of the network with various node density for the duty cycle equals to 0.5

node density with the duty cycle equal to 0.5 and again the same range of preamble lengths. Comparing this Figure 3-18 to Figure 3-17 it can be seen that the needed time to reach 80% of the network is shorter. The cause of this is the use of a larger duty cycle. It also shows the same effects of that in Figure 3-17 namely that with a larger preamble length or a denser network the needed time to reach the desired 80% of the network is shorter.

From these figures it can be concluded that in general with the growth of the preamble length the reachability increases for the same network topology. However the reachability from the source node to the sensor nodes is not only dependent on the preamble length but also dependent on the random deployment of the sensor nodes. Because sometimes the source node is in the corner of the field or there are few neighboring nodes within the transmission range of the source node. Though for the same network typology the number of sensor nodes that receive the packet from the source node always increase with the preamble length. Hence the simulations here are done for similar node deployment.

Another conclusion from this session is that a longer preamble does not necessarily has to lead to a higher reachability for the network. At one point an increase in the length of the preamble results in almost the same reachability. Meaning that for a long preamble a lower duty cycle can be used for the received sensor nodes. When the preamble is too long the energy consumption will increase but the gain in reachability is neglect able. So there is a trade off between a long and a short preamble in combination with the trade off between the length of the duty cycle of the received sensor nodes. Because as seen before for a long preamble the duty cycle can become smaller for the same reachability and that for a large duty cycle the preamble length can become smaller and again the same reachability is achieved. From all the above it can be seen that the length of the preamble is also an important factor in choosing the duty cycle.

3-6 Validation of the Analytical model

In this section the analytical modeling was validated by using the matlab simulations and a number of 100 times matlab simulations are done. For the validation the following assumptions are made: within a 100m x 100m field a number of 50, 100 and 200 sensor nodes are randomly deployed, the maximum transmission range equals to 35 m and no collisions occur. The source node choses a random starting time between 0 and T_{period} and the number of reached nodes shall be simulated for 10 periods of time. For the simulations a preamble length of 0.3s is chosen in combination with various duty cycles that range from 0.01 to 1. The simulation results from these scenarios are then compared to the expected values that originate from the analytical model for the given parameters.

Figure 3-19 shows the results from the analytical model versus the simulation results for a WSN with 50 sensor nodes. For various duty cycles the averaged number of reached neighbors is plotted. From this figure it can been that the analytical model is in the range of the simulation results and the averaged maximum reached sensor nodes is 21 sensor nodes.

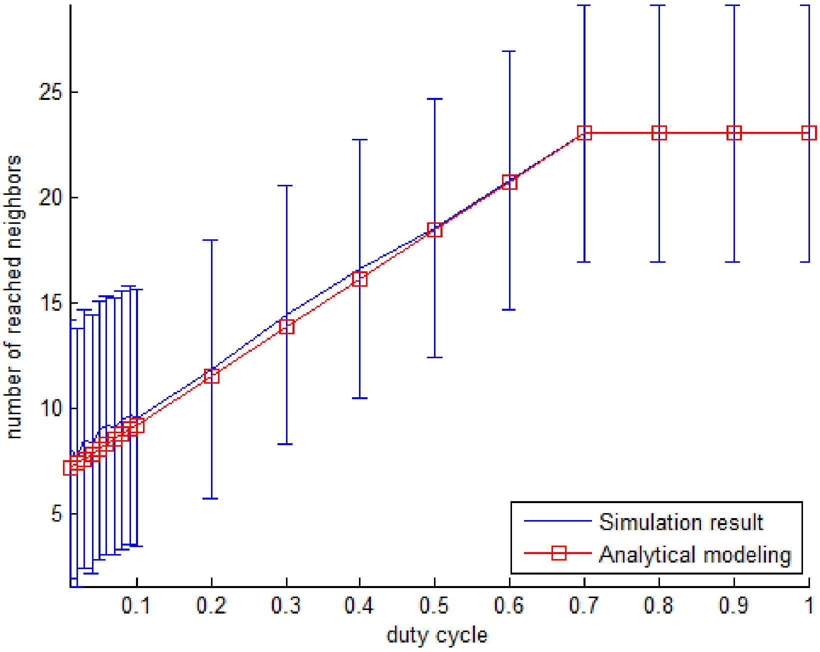

Figure 3-19: Validation between the simulation results and analytical model for a WNS of 50 sensor nodes and preamble equals to 0.3s

Figure 3-20 shows the validation of the analytical mode versus the simulation results of a WSN of 100 sensor nodes as in the previous figure, the only difference is that the averaged maximum reached neighbors increases to 43 nodes. Again the analytical model seems to be within the range of the simulation results.

Finally in Figure 3-21 for a WSN with 200 sensor nodes the model is plotted against the simulation results, the averaged maximum reached neighbors is increased to 71 sensor nodes. From all the above it can be seen that the analytical model matches the matlab simulation results quite accurately, it was also shown that with the increases of the number of the sensor nodes, the number of the reached sensor nodes are also increased.

Figure 3-22 shows the results from the analytical model versus the simulation results with a various number of sensor nodes. With a node density of 0.005 $nodes/m^2$, 0.01 $nodes/m^2$ and 0.02 $nodes/m^2$. From this figure it can be seen that with an increase of the node density in the network, the number of reached neighbors also increases, but the ratio of the number of reached neighbors over the total number of neighbors are the same.

Figure 3-23 shows the results from the analytical model and the simulation results of a WSN of 100 sensor nodes for different transmission ranges. The number of the reached neighbors versus various duty cycles is plotted. The transmission range varies from $20m$, $35m$ and $50m$, respectively. From this figure, with the increasing of the transmission range, the number of the reached neighbors also increases and the ratio of the number of the reached neighbors over the total number of neighbors keeps the same.

Figure 3-24 shows the results from the analytical model and simulation results for a WSN with 100 sensor nodes with different preamble lengths. The number of reached

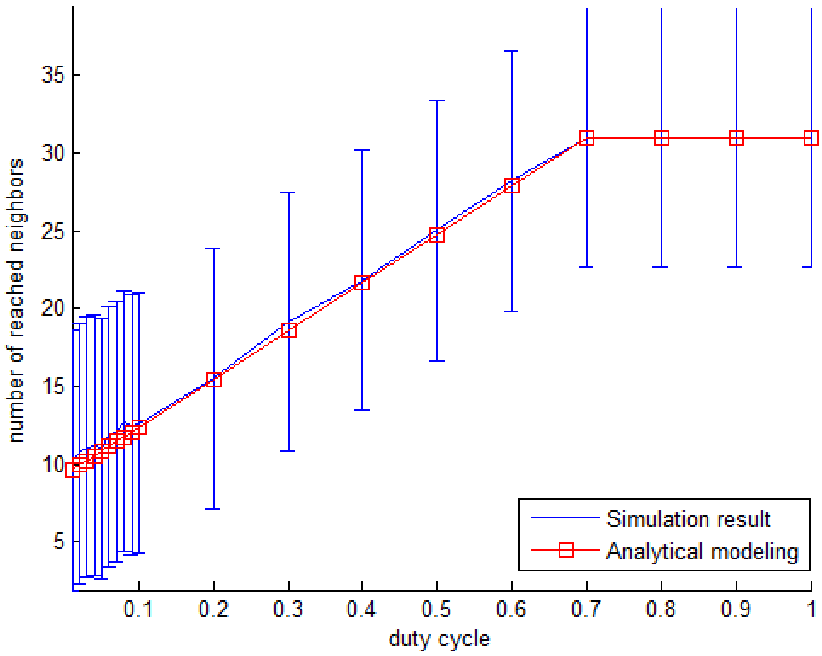

Figure 3-20: Validation between the simulation results and analytical model for a WNS of 100 sensor nodes and preamble equals to 0.3s

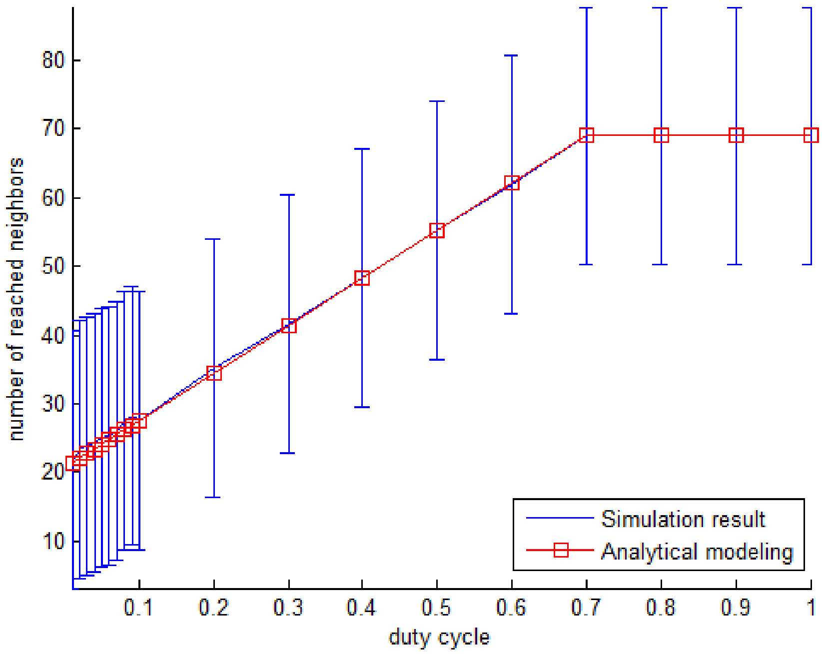

Figure 3-21: Validation between the simulation results and analytical model for a WNS of 200 sensor nodes and preamble equals to 0.3s

