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Duty-cycle Medium Access Control for Directional Wireless Sensor Networks

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Doctor of Philosophy

As the candidate's supervisor, I have approved this dissertation for submission.

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Declaration of Authorship

We declare that this thesis titled "Duty-cycle Medium Access Control for Directional Wireless Sensor Networks" and the works presented in it are our own. We confirm that:

- The full part of the work is done during PhD research study in University of Dhaka, Bangladesh.
- Any part of this thesis has not previously been submitted for a degree or any other qualification in this University or any other institution.
- We have consulted the published works of others with appropriate references.
- This thesis work is done entirely by us and our contributions and enhancements from other works are clearly stated.

Signed: ________________________

Candidate

Countersigned: ________________________

Supervisor: Dr. Md. Abdur Razzaque

Co-supervisor: Dr. Md. Shariful Islam

Abstract

Directional communication in wireless sensor network minimizes interference and thereby increases reliability and throughput performances of the network. Such advantages of Directional Wireless Sensor Networks (DSNs) have attracted the interests of researchers and industry experts around the globe. Furthermore, the sensor nodes with directional antennas provide extended network lifetime and better coverage performances. However, designing a communication protocol for wireless networks with directional antennas is a challenging problem due to lack of synchronization, asymmetry-in-gain, hidden terminal and deafness problems. Our endeavor in this dissertation is to address the aforementioned challenges in neighbor discovery and medium access control in Directional Sensor Networks.

One of the key challenges of a directional node is to discover its neighbors due to difficulty in achieving synchronization among directed transmissions and receptions. Existing solutions suffer from high discovery latency and poor percentage of neighbor discovery either due to lack of proper coordination or centralized management of the discovery operation. In this thesis, we develop a collaborative neighbor discovery (COND) mechanism for DSNs. Using polling mechanism, each COND node directly discovers its neighbors in a distributed way and collaborates with other discovered nodes so as to allow indirect discovery. It helps to increase the neighbor discovery performance significantly. A Markov chain-based analysis has been carried out to quantify theoretical performances of the proposed COND system. The performance of the COND system is evaluated in Network

Simulator Version-3 (NS-3), and the results reveal that it greatly reduces the discovery latency and increases neighbor discovery ratio compared to state-of-the-art approaches.

The second contribution of this thesis is to develop a low duty-cycle directional medium access control protocol, termed as DCD-MAC, where, each pair of (parent and child sensor) nodes performs synchronization with each other before data communication. Each parent node in the network schedules data transmissions of its childs in such a way that the number of collisions occurred during transmissions from multiple nodes is minimized. A sensor node remains active only when it needs to communicate with others; otherwise, it goes to sleep state. The DCD-MAC exploits localized information of nodes in a distributed manner and it gives weighted-fair access of transmission slots to the nodes. As a final point, we have studied the performances of our proposed MAC protocol through extensive simulations in NS-3 and the results show that the DCD-MAC gives better reliability, throughput, end-to-end delay and network lifetime compared to the related directional MAC protocols.

Acknowledgment

The sense of accomplishment is an immense pleasure that can be felt in heart but hardly be expressed in words. I am truly overwhelmed with joy to be able to complete my PhD research work fulfilling the standards and reaching to the obligatory benchmarks set by my supervisor and alma mater. As I look back to the trail of the long journey of tenacious research effort, I honestly confess, it would not be possible without the help of many who were the cause of my strength and inspiration in every moment of such arduous journey.

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Chapter 1

Introduction

1.1 Introduction

Today, computing devices, embedded with a plethora of sensors, are available all around us. There are sensors in our vehicles, smart phones, factories controlling CO_2 emissions, and even in ground monitoring soil conditions in yards. While it seems that sensors have been around for a while, research on wireless sensor networks (WSNs) started back in the 1980s, and it is only since 2001 that WSNs generated an increased research interests both from industry and academia. A WSN is a network formed by a large number of sensor nodes, where each node is equipped with sensors (to detect physical phenomena such as light, heat, pressure, etc) and wireless transceivers. The WSNs are being used for intelligent monitoring of temperature, humidity, water level, pressure, vehicular activity on roads, strength of mega structures like bridges, tunnels and buildings, criminal surveillance in alleyways and roads, remote health monitoring of multiple patients and many other applications [1, 2, 3, 4, 5]. Past several years have witnessed a great success of WSNs, where through the use of sensors, the entire physical infrastructure is closely coupled with information and communication technologies, where intelligent monitoring and management can be achieved via the usage of networked embedded devices. In such a sophisticated dynamic system, devices are interconnected to transmit useful measurement information and control instructions via distributed sensor networks. In WSNs, the nodes are battery driven and are typically deployed at inaccessible locations, making it difficult to replace the battery. By working together, sensor nodes coordinate to finish a common task [6, 7, 8].

Typically, wireless devices communicate with one another by using omni-directional antennas. These antennas radiate the signals in all directions resulting in a circular transmission/reception pattern. The omni-directional nature of transmission propagates the signal in all directions away from the node; the signal is received by all the neighboring nodes surrounding the sender. Since the sensed data is usually intended for a specific receiver, it is not necessary for all the surrounding nodes to receive the signal. Such transmission pattern adds no advantage because the receiver gets only a small part of the energy of the omni-directionally transmitted signal. In fact, the remaining wasted energy also possibly interferes with other ongoing transmissions. In Directional Sensor Networks (DSNs), nodes have directional antenna elements that can focus the beam only towards the receiver, then the nodes that are not in the direction of the receiver are free to go ahead with their communications. Now a days, DSNs are being used for the implementation of many real-time applications including infrastructure monitoring, health-care monitoring, robotic exploration, battlefield surveillance, target tracking, disaster response, etc. [9, 10].

The directional sensors have been proved to provide better energy-efficiency, sensing quality, bandwidth utilization, etc [11, 12]. Beam-steerable smart antennas can give significant improvement in communications performance, and recent developments in parasitic array techniques have led to low power, low cost smart antennas. Protocol design for wireless networks with directional antennas is a challenging problem due to the problems related to directional antennas such as neighbor discovery, Head-of-Line problem, hidden terminal problem and deafness problem [13, 14, 12]. In addition to these problems, basic network operations such as neighbor discovery become more complicated, as well.

The problem of neighbor discovery in directional sensor network is not only more challenging than that in its omni-directional counterpart, but also it requires complete redesign, implementation and evaluation. In this dissertation, we have proposed a new solution for discovering the neighbor nodes in DSNs. However, in the environment of wireless network, the directional transmission sometimes creates multifarious problems for the features of sensor networks, thus it demands a specialized MAC protocol for DSNs. Our second contribution is the development of a new distributed duty-cycle directional medium access control protocol for DSNs.

The rest of this chapter is organized as follows. The overview of DSNs with their characteristics, challenges, applications, communication protocols are briefly described in Section 1.2. The neighbor discovery and medium access control in DSNs along with their challenges are discussed in Section 1.3 and Section 1.4, respectively. Section 1.5 reflects our dissertation problem and solution methodology. Finally, the thesis organization is presented in Section 1.6.

1.2 Overview of Directional Sensor Networks

As omni-directional antennas spread radio signals in all directions, all neighboring nodes around a pair of communication nodes (i.e., the transmitter and the receiver) are prevented from transmitting to avoid collisions. Therefore, the capacity of wireless networks using omni-directional antenna is limited because of the high interference and the low spatial reuse. Compared with an omni-directional antenna, a directional antenna can concentrate its transmitting or receiving capabilities to a certain direction. Thus, the use of directional antennas in wireless networks allows more concurrent transmissions in the vicinity of a pair of communication nodes and consequently it leads to less interference to other on-going transmissions. We call such wireless networks using directional antennas as DSNs, which usually have much higher network capacity than WSNs. An example network scenario is given in Figure 1.1.

Directional transmission is a novel approach to networking which leverage recent

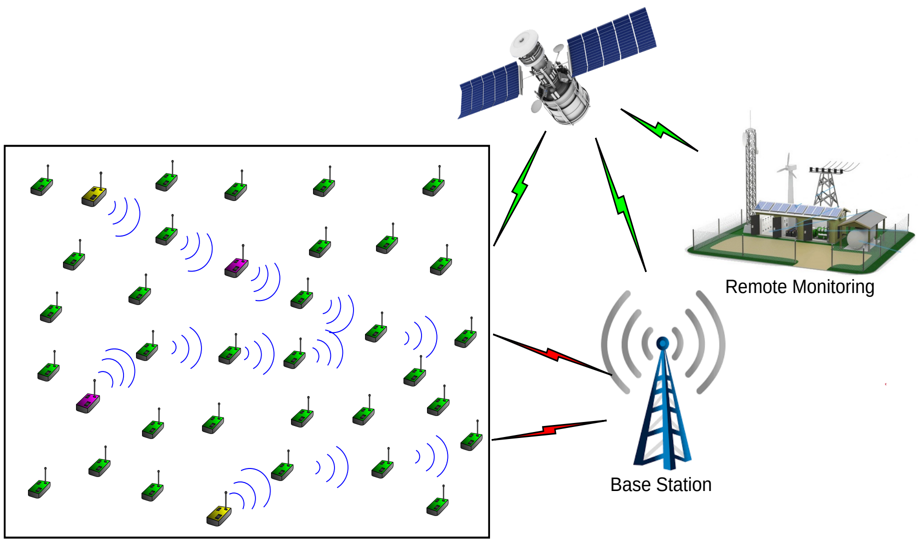


Figure 1.1: A network scenario of Directional Sensor Network

advances in physical layer technology, allowing formation of multiple beams in both transmitter and receiver [15].

1.2.1 Features of Directional Sensor Networks

A Directional Sensor Network (DSN) has spatially distributed autonomous sensors to monitor physical or environmental conditions, such as temperature, sound, pressure, etc. and to cooperatively pass their data through the network to a central location. Sensor nodes are usually powered by battery and thus they are limited by power capacity. It is often difficult to change or recharge batteries of these nodes. The lifetime of a sensor network largely depends on the lifetime of its sensor nodes. Sensor nodes in the network are often deployed in an ad hoc fashion and they are able to organize themselves and form a communication network [7]. We have studied the various characteristics of DSNs and compared them with WSNs in the following sections.

1.2.1.1 Differences between WSNs and DSNs

Deploying nodes with directional antennas is very different from deploying omni-directional ones. More factors, such as communication angle, node orientation and link asymmetry, must be taken into consideration. DSNs also provide some unique features which make them curiously different from their omni-directional counterpart. Compared with WSNs, DSNs have the following advantages [16, 15].

- **Reduced interference:** At transmitter side, a directional antenna concentrates transmitting signals to one direction, which leads to no interference or less interference with other transmissions. On the other hand, at receiver side, a directional antenna can shield interference from other transmitters.

- **Improved spatial reuse:** Compared with omni-directional antennas, directional antennas allow more concurrent transmissions in the vicinity of the transmitter or the receiver. Thus, nodes of DSNs can enjoy better bandwidth utilization compared to those in WSMs.

- **Longer transmission range:** By focusing radio signals to a certain direction, a directional antenna acquires a higher antenna gain than an omni-directional antenna, which consequently leads to cover a longer transmission range.

- **Reduced power requirement:** To maintain a successful link, the minimum transmission power is inversely proportional to the product of the antenna gains of both the transmitter and the receiver. As directional antennas have higher antenna gains than omni-directional antennas, the use of directional antennas results in the reduced power requirement.

Despite their numerous advantages, directional antennas also have the following drawbacks and limitations, which restrict their applications in many areas [16].

- **Device complexity:** It often requires complicated algorithms to direct the antenna beams, combine the multi-path signals, and adjust nulling to interfering nodes. Therefore, the transceivers equipped with directional antennas must include more powerful processors and control units. It is a challenge to equip directional antennas with the portable devices that often only have a low-processing capability.

- **Physical size:** A directional antenna is usually implemented through a number of antenna elements. In general, the antenna gain, which determines the antenna capability, is proportional to the number of antenna elements. This means that a number of antenna elements are necessary to obtain a reasonable antenna gain. However, a large number of antenna elements inevitably lead to the bulky size of antennas, which limits the application of directional antennas in wireless networks, especially for wireless networks.

- **Unique physical characteristics:** Directional antennas have unique characteristics in physical layer (e.g., the directionality), which have impacts on the upper layers. In particular, there are many research challenges in medium access control (MAC) layer, the routing layer, and the transport layer.

1.2.1.2 Directional sensor device

Different mechanical, seismic, volcanic, thermal, humidity, visual, biological, acoustic, chemical, optical and magnetic sensors can be attached to a sensor node to measure various properties of the environment [17, 18]. The sensors in a smart sensor node are equipped with a signal conditioning unit and analog to digital converters (ADCs). The digital electrical signals, produced according to the sensed quantity, are then fed into the processor. The processor together with the associated small memory controls the collaboration between the different nodes in a network. Different micro-controllers with a flash memory are built and integrated to wireless sensor nodes to serve as processors. The

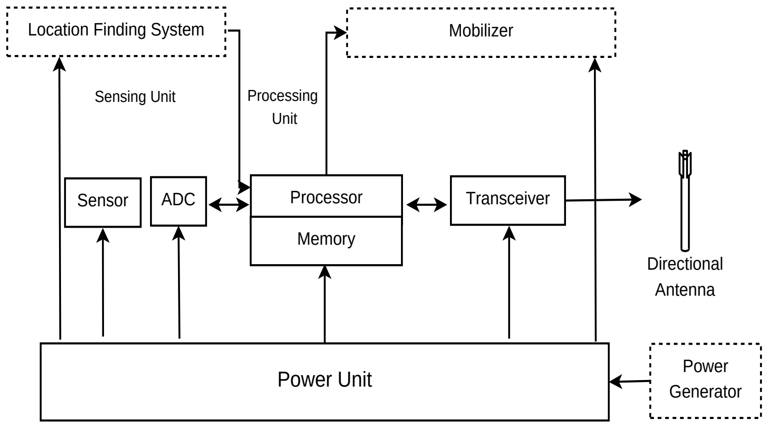


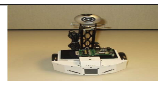
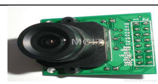
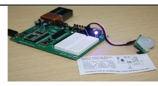
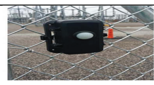
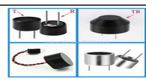
Figure 1.2: Block diagram of a typical directional sensor node

nodes are normally powered by batteries which may be supported by power harvesting devices such as solar cells [1, 19]. A block diagram of a directional sensor node is given in Figure 1.2 and some sample sensors with their specifications are given in Table 1.1.