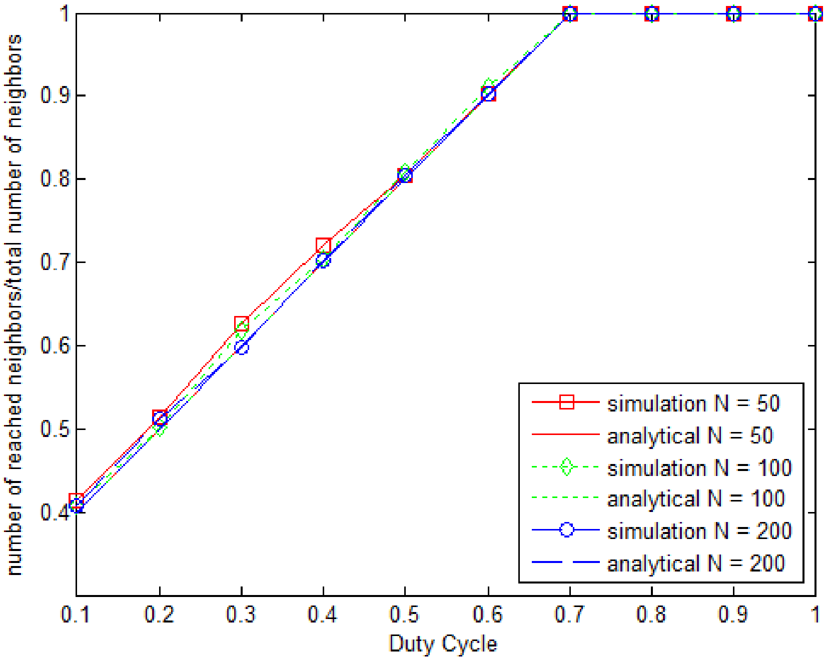

Figure 3-22: Validation between the simulation results and analytical model for a WNS of various sensor nodes and preamble equals to 0.3s

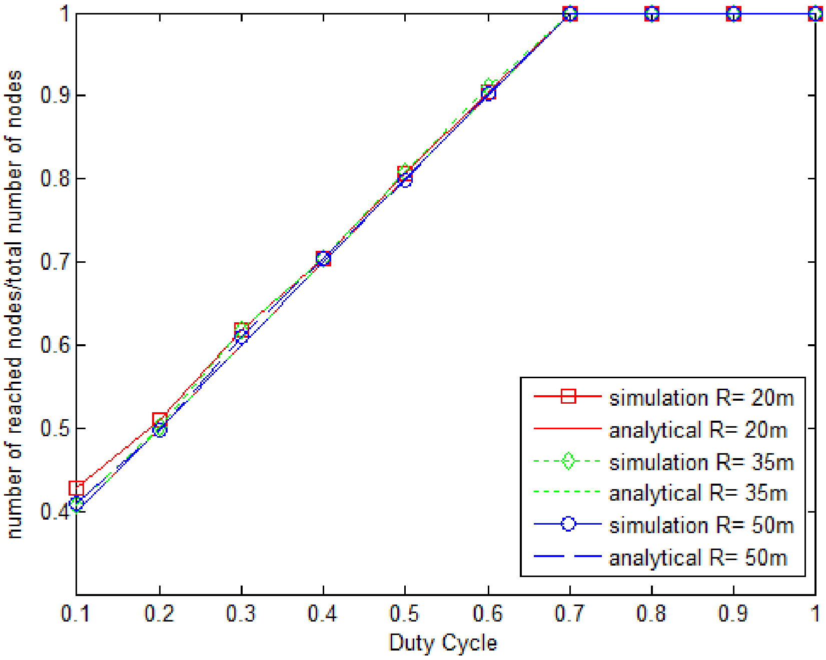

Figure 3-23: Validation between the simulation results and analytical model for a WNS of various transmission range and 100 sensor nodes and preamble equals to 0.3s

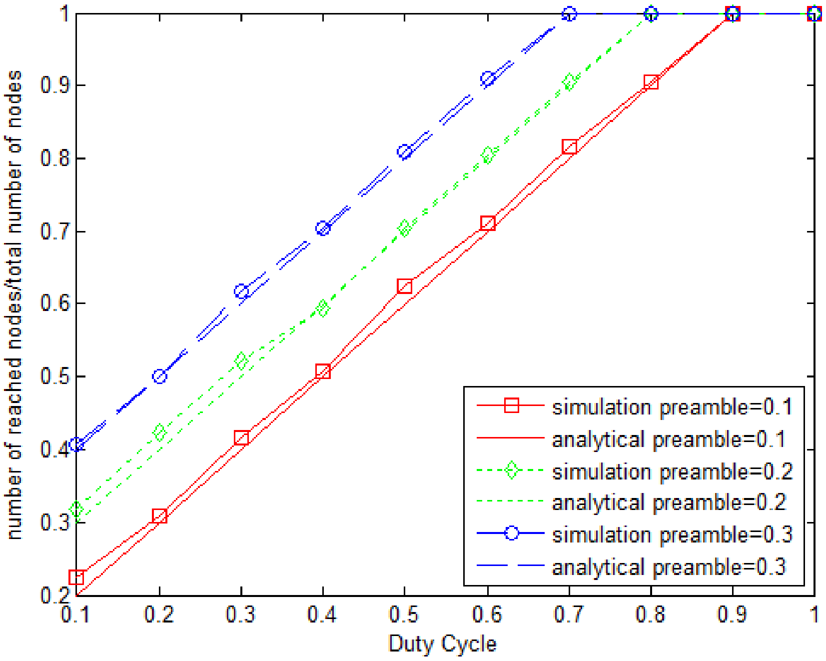

Figure 3-24: Validation between the simulation results and analytical model for a WNS of various preamble length and 100 sensor nodes and transmission range equals to 35m

neighbors versus the duty cycle, which ranged from 0.1 to 1, is plotted. The preamble length equals to 0.1s, 0.2s and 0.3s, respectively. This figure shows that with the increasing of the preamble length, the number of reached neighbors also increases, the ratio of the number of the reached neighbors over the total number of the neighbors increases with the increase of the preamble length.

Various node densities and the number of desirable received nodes is listed in table 3-4. The duty cycle can be calculated by using the analytical model for a given preamble. Based on the following assumptions for preamble length sensor node densities and desired number of received nodes that are made in table 3-4 below the duty cycle can be calculated:

In Figure 3-25 the preamble length versus the duty cycle is plotted where the above assumptions are made and the analytical model is used. This figure shows the relationship between the preamble and the duty cycle and that with an increases of the

transmission range	node density	% of the reached neighbors	preamble length
35m	0.005 $nodes/m^2$	80%	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8
35m	0.01 $nodes/m^2$	80%	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8
35m	0.02 $nodes/m^2$	80%	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8

Table 3-4: Assumed parameters in order to calculate the needed duty cycle

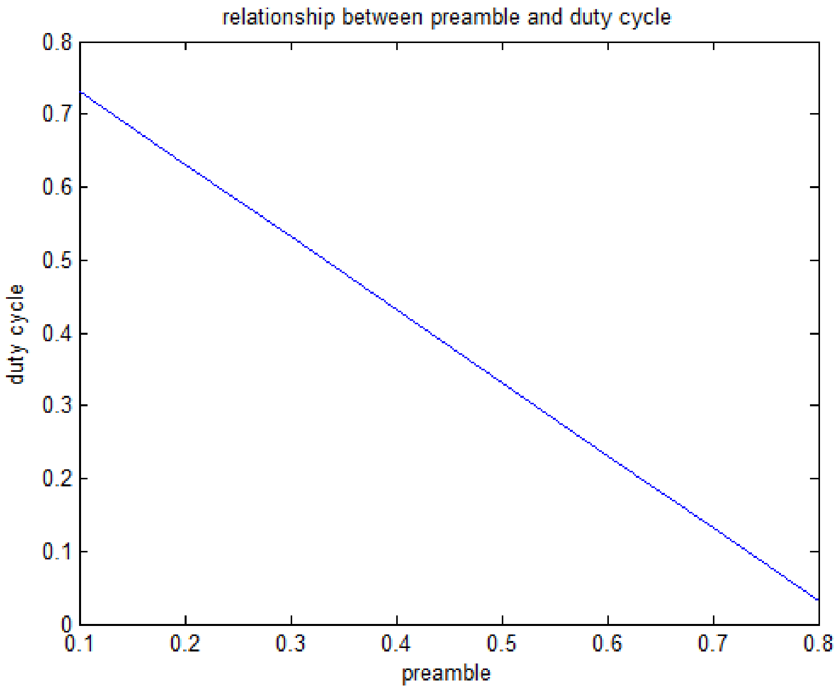

Figure 3-25: Relationship between the preamble and duty cycle for 100 sensor nodes

preamble length the duty cycle decreases. This result matches the outcome of the matlab simulations which were done in the last session. The total sum of the preamble and duty cycle is always fixed for the same amount of desirable received nodes. This means that for if a total sum of 0.4 seconds should be used for reaching 20 sensor nodes the preamble length plus the duty cycle length is always 0.4 seconds. Choosing a duty cycle of 0.1 second automatically implies choosing the preamble length equal to 0.3 seconds else the number of desired nodes is not reached.

The needed duty cycle is calculated by using the analytical model and the earlier made assumptions above for the node densities 0.005 $nodes/m^2$, 0.01 $nodes/m^2$ and 0.02 $nodes/m^2$. Afterwards, the calculated duty cycle and preamble are used in matlab simulations. For example, in the case of 100 sensor nodes, a duty cycle of 0.6315 seconds and preamble length equal to 0.2 seconds are used in the matlab simulation. The obtained reachability will be compared to the reachability that was obtained with a duty cycle equal to 0.1315 seconds and preamble length equal to 0.7 seconds. In the analytical model these two scenarios should reproduce almost the same reachability. The following matlab simulations show if these two scenarios indeed reproduce the same reachability.

Figure 3-26 shows the average reachability of the two scenarios mentioned above for a WSN with a number of 50 sensor nodes, there is a small difference in the reachability between the two lines. Figure 3-27 shows the average reachability for a WSN with a number of 100 sensor nodes and Figure 3-28 shows the average reachability of the scenarios for a WSN with 200 sensor nodes. From these 3 figures it can be seen that almost the same reachability is achieved.

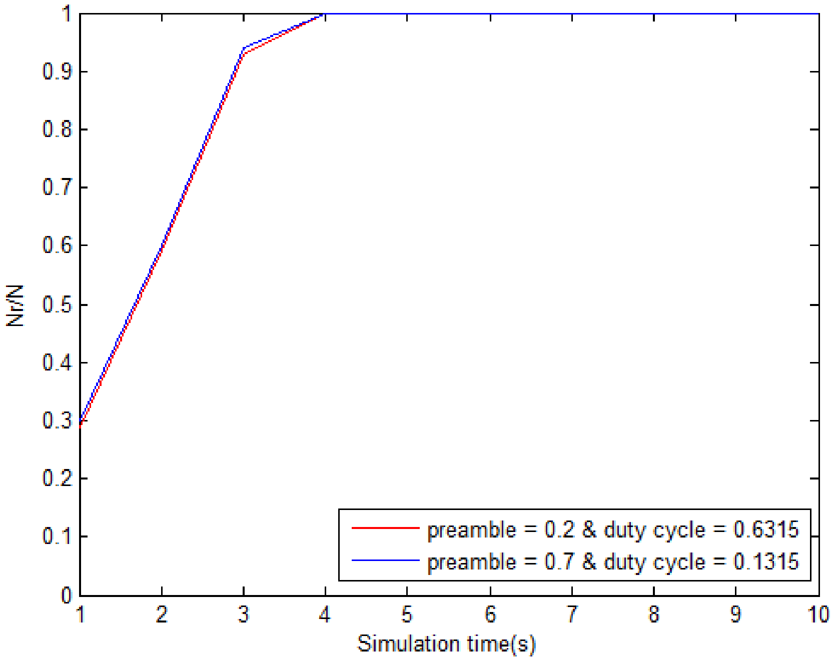

Figure 3-26: The average reachability for a WSN of 50 sensor nodes for a scenario with a total equal active time

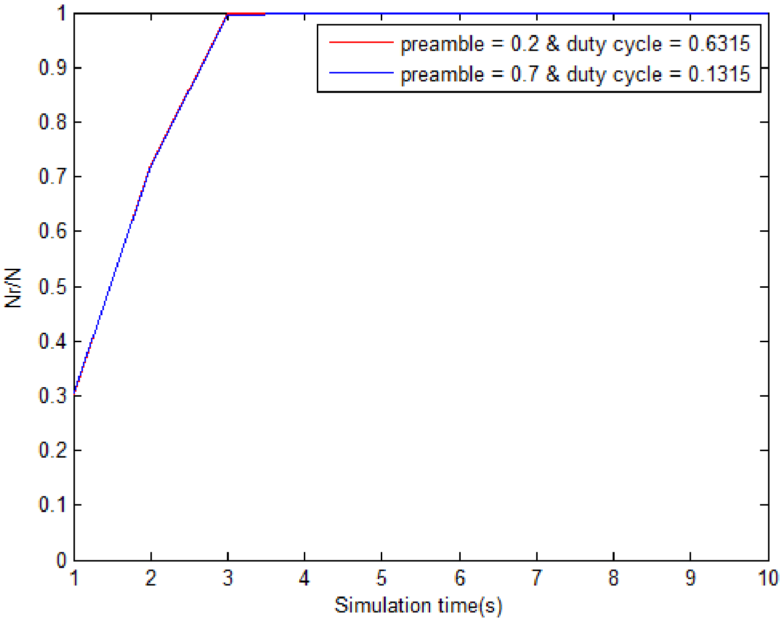

Figure 3-27: The average reachability for a WSN of 100 sensor nodes for a scenario with a total equal active time

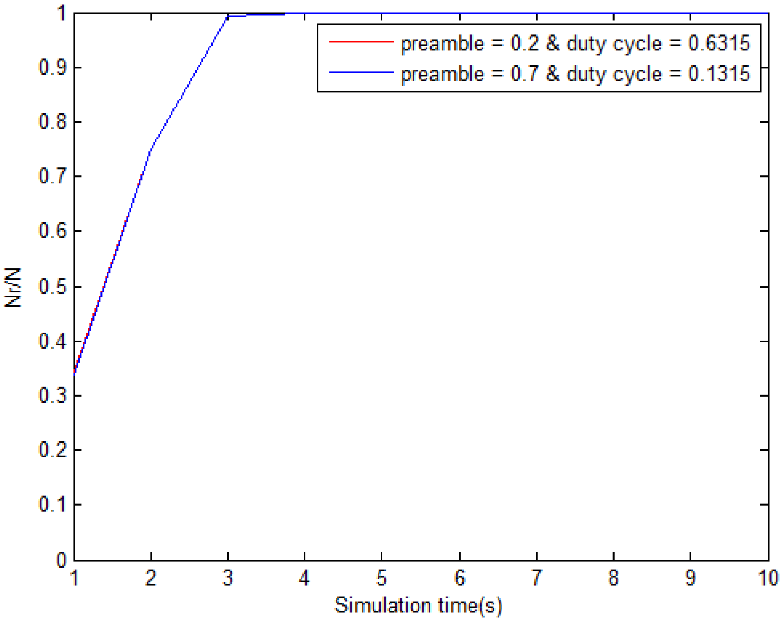

Figure 3-28: The average reachability for a WSN of 200 sensor nodes for a scenario with a total equal active time

3-7 Conclusion

This chapter shows the effects of the sensor node density on the needed duty cycle in order to reach the same reachability. From the matlab simulations it can be concluded that when the network density increases then the reachability also increases for the same duty cycle. For the same amount of the reachability in combination with a higher sensor node density a lower duty cycle can be used and that within a shorter time the same reachability is reached. For a WNS with a lower sensor nodes density a higher duty cycle needs to be used and it may take a longer time to reach the same reachability. This indicates that the duty cycle needs to be adapted to the network density. In WSNs a sensor node with a low duty cycle has a much longer lifetime than a sensor with a high duty cycle. However, if the sensor nodes density is too low then the reachability does not include the entire WSN so making the duty cycle as low as possible does not work.

Besides the effects of the duty cycle, the preamble, if present, also plays an important role. With the increases of the preamble length, the reachability also increases for the same network topology. In order to reach the same amount of reachability in a shorter time a longer preamble length can be used. But the tradeoff is that a longer preamble length costs more energy of the transmitter. However, for a smaller preamble length a longer time is needed to reach the same reachability. For reaching the same amount of reachability in a dense network a smaller preamble length is needed. In contrary, in a sparse network a longer preamble length should be used.

In this chapter an analytical model was given which shows that the expected number of the received nodes is a function of the sensor node density λ $nodes/m^2$, the trans-

mission range R m, the preamble p and the duty cycle d. If the effect of the preamble length, duty cycle and node density are neglected then in the case of an increase of the transmission range the number of reached neighbors also increases.
Finally, the analytical model and the matlab simulation were validated, the analytical model is much closer to the simulation result. By increasing the node density, the variance decreases. Through the validation it can be seen that by increasing the duty cycle, the number of the reached neighbors always increases. Further effect that influence the number of reached neighbors are if the node density increases, or the transmission range increases, or the preamble length increases then the number of reached neighbors also increases. The percentage of the number of the reached neighbors over the total number of the neighbors keeps the same if the transmission range increases, or the node density increase. With the increase of the preamble the percentage of the number of the reached neighbors over the total number of the neighbors also increases. In short it can be said that for a WSN the same amount of reachability can be achieved by either using a smaller preamble length in combination with a larger duty cycle or a larger preamble length in combination with a smaller duty cycle.