1.2.1.3 Types of directional antennas

A directional antenna is an antenna, which can radiate or receive radio signals more effectively in particular direction than in others. There are two major types of directional antennas: traditional directed antenna and smart antenna [16, 20]. The beam formed by the antennas is either fixed or adjusted to point to a certain direction by mechanical rotation in Traditional directed antenna. A smart antenna is an antenna array consisting of a set of antenna elements with digital signal processing capability to transmit and receive adaptively. The first smart antennas were developed for military communications and intelligence gathering. The growth of cellular telephone in the 1980s attracted interest in commercial applications. The upgrade to digital radio technology in the mobile phone, indoor wireless network, and satellite broadcasting industries created new opportunities for smart antennas in the 1990s. Compared with traditional directed antennas, smart antennas usually possess superior capabilities, such as directional beam-forming,

Table 1.1: Directional sensor motes and their characteristics

Sensor types	Model	Manufacturers	Platform	Lens size	Sensing radius (m)	Angle of view	Sample figure
Video	ADCM-1700	Agilent	Mesheye	N/A	-	-	
Video	OV6620	Omnivision	CMUCam3	1/3'	-	-	
People	DS-10	Infodev	DL-10	N/A	-	-	
IR	Parallax	-	Squid Bee	-	4	60^0	
IR	Hydra	-	N/A	-	15	30^0	
Video	Ultra-U	-	Senix	-	7	15^0	
Video	RU18-D160	-	Riko	-	16	8^0	

diversity processing, and adaptive spatial reusing [15, 17, 18]. Smart antennas can be categorized as the following types [16] :

1. **Switched beam antennas:** In the case of switched beam antennas, the area around the antenna system is divided into a fixed number of equal-size sectors. Each antenna element transmits a beam such that it covers one sector. Hence for an m sectored antenna, there are m antenna elements covering $(\frac{360^0}{m})$ sectors each. Normally, the sectors in the coverage pattern are not ideal circular sectors, the transmission pattern of each antenna has a lobe. The coverage pattern consists of

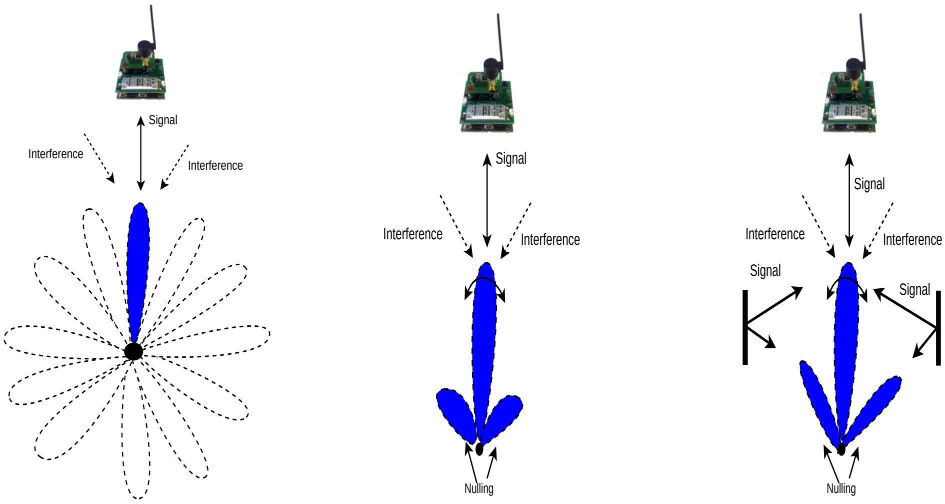
a main lobe and some side lobes. There can be often a tail lobe as well; however these are more commonly found in steerable antennas. The simulations done in the thesis use a switched beam antenna that does not contain a tail or any side lobes. The antenna beam patterns are predetermined by shifting every antenna elements signal phase. Weights for antenna elements, which are used to produce the desired beam pattern, can be locally saved in memory and instantaneously switched. Figure 1.3-(a) is an example of switched-beam antennas [21].

2. **Steerable antennas:** Steerable antennas are also called phased array antenna. In this system, as shown in Figure 1.3-(b), arbitrary beam patterns are formed on the fly. Besides, the radiation pattern can be adjusted toward the users whereas directions toward interference sources are set to be null (or zero), which is called nulling capability. These techniques can maximize the signal to interference and noise ratio (SINR) [22].

3. **Adaptive array antennas:** In additional to the nulling capability and the dynamical formation of beam patterns, the radiation pattern can be adapted to receive multi-path signals by using space diversity algorithms and techniques, as shown in Figure 1.3-(c). Moreover, the use of multiple adaptive array antennas at both the transmitter and the receiver, which is also called MIMO beam-forming can further improve the performance in multi-path environments [23].

1.2.2 Challenges of Directional Communication

Although directional antennas have key benefits, they also lead to key problems like neighbor discovery, directional hidden/exposed terminals, deafness and neighborhood, head-of-line blocking, MAC-layer capture, routing, coverage problem etc. [1, 15, 24, 25, 26], which need to be overcome. Compared to WSNs, DSNs must satisfy some additional requirements including antenna-beam synchronization, scheduling prior to any



(a) Switched beam (b) Steerable single beam (c) Adaptive array

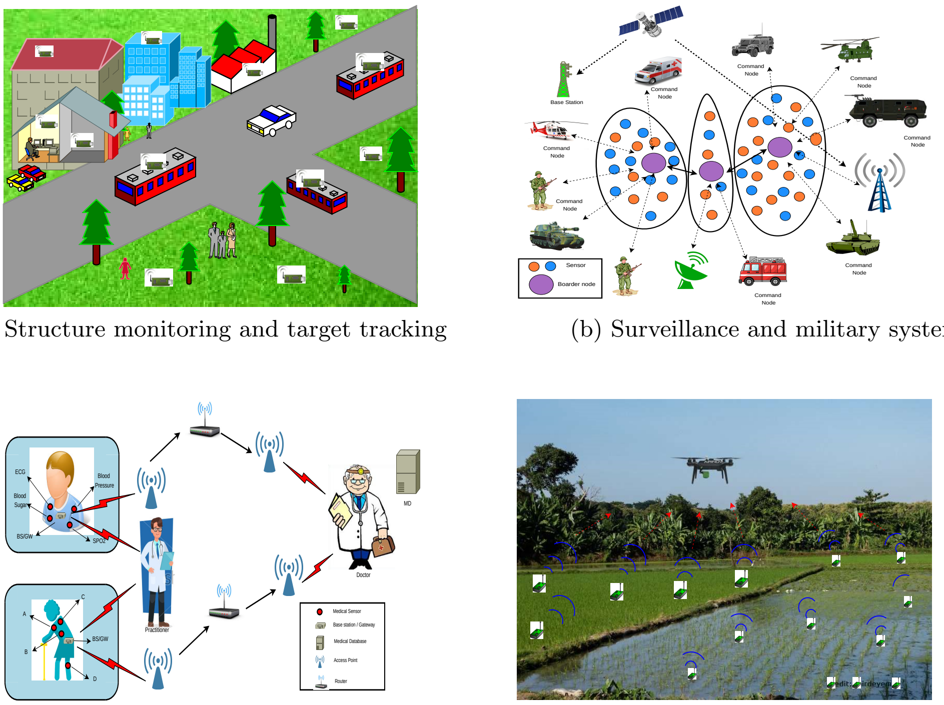
Figure 1.3: Smart directional antennas

data communication to achieve better performance. These major challenges are to be addressed for encashing the potentials of using directional antennas.

1.2.3 Applications of Directional Sensor Networks

The development of WSNs was inspired by military applications, notably surveillance in conflict zones. Sensor nodes are used for continuous sensing, event detection, event ID, location sensing, and local control of actuators. The concept of micro-sensing and wireless connection of these nodes promise many new application areas. The DSN is a rapidly emerging technology in recent years due to its potential use in a broad variety of applications [6]. Some examples of such applications are given in Figure 1.4. The following areas are major categories of DSN applications.

- **Environmental and Habitat Monitoring:** Environmental monitoring is one of the earliest applications of sensor networks. In environmental monitoring, sensors are used to monitor a variety of environmental parameters or conditions. Sensors



(a) Structure monitoring and target tracking
(b) Surveillance and military systems
(c) Health-care system
(d) Precision agriculture

Figure 1.4: Applications of Directional Sensor Networks

can be used to monitor the conditions of wild animals or plants in wild habitats as well as the environmental parameters of the habitats [27].

- **Military Surveillance:** Sensor networks are becoming an integral part of military command, control, communication and intelligence systems. Sensors can be rapidly deployed in a battlefield or hostile region without any infrastructure. Battlefield monitoring, object protection, intelligent guiding, remote sensing are some common applications for military surveillance [28].

- **Wildfire instrumentation:** Collecting real-time data from wildfires is important for life safety considerations and allows predictive analysis of evolving fire behavior [29].

- **Health-care:** Sensor networks can be used to monitor and track elders and patients for health-care purposes, which can significantly relieve the severe shortage of clinical personnel and reduce the expenditures in the current systems [30].

- **Intelligent transportations:** The DSN has a potential to revolutionize Intelligent transportation applications involved with information sensing, collection and dissemination. The intelligent Transportation seems to be one of the most effective approaches to deal with the problems such as traffic jam. Currently used traffic sensor technologies (video, sonar, radar, inductive, magnetic, capacitive, and pneumatic) are used to implement such systems [31].

- **Home intelligence:** DSNs can be used to provide more convenient and intelligent living environments for human beings. Sensors can be embedded into a home and connected to form an autonomous home network. Directional sensors can also be used to remotely read utility meters in a home [32].

- **Structural monitoring:** Structural health monitoring is a typical area amongst the many possible applications of DSNs. Structural health monitoring systems seek to detect and localize damage in buildings, bridges, ships, and aircraft [6, 27].

- **Nanoscopic sensor applications:** Now a days, there is keen interest in sensor networks for biological sensing. One can detect bio warfare pathogens and can use it s a diagnostic tool in medicine [33].

1.2.4 Communication Protocols for Directional Sensor Networks

Protocol stacks are developed for power efficient communication, delivery of packets and collaboration between sensor nodes in a DSN. The protocol stack for WSNs consists of five protocol layers: the physical layer, data link layer, network layer, and application layer. The wireless medium and the antenna system forms the physical layer in the

DSN. There are four other important layers above the physical layer that processes the packet received from the antenna. The Medium Access Control (MAC) layer is just above the physical layer and is mainly responsible for sensing the channel. It sends the packet only when the channel is idle, receives the packet from the antenna, checks for packet corruption and propagates the received packet to the upper layer if the node is the intended recipient. The routing layer is responsible forwarding the data packet in the defined routes, possibly multi-hop routes, to the destination and for directing the packet towards the final destination. The transport layer and the application layer have the functionalities similar to the WSNs. The protocol stack of a DSN node is shown in Figure 1.5.

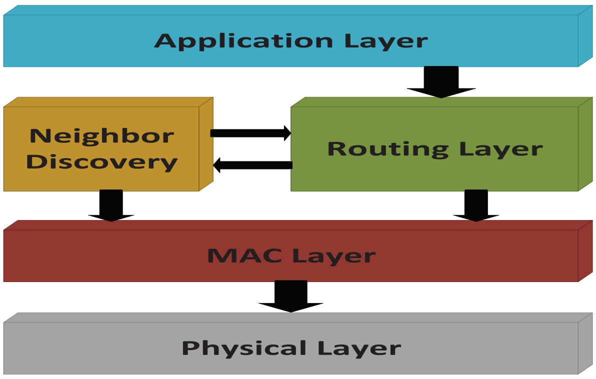


Figure 1.5: Protocol stack in a DSN node

More specifically, we categorize the research issues on DSNs into the following types according to the different network layers.

- **Physical layer:** The physical layer is responsible for converting bit streams from the data link layer to signals that are suitable for transmission over the communication medium. It also deal with the design of the underlying hardware, and various electrical and mechanical interfaces. The impacts of directional antennas on the physical layer include the different types of directional antennas, the antenna radiation pattern, the directionality of directional antennas, the antenna size, and computation complexity.

- **MAC layer:** The primary objective of the MAC layer is to fairly and efficiently share the communication resources or medium among multiple sensor nodes in order to achieve good network performance in terms of energy consumption, network throughput and delivery latency etc. The unique properties of directional antennas introduce difficulties in designing MAC protocols in DSNs. In particular, directional beamforming leads to the new location-dependent carrier-sensing problems, for example, the hidden terminal problem and the deafness problem, which significantly affect the network performance. Besides these challenges, localization and neighbor discovery also lead to challenges on the MAC design on DSNs.

- **Routing layer:** The routing layer is responsible for routing the data sensed by source sensor nodes to the sink(s). The impacts of directional antennas on both the physical layer and the MAC layer affect the protocol design in other layers, especially for the routing layer. More specifically, directional localization and neighbor discovery bring difficulties in building and maintaining the routing paths. In addition, the routing performance significantly degrades because of the hidden terminal problem and the deafness problem in DSNs.

- **Other research issues:** Area coverage, target coverage, deployment of nodes are some common challenges happen in application layer due to the directionality of DSNs. In the transport layer, because of the impacts of directional routing and the head-of-line blocking (HOL), many additional challenges also occur in DSNs.

Among these layers, we have focused in neighbor discovery and medium access control for DSNs in this thesis.

1.3 Neighbor Discovery in Directional Sensor Networks

In DSNs, after nodes are deployed, they need to discover their one-hop neighbors. Knowledge on one-hop neighbors is very important for almost all routing and medium-access control protocols, clustering and several other topology control protocols. Neighbor discovery is a crucial first step in the process of self organization of a network. Ideally, nodes should discover their neighboring nodes as early as possible so that they spend less energy. Again, fast neighbor discovery allows other communication protocols to quickly start their execution.

1.3.1 Challenges of Directional Neighbor Discovery

Neighbor discovery, one of the most fundamental bootstrapping networking premitives, is particularly challenging in a network where nodes have directional antennas. Compared to traditional WSNs, neighbor discovery in DSNs is more challenging since directional antennas can only cover a fraction of the azimuth. In DSNs, the sender/receiver nodes may be within the transmission range of each other, but they cannot be discovered for the lacking of beam synchronization. Consequently, directional sensors take longer time to discover their neighbors which also increases the overhead and energy consumption in the network. Hence, nodes must synchronize their antenna directions with the other nodes. Neighbor discovery algorithms should be able to guarantee discovery within a bounded delay in a fully decentralized manner [34, 14].

1.4 Directional Medium Access Control

Medium Access Control (MAC) is one of the critical issues in the design of DSNs. As in most wireless networks, collisions among multiple transmissions, which is caused by two nodes sending data at the same time over the same transmission medium, is a great concern in DSNs. The DSNs have some special characteristics over WSNs. To address these problems, a DSN must employ a MAC protocol to arbitrate access to the shared medium in order to avoid data collision from different nodes and at the same time to fairly and efficiently share the resources among multiple sensor nodes.

1.4.1 Challenges of Directional Medium Access Control

We have discussed the challenges of directional medium access control in the following sections.

1.4.1.1 Asymmetry-in-gain problem

Asymmetry-in-gain problem [35] occurs due to the combination of directional and omni-directional transmissions. When a directional transmission for data packets and an omni-directional transmission for control packets such as RTS/CTS are used, different communication ranges direct to the asymmetry-in-gain problem because the transmission range of a directed signal and the transmission range of an omni-directional signal are not identical. In Figure 1.6, when the nodes transmit or listen in omni-directional mode,

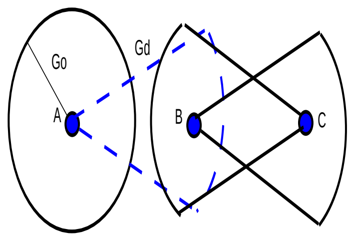


Figure 1.6: Asymmetry-in-gain problem

they communicate with a gain of G_0. For example, B initiates transmission to node C by sending DRTS. Then node C sends DCTS to node B. At that moment node A is in omni-directional mode. Node A is far enough away from node C, so A cannot hear the DCTS from C because the omni-directional gain G_0 is smaller than the directional gain G_d. When nodes B and C begin data transmission by pointing their transmission and reception beams to each other with a gain G_d, at the same time A also wants to communicate with B using DRTS which interfere the ongoing data transmission.

1.4.1.2 Hidden terminal problem

In DSNs, hidden terminal terminals problem can be happen due to unheard RTS/CTS frame transmissions [13] which can be always situated near the source node. A hidden terminal is a node that is not aware of an ongoing directional transmission between a pair of nodes and its directional transmission causes frame collisions with the ongoing transmission. Tentatively, all nodes those are located surrounded by the destination node's coverage region and are far from the source node's coverage area are hidden terminals. For illustration, in Figure 1.7, while node C is sending DRTS to node B, node

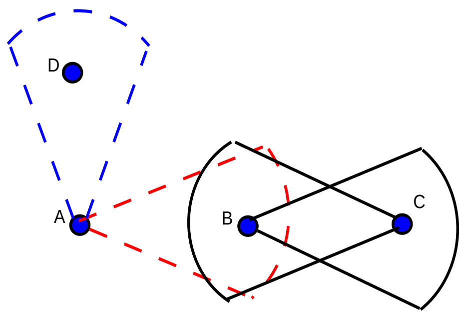


Figure 1.7: Hidden terminal problem

A is busy in communication with D. Node B's DCTS cannot reach to node A, as it is beam formed in the direction of D. When the communication between nodes B and C is in progress, A has completed its transferring to D and has a packet to send to node B. during that time A initiates messaging with B by sending DRTS to B, and it will lead to a collision with C's transmission. Hidden terminals can severely degrade the network performance in DSN.