Chapter 4

Performance Analysis

4-1 The Density Estimation

Previous work about density estimation has been done by sharing the received power measurements from the neighboring nodes in [20]. Based on these collected measurements from the neighboring nodes, the maximum likelihood estimate (MLE) of the density λ $nodes/m^2$ is computed. In this previous work two models are proposed, namely the individual density estimation and the cooperative density estimation. The result of [20] shows that cooperative density estimation has better a accuracy with less variance than individual estimation. When nodes share received power measurements from neighboring nodes further away, the density estimation has a even much better accuracy because of the further reduced variance. In this thesis work only the individual density estimation is used to adapt the duty cycle.

In the individual density estimation model, for each node the received power from k_j^{th} neighboring nodes is collected to compute the estimate for j=1, 2, 3, ..., n. For a homogeneous network, each sensor node has the same following assumed parameter and it is listed in table 4-1. The antenna gains of the transmitting and receiving are equal to 1.

Since the path loss exponent equals to 2 in this scenario, according to the Friis transmission equation [33] in 4-1, the distance is known.

$$P_r = P_t \cdot G_t \cdot G_r \cdot (\frac{c}{f \cdot 4 \cdot \pi \cdot R})^2, \tag{4-1}$$

Transmission power (P_t)	Frequency (f)	Path loss exponent (η)	Speed of light (c)
100 mW	900 MHz	2	$3.0 \cdot 10^8 m/s$

Table 4-1: The assumed parameters

In 4-1 C=$(c/4\pi \cdot f)$ is a constant. Then the received power P_r is:

$$P_r = P_t \cdot G_t \cdot G_r \cdot (\frac{c}{f \cdot 4 \cdot \pi \cdot R})^2 = P_t C(\frac{1}{R})^2, \tag{4-2}$$

The MLE of the density $\hat{\lambda}$ is written in 4-3 [20]:

$$\hat{\lambda} = \frac{K}{\pi \sum_{j=1}^{n}(R^2)} = \frac{K}{\pi \sum_{j=1}^{n}(\frac{P_r}{P_t \cdot C})^{-1}}, \tag{4-3}$$

where $K = \sum_{j=1}^{n} k_j$. k represents the number of nearest neighbors and the denominator represents the areas of circles. Since $\hat{\lambda}$ is biased, then the estimated density can be written in 4-4 [20]:

$$\hat{\lambda} = \frac{K-1}{\pi \sum_{j=1}^{n}(\frac{P_r}{P_t \cdot C})^{-1}}. \tag{4-4}$$

4-2 Comparing with the fixed duty cycle

4-2-1 The Reachability

In this section the adapted duty cycle for each sensor node is calculated based on the individual estimated density. Instead of fixed duty cycle for all the sensor nodes, the adapted duty cycle for each sensor node is used. The preamble length assumed to be 0.1 s and for this scenario there are 9 neighbors can be reached. In Figure 4-1 the reachability for 50 sensor nodes is plotted versus simulation time by using the adapted duty cycle, a low fixed duty cycle of 0.1 and a high fixed duty cycle of 0.9. This figure shows that the adapted duty cycle has almost the same reachability with the fixed duty cycle which equals to 0.9, both of them reached maximal reachability at the same time. However, the averaged adapted duty cycle is only 0.35. The reachability of a fixed duty cycle which is equal to 0.1 has the lowest reachability and at T= 10 seconds it reaches its maximum reachability of 46% of the whole network. But for the adapted duty cycle and a fixed duty cycle equals to 0.9 the reachability reaches 96% at T=4 seconds. In Figure 4-2 the reachability is plotted versus the simulation time, in this figure it is assumed that there are 16 neighbors are reached. The other simulation parameters are all the same as in the previous simulation. In this case the averaged adapted duty cycle equals to 0.76 which almost overlaps with the fixed duty cycle of 0.9. This shows that with a higher number of desirable received node, a higher duty cycle is needed. In Figure 4-3 the reachability for various duty cycles versus the simulation time in combination with 100 sensor nodes is plotted. It is assumed that there are 16 neighbors are reached. and the preamble length equals to 0.1s. The averaged adapted duty cycle equals to 0.32 which has the same reachability as the fixed 0.9 duty cycle. In a dense network for the same amount of expected received nodes a smaller preamble is needed and has almost the same reachability as in the sparse network.

For the simulation plotted in Figure 4-4 the preamble length equals to 0.1s and there are 200 sensor nodes are deployed in the field. It is assumed that there are 32 neighbors

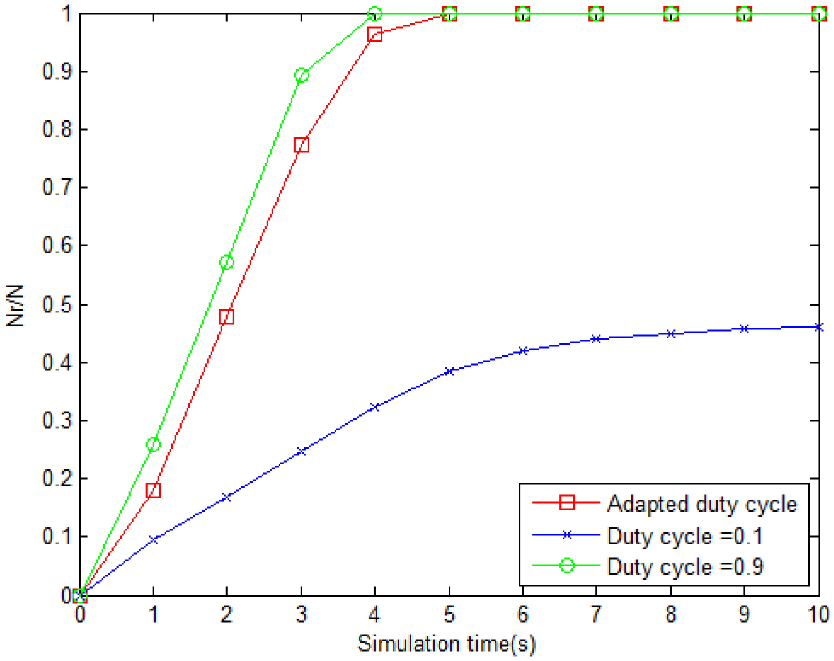

Figure 4-1: The averaged reachability of 50 sensor nodes with various duty cycle, where preamble length=0.1s,9 neighbors can be reached

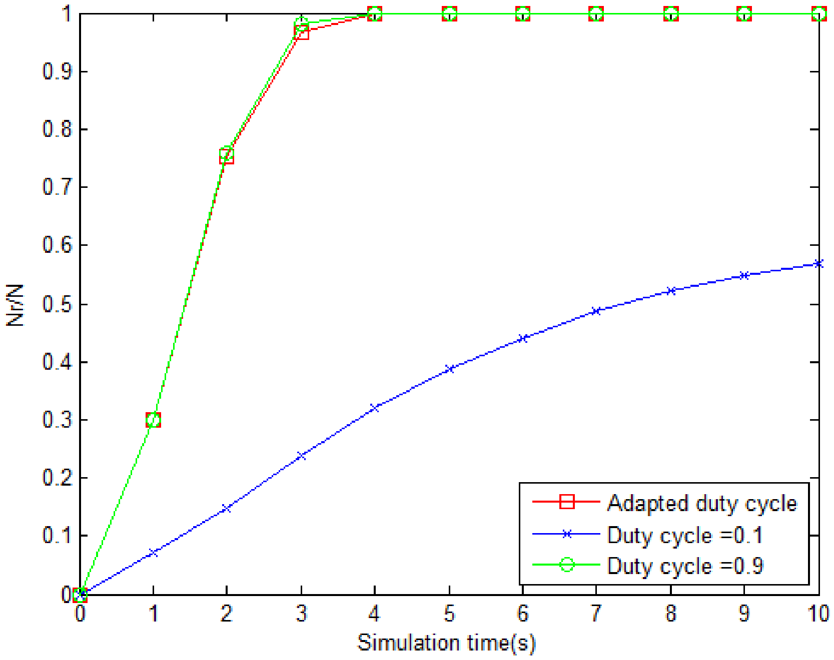

Figure 4-2: The averaged reachability of 50 sensor nodes for various duty cycles, where preamble length=0.1s, 15 neighbors can be reached

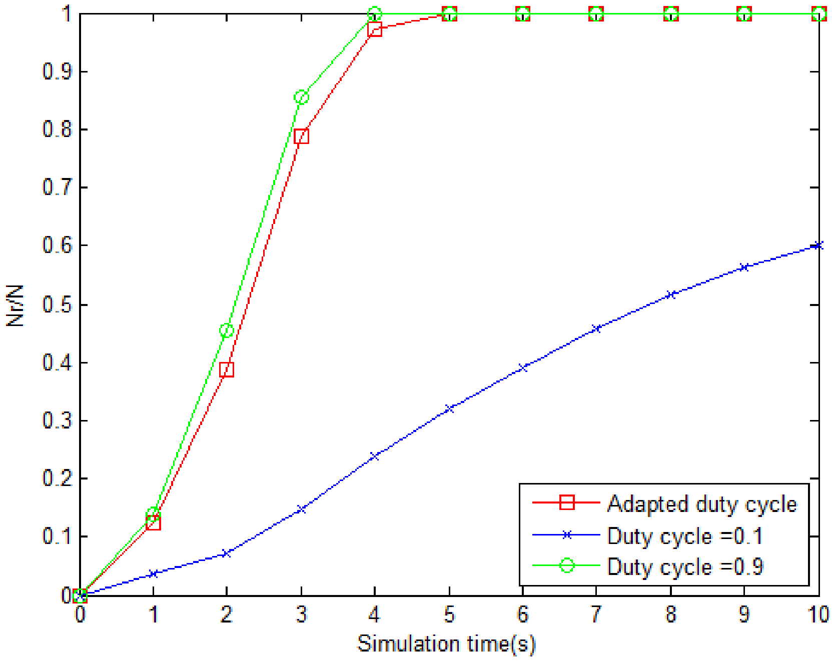

Figure 4-3: The averaged reachability of 100 sensor nodes for various duty cycles, where preamble length=0.1s,16 neighbors can be reached

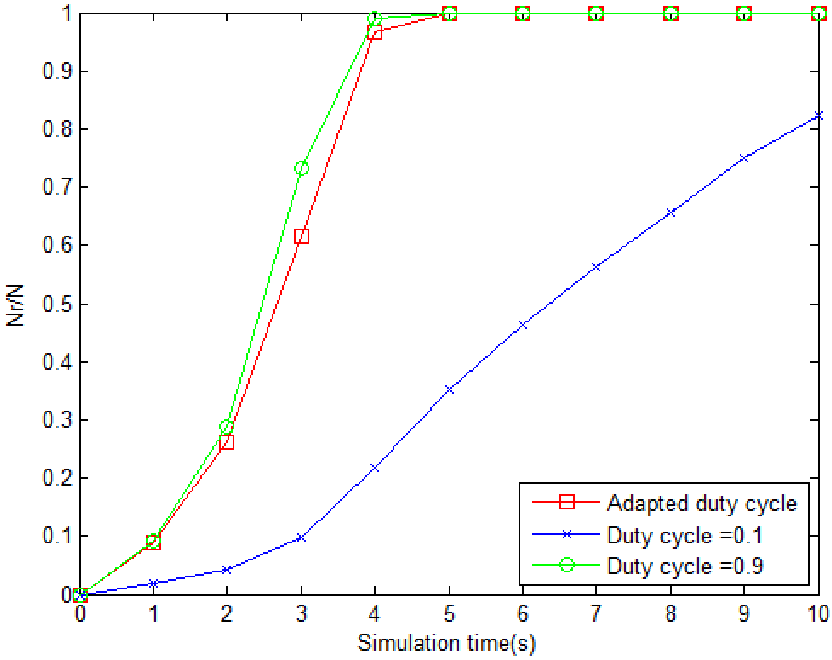

Figure 4-4: The averaged reachability of 200 sensor nodes for various duty cycles, where preamble length=0.1s,32 neighbors can be reached

can be reached. Therefore, the averaged adapted duty cycle is 0.31, but the reachability is almost the same as with a 0.9 duty cycle. This shows that with a denser network, a higher node density, there are more nodes reachable.
This shows that the adapted duty cycle reaches the same reachability as with a fixed 90% duty cycle at the same time, for a dense network the number of reached node are increased for each sensor node. The node density estimation has an important role in the network, the optimal attainable reachability can be achieved by using an density adaptive sleep scheduling.

4-2-2 The Energy Consumption

In the previous section the reachability of various duty cycles was plotted versus the simulation time and it was shown that the adapted duty cycle has almost the same reachability as in the case of a fixed duty cycle of 0.9, which means that the sensor node is almost active all the time. Nevertheless this consumes too much energy so in this section the energy consumption difference of the active period between the adapted duty cycle and a fixed 0.9 duty cycle is compared. Since both of the protocols have almost the same reachability this means that the total number of transmitting nodes are almost the same. The receiving nodes with a larger duty cycle which have a even greater chance to receive the packets consume even more energy. Thus the energy for transmitting and receiving/processing of the transmitted data is not considered in this section. The energy consumption in sleeping is very small, so it is neglected in this scenario. Only the energy consumption when a node is active was taken into account which is 12 mW [27].

Figure 4-5 shows the activated energy consumption difference between the adapted duty cycle and the fixed 90% duty cycle for 50 sensor nodes in order to reach 8 desirable nodes for each node. This figure only compares the energy consumption difference for these two mentioned duty cycles. Because both of them achieved almost the same amount of reachability at the same time although a fixed duty cycle of 10% uses even less energy, the obtained reachability is not the same compared to the 90% duty cycle. Thus only the energy consumption of the adapted duty cycle and the 90% duty cycle is compared.The result shows that the adapted duty cycle reduces the activated energy consumption by 61%. Since the adapted duty cycle is smaller than the 90% duty cycle, so the receiving power consumption is also smaller than that of the 90% duty cycle.

Figure 4-6 shows the activated energy consumption difference between the adapted duty cycle and a fixed 90% duty cycle for 50 sensor nodes in order to reach 12 desirable received nodes for each sensor node. This shows that the activated energy consumption is reduced by 15%.

Figure 4-7 shows the energy consumption difference between the adapted duty cycle and a fixed 90% duty cycle for 100 sensor nodes in order to reach 12 desirable nodes for each node. The activated energy consumption is reduced by 61% . It can be seen that for a dense network and for the same number of desirable received nodes for each sensor node that in the densre network the energy consumption for each node is less than that of the sparser network. It can be concluded that for the same amount of reachability a WSN with a high density network the lifetime is longer.

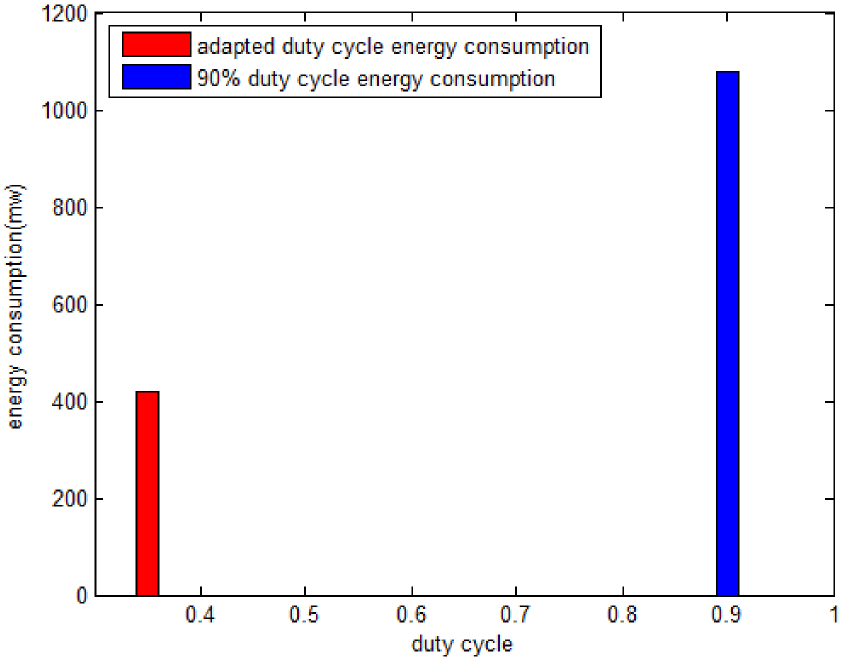

Figure 4-5: The energy consumption of 50 sensor nodes with various duty cycle to reach 8 desirable neighbors

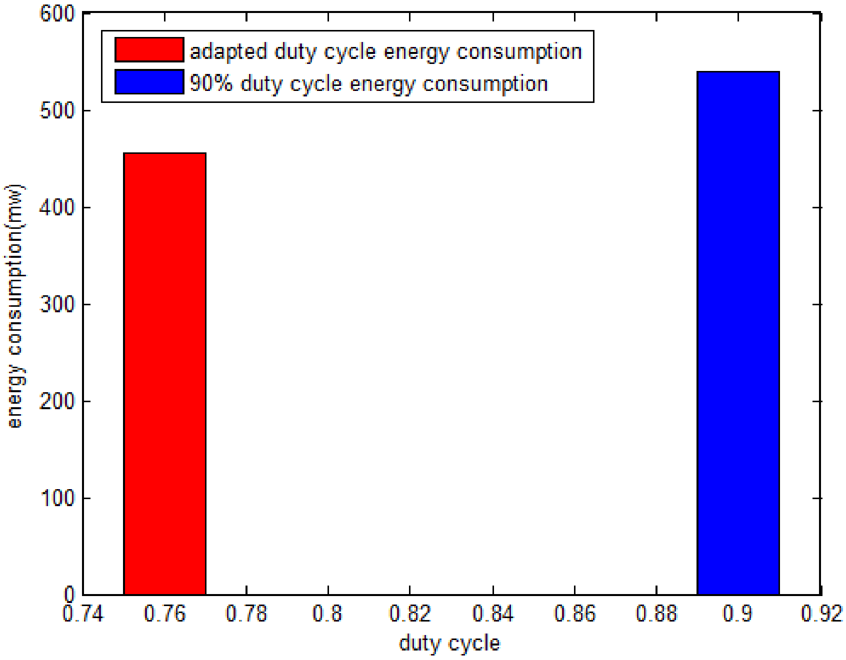

Figure 4-6: The energy consumption of 50 sensor nodes with various duty cycles to reach 12 desirable neighbors