1.4.1.3 Deafness problem

Deafness occurs when a node tries to communicate with another node which is beam formed to another direction [36, 37]. In Figure 1.8, node A and B is communicating with

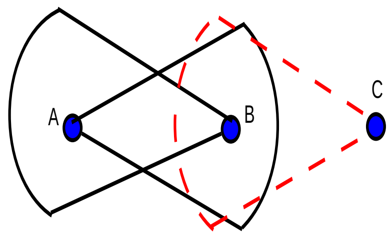


Figure 1.8: Deafness problem

each other. Node C is trying to initialize communication with node B where node B is beam formed to node A. For that, node C will not get DCTS in time and twice its backoff time for retransmission, since it shows that a conflict has occurred. When node C experiences maximum retries, it concludes that node B is unreachable.

1.4.1.4 Head of line blocking problem

Head-of-Line (HoL) blocking [16], is the scenario where the second data packet in a node queue can be transmitted to another node, but is blocked because the first data packet cannot be sent to yet another node which is beamformed to another direction for frame transmissions with a corresponding node.

1.4.1.5 Duty cycling in MAC

The primary objective of duty cycling is to reduce the energy consumption of sensor nodes and to increase the overall network longevity as a consequence. More specifically, duty cycling aims at reducing idle listening, i.e. having the radio transceiver waiting in vain for a frame. The difficulty of keeping the radio on only when necessary is that, for most applications, nodes do not know beforehand when data is coming [38]. Idle listening is not the only source of energy waste. Overhearing, control packet overhead and collisions also waste power. These causes are important to identify since, while attempting to reduce idle listening, duty cycling can increase the collision rates and introduce more control traffic side effects that can increase the very energy consumption duty cycling is trying to reduce.

1.5 Dissertation Problem and Solution Methodology

The challenges addressed in the dissertation and their solution methodologies have been briefly introduced in this section.

1.5.1 Scope of The Work

Fast neighbor discovery and reliable medium access control protocol are emerging requirement for many real-time applications in DSNs. Neighbor discovery in DSNs is more challenging than that in traditional WSNs as directional nodes have limited width of communication sectors and thus two nearby nodes must steer their communication sectors to each other for a successful communication [39, 40]. Efficient strategies need to be employed so that a pair of neighbor nodes eventually beam form their antennas to each other at a certain time instance and can discover themselves. The primary challenge lies in increasing the number of nodes discovered in bounded delay through better coordination in a distributed way. This problem has been attacked before, proposing several schemes such as SAND [41], Randomized 2-way discovery [42] etc. A fully distributed neighbor discovery mechanism is needed, where both the transmissions and receptions are directional and nodes collaborate with their (already discovered) neighbors to find other neighbors, reducing neighbor discovery latency significantly. In addition to that, dynamic waiting time for the nodes at different directions is required while discovering nodes that greatly helps to mitigate the deafness problem. As sensor nodes are battery constrained devices, duty-cycle based MAC protocols are required to get better performance in the network. A good number of duty-cycle based medium access control (MAC) protocols for WSNs are already proposed in the literature. However, most existing MAC protocols, R-MAC [43], S-MAC [44], B-MAC [45], [46] etc. are designed for omni-directional WSNs, which are not applicable for DSNs because these works designed their protocols assuming that the a node can overhear the transmission signal of all its neighboring nodes. The DSNs has some unique characteristics for data collection from sensor nodes to the sink node. In the environment of wireless network, the directional transmission sometimes creates multifarious problems for the features of sensor networks, thus it demands a specialized MAC protocol for directional WSNs.

In this thesis, we have developed a low duty-cycle medium access control protocol along with a collaborative neighbor discovery mechanism to exploit the use of directional antennas because of their benefits like - increase in network throughput and network capacity, reduction in packet latency through spatial reuse, reduction in energy consumption owing to reduction in transmit power, and increase in packet delivery ratio due to reduction in interference. The detail discussion on the developed neighbor discovery algorithm and directional MAC protocols are given in Chapter 3 and Chapter 4.

1.5.2 Design Goals

The design goals of our approach are as follows:

- **Energy efficiency:** Energy-efficiency is one of the most important factors that must be considered in designing neighbor discovery and Medium Access Control in DSNs. It refers to the energy consumed per unit for successful communication. The protocols must be energy efficient in order to maximize not only the lifetime of individual sensor nodes, but also the lifetime of the entire network.

- **Distributed approach:** The flow in sensor networks greatly varies with network size, node density, etc. Thus, a centralized approach in DSNs, would increase discovery latency, scheduling delays and also cause a single point of failure. To counteract the aforementioned challenges, a distributed approach is needed for neighbor discovery and medium access control in DSNs.

- **Scalability:** Scalability is the ability to accommodate the change in network size. It is the ability of a system to meet its performance characteristics in spite of its size of the network or the number of nodes.

- **Adaptability:** Adaptability refers to the ability to accommodate the changes in node density. In sensor networks, node density can be very high and nodes can fail, join, or move, which would result in changes in node density. A neighbor discovery protocol and MAC protocol must be adaptive to such changes efficiently.

- **Throughput:** Throughput is defined as the rate at which messages are serviced by a communication system. It is usually measured either in messages per second or bits per second. An important objective of a MAC protocol is to maximize the throughput in the network while minimizing end-to-end packet delivery delay.

- **Latency:** Latency is defined as the delay from the time a sends a packet until the time the packet is successfully received by the receiver. In our proposed DCD-MAC the experience delay is least as it schedules the data transfer before transmitting data.

- **Control overhead:** A neighbor discovery algorithm or MAC protocol require sending, receiving, and listening to a certain necessary control packets, which is not for data communication and they also consume energy.

- **Duty-cycle:** Using the duty-cycle sensors alternate between sleeping and awaking periods in order to save energy over the idle listening time. To reduce energy consumption due to idle listening, duty-cycling is extensively used in WSNs.

1.5.3 Solution Methodology

Even though, the directional antenna provides potential benefits in WSNs, exploiting these benefits is challenging as a communicating pair must select the appropriate sectors to point to each other during their communication sessions. Otherwise, the receiving node cannot receive the message. As a consequence, trivial functions like neighbor discovery, medium access become extremely challenging. To design appropriate mechanisms for DSNs, additional functions should be performed before data forwarding starts so that

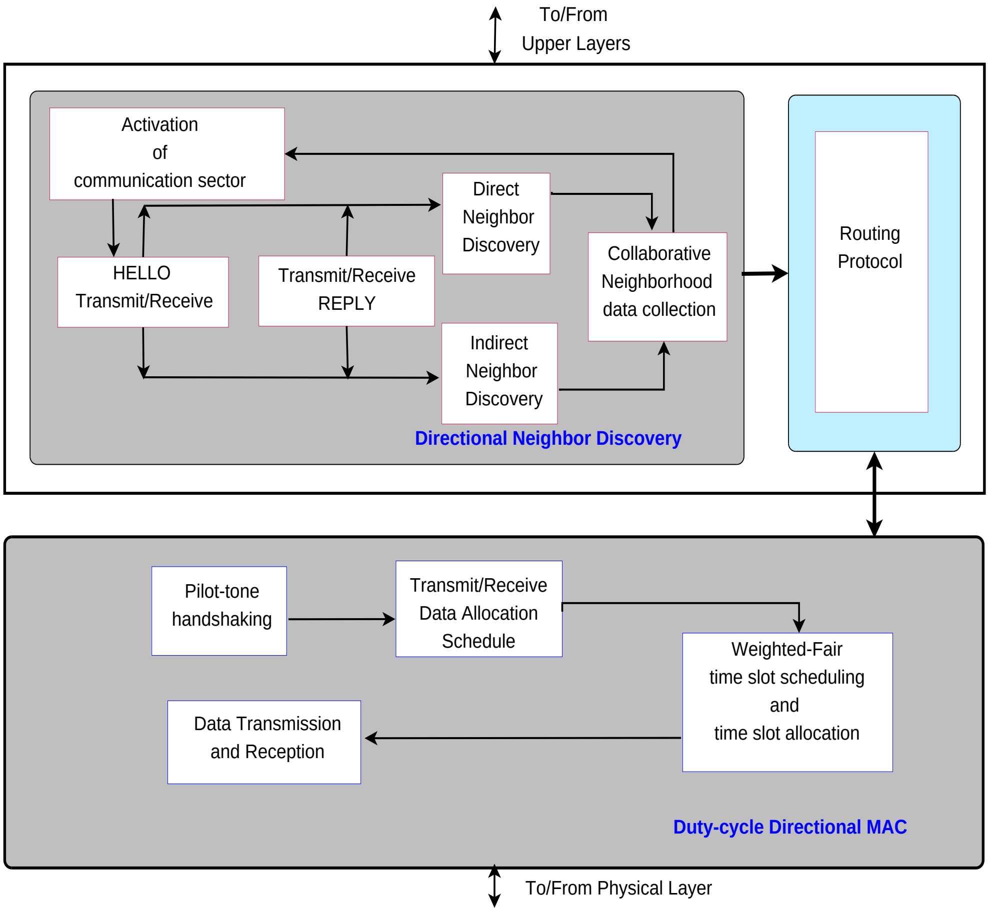


Figure 1.9: System model for the proposed mechanisms

they allow high utilization of sectored antenna in WSNs.

In this thesis, a collaborative neighbor discovery mechanism (COND) is designed that does not require an additional omni-directional antenna unlike many other proposed directional neighbor discovery algorithms [41, 47, 42]. Each directional node performs neighbor discovery in each sector using a contention based polling mechanism and discover their neighbors collaboratively by sharing the discovered neighborhood information with the surrounding nodes. The goal of neighbor discovery mechanism is to increase the number of discovered nodes with minimum delay using a two-way collaborative polling mechanism. In this thesis, we have also proposed a duty-cycle medium access control protocol, named DCD-MAC. The DCD-MAC cooperatively determines the transmission and reception schedules of the sensor nodes. From a periodic neighbor discovery protocol using COND[14], each node gets the neighbor list of the network. In the proposed protocol, neither the parent nor the child nodes need to continuously rotate their beams. Hence, a sensor in the network does not need to be active when it is not scheduled to receive or transmit any data packets. The proposed protocol is fully distributed and the scheduling mechanism exploits sensor mote's local information only which made DCD-MAC highly scalable. Figure 1.9 shows the basic layout and the interaction of the different functionalities of our proposed mechanisms.

1.5.4 Thesis Contributions

In DSNs, efficient neighbor discovery along with neighbor discovery strategies need to be employed so that a pair of neighbor nodes eventually beam form their antennas to each other at a certain time instance to discover themselves and schedule their time slots for successful data communications.

The first contribution of this dissertation is to develop a Neighbor Discovery algorithm, where the directional sensors discover their neighboring nodes collaboratively by sharing the discovered neighborhood information with the surrounding nodes. Each directional node performs neighbor discovery in each sector using a contention based polling mechanism. The goal of neighbor discovery mechanism is to increase the number of discovered nodes with minimum delay using a two-way collaborative polling mechanism.

The second contribution of this work is the formulation of a duty-cycle medium access control protocol, which cooperatively determines the transmission and reception schedules of the sensor nodes. To facilitate a synchronized energy-efficient and collision-free data transmission and reception among the nodes, a novel data transmission a novel frame is to develop. After getting the neighbor table from the periodic neighbor discovery protocol, all the sensor nodes construct a sink-rooted tree in the DSN. In the network, a parent node may have multiple children and a child has only one parent. As nodes are synchronize with each other in the protocol, so neither the parent nor the child nodes need to continuously rotate their beams and they need not to be active when they are not scheduled to receive or transmit any data packets.

Our proposed COND and DCD-MAC algorithms are fully distributed and scalable with the network. Hence, the distributed decision making with collaboration among the nodes in the proposed mechanisms make the system adaptable. Node synchronization, slot scheduling with weighted-share in the proposed mechanisms have made the network adaptable. Finally, as the developed mechanisms work locally at each node in a distributed manner, simulation results show significant improvement in performance over state-of-the-art works in terms of average discovery latency per node, sensing wastage, reliability, end-to-end delay, energy-efficiency, protocol operation overhead, etc. The duty-cycle of DCD-MAC is always lower than the studied protocols as in the transmission slots, the nodes that have no scheduled transmission always remain in sleep node and preserve their energy.

1.6 Thesis Organization

The remainder of the thesis follows this organization. In Chapter 2, we overview state-of-the-art Directional Medium Access Protocols along with Neighbor Discovery algorithms in DSNs and discuss on the motivation of those solutions. In Chapter 3, we develop a neighbor discovery mechanism that speeds up any communication protocol in DSNs. A duty-cycle based directional MAC protocol is presented in Chapter 4. Finally, we conclude the thesis in Chapter 5 by summarizing the findings in the thesis and describing avenues of possible extensions to this work.

Chapter 2

Literature Review

In this chapter, we overview necessary background studies for neighbor discovery and medium access control (MAC) protocols in Directional Wireless Sensor Networks (DSNs). We also discuss the effects of neighbor discovery and medium access control protocols in a dense network.

2.1 Introduction

Many directional communication protocols for supporting the usage of directional antennas in DSNs have been proposed in the literature. However, there remain two open issues that are yet to be resolved completely. Firstly, there should be appropriate algorithm in which a node can efficiently discover and track its neighbors. Secondly, this is essential to design an efficient Medium Access Control (MAC) protocol for transmission and reception of directional antennas so as to increase the spatial diversity gain.

In this Chapter, the state-of-the-art works on neighbor discovery and medium access control in DSNs have been scrutinized and compared the works in Table 2.1 and Table 2.2. The subsequent sections in this Chapter is organized as follows. In Section 2.2, different neighbor discovery algorithms are discussed. Section 2.3 examines state-of-the-art Directional Medium Access Control (DMAC) protocols to enhance network throughput with minimum latency in DSNs. The combined effort of neighbor discovery algorithms with directional medium access control protocols are discussed in Section 2.4. Finally, we summarize this Chapter in Section 2.5.

2.2 Neighbor Discovery in Directional Sensor Networks

Directional Sensor Networks (DSNs) are gaining much popularity in the recent years, due to their improved performance gains through directional antennas [48, 49, 47, 50, 26, 3, 40]. Even though the problem of neighbor discovery was well investigated in the literature for omni-directional and wireless ad hoc networks, that for directional sensor networks kept less focused. However, in recent years, we find a few of neighbor discovery algorithms that are based on directional antennas. The existing works can broadly be categorized in two types: one way broadcasting mechanisms [51, 52, 53, 54, 55, 56, 57, 39] and two-or three-ways handshaking mechanisms [47, 58, 59, 60, 61, 42, 41, 34].

2.2.1 One-way Broadcasting Mechanisms

In one-way broadcast based neighbor discovery mechanisms, nodes periodically broadcast their presence. On reception of at least one message successfully, a nearby node discovers the sender node. A randomized algorithm is proposed in [53, 54], where each node makes independent decisions on whether to transmit or not at a given time instant. Another state-of-the-art work, PMAC [55], incorporates an efficient mechanism for neighbor discovery. The protocol facilitates the discovery of one-hop neighbors, and using polling, the maintenance of links to the discovered neighbors until they are outside the possible radial range of the node. A probability based neighbor discovery algorithm, namely Improved Scan-based algorithm, (I-SBA) is proposed in [56], where nodes transmit, receive and remain idle with certain probabilities. The mechanism decreases number of collisions among the neighboring nodes when the probabilities are selected properly. Nevertheless, with the growing number of nodes in the network, the possibility of directional synchronizations among the nodes is gradually decreased. In [57], authors develop a directional neighbor discovery mechanism, where the number of slots for neighbor discovery is dependent on the order of the average number of nodes in the network. The base station sends a beacon signal toward all the nodes in the network to start the discovery process and all the nodes are time-synchronized with each other. Their neighbor discovery mechanisms exploit hybrid usage of omni-directional and directional antennas; hence with the increasing number of nodes in the network, the mechanism initiates extra overhead for the node synchronization. A directional neighbor discovery protocol was developed in [39], which is based on 1-way broadcast mechanism. A Hello message is broadcasted by each node and, after hearing the message, the neighboring nodes learn about information of that node.

In none of the above one-way broadcast based neighbor discovery mechanisms, the sender nodes know whether the neighboring nodes receive their messages successfully or not. Thus, the one-way neighbor discovery algorithms might be suitable for omni-directional networks but not for directional sensor networks. Because, the later requires synchronization between the transmitting and receiving nodes to make the communication a successful one. Therefore, two-or three-ways handshaking protocols are more desirable for DSNs.