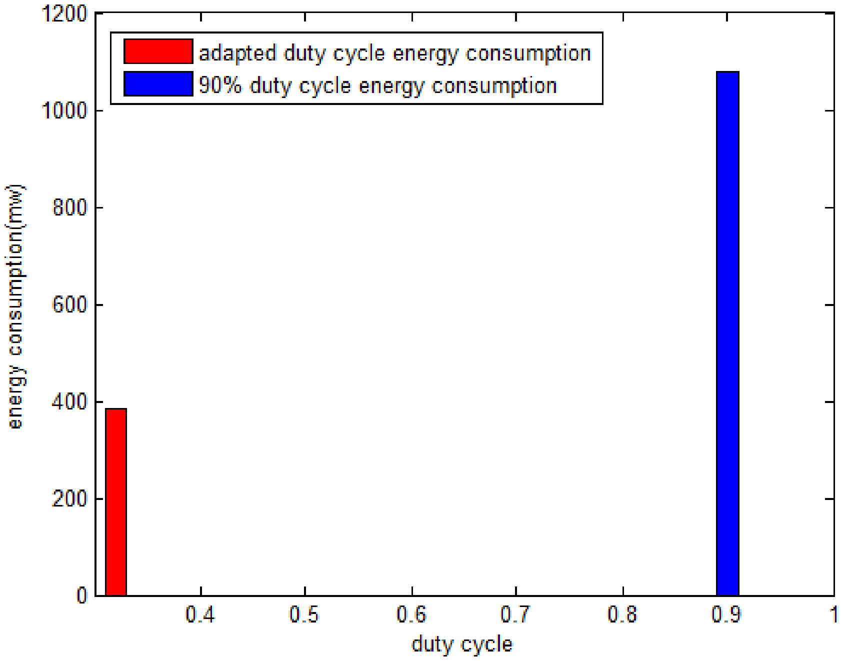

Figure 4-7: The energy consumption of 100 sensor nodes with various duty cycles

Figure 4-8 shows the energy consumption difference between the adapted duty cycle

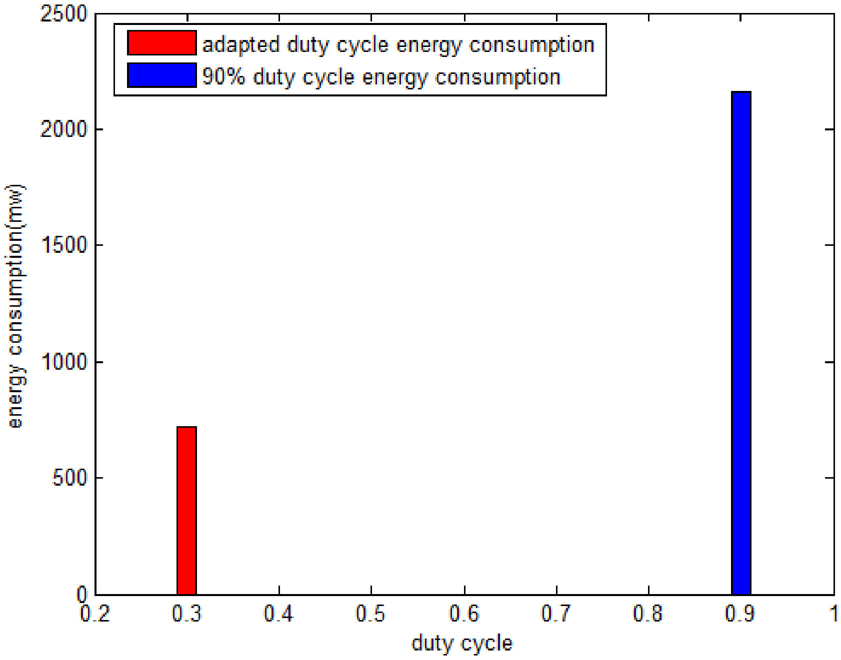

Figure 4-8: The energy consumption of 200 sensor nodes with various duty cycles

and a fixed 90% duty cycle for 200 sensor nodes in order to reach 60 desirable nodes

for each node. The activated energy consumption is reduced by 61% .
In summary, by using the density adaptive sleep scheduling for the same amount of reachability, the energy consumption can be reduced. The energy consumption for each node can also be reduced by increasing the node density in the network. These two ways can both extend the network lifetime.

4-3 Comparing with the neighborhood discovery density estimation

There are few models to estimate the network density, one of them is based on the received power strength (RSS) which is introduced in the first section, besides this model there is also the neighborhood discovery model which is also one of the popular models to estimate the network density. The density estimation of the neighborhood discovery model can also be used to adapt the duty cycle [14]. The formula for the adapted duty cycle in [14] is written as:

$$d(t) = d_0(\frac{1}{N(t)+1}) \tag{4-5}$$

d_0 is constant which equals to 0.5, $N(t)$ is the number of the neighboring sensor nodes. The needed duty cycle for each sensor node is calculated. With the increase of the number of neighboring sensor nodes, the duty cycle is very small. The reachability by using this adapted duty cycle is compared with the duty cycle which is proposed in this work. For each sensor node there are 40% neighbors can be reached.

Figure 4-9 shows the reachability versus the simulation time for a WSN with 50 sensor nodes in the field. From this figure it can be seen that the reachability in combination with the adapted duty cycle by using neighborhood discovery is lower than the reachability in the case of the adapted duty cycle in combination with RSS based density estimation. The preamble length of 0.1s was used in this simulation.

Figure 4-10 shows the reachability versus the simulation time for a WSN with 100 sensor nodes in the field. From this figure it can be seen that the reachability in combination with the adapted duty cycle by using RSS based density estimation is larger than the reachability in the case of the adapted duty cycle by using neighborhood discovery. The preamble length of 0.1s was used in this simulation.
Figure 4-11 shows the reachability versus simulation time for a WSN with 200 sensor nodes in the field. From this figure it can be seen that the reachability in combination with the adapted duty cycle by using RSS based density estimation is larger than the reachability in the case of the adapted duty cycle by using neighborhood discovery. The preamble length of 0.1s is used in this simulation.
From this comparison it can be concluded that the adapted duty cycle by using RSS based density estimation has a much better reachability, it does not matter if it is in a dense network or in a sparse network. The method with RSS based density estimation uses a larger duty cycle,thus it consumes more energy than the other model. The adapted duty cycle by using neighborhood discovery density estimation has a better reachability in the sparse network than in the dense network. Therefore, there is a trade off between these two models. It depends on what the purpose of the network is,

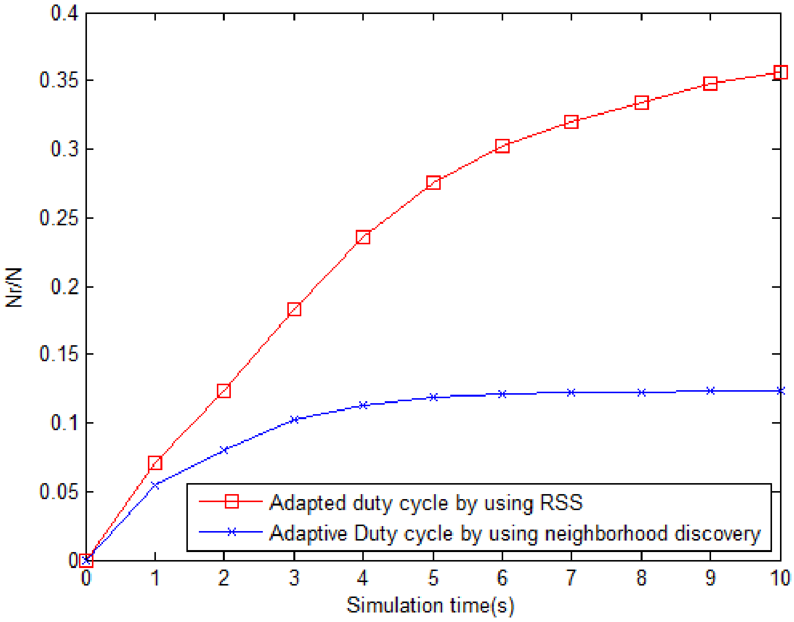

Figure 4-9: The comparison of the averaged reachability for 50 sensor nodes between the adapted duty cycle by using RSS and the adapted duty cycle by using neighborhood discovery, preamble length = 0.1s

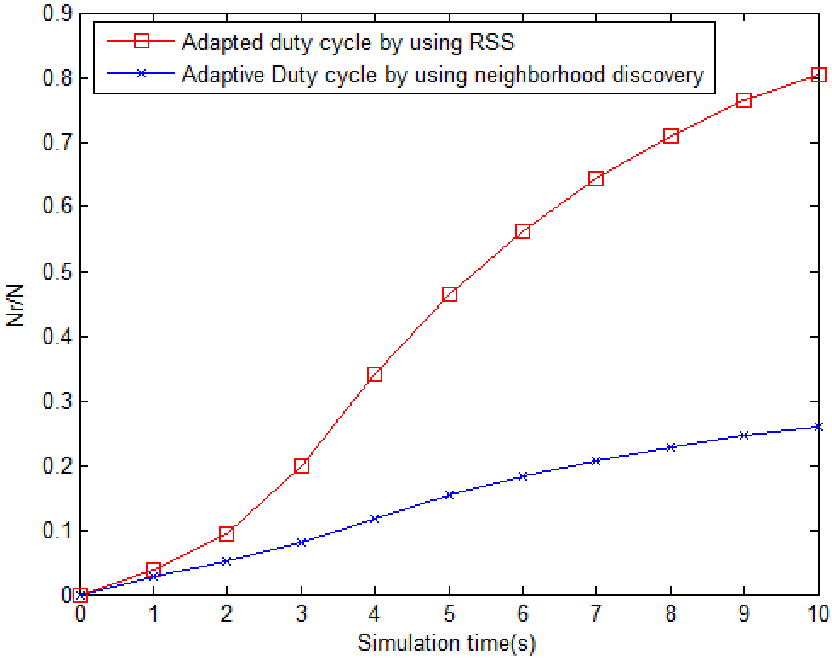

Figure 4-10: The comparison of the averaged reachability for 100 sensor nodes between the adapted duty cycle by using RSS and the adapted duty cycle by using neighborhood discovery, preamble length = 0.1s

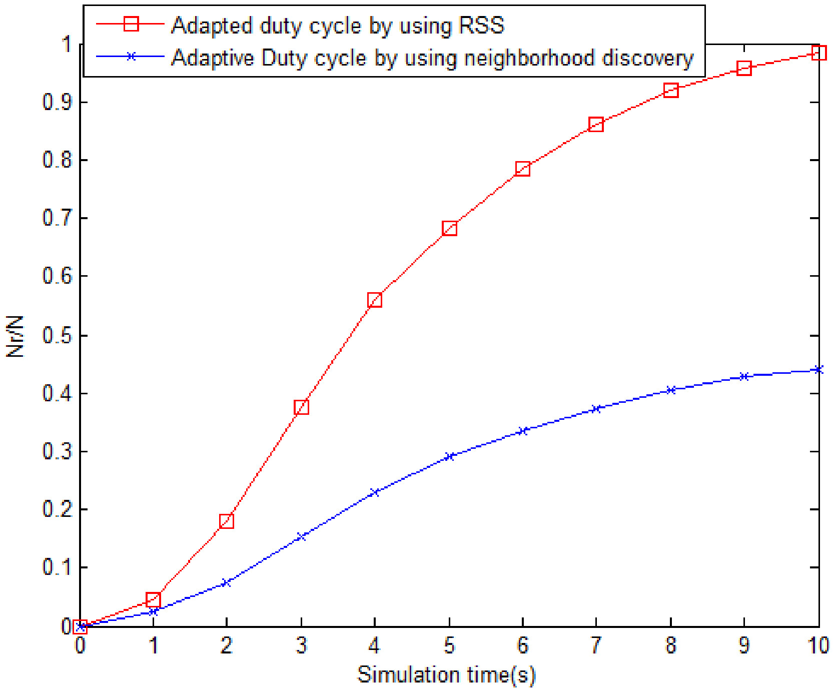

Figure 4-11: The comparison of the averaged reachability between the adapted duty cycle by using RSS and the adapted duty cycle by using neighborhood discovery, preamble length = 0.1s

if the reachability is more important than energy conservation then the model proposed in this work should be applied.

In order to avoid the collision problem, it is assumed that there is only one neighbor can be reached for each sensor node. Based on this assumption, the reachability versus simulation time for 50 sensor nodes are plotted in Figure 4-12. It is can be seen that the reachability in combination with the adapted duty cycle by using RSS based density estimation is two times more than the reachability in the case of the adapted duty cycle by using neighborhood discovery. The preamble length is 0.005s in this simulation.

4-4 Conclusion

In this chapter the proposed adapted duty cycle is first compared with the fixed duty cycle and afterwards it was compared with the adapted duty cycle in combination with using neighborhood discovery density estimation. From the first comparison it shows that the adapted duty cycle has almost the same reachability as the 90% fixed duty cycle however it consumes less energy than the 90% duty cycle. Although the 10% duty cycle consumes even less energy, the reachability is incomparable with the reachability of the adapted duty cycle since it is much lower. Not only the duty cycle but also the preamble length can be reduced by increasing the node density and still maintaining the same amount of reachability.

From the second comparison it can be seen that the proposed model has a much better

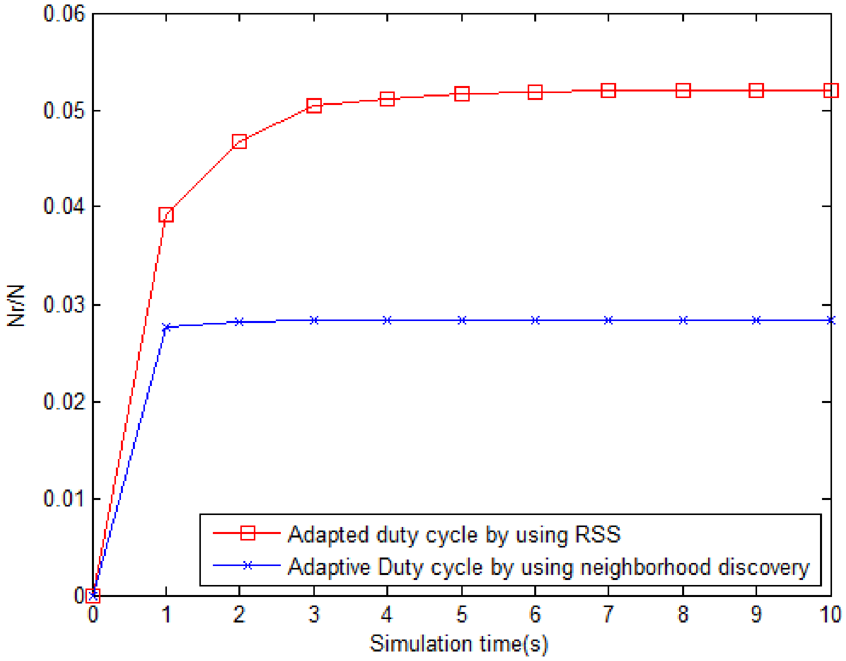

Figure 4-12: The comparison of the averaged reachability between the adapted duty cycle by using RSS and the adapted duty cycle by using neighborhood discovery, preamble length = 0.005s, only one neighbor can be reached

reachability than the other method. There is also a trade off between the reachability and the energy consumption, if the energy consumption is more desirable then model [14] is preferred. Otherwise the model proposed in this work should be used, it gives a high reachability within a short time.

Chapter 5

Conclusion

5-1 Conclustion

In a WSN it is not necessary for each sensor node to be active all the time so in this work an asynchronous sleep scheduling is proposed by using an adapted duty cycle where the duty cycle is based on the RSS density estimation for each sensor node.

In this work it shows that the effects of the sensor node density on the needed duty cycle in order to reach the same reachability. From Chapter 3 it was concluded that with the increases of the duty cycle, the reachability also increases. When the network density increases then the reachability also increases for the same duty cycle. For the same amount of reachability in combination with a higher sensor node density a lower duty cycle can be used and within a shorter time. However, for a WSN with a lower sensor node density a higher duty cycle is needed and it may take a longer time to reach the same reachability. This indicated that the duty cycle needs to be adapted to the network density.

Besides the effects of the duty cycle, the preamble also plays an important role. From the simulation results it can be seen that with the increase of the preamble length, the reachability also increases for the same network typology. In order to reach the same amount of reachability in a shorter time a longer preamble can be used. But the trade off is that a longer preamble length costs more energy of the transmitter. However, a smaller preamble length needs a longer time to reach the same reachability. For reaching the same amount of reachability in a dense network a smaller preamble length is needed. In contrary, in a sparse network a longer preamble length should be used.

Based on the effects described above an analytical model was given which shows that the expected number of the received nodes is a function of the sensor node density λ $nodes/m^2$, the transmission range R m, the preamble p and the duty cycle d.

Through the validation it can be seen that the analytical model and matlab simulation matches to each other. It can be concluded that by increasing the duty cycle, the number of the reached nodes always increases. Further effects that influence the number of the reached nodes are if the node density increases, or the transmission range increases, or the preamble length increases then the number of the reached nodes also increases. The percentage of the number of the reached neighbors over the total number of the neighbors keeps the same if the transmission range increases, or the node density increase. With the increase of the preamble the percentage of the number of the reached neighbors over the total number of the neighbors also increases. It was also proved that for a WSN the same amount of reachability can be achieved by either using a smaller preamble length in combination with a larger duty cycle or a lager preamble length in combination with a smaller duty cycle.