2.2.2 Two-or Three ways Handshaking Mechanisms

In two-ways handshaking based neighbor discovery mechanisms, a receiver node, after reception of a message, sends back a reply message towards the sender node, facilitating both nodes to discover each other in one event of communications. In directional transmission, a receiver node can only hear the message if it faces its antenna towards the sender and thus a feedback message is very important for neighbor discovery among the nodes. Hence, at least two-ways handshaking is required for effective directional neighbor discovery as the nodes can agree on a future period for communication after the discovery. A fully directional scan based asynchronous neighbor discovery algorithm is proposed in [59], where each node senses the medium and transmits hello message in a random direction and gathers location of the neighbor nodes, reducing the number of collisions among reply packets. The urgent requirement of synchronization in between a transmitter and a receiver is kept unexplored in the above work. Moreover, nodes wait at each sector for a fixed period of time for neighbor discovery, which is highly inefficient. In [58], a directional neighbor discovery mechanism has been developed, where only the sink node of the network uses directional antenna; whereas, the other sensors use omni-directional antennas. The sink node applies contention-based and contention-free methods to medium access and sequentially scans all of its sectors to discover its neighbors. To minimize the medium access delay, the authors presented an optimization method for selecting the beam width and the persistence probability of neighbor discovery. This mechanism results asymmetry-in-gain problem [13] due to the difference between the antenna gain patterns of the sink node and other sensors. A Randomized two-ways neighbor discovery mechanism is proposed in [61], where the authors have presented an asymptotic analysis of one-way and two-ways directional neighbor discovery algorithms. Their two-ways neighbor discovery mechanism exploits selective feedback policy so as to reduce collisions among the reply packets and thus to further decrease neighbor discovery time. A directional neighbor discovery algorithm named Limited Random Algorithm(LRA) is proposed in [42], which has adopted a 2-way interactive mode by taking the advantage of the approximate location information of neighbors obtained from global positioning system (GPS) or any other similar technologies, which is not exact but fuzzy. However, the reception of a reply packet is not certain in the above works due to lack of synchronization between the sender and receiver nodes.

A fully directional and centralized three-ways sectored antenna neighbor discovery (SAND) algorithm is proposed in [41], where a token is passed among network nodes sequentially to discover their surrounding neighbors. However, for token management, it requires a central node, which is not only often infeasible for many DSN applications but also limited by scalability. Furthermore, the rotational latency of a token affects the neighbor discovery accuracy and increases the overall neighbor discovery latency. The SAND mechanism also has not considered the directional synchronization issue among the nodes, causing deafness problem and as a central controller controls the whole mechanism, the discovery latency sharply increases.

The existing works cannot realize the optimal worst-case latency because of the absence of node synchronization, and their performances can still be improved. The proposed algorithm COND [14] in this thesis is different from the above studies in that we develop a fully distributed neighbor discovery mechanism, where both the transmissions and receptions are directional and nodes collaborate with their (already discovered) neighbors to find other neighbors, reducing neighbor discovery latency significantly.

2.2.3 Comparative Characteristics of Neighbor Discovery Algorithms

The key characteristics of some of the neighbor discovery mechanisms are summarized in Table 2.1. By reviewing the state-of-the-art algorithms, we have found that two-three way synchronous neighbor discovery algorithms give better performance than the other algorithms in DSNs.

2.3 Directional Medium Access Control Protocols

To occupy the improvement of directional antenna technology, researchers have proposed several MAC protocols for wireless ad hoc networks in recent years. Researchers are actively studying the directional transmission technique and attempt to design specific MAC protocols that take advantage of the strengths of this new technology. However, very few works have addressed the challenges related to medium access with directional antennas in wireless sensor networks. Recently, a few directional MAC protocols have been developed that address challenges related to directional antennas - deafness, hidden

Table 2.1: Characteristic comparison of neighbor discovery algorithms in DSNs.

ND Algorithms	Centralized	Distributed	Collaboration	One-way	Two-or three-ways	Synchronous	Asynchronous	Directional Transmission	Directional Reception	Energy Awareness
PMAC [55]	✗	✓	✗	✓	✗	✗	✓	✓	✓	✓
I-SBA [56]	✓	✗	✗	✓	✗	✓	✗	✓	✓	✗
Directional ZigZag [57]	✓	✗	✗	✓	✗	✓	✗	✓	✓	✗
LRA [42]	✗	✓	✗	✗	✓	✓	✗	✓	✗	✗
Contention-based ND [58]	✓	✗	✗	✗	✓	✓	✗	✗	✓	✓
SBAN [59]	✗	✓	✗	✗	✓	✗	✓	✓	✓	✗
SAMAC [47]	✓	✗	✗	✗	✓	✗	✓	✓	✓	✗
SAND [41]	✓	✗	✗	✗	✓	✗	✓	✓	✓	✗
COND [14]	✗	✓	✓	✗	✓	✓	✗	✓	✓	✓

terminal etc. and have resolved those by transmitting frequent control packets directionally to notify all neighbors about all ongoing transmissions [36, 37, 62]. Asymmetry-in-gain problem of directional antenna based networks has also been discovered and addressed in [35, 63]. The hidden and exposed terminal problems in directional sensor networks have been addressed in [64, 65]. Though these methodologies reduce the challenges, protocol operation overhead is very high and it limits the spatial reusability. Medium access control protocols for DSNs can be classified as contention-based, non-contention based and hybrid based. Contention-based DMAC protocols can be classified into pure RTS/CTS based, tone based and power controlled based DMAC protocols, while a non-contention based DMAC protocols can be classified as synchronization based and non-synchronization based.

2.3.1 Contention Aware DMAC Protocols

The contention based DMAC protocols use CSMA/CA approach. A node with a DATA frame can only transmit the RTS frame when its backoff counter counts down to zero, the channel is sensed idle and its DNAV(s) for the directions of its antenna is off. Contention-based DMAC protocols use different types of RTS and CTS frames to reserve the channel within the vicinity of the nodes antennas. DATA and Directional ACK frames are sent after the RTS and CTS frames. In these protocols, backoff algorithm and CTS timeout are similar to that in IEEE 802.11 CSMA/CA MAC.

2.3.1.1 DMAC protocols based on pure RTS/CTS

This section surveys pure Ready-To-Send/Clear-To-Send (RTS/CTS) based single-channel DMAC protocols. These DMAC protocols can be based on circular or non-circular RTS/CTS. For pure RTS/CTS-based non-circular DMAC protocols, no extra delay is incurred in the RTS/CTS frames transmissions.

Several researchers have developed random access based MAC protocol for ad hoc networks [19, 66, 67, 68, 55]. One of the most primitive directional medium access control protocol is DMAC [67]. The DMAC has a prior knowledge of all surrounding neighbors and have used per sector blocking methodology so that once a node senses an ongoing RTS or CTS packet, it blocks that particular sector for any further communication for that certain period. In this protocol, a node uses omni directional antenna for transmitting its own RTS packet which causes asymmetry in gain problem and for unnecessary blocking the performance of the proposed protocol degrades.

An opportunistic directional MAC protocol (OPDMAC) is proposed in [69], which is motivated by the possibility of achieving higher spatial reuse using backoff mechanism with directional antennas. The nodes explore alternative directions for transmission if they miss CTS or acknowledgement in one direction. This minimizes the idle wait time and increase the channel utilization. In addition, OPDMAC is found to decrease the effect of deafness without additional control overhead. A directional antenna based MAC protocol is presented in Sensor-MAC [70], where the authors conquer the MAC-deadlock, hidden and exposed terminal problems with efficient energy usage. In Sensor-MAC, the antenna is rotated during idle time by hearing its nearest node transmission schedules specified antenna beams. Whenever a node receives antenna beams from its nearest node, the node wakes up and starts its communication. A directional MAC protocol is proposed in [71], where each node maintains a Directional Network Allocation Vector(DNAV) table, wherein the information about received CTS, total time of transmission and blocked directional antenna is recorded. The RTS frames are sent directionally, whereas the CTS frames are sent on all the unblocked directional antennas. Finally, DATA and ACK frames are sent using directional antennas, as a result it allows simultaneous transmission and reception of data frames from the neighboring nodes thereby increasing network performance and throughput. Hence, the circular CTS increases the overhead and penalize the network lifetime. In [64], the authors contributed a directional based wireless sensor MAC protocol that conquers the MAC-deadlock, hidden and exposed terminal problems with efficient energy usage. The directional antenna of each node is rotated during idle time by hearing its nearest node transmission schedules. The nodes are not synchronized with each other which results packet loss in the network. A fully directional MAC protocol named MBDMAC is proposed in [72], where a single dedicated channel for each sector is available to the multi-beam antenna and this channel will be used as a control channel(CCH). The control channel is supported by the RF-chain so that communication in the CCH can take place simultaneously with data communication. The MBDMAC protocol consists of three phases: connection initialization, channel contention and data communication. To minimize the effects of the directional deafness, the antenna continuously switches the sensing direction(beam-sectors) of its idle node in a clockwise or anticlockwise manner. In addition to this, to cooperate with each node and each sector, the network allocation vector (NAV) is used in the proposed mechanism. Continuously scanning for control messages effects on lifetime of each node. Furthermore, in most works, the authors assume the providence of neighbors physical location by an upper layer or by means of a GPS, which is not always feasible.

2.3.1.2 DMAC protocols based on tone/pulse transmission

For tone/pulse-based DMAC protocols, tones/pulse are transmitted in the channel in addition to different types of control message transmissions. The tones are used to reserve the data channel for DDATA and DACK frame transmissions as well. A pulse can also be used to act as a DRTS frame in tone based DMAC protocols. Tones are normally, continuous busy tone signals or On/Off signals. Tones can be transmitted omni-directionally or directionally as well, while a pulse is just a signal. Extra energy is needed for tone transmissions.

A directional MAC protocol called Directional Pulse/Tone Channel Reservation (DPTCR) is proposed in [73], where a channel reservation technique is used based on pulse/tone signals which reduces the latency. After the backoff, a source node sends a pulse signal omni-directionally or directionally to receiver node to reserve the channel for data transmission. Similarly, the receiver node also sends a tone signal omni-directionally or directionally to sender node to reserve the channel. Then the sender sends the DDATA frame. Finally, receiver node replies with a DACK frame to the sender. A Tone-based single-channel DMAC protocol. This DMAC protocol is used to mitigate the unheard RTS/CTS problem in switched beam antennas DMAC protocol [74], uses a combination of three features to combat the DMAC challenges. The features include fragmentation of packets, the use of a tone signal to alert potential collision-causing nodes during on-going transmission and the use of a pause period when a transmission is likely to lead to a collision. PMAC [55] is another tone-based directional medium access control (MAC) protocol that uses a polling strategy to discover neighbors periodically and schedule their data transmission. This strategy enables a PMAC node to adjust its antenna sector so as to continuously track its neighbors communications. The main difference of these tone-based DMAC protocols [74, 55], as compared to DPTCR [73] and PMAC [55], is that these protocols use only tones instead of both tones and pulses.

2.3.1.3 DMAC protocols based on power-control

One of the main considerations in designing MAC protocols for DSNs is to reduce power consumption at the sensor nodes. This is usually done by imposing transmission and receiving schedules on the sensor nodes from only one side at same time. Since it is desirable for a sensor network to be self-managed, these schedules need to be worked out by individual nodes in a distributed fashion. Power control in a node determines the range and quality of a transmission as well the interference that it causes to other nodes [16]. Thus, it affects the medium access environment for the channel, the throughput of the network and the end-to-end delay in the network.

Such power-control based DMAC protocols are proposed in [75, 76, 77, 78, 64]. A transmission power control scheme for DMAC in mobile ad hoc networks (MANETs) is proposed in [75], which can be integrated to any directional MAC protocol that adopts a single channel for transmission and reception of IEEE 802.11 frames. While in [76], the authors proposes a distributed correlative power control scheme for mobile ad hoc networks using directional antennas. They present a model to calculate future interference in networks with directional antennas, and based on this model, they derive some relations that should exist between the required Transission Power of RTS, CTS, DATA, and ACK frames for successful data packet delivery in MANETs based on the directional version of the IEEE 802.11 distributed coordination function. In [77] authors have proposed a DMAC with power control and directional receiving (DMAC-PCDR) protocol for directional hidden terminal and minor lobes problems. It is an ORTS or DRTS/DCTS-based single-channel non-circular power-controlled DMAC protocol. Its throughput is better than that of IEEE 802.11DCF MAC protocols for successful communication with consideration to directional challenges such as hidden terminal problems, deafness and side lobe interference. On the other hand, [78] proposes a power-aware DMAC protocol for ad hoc network with directional antennas. The authors construct an interference model for directional antenna based on a honey grid model to calculate the maximum interference and further derive a directional collision avoidance model based on the integrated interference/collision model which enhance the performance of DSNs.

As characteristics of a DSN is quite different from Wireless AdHoc network, an energy-efficient directional MAC protocol is proposed for WSNs in Sensor-MAC [64], where an energy-efficient mechanism is adopted for solving the usual hidden and exposed terminal challenges. The Sensor-MAC schedule the transmission of all nodes in the network for avoiding packet collisions that conserves energy of the network. Nevertheless, the Sensor MAC considers a single hop network, where a central/sink node manages the transmission schedule of all sensor nodes in the network.

2.3.2 Non-contending DMAC Protocols

Pure non-contention-based MAC protocols using TDMA, FDMA and CDMA are difficult to implement for multi-hop DSNs. Nevertheless, there are few works on Spatial Reuse TDMA DMAC protocols [79, 80, 81, 4, 47].

Spatial Time Division Multiple Access (STDMA) is proposed in [79], which utilizes the radio spectrum more efficiently compared to TDMA. This is done by allowing more than one radio units to use the same time slot when the interference is sufficiently small. When the nodes are closely connected, this protocol looses its main purpose and works like TDMA. In addition, when using spatial reuse the schedules are sensitive and it is difficult to handle bursty data traffic. A novel TDMA based MAC protocol, termed as TDMA-SB (TDMA slot borrowing scheme) is proposed in [80], which utilizes smart antennas and location awareness of the nodes provided by GNSS (global navigation satellite system). It also introduces a novel slot borrowing scheme to utilize the unused time slots in a TDMA frame which can adapt effectively to the bursy data traffic. The improved performance of TDMA-SB is gained with the cost of additional control traffic in the slot borrowing scheme.

A sectored-antenna-based MAC protocol, SAMAC [47] is proposed for WSNs which uses a TDMA approach for nodes discovery and also for activating certain sectors. It computes the time schedule in the sink node and then distributes the schedule to the whole network. Central schedule computation increases the overhead for a large dense network.

2.3.3 Hybrid DMAC Protocols

The main difference between this hybrid DMAC protocol and other DMAC protocols is that it uses Contention Window/DDATA/DACK periods. The advantage of this hybrid DMAC protocol is that, normally there is no deafness and hidden terminal problems. In addition, another advantage of using hybrid DMAC protocol is that there is no extra delay incurred in the network as a whole.

An non-circular hybrid DMAC protocol is proposed in [82], where the Balanced Incomplete Block Design theory has been exploited to develop a MAC protocol for wireless ad hoc networks using directional antennas. It is an ORTS/DCTS-based single-channel non-circular hybrid DMAC protocol. It aims to reduce deafness problem in an efficient way and to provide a fair bandwidth sharing among nodes. The main difference between BIBD-MAC protocol and other DMAC protocols presented in previous sections is that it is highly scalable. This solves the deafness problem but results in poor spatial reuse. To solve the directional hidden terminal and deafness problems, the authors in [83] has designed a MAC protocol that solves these challenges comprehensively using a single channel. It is an ORTS/OCTS-based single-channel non-circular hybrid DMAC protocol. In this algorithm, the transmitter and the receiver can somehow inform their neighboring nodes about their impending transmission. The receiver that has a blocked beam finds a way to inform the sender that the transmission cannot happen without disturbing other ongoing transmissions in its neighborhood. There are three periods in this DMAP protocol, a contention window period, a DDATA period and a DACK period. Due to poor synchronization among the nodes in the network, the performance of the network degrades in a dense multi-hop network. Another variant of such DMAC protocols are presented in [84, 85, 86]. These protocols are ORTS/OCTS/DRTS/DCTS-based single-channel non-circular hybrid DMAC protocols in the contention period. They propose a reservation-based MAC protocol for multi-hop wireless networks with directional antennas. The main difference of this kind of hybrid-based DMAC protocol as compared to the contention-based DMAC protocols is that each node contends the transmission opportunities in the Synchronization phase and then transmits without collision in the Data Transfer phase.

In the above mentioned directional MAC protocols, the energy consumption of the sensor nodes is greatly increased for continuous rotations for sending the preambles prior to packet transmission. Furthermore, those protocols do not study the many-to-one data communication policy of DSNs during the selection of the transmission and reception beams of the sensors. Hence, it is hard to maintain the data transmission and reception schedule properly that results loss of data. By considering the aforementioned characteristics of DSNs, we have proposed a duty-cycle directional MAC protocol called DCD-MAC [14]. In DCD-MAC, all nodes are synchronized with the neighbors and also know their next hop routing path to the sink node, i.e., each parent node and its child nodes are deterministic. DCD-MAC divides the medium access time into frames and sensor nodes periodically alternate between active state and sleep state in the duty cycling period.

2.3.4 Comparative Characteristics of DMAC Protocols

The key characteristics of some of the Directional Medium Access Control Protocols are summarized in Table 2.2.

Table 2.2: Characteristic comparison of DMAC protocols in DSNs.

DMAC protocols	Centralized	Distributed	ORTS/OCTS	DRTS/DCTS	Circular RTS/CTS	Synchronous	Asynchronous	Energy Awareness	Tuned for Sensor Network	Complexity
DMAC [67]	✗	✓	✓	✗	✓	✗	✓	✗	✗	MED
OPD-MAC [69]	✗	✓	✗	✓	✓	✗	✓	✗	✗	MED
Sensor-MAC [70]	✗	✓	✗	✗	✗	✗	✓	✓	✓	HIGH
DPTCR [73]	✗	✓	✗	✗	✗	✗	✓	✗	✗	HIGH
PMAC [55]	✗	✓	✗	✓	✗	✓	✗	✓	✗	LOW
DMAC-PCDR [77]	✗	✓	✗	✓	✓	✗	✓	✗	✗	HIGH
Power-aware DMAC [78]	✗	✓	✗	✓	✗	✗	✓	✗	✓	HIGH
STDMA [79]	✓	✗	✗	✗	✗	✓	✗	✗	✗	HIGH
SAMAC [47]	✓	✗	✓	✗	✓	✓	✗	✓	✓	MED
DUMAC [87]	✓	✗	✗	✓	✓	✗	✓	✓	✓	HIGH
BIBD-MAC [82]	✓	✗	✓	✗	✗	✓	✗	✓	✗	HIGH
DMAP [83]	✗	✓	✓	✗	✗	✗	✓	✗	✗	HIGH
DCD-MAC [12]	✗	✓	✗	✓	✗	✓	✗	✓	✓	LOW

2.4 Medium Access Control Along With Neighbor Discovery

In the literature, there are a good number of works that has done neighbor discovery before medium access. Directional transmission and reception based neighbor discovery algorithms and medium access protocols are presented in [88, 89]. They are single-channel non-circular Neighbor-Discovery/Reservation/ Data-Transmission Periods based DMAC protocols. In these protocols, GPS and other methods are assumed for nodes synchronization. There are three periods in this DTRA [89] protocol a Neighbor Discovery period, a Reservation period and a Data Transmission period. In the neighbor discovery period, neighbor discovery algorithms are used to find neighboring nodes. In the reservation period, nodes can make reservations for data transmission. In the data transmission period, data frames are transmitted. Power control is used for directional transmission and reception. The disadvantages of these protocols are GPS is needed in all nodes and time is used for neighbor discovery.

An integrated cross-layer protocol SAMAC is proposed in [47], which consists of different communication functionalities that allow high utilization of sectored antenna in DSNs. Before sensor nodes can forward data packets, SAMAC needs initialize the network by discovering and collecting neighborhood information. Then each node compute and distribute the time schedule with the surrounding nodes and finally establish initial time synchronization for all nodes. As SAMAC is a centralized protocol, the performance of the network degrades drastically with the increasing number of nodes in the network. The PMAC [55] is another directional MAC protocol that discovers the one-hop neighbors of each node. PMAC incorporates an efficient mechanism for neighbor discovery, and a scheduling based medium sharing that allows for exclusive directional transmissions and receptions. It uses polling mechanism to maintain the links of the discovered neighbors. The protocol schedules the transmission and reception among all the nodes and at the scheduled time the nodes communicate with each other using directional antenna. There are three periods in this PMAC protocol a search period, a Poll period and a Data Transfer period. In the search state of the search period, new neighboring nodes can be searched for. In the polling state of the poll period, known neighboring nodes are polled. Finally, in the data transfer state of the data transfer period, actual data information is transferred. All frame transmissions and receptions are done directionally. Pilot tones are used in the search period. These protocols do not fully exploit the behavior of WSNs and they do not fully handle the new challenges that come along with the directional antenna. None of these protocols introduce the Conflict Of Interest problem, which is a very common problem in WSNs that happens when scheduling is done before data transmission. The DU-MAC [87] is proposed for UWB-WSN, does not rely on prior availability of neighbors location. In order to accomplish that, it employs a directional blind discovery mechanism to learn and cache information about the sectors where neighbors exist. The idle nodes in the network continuously rotate their receiving beams over 360 degree till a predefined preamble trailer is detected. The protocol deals effectively with the problem of deafness and effectively determines the neighbors location in the network. SAMAC protocol can be described as an

2.5 Summary

In this Chapter, we present a comprehensive analysis of existing neighbor discovery mechanism and Directional Medium Access Control (DMAC) protocols adopted in DSNs to enhance the network performances. In Chapter 1, we pointed the various design issues to be addressed by an effective solution for a network with directional antenna. Based on that, we studied the state-of-the-art works in this Chapter, those attempted in differing aspects to provide an efficient solution. Fast neighbor positioning reduces the network initialization overhead and leaves more time for executing other protocols. Fast medium access leads to larger volume of transmitted data per unit of time. These two problems are studied in a unified manner in this Chapter.

Chapter 3
Collaborative Neighbor Discovery

We have discussed and compared the state-of-the-art works on different neighbor discovery mechanisms and MAC protocols proposed by the researchers in the previous chapter. By motivating from the limitations of the related works and to overcome the challenges of directional neighbor discovery, we develop and evaluate a collaborative neighbor discovery mechanism in this chapter.

3.1 Introduction

In Directional Wireless Sensor Networks (DSNs), sensor devices with directional antennas sense data and deliver them in a multihop fashion toward the sink node. Now a days, DSNs are being used for the implementation of many real-time applications including infrastructure monitoring, health-care monitoring, robotic exploration, battlefield surveillance, target tracking, disaster response, etc. [9, 10]. The directional sensors have been proved to provide better energy-efficiency, sensing quality, bandwidth utilization, etc [11, 12]. However, the directional transmissions and receptions of the sensor nodes have made the development of data communication and networking protocols for DSNs more challenging.

Neighbor discovery is defined as the problem of identifying all nodes within the communication range of a sensor device. The problem of neighbor discovery in directional sensor network is not only more challenging than that in its omni-directional counterpart, but also it requires complete redesign and implementation. The key fact behind this requirement is that the directional nodes have limited width of communication sectors and thus two nearby nodes must steer their communication sectors to each other for a successful communication [25, 90, 40]. Efficient strategies need to be employed so that a pair of neighbor nodes eventually beam form their antennas to each other at a certain time instance and can discover themselves. The primary challenge lies in increasing the number of nodes discovered in bounded delay through better coordination in a distributed way, when the nodes are not clock-synchronized.

In the literature, the problem of neighbor discovery with omni-directional antenna has well been explored [9, 20]. Nevertheless, recently, a few neighbor discovery mechanisms are developed that are based on directional communications. A neighbor discovery algorithm based on contention-based and contention-free approaches have been developed in [8], where only the sink node uses directional antenna, whereas the other nodes use omni-directional one, resulting in asymmetry-in-gain problem [13, 35]. A scan based asynchronous neighbor discovery algorithm (SBAN) is proposed in [59], where the neighbor discovery is based on fully directional transmissions and receptions. The probabilistic Hello message broadcasting with fast reply mechanism reduces collisions among the sensors. A randomized 2-way neighbor discovery algorithm has been developed in [61]. The authors have presented an asymptotic analysis of 1-way and 2-way directional neighbor discovery algorithms and have designed a 2-way neighbor discovery mechanism with selective feedback that reduces the neighbor discovery time. However, both the works [59, 61], lack in guaranteeing responder the reception of reply packets which increases the discovery latency for a dense network. A fully directional and centralized sectored antenna neighbor discovery (SAND) algorithm is developed in [41], where a token is passed among the nearby nodes to successfully learn each other. However, for token management, a central node is required that is not feasible for many applications of DSNs, especially in achieving scalability. Moreover, the rotational latency of a token affects the neighbor discovery accuracy and it increases the overall neighbor discovery latency. None of these works have well-thought-out the directional coordination between two nodes. The proposed algorithm COND in this thesis is different from the above studies in that we develop a fully distributed neighbor discovery mechanism, where both the transmissions and receptions are directional and nodes collaborate with their (already discovered) neighbors to find other neighbors, reducing neighbor discovery latency significantly. This indirect neighbor discovery and selective feedback policies jointly help our algorithm to decrease the collisions in the network. In addition to that, a COND node employs dynamic waiting time at different directions while discovering nodes in the neighbor that greatly helps to mitigate the deafness problem.

In this Chapter, a Collaborative Neighbor Discovery (COND) algorithm is proposed, where the directional sensors discover their neighboring nodes collaboratively by sharing the discovered neighborhood information with the surrounding nodes. The key idea behind the COND mechanism is that, each directional node performs neighbor discovery in each sector using a contention based polling mechanism. The goal of neighbor discovery mechanism is to increase the number of discovered nodes with minimum delay using a two-way collaborative polling mechanism. In this work, we augment the detail operation method of indirect neighbor discovery through collaboration. We carry out theoretical analysis using Markov chain model that quantifies expected number of discovered neighbors and the corresponding delay incurred. We also present performance analysis and results for average discovery latency per node, sensing wastage and energy cost per neighbor discovery. The results show that, the proposed COND mechanism greatly outperforms the state-of-the-art systems - Randomized 2-way [61] and SAND [41].

The main contributions of this work are summarized as follows:

- A fully distributed novel neighbor discovery mechanism, COllaborative Neighbor Discovery (COND) algorithm is developed for sensor nodes in DSNs.
- A two-way polling based collaborative mechanism is designed to decrease the pos-

sibility of conflict and to speed up the handshaking process. In this mechanism, each node learns about its neighbors collaboratively by direct and indirect neighbor discovery through sharing information of already discovered nodes to and from its neighbors.

- We develop a Markov chain model to analyze theoretically the expected number of neighbors discovered and the number of iterations required for discovery.

- Finally, the results of performance evaluations, carried out in NS-3 [91], show that our proposed COND mechanism outperforms SAND and Randomized two-way mechanisms in terms of neighbor discovery latency and ratio, energy consumption, etc.

The rest of this Chapter is organized as follows. In Section 3.2, we describe the network model and assumptions. The proposed algorithm for the neighbor discovery using directional antenna is discussed in detail in Section 3.3 and an the theoretical analysis and performance studies for the given algorithm are discussed in Sections 3.4 and 3.5, respectively. Finally, we conclude the paper in Section 3.6.

3.2 Network Model and Assumption

We assume a directional sensor network of an area A where a set $\mathcal{S}$ of directional sensor nodes are deployed with uniform random distribution, resulting in deployment density,

$$\rho = \frac{|\mathcal{S}|}{A}. \tag{3.1}$$

Each node is designed with $\mathcal{M}$ sectored switched-beam directional antennas, as shown in Fig 3.1. To cover the whole azimuth, fixed number of fixed beam width antenna elements are attached in each antenna of a sensor. Each node can activate one sector at a particular time. Nodes can switch from one sector to another by activating different antenna elements and each element has high antenna gain to a particular sector. Basically they direct a major or almost their entire signal in just one direction instead of dispersing all around a 360^0 circle. Typically, the switching delay from one sector to another is 5×10^{-6} μs for a traditional switched beam directional antenna [41, 92].

Each node has one transceiver and can form one directional beam in a sector at a given time. For the network nodes, all transmissions and receptions are directional and they do not require any additional omni-directional antenna. Note that, the usage of both directional and omni-directional antennas causes additional hardware cost, complexity and two other major problems. First, the transmission ranges of the omnidirectional antenna and directional antenna are different which introduces asymmetry gain problem in communication links. Again, the spatial reuse benefits are greatly reduced since omnidirectional communication inhibits more simultaneous transmissions.

The communication radius (r) of all nodes in the network is homogeneous. Nodes in the network are not clock-synchronized with each other. Each node independently discovers its neighbors. The success event of a transmission is probabilistic; however, our

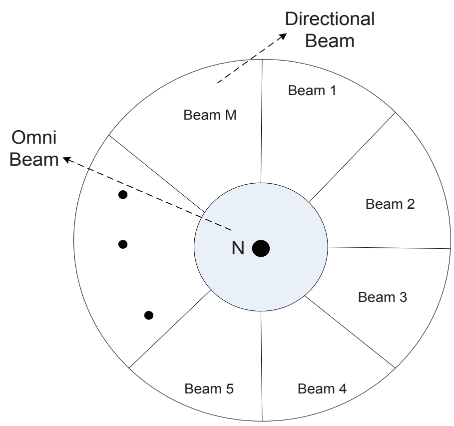


Figure 3.1: Antenna model for a node

dynamic polling period and selected response REPLY to HELLO messages decrease the probability of collision and increase the number of successful transmission events. If the discovery message is exchanged between two nodes for at least half of a slot, two nodes can discover at the same time slot [40]. Subsequently, in a distributed system, without any clock synchronization two sensor nodes can discover each other within a bounded delay.

Initially, a node learns its position using a localization method [93]. We assume that the time is divided into contiguous slots and all nodes independently discover their neighbors within a bounded time. The total time frame is logically separated into transmit and receive time slots. Each slot is further divided into multiple mini-slots. A node either transmits *Hello* message or listen to the medium for any message from its neighbor(s) in an individual slot. While communicating with each other, a node can identify the angular position of its neighbor by capturing its spatial signature vector [58]. After the deployment of the sensor nodes in the network, nodes discovers their neighbors using COND mechanism and during the neighbor discovery period all the nodes will be active to discover most of the neighbors within short period of time. Later, the sensors collect sense data and start data transmission towards the sink node. An underlying medium access control protocol (e.g., S-MAC [94], T-MAC [44], B-MAC [45], DMAC [67], SAMAC [47] etc.) can determine and control the energy-saving states of a sensor node, which is beyond the scope of this work. The notations used in this paper are summarized in Table 3.1.

3.3 Collaborative Neighbor Discovery Mechanism

In this section, we present detail operation method of the proposed 2-way collaborative neighbor discovery algorithm, COND, for DSNs. Each COND node tries to explore maximum number of neighboring nodes in different sectors. A COND node stays in each

Table 3.1: List of notations for COND mechanism

Symbol	**Definition**
$\mathcal{S}$	Set of all sensor nodes
$\mathcal{M}$	Set of sectors of directional antenna
P_t	Transmission probability
r	Communication radius of each sensor
$\mathcal{K}$	Delay tuning parameter
A	Deployment area of the network
ρ	Network density
$\mathcal{T}_a$	Neighbor table of node $a \in \mathcal{S}$
E_n	Expected number of nodes in the neighborhood
$\mathcal{N}_e^m$	Number of expected neighbor nodes in a sector $m \in \mathcal{M}$
$\mathcal{N}_d^m$	Number of discovered neighbor nodes after an iteration
$\mathcal{F}$	Flag indicating a neighbor is discovered directly or indirectly
$\mathcal{R}$	Iteration for neighbor discovery
x'	Mini sub-slot of a slot x
δ_m	Parameter that tunes $\mathcal{K}$
α, β, γ	Threshold values for tuning parameter δ_m

of its sectors for a particular time duration and performs direct and indirect neighbor discovery processes using polling mechanism. Unlike [59, 60, 41], we allow COND nodes to dynamically vary the time duration operating in a sector based on percentage of its neighbors already discovered. Furthermore, unlike in our previous work [34], we allow COND nodes to explicitly track the neighbors discovered indirectly and take actions differently, facilitating to increase the neighbor discovery performance. In summary, the COND mechanism is condensed into following three steps:

- Initialization of neighbor discovery with appropriate value of a delay tuning parameter ($\mathcal{K}$).
- Discovery of neighbor nodes in different sectors using contention based polling mechanism.
- Maintaining and updating the neighbor tables of COND nodes in collaborative

fashion.

What follows next, we present the detail operations of the COND steps.

3.3.1 Initialization

Each node in the network first calculates the approximate number of neighbors around them after the deployment of the nodes in the network. The expected number of neighbors of each node can be calculated as,

$$E_n = \rho \times \pi \times r^2, \tag{3.2}$$

where, r is the communication radius of a sensor node and ρ is the node deployment density. Then, the expected number of neighbors in a particular sector $m \in \mathcal{M}$ of a node is given by

$$\mathcal{N}_e^m = \frac{E_n}{|\mathcal{M}|}. \tag{3.3}$$

Initially, each sensor node $s \in \mathcal{S}$ starts to explore neighbors in all of its sectors $m \in \mathcal{M}$ by switching its direction clockwise after a certain interval of T seconds. T is the time interval for staying in a particular sector of each node. As we are assuming that each node switches its sector one by one for neighbor discovery, it is necessary to stay in a particular sector for a certain period so that two nodes can steer their antennas to each other in that period. Hence, T depends on the number of sectors of a node and the delay incurred for switching a direction; and, it is determined as follows,

$$T = T_{switch} \times (|\mathcal{M}| - 1) \times \mathcal{K}, \tag{3.4}$$

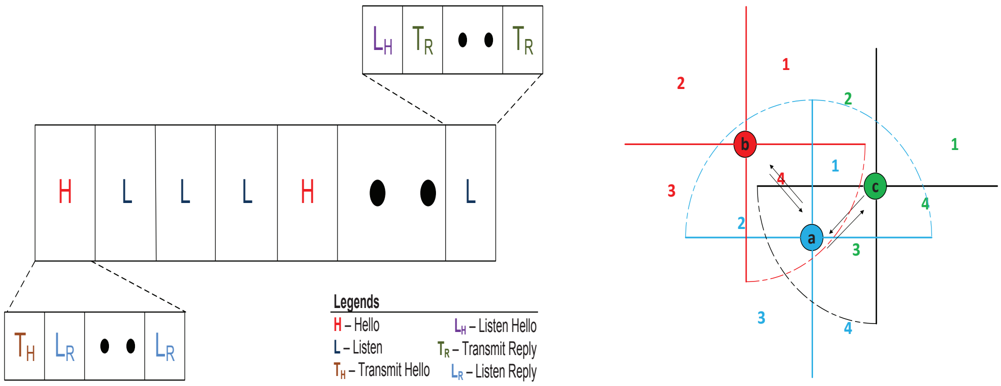
where, T_{switch} is the switching delay and $\mathcal{M}$ is the set of sectors. Furthermore, when a good number of nodes are discovered in a particular sector of a node, it must stay less period of time over there so as to reduce the discovery overhead. On the other hand, when a node has discovered very less number of neighbors in a sector, it must stay longer period in that particular sector in order to reduce the discovery latency. Thus, for determining the value of time period T, we introduce a delay tuning parameter $\mathcal{K}$, that is updated after each iteration depending on the number of discovered neighbor nodes in a particular sector as follows,

$$\mathcal{K} = \delta_m \times \mathcal{K}, \tag{3.5}$$

where, the value of δ_m is chosen in such a way that the discovery latency in each sector $m \in \mathcal{M}$ is minimized. If a node discovers most of its neighbors in a given sector $m \in \mathcal{M}$, then it is wise for the node to stay for less period of time there and vice-versa; otherwise, discovery overhead will unnecessarily be increased. Thus, the value of δ_m helps us to dynamically control the staying period of a sensor node in a certain sector $m \in \mathcal{M}$ for neighbor discovery. Let N_d^m represents the percentage of nodes that are already discovered in sector $m \in \mathcal{M}$, then the value of δ_m is determined as follows,

$$\delta_m = \begin{cases} 0.5, & \alpha < N_d^m, \\ 1.0, & \beta < N_d^m \leq \alpha, \\ 1.5, & \gamma < N_d^m \leq \beta, \\ 2.0, & N_d^m \leq \gamma. \end{cases} \tag{3.6}$$

Here, α, β and γ are the threshold valued for tuning parameter δ_m. Note that, the numerical values of α, β and γ in Eq. (3.6), are not strict choices; rather, the values are depicted through numerous simulation experiments for a given network environment (stated in Section 6) and they are tunable by the network administrator. In the case the number of already discovered nodes in a certain sector crosses the expected number of neighbors, the node may stop staying in that sector. Hence, it may happen that a node



(a) Frame structure (b) Neighbor discovery

Figure 3.2: Frame structure and neighbor discovery in COND system

misses a good number of neighbors to discover if the calculation of expected number of neighbors is incorrect (due to distortions in deployment). Therefore, we allow a COND node to continue the discovery process until it fails repeatedly (say, up to 2 iterations) to find a new neighbor in a particular sector.

3.3.2 Contention Based Polling Mechanism

The COND nodes contend amongst them to poll their neighbors in different sectors so as to discover those. The frame structure followed by the polling mechanism contains 'H' (Hello) and 'L' (Listen) slots, as shown in Fig. 3.2-(a). In 'H' slots, a node broadcasts HELLO messages in random time slots with persistent probability P_t. In the remaining slots, the node listens to the medium for any HELLO message from the neighboring nodes.

Each slot is further divided into several mini sub-slots, as shown in Fig 3.2-(a). If a node decides to transmit a HELLO message in a slot, it does so in the first mini-slot and listens to the channel for any REPLY message(s) from its neighboring node(s). The HELLO message contains the node's ID, (x,y) coordinate, sector number, neighbor table, i.e, $\Gamma_H = \{ID,\ coord(x, y),\ m,\ \mathcal{T}\}$. On reception of HELLO message, the surrounding nodes update their neighbor tables and relay back their information in a randomly chosen mini slot. The REPLY message contains the same information, i.e, $\Gamma_R = \{ID,\ coord(x, y),\ m,\ \mathcal{T}\}$.Thus, the nodes develop their neighbor tables for each sector with so far discovered nodes. The structure of the neighbor table is represented by the tuple, $< ID, coord(x, y), m, \mathcal{F} >$, where the fourth field is a flag that contains 1 if the designated neighbor is discovered through direct exchange of messages and 0, if it is discovered indirectly. The details of *direct* and *indirect* discovery processes are discussed in the following section.

3.3.3 Collaborative Discovery of Neighbor Nodes

The key challenge in reducing neighbor discovery latency in DSNs is the synchronization of HELLO-REPLY transmissions among the nodes in a neighborhood. Therefore, in addition to discover neighbors through direct exchange of messages, we allow COND nodes to share their neighbor tables with each other and to update their tables collaboratively so as to further decrease the discovery latency. Thus, some neighbor nodes are discovered indirectly (via other nodes).

3.3.3.1 Direct discovery

When two nodes are beamformed to each other and successfully exchange HELLO and REPLY messages, they can directly discover each other. After the HELLO-REPLY handshaking two nodes update their neighbor tables accordingly. Thus, it is highly dependent on the synchronization of corresponding sectors of two neighbors. In Fig. 3.2-(b), when the node a discovers a neighbor node b through direct handshaking, the flag entry for b in a's neighbor table is set to 1. Unlike existing works in the literature that depend only on direct discovery, we allow indirect discovery of neighbor nodes through collaboration among them.

Algorithm 1 COllaborative Neighbor Discovery (COND) at each node $a \in \mathcal{S}$

INPUT: $\rho, E_n, \mathcal{M}, \delta_m$

OUTPUT: Neighbor Table $\mathcal{T}_{\dashv} fornodea$

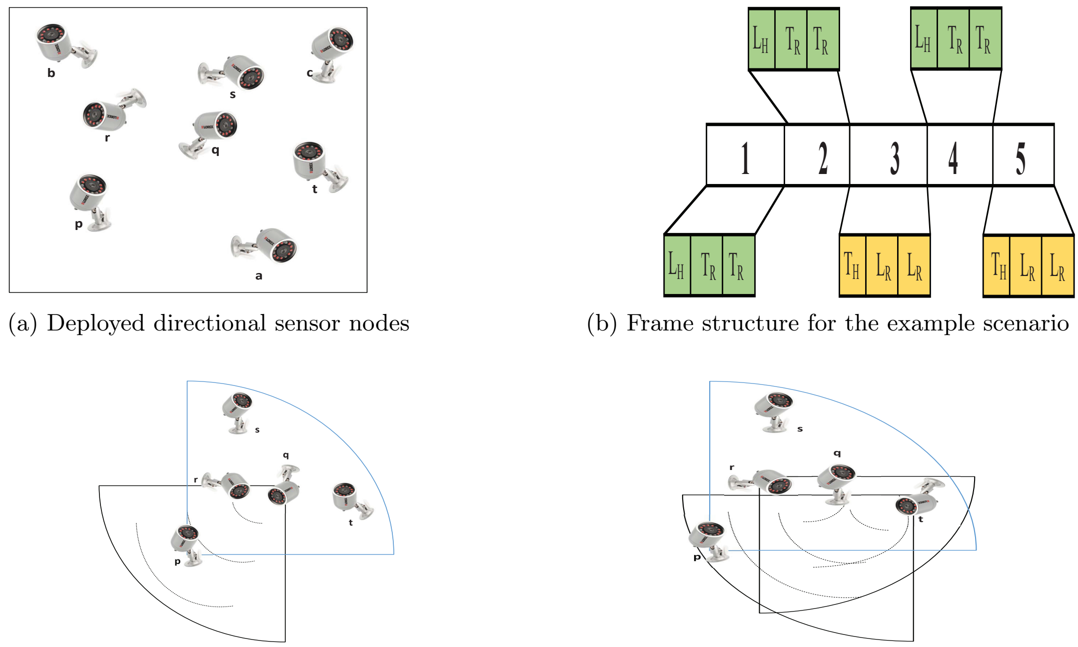
for each sector $m \in \mathcal{M}$ **do**
  set $\mathcal{R}_m \leftarrow 1$
  Calculate $\mathcal{N}_m, T$ and $\mathcal{K}$ using Eqs. 3.3 -3.6
  for each time slot $x \in T$ **do**
    if x is a HELLO slot **then**
      a broadcasts Γ_H message in the first mini-slot
      if a receives Γ_R from any node b **then**
        add b in neighbor table $\mathcal{T}_a$ and **set** flag $\mathcal{F} \leftarrow 1$
        add $w \in \mathcal{T}_b$ that falls in sector m of node a to $\mathcal{T}_a$
        set flags $\mathcal{F} \leftarrow 0$ for the added nodes of $\mathcal{T}_b$
      end if
    else
      a **listens** the medium
      if a receives a Γ_H from any neighbor b **then**
        if $(b \notin \mathcal{T}_a)$ **OR** $(b \in \mathcal{T}_a$ **AND** $\mathcal{F} = 0)$ **then**
          add b in neighbor table $\mathcal{T}_a$ and **set** flag $\mathcal{F} \leftarrow 1$
          add $w \in \mathcal{T}_b$ that falls in sector m of node a to $\mathcal{T}_p$
          set flags $\mathcal{F} \leftarrow 0$ for the added nodes of $\mathcal{T}_b$
          a **replies** back Γ_R to b
        end if
      end if
    end if
  end for
  update $\mathcal{N}_d^m$, *i.e.*, the number of nodes discovered in sector m during current iteration
  if $\left(\mathcal{N}_d^m(\mathcal{R}_m - 1) == 0 \;\&\&\; \mathcal{N}_d^m(\mathcal{R}_m) == 0\right)$ **then**
    $\mathcal{M} \leftarrow \mathcal{M} \backslash m$
  end if
  if $\mathcal{M} = \emptyset$ **then**
    exit
  end if
  $\mathcal{R}_m \leftarrow \mathcal{R}_m + 1$
end for

3.3.3.2 Indirect discovery

In omni-directional communication, only direct discovery is sufficient for neighbor discovery. For directional nodes, it is the most important that two nodes are beamforming their antennas to each other; otherwise, the handshaking between the nodes would never occur. So, it may happen that when a node is broadcasting HELLO message in a particular sector, some of the neighbor nodes can't receive the message because of the deafness problem [13]. Hence, the strict requirement of directional synchronization among nodes upsurges the discovery latency among the sensor nodes.

Consider a scenario in Fig. 3.2-(b), where pairs a, b and a, c have already discovered themselves in the present or previous time frame, but node b has not yet been discovered by c or vice-versa, as their antenna directions didn't match during the direct neighbor discovery process. In order to ease the problem and to accelerate the discovery process, we allow COND nodes to share their neighbor tables with already discovered nodes. That is, node a shares its table with b and c so that they can discover each other as a neighbor of the respective sectors by checking their coordinates. We term this update of neighbor table as *indirect discovery* and the flag entry for such discovered node is set to 0.

The proposed collaborative neighbor discovery (COND) mechanism has been summarized in Algorithm 1. Initially, the neighbor table of each node remains empty. After getting a HELLO/REPLY message from any neighbor, a node updates its own table (lines 6-23). The node that receives a HELLO message, checks its neighbor table to find whether the node is discovered earlier or not. If there exists a record, the node checks the flag value and if the value is 1, it doesn't give any reply message to that node assuming that, it has exchanged messages in the earlier slots with that node; otherwise, it updates the information in the neighbor table and sends a REPLY message in a random sub-slot to the direction of the sender node (lines 15-22). If the sender node receives a REPLY message (without any collision) from any neighbor, it adds the node in the neighbor table (lines 8-12). In this way, two nodes discover each other using two-way handshaking.



(a) Deployed directional sensor nodes

(b) Frame structure for the example scenario

(c) Node q is sending hello message

(d) Collision occurs due to simultaneous transmission

Figure 3.3: An illustrative example for COND

In the case, a node can't discover any new node in a certain sector in consecutive two iterations, we stop COND process in that sector (lines 25-27).

The time complexity of Algorithm 1 for one iteration is quite straightforward to follow. The lines 1 - 31, enclosed in a loop, iterate $|\mathcal{M}|$ times having a complexity of $\mathcal{O}(|\mathcal{M}|)$ in the worst case. Again, the statements 4 - 23 iterate $|T|$ times in a nested loop. The rest of the statements have constant unit time complexities. Therefore, the overall time complexity of the proposed COND algorithm is $\mathcal{O}(|\mathcal{M}| \times |T|)$.

3.3.4 Illustrative Example for COND Mechanism

An illustrative example for COND mechanism is given in Fig 3.3. Some nodes are deployed in an area as shown in Fig 3.3-(a). The time frame is divided into five slots where each slot has three mini-slots as in Fig 3.3-(b).

Initially all nodes remains in all sectors for the same time interval. After each iteration each node dynamically changes the discovery duration in each sectors using Eqn. 3.4. Suppose, node p is searching for it's neighbors in a particular sector for T sec. In the time frame p decides to transmit HELLO message in 2, 5 slots with probability P_t and listens the medium in the remaining slots. Initially, the neighbor table of each node remain empty. After getting any HELLO message from a neighbor node the receiver node will send a Reply if there is no information in its own table or the node is discovered indirectly in the previous slots. When a node gets a new HELLO/REPLY message from a neighboring node, update the neighbor table with the information of directly and indirectly discovered neighbors.

Table 3.2: Neighbor table for the example scenario

	$\mathcal{T}_p$				$\mathcal{T}_q$				$\mathcal{T}_r$				$\mathcal{T}_s$			
	ID	(x,y)	m	$\mathcal{F}$	ID	(x,y)	m	$\mathcal{F}$	ID	(x,y)	m	$\mathcal{F}$	ID	(x,y)	m	$\mathcal{F}$
Slot-1	q	10,21	1	1	p	5,2	3	1	q	10,5	3	1				
					r	2,2	2	1								
Slot-2	q	10,21	1	1	p	5,2	3	1	q	10,5	3	1				
					r	2,2	2	1								
Slot-3	q	10,21	1	1	p	5,2	3	1	q	10,5	3	1	p	5,2	3	1
	s	5,10	1	1	r	2,2	2	1	p	5,2	3	1	q	10,5	2	0
Slot-4	q	10,21	1	1	p	5,2	3	1	q	10,5	3	1	p	5,2	3	1
	s	5,10	1	1	r	2,2	2	1	p	5,2	3	1	q	10,5	2	0
	r	2,2	1	1					s	5,10	4	0				
Slot-5	q	10,21	1	1	p	5,2	3	1	q	10,5	3	1	p	5,2	3	1
	s	5,10	1	1	r	2,2	2	1	p	5,2	3	1	q	10,5	2	0
	r	2,2	1	1					s	5,10	4	0				
	t	17,4	1	1												

As p listens the medium in slot-1, it listens the medium in the first mini-slot and at the same time slot q is sending HELLO message toward i's direction as shown in Fig 3.3-

(c). Node p and node r receives the message without any collision and sends a REPLY message with their information in a random mini-slot. After getting the messages node p, q and r update their tables according to the new information of their neighbors as shown in Table 3.2. In the second slot both t and r send HELLO message, and a collision occurs in that particular slot. As a result no update can take place in the neighbor tables. As defined earlier, p sends HELLO message in the next slot as in Fig 3.3-(d). After receiving the hello message q and s replies to the sender in the different mini-slots. Hence, the nodes s and t tries to send reply in the same mini-slot, no reply is received due to the collision. Accordingly, in the last two slots nodes r and p sends HELLO message and all the nodes update their table with the received neighbor information as given in Table 3.2.

3.4 Theoretical Analysis of Collaborative Neighbor Discovery Algorithm

At each iteration, a COND node performs neighbor discovery around its all sectors and, on completion of one iteration, the node gets an updated neighbor table with the newly discovered neighbors. In this section, we formulate a theoretical model for analyzing the neighbor discovery delay, average number of discovered nodes per iteration and corresponding energy consumption of the COND system.

3.4.1 Discrete Time Markov Chain Model

We have developed a discrete time markov chain model for analyzing the performance of the proposed algorithm. In this model, a node can stay in one of the following six states: *idle (I)*, *Transmitting HELLO message (T)*, *Listening REPLY message (L)*, *Receiving HELLO message (R)*, *Transmitting REPLY message (A)* or *Collided (C)*.

Here, L is the set of reply message listening states, i.e., $L = \{L_0^2,\ L_1^2, \dots,\ L_v^2 \dots L_0^u,\ L_1^u, \dots, L_v^u\}$ and each $L_v^u \in L$ denotes that, the v number of neighbor nodes is

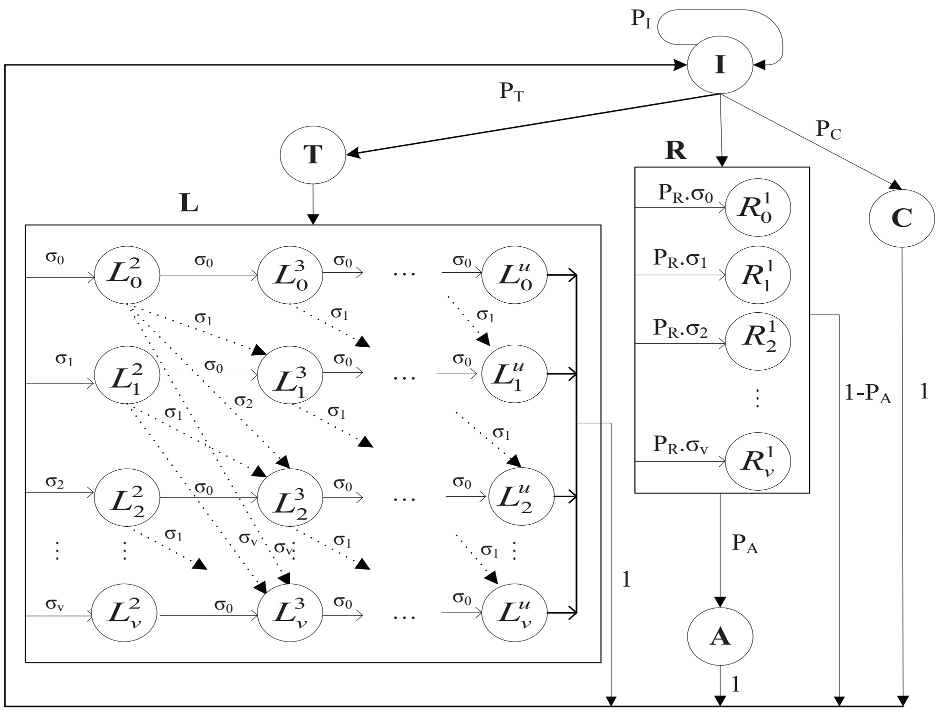


Figure 3.4: State transition diagram for the COND mechanism

discovered in reply mini-slot u. Similarly, R is the set of states after receiving a hello message, i.e., $R = \{R_0^1,\ R_1^1, \ldots,\ R_v^1\}$, where each state R_v^1 represents that the v number of neighbors is discovered during the first mini-slot. The value of u is from 2 to the number of mini-slots (x') available in a slot and the maximum value of v can be $\mathcal{N}_e^m$, the expected number of neighbors in a certain sector m.

Figure 3.4 shows the state transition diagram of the COND mechanism. Given that, a node transmits HELLO message with probability P_t, we can calculate the *idle* state (*i.e.,* listening for any HELLO message) probability for a node as follows,

$$P_I = 1 - P_t, \tag{3.7}$$

where, P_t is the probability that a node transmits HELLO message in a given slot.

Suppose, a COND node a has sent a HELLO message in sector m. Another node b can only receive this HELLO message if it beam forms the antenna toward a in sector m', where $m \neq m'$ and $|m - m'| = 1$ for 3 sector nodes, $|m - m'| = 2$ for 4 sector nodes, etc. The joint probability that the two nodes a and b will beam form to each other is thus calculated as follows,

$$P((b, m'),\ (a, m)) = P((a, m) \times P((b, m')|(a, m)) = \frac{1}{m^2}, \tag{3.8}$$

where, the event (a, m) represents that the node a beam forms its antenna in sector m. Hence, in a given slot, a node a changes its state from I to T with probability,

$$P_T = P((b, m'),\ (a, m)) \times P_t^a \times (1 - P_t^b) \times (1 - P_t)^{\mathcal{N}_e^{b,m'}-1}, \tag{3.9}$$

where, the last part $(1 - P_t)^{\mathcal{N}_e^{b,m'}-1}$ denotes the probability that no other nodes except a in the sector area of node b is transmitting any HELLO message at that time slot. Similarly, the receiving node b changes its state from I to R with probability,

$$P_R = P((a, m'),\ (b, m)) \times P_t^a \times (1 - P_t^b) \times (1 - P_t)^{\mathcal{N}_e^{b,m}-1}. \tag{3.10}$$

Therefore, the probability of occurring a collision event is given by,

$$P_C = 1 - (P_I + P_T + P_R). \tag{3.11}$$

Note that, on successful reception of HELLO or REPLY messages, a node discovers neighbor(s) *directly* or *indirectly* in one of the L or R states. The probability of discovering v number of nodes in a mini-slot is,

$$\sigma_v = \sigma^d \times \sigma_{v-1}^i + \sigma_v^i, \tag{3.12}$$

where, $\sigma^d = \mu \times P_R$ is the probability that the sender node is directly discovered; μ is a binary variable representing whether the sender node is already discovered ($\mu = 0$) or not ($\mu = 1$). The receiver node indirectly discovers a neighbor with probability, $\sigma^i = \eta \times P_R$, where, binary variable $\eta = 1$ if there remains a node in the sender's table that is not yet discovered and is located in the sector area of the receiver node. Thus, the probability that the k number of neighbors are indirectly discovered in a mini-slot is given by,

$$\sigma_v^i = \binom{\mathcal{N}_e^m}{v} \times (\sigma^i)^v \times (1 - \sigma^i)^{\mathcal{N}_e^m - v}. \tag{3.13}$$

Now, the probability that no neighbor is discovered in a mini-slot is given by,

$$\sigma_0 = 1 - (\sigma^d + \sigma^i). \tag{3.14}$$

Note that, after receiving a HELLO message successfully from a sender node a, the receiver node b sends back a reply message to the sender a if any of the following three conditions is met: (i) the information of a is not present in b's neighbor table, (ii) the node a is discovered indirectly, and (iii) the node b finds that $\mathcal{T}_b \setminus \mathcal{T}_a \neq \phi$. Let P_A denotes the probability of occurring any of the above events. Thus, the receiver node b transmits a REPLY message with probability P_A; otherwise, it returns to *idle* state. The probability distribution vector, S, at a given time slot x at equilibrium is expressed as,

$$\mathbf{S} = [S_I \quad S_T \quad S_v^u \quad S_v^1 \quad S_A \quad S_C]^x. \tag{3.15}$$

We can find the distribution vector at equilibrium by solving the equations $P\mathbf{S} = S$ and $\sum \mathbf{S} = 1$.

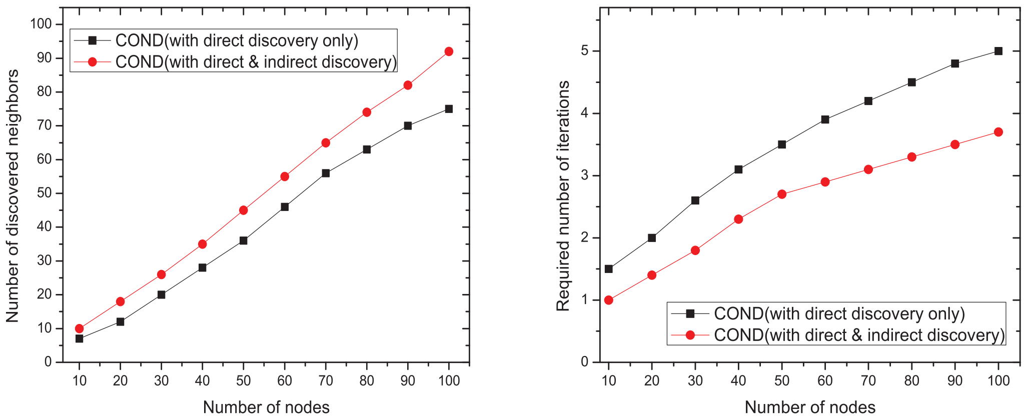
The solution of the above two equations is given below,

$$s = \frac{1}{\xi} \times \begin{bmatrix} 1 \\ P_T \\ \sigma_0 \times P_T \\ \vdots \\ \sigma_v \times P_T \\ (\sigma_0)^2 \times P_T \\ 2 \times \sigma_0 \times \sigma_1 \times P_T \\ \vdots \\ P_T(2 \times \sigma_v \times \sigma_1 + (\sigma_2)^2 + \sigma_0 \times \sigma 4 + \sigma 4) \\ \sigma_0 \times P_R \\ \vdots \\ \sigma_v \times P_R \\ P_A \times P_R(\sigma_0 + \sigma_1 + \sigma_2 + \sigma_3 + \sigma_4 + \ldots \sigma_v) \\ P_C \end{bmatrix}, \tag{3.16}$$

where, $\xi = 1 + P_T + (\sigma_0 + \sigma_1 + \sigma_2 + \sigma_3 + \cdots + \sigma_v)(P_T + P_R + P_A P_R) + P_T[(\sigma_0)^2 + 2\sigma_0\sigma_1 + 2\sigma_0(\sigma_1)^2 + 2\sigma_0\sigma_1\sigma_2\sigma_3 + 2\sigma_0\sigma_1(\sigma_2)^2\sigma_3(\sigma_4)^2 + \cdots + (P_T)^2] + P_C$.

The performance of the proposed COND mechanism greatly depends on the number of discovered neighbors in a time frame. From the markov chain analysis we find the total number of neighbors discovered per slot. Thus, the expected number of discovered neighbors by a particular node is,

$$E_v = \sum_{x=1}^{T} [v \times \sigma_u^v(x) + v \times \sigma_1^v(x)]. \tag{3.17}$$



(a) Neighbor discovery (b) Required iterations

Figure 3.5: Theoretical analysis for varying number of sensor nodes

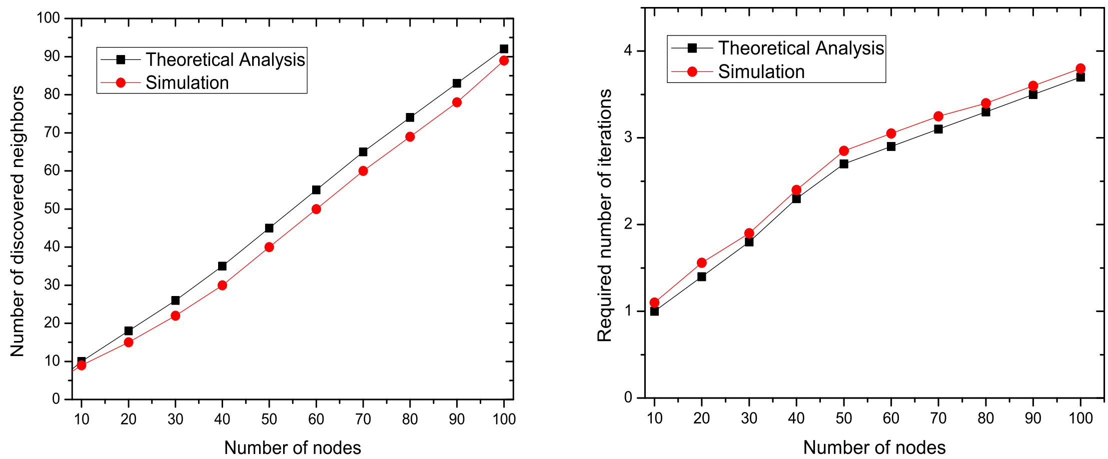
Now, the neighbor discovery rate ζ of a particular node is,

$$\zeta = \frac{E_v}{T}. \tag{3.18}$$

Figure 3.5-(a),(b) show the number discovered nodes and required number of iterations for the varying number of nodes in the network when there are 15 slots in a time frame and each slot has three mini-slots.

3.4.2 Comparison of Analytical and Simulation Results

In this section, we compare the simulation experiment results with those of theoretical analysis. We perform our simulation experiments in NS-3 for varying number of sensors, ranging from $5 \sim 50$. We have fixed the transmission range of each node at $100m$ and the number of sectors at 4. With the growing number of sensors in the network, the number of discovered nodes increases linearly in both theoretical and simulation results, as shown in Fig. 3.6-(a). Unsurprisingly, as depicted in graphs of Fig. 3.6-(b), the number of iterations also increases with growing number of nodes both in theoretical and simulation results.



(a) Number of discovered neighbors (b) Number of iterations

Figure 3.6: Comparison of results from theoretical analysis and simulation experiments

However, the rate of increase is not that much higher because of the incorporation of indirect discovery in COND. Finally, the graphs of Fig. 3.6-(a) and (b) show that the analytical results are quite closer to simulation outcomes in estimating the number of discovered neighbors and the required number of iterations for neighbor discovery.

3.5 Performance Evaluation

We have implemented our proposed COND system in Network Simulator Version 3 (NS-3) [91], a discrete-event network simulator to verify the effectiveness of proposed algorithm. We have done a comparative study of COND performances with those of two state-of-the-art algorithms - Randomized 2-way neighbor discovery mechanism [61] and SAND [41].

3.5.1 Simulation Environment

We use wifiSimpleAdhocGrid model for sensor nodes and YansWifiPhy model to define the channel properties such as propagation and loss characteristics. Each node has the

Table 3.3: Simulation parameters for the COND algorithm

Parameters	**Value**
Area deployment	$500m \times 500m$
Type of deployment	Uniform random
Number of nodes deployed	$100 \sim 1000$
Number of sectors	$2 \sim 6$
Transmission range	$100m$
Slot duration	$1\ ms$
Packet size	$40Bytes$
Initial energy	$3J$
Data transmission rate	$1Mbps$
Bandwidth	5 MHz
Routing protocol	AODV
Channel model	Yans WiFi Model
Propagation model	Friis Propagation Loss Model
Simulation time	1000 Seconds

information about network density and it calculates the expected number of neighbor nodes in each sector based on that information. The COND mechanism stops when no neighbor is discovered in two subsequent rounds. The simulation configuration parameters are shown in Table 3.3. The threshold value of α, β and γ for the delay tuning parameter in COND algorithm are 80%, 50% and 30% for the network. We run the simulation experiments 30 times with different random seed values, and take the average of the results for each graph data points.

3.5.2 Performance Metrics

- *Average discovery latency per node* A round of node discovery is completed when a node finishes the operation in all sectors (either clockwise or anti-clockwise). Average discovery latency per node is the ratio of total discovery time to the number of discovered nodes.

- *Sensing wastage* is the count of wastage of time slots for neighbor discovery. A sensing time slot is regarded as wastage if no neighbor is discovered in it.

- *Average discovery ratio* is the ratio of the number of neighbor nodes successfully discovered to the total number of nodes in the network.

- *Control byte overhead* is the ratio of total number of control bytes (HELLO and REPLY messages) exchanged during the simulation period to the total number of neighbors discovered.

- *Average energy cost per node* discovery is the measure of average amount of energy consumed during the simulation period for discovering a single node in the network.

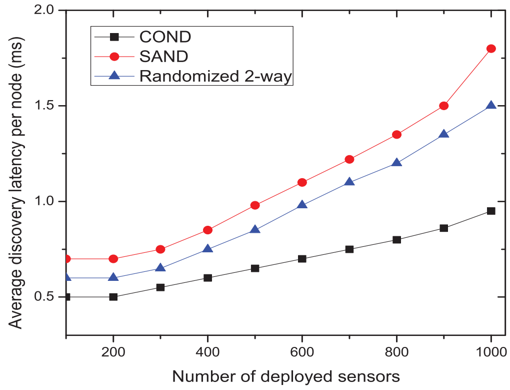
3.5.3 Simulation Results

The comparative performance results are plotted for varying number of sensors deployed in the network, number of sectors a node has and the size of the sensing time frame.

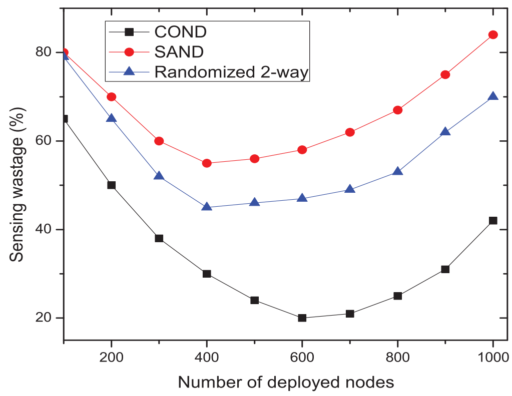
3.5.3.1 Impacts of varying number of nodes

We have varied the number of nodes from 100 to 1000 and compared the performances of the proposed COND mechanism with those of other systems. The number of sectors for each node is fixed at 4 and we call a round of sensing is completed when a node is switched to all of its sectors for neighbor discovery. Each time frame contains 25 slots and each slot has 4 mini-slots.

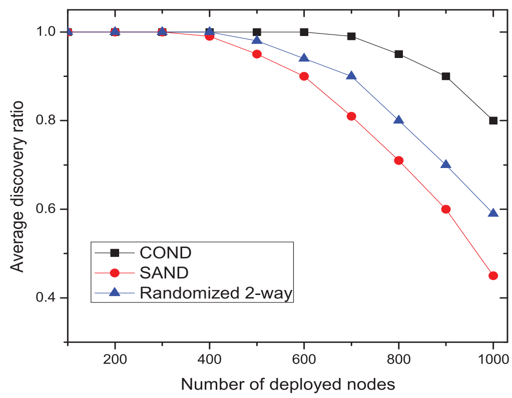
The graph of Figure 3.7-(a) shows that the discovery latency increases with the growing number of nodes in all the studied systems. However, the rate of increase in our proposed COND mechanism is significantly lower than those in other two systems. This is achieved because of incorporating indirect discovery in COND and reduction of transmission collisions through randomized and controlled accesses of medium by its nodes.



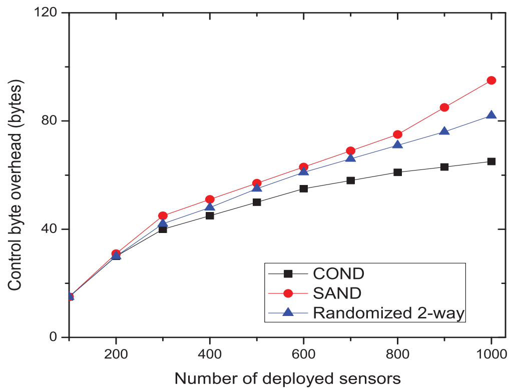
(a) Average discovery latency



(b) Sensing wastage of discovery slots



(c) Average discovery ratio



(d) Control byte overhead

Figure 3.7: Impacts of number of sensor nodes on performances of the studied neighbor discovery algorithms

The graphs also depict that the latency is increased linearly in SAND with growing number of nodes as a central node manages the neighbor discovery.

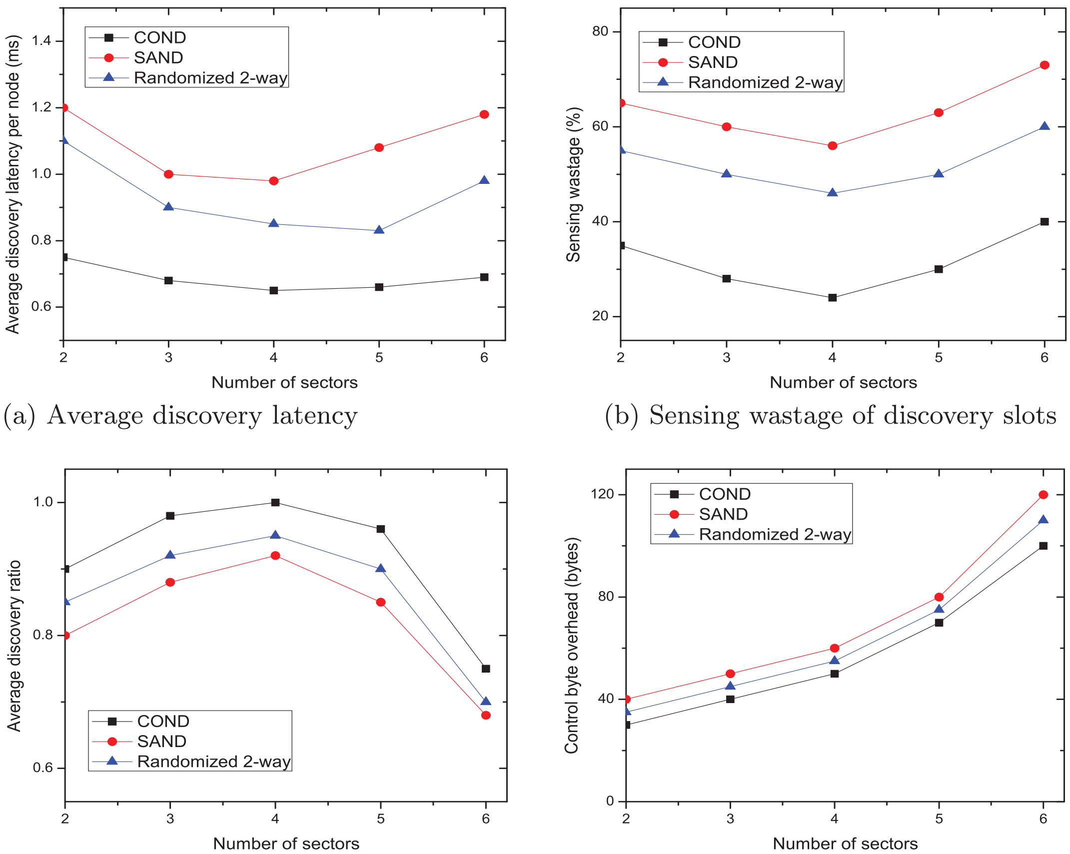
As we have fixed the number of slots in each time frame, the sensing wastage is very high for a low dense network in all the studied approaches, causing poor utilization of time slots. The wastage of slots reduces with the growing number of nodes upto approximately 600 nodes in COND due to collision and conflicts of nodes in competing environment of node discovery. The COND has the minimum wastage of slots because of allowing indirect node discovery; whereas, many slots are wasted in the other algorithms especially for the lack of sector synchronization, as shown in Figure 3.7-(b).

The graphs in Figure 3.7-(c) depict that the discovery ratio of the neighboring nodes during the simulation period. The discovery ratio is 100% for all the proposed algorithms when the network density is low. The discovery ratio decreases with the growing number of nodes. Our in depth look into the simulation trace files, depicts that, the last 10% of nodes take the longer time to discover. The COND mechanism performs better than the other two mechanisms with higher network density as the indirect discovery of COND mechanism increases the neighbor discovery ratio. In the 2-way randomized protocol and SAND, the overheads are higher than that of COND because of additional control packet exchanges among nodes at random times due to collision and loss of token, as depicted in Figure 3.7-(d). The SAND has higher overhead among all the algorithms as it uses tokens to control and manage transmissions in the network.

3.5.3.2 Impacts of varying number of sectors

In this experiment, we allow each node to have 2 to 6 sectors. Here, the number of sensor nodes is fixed at 500 and the frame size at 25 time slots. The graphs of Figure 3.8-(a) depict that the discovery latencies of the evaluated algorithms decrease with growing number of sectors from 2 to 4. This result is achieved due to increased spatial reusability with higher number of sectors. However, our COND mechanism achieves minimum latency and it becomes stable gradually. On the contrary, in other mechanisms, the latency increases again with beamforming angle less than 90^0. The reason is that, in this situation, nodes need longer period to discover their neighbors as synchronization of antenna beams is quite challenging for narrow beam widths. For the same reason, the wastage of time slots is also minimum in COND compared to the other mechanisms, as shown in Figure 3.8-(b).

Directional antenna reduces the chance of collision among the neighboring nodes. The



(a) Average discovery latency

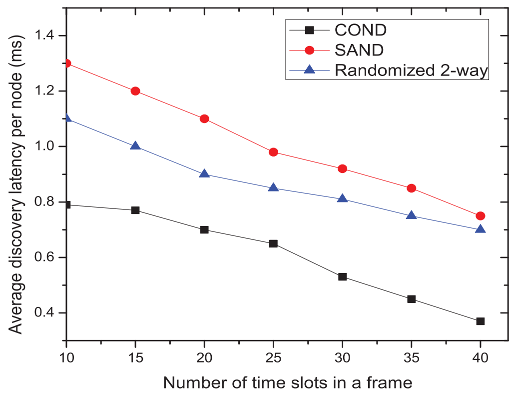
(b) Sensing wastage of discovery slots

(c) Average discovery ratio

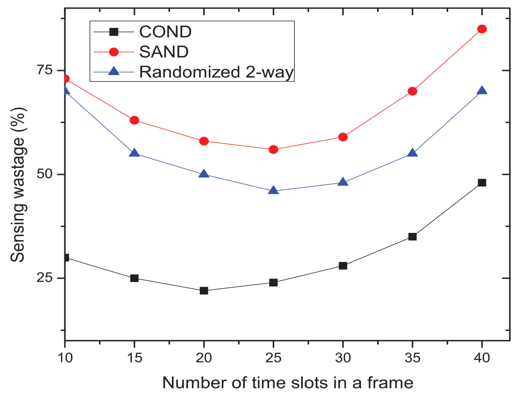
(d) Control byte overhead

Figure 3.8: Impacts of number of sectors on performances of the studied neighbor discovery algorithms

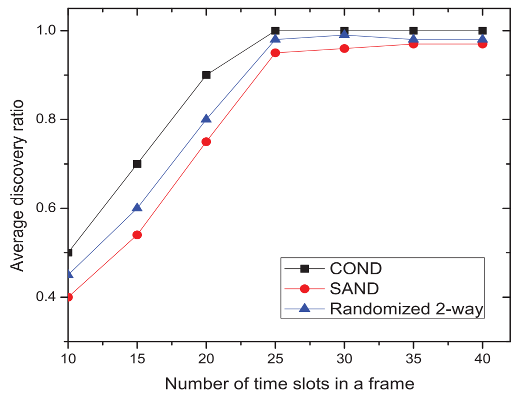
Figure 3.8-(c) shows that the neighbor discovery ratio gradually increases with increasing sectors in all the mechanisms, which is as expected theoretically. Nevertheless, excessive reduction of sensing angle reduces the chance of direction synchronization among nodes, and thus it decreases the neighbor discovery ratio. Yet again, higher number of sectors causes the nodes to switch from one sector to another frequently, resulting in transmission of more Hello/Reply messages. Hence the control byte overheads is increased with the growing number of sectors, as shown in Figure 3.8-(d). Our COND mechanism



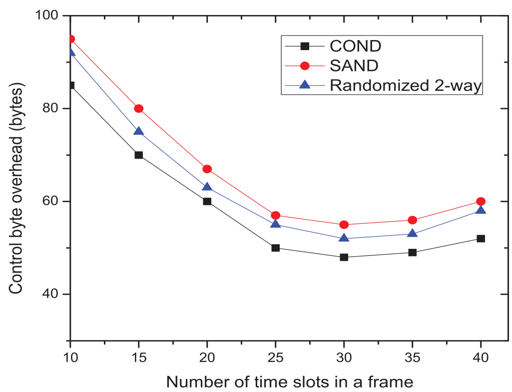
(a) Average discovery latency



(b) Sensing wastage of discovery slots



(c) Average discovery ratio



(d) Control byte overhead

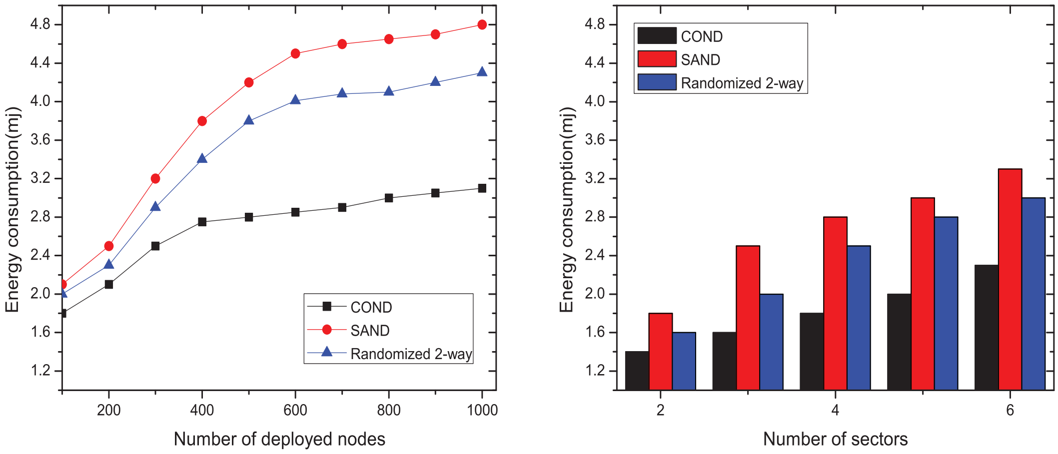
Figure 3.9: Impacts of number of time slots in a frame on performances of the studied neighbor discovery algorithms

outperforms the state-of-the-art mechanisms as it needs less control byte overheads.

3.5.3.3 Impacts of varying number of time slots

The number of time slots per round are varied from 10 to 40 for the simulation. Here, we assume fixed number of 500 sensor nodes and each node has 4 sensing sectors.

The graphs of Figure 3.9-(a), show that the average latency for all the mechanisms decrease progressively with the growing number of time slots as each node gets longer



(a) Impact on varying number of sensors (b) Impact on varying number of sectors

Figure 3.10: Energy consumption performances of the studied algorithms

time to discover it's neighbors in each sector. The COND utilizes the time slots more efficiently and has the minimum latency by the way of indirect neighbor discovery. But unfortunately, with the growing number of slots the sensing wastage increases as shown in Figure 3.9-(b). As the number of nodes are fixed at 500 and there are many time slots for neighbor discovery, the wastage increases. For the same reason, the neighbor discovery ratio increases with the growing number of time slots. However, when the number of slots are greater than 25 it becomes stable as large number of time slots are not required for neighbor discovery in a low dense network. The COND has maximum discovery ratio compared to the other systems, as shown in Figure 3.9-(c). The control byte overhead also decreases with the growing number of slots as the discovery ratio increases