Finally the proposed duty cycle is compared with the fixed duty cycle and the adapted duty cycle in combination with using neighborhood discovery density estimation. From the first comparison it shows that the adapted duty cycle has almost the same reachability as the 90% fixed duty cycle however it consumes less energy than the 90% duty cycle. Although the 10% duty cycle consumes even less energy, the reachability is incomparable with the reachability of the adapted duty cycle since it is much lower. Not only the duty cycle but also the preamble length can be reduced by increasing the node density and still maintaining the same amount of reachability.

From the second comparison it can be seen that the proposed model has a much better reachability than the other method. There is also a trade off between the reachability and the energy consumption, if the energy consumption is more desirable then model [14] is preferred. Otherwise the model proposed in this work should be used, it gives a high reachability within a short time.

5-2 Future work

Possible future works concerning extensions or improvements for the adapted duty cycle algorithm based on the RSS density estimation of each sensor node can be:

- Since cooperative density estimation has less variance, the cooperative density estimation can be simulated to adapt the duty cycle.
- Collision detection.
- Energy consumption can be simulated.
- Path loss exponent can be changed from 3 to 6, consider the shadowing effect, multi-path effect, etc.
- A real life application can be implemented.

Bibliography

[1] *http://en.wikipedia.org/wiki/Sensor*

[2] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci. "A Survey on Sensor Networks," IEEE Comm. Magazine, Vol. 40, No. 8, pp. 102-114, August 2002.

[3] *http://en.wikipedia.org/wiki/Wireless_sensor_network*

[4] C. E. Perkins, "Ad hoc Networking". Upper Saddle River, NJ: Addison-Wesley, 2001.

[5] P.Kavitha, Prof.M.Sayee kumar "energy efficient on-demand sleep wake protocol in wireless sensor networks" International Journal of Communications and Engineering, Volume 06- No.6, Issue: 02. March 2012.

[6] Sami M. Lasassmeh and James M. Conrad,"Time Synchronization in Wireless Sensor Networks:A Survey", IEEE SoutheastCon 2010 (SoutheastCon), Proceedings of the, pp. 242-245, March 2012.

[7] W. Ye, J. Heidemann, and D. Estrin. "Medium Access Control with Coordinated Adaptive Sleeping for Wireless Sensor Network". IEEE/ACM Transactions on Networking, 12(3):493-506, June 2004.

[8] J. Polastre, J. Hill, and D. Culler. "Versatile Low Power Media Access for Wireless Sensor Networks". pages 95-107. Proceedings of 2nd ACM Conference on Embedded Networked Sensor Systems, November 2004.

[9] Jaehyun Kim, Jeongseok On, Seoggyu Kim, Jaiyong Lee, "Performance Evaluation of Synchronous and Asynchronous MAC Protocols forWireless Sensor Networks", The Second International Conference on Sensor Technologies and Applications, Aug. 2008, pp.500-506.

[10] A. Boukerche, "Algorithms and Protocols for Wireless Sensor Networks". Hoboken, New Jersey: John Wiley & Sons, Inc., 2009.

[11] Qing Gao, Shanping Li, and Wei Shi, "Power-Efficient Routing Mechanism in Sensor Networks based on Node-Densit", IMSCCS (2) 2006: 654-656.

[12] Bo-Si Lee, Hao-Wei Lin, Wernhuar Tarng, "A Cluster Allocation and Routing Algorithm based on Node Density for Extending the Lifetime of Wireless Sensor Networks", 2012, 26th International Conference on Advanced Information Networking and Applications Workshops, pp. 496 - 501.

[13] D. Estrin, R. Govindan, J. Heidemann, S. Kumar, Next century challenges: scalable coordination in sensor net-works, ACM MobiCom '99, Washingtion, USA, 1999, pp. 263-270.

[14] Azlan Awang, Xavier Lagrange, and David Ros."Adaptive Duty Cycle using Density Control in Multihop Wireless Sensor Networks". 2011, 17th Asia-Pacific Conference on Communications (APCC) Sutera Harbour Resort, Kota Kinabalu, Sabah, Malaysia, pp. 127 - 132.

[15] Nidhi Batra, Anuj Jain, Surender Dhiman, "An Optimized Energy Efficient Routing Algorithm For Wireless Sensor Network", International Journal of Innovative Technology & Creative Engineering(ISSN:2045-8711) VOL.1 NO.5 MAY 2011.

[16] M. Buettner, G. V. Yee, E. Anderson, and R. Han, "X-mac: a short preamble mac protocol for duty-cycled wireless sensor networks", in Proceedings of the 4th international conference on Embedded networked sensor systems (Sensys), 2006, pp. 307-320.

[17] H. Wang, X. Zhang, F. Abdesselam, and A. Khokhar, "DPS-MAC: An asynchronous MAC protocol for wireless sensor networks," vol. 7, June 2007, pp. 393-404.

[18] Arun Kumar, Kai-Juan Wong, "A Variable Preamble Length-Based Broadcasting Scheme for Wireless Sensor Networks", Communications and Network, 2011 IEEE, pp. 1-4.

[19] Shuo Guo, Song Min Kim, Ting Zhu, Yu Gu, and Tian He, Correlated Flooding in Low-Duty-Cycle Wireless Sensor Networks, 2011, 19th IEEE International Conference on Network Protocols.

[20] Ertan Onur, Yunus Durmus, Ignas Niemegeers, "Cooperative Density Estimation in Random Wireless Ad Hoc Networks", Communications Letters, IEEE (Volume:16 , Issue: 3), March 2012, pp. 331-333.

[21] Giuseppe Anastasi, Marco Conti, Mario Di Francesco, Andrea Passarella: "Energy conservation in wireless sensor networks: A survey". Ad Hoc Networks 7(3): 537-568 (2009).

[22] Wendi Rabiner Heinzelman, Anantha Chandrakasan, and Hari Balakrishnan, "energy-efficient communication protocol for wireless microsensor networks", proceeding of the 33rd Hawaii International Conference on System Sciences, 2000.

[23] Qin Wang, Mark Hempstead and Woodward Yang, "A Realistic Power Consumption Model for Wireless Sensor Network Devices", Sensor and Ad Hoc Communications and Networks, 2006. 3rd Annual IEEE Communications Society on (Volume:1), pp.286-295.

[24] R. Zheng and R. Kravets, "On-demand power management for ad hoc networks," in IEEE Computer and Communications Societies (Infocom), vol. 1, 2003, pp. 481-491.

[25] Y. Sun, S. Du, O. Gurewitz, and D. B. Johnson, "DW-MAC: a low latency, energy efficient demand-wakeup MAC protocol for wireless sensor networks," in Proceedings of the 9th ACM international symposium on Mobile ad hoc networking and computing (MobiHoc08:), 2008, pp. 53-62.

[26] T. Dam and K. Langendoen, "An adaptive energy-efficient mac protocol for wireless sensor networks," in The First ACM Conference on Embedded Networked Sensor Systems (Sensys), 2003.

[27] N.A Vasanthi, S. Annadurai, "AWS: Asynchronous Wakeup Schedule to Minimize Latency in Wireless Sensor Networks", Proceedings of the IEEE International Conference on Sensor Networks, Ubiquitous, and Trustworthy Computing (SUTC06), 2006.

[28] A. Bachir, M. Dohler, T. Watteyne, and K. K. Leung, "MAC Essentials for Wireless Sensor Networks,"IEEE Communications Surveys and Tutorials, vol.12, No.2, pp. 222-248, 2010.

[29] Piet van Mieghem, Data communications networking, ISBN-10: 9085940087, Purdue University Press (October 1, 2006).

[30] Y. Sun, O. Gurewitz, S. Du, Lei Tang, David B.Johnson, "ADB: An Efficient Multihop Broadcast Protocol Based on Asynchronous Duty-Cycling in Wireless Sensor Networks," Proceedings of the 7th ACM Conference on Embedded Networked Sensor Systems, Berkeley, 4-6 November 2009, pp. 43-56.

[31] B. Williams and T. Camp, "Comparison of Broadcasting Techniques for Mobile Ad Hoc Networks," Proceedings of the 3rd ACM International Symposium on Mobile Ad Hoc Networking & Computing, Lausanne, 2002, pp. 9-12.

[32] C.H. See, R.A. Abd-Alhameed, D. Zhou, Y.F Hu and K.V Horoshenkov "Measure The Range of Sensor Network", Microwaves & RF, vol. 54, no.10, pp.69-76, Oct. 2008.

[33] Couch, L.W., Digital and Analog Communication Systems, 7th ed., ISBN 0-13-142492-0, Prentice Hall, 2007.

[34] Z. J. Haas, J. Y. Halpern, and L. Li, "Gossip-based ad hoc routing," in Proceedings of IEEE INFOCOM, 2002, pp. 3-12.

[35] Pradeep Kyasanur Romit Roy Choudhury Indranil Gupta,"Smart Gossip: An Adaptive Gossip-based Broadcasting Service for Sensor Networks", Mobile Adhoc and Sensor Systems (MASS), 2006 IEEE International Conference on, pp. 91-100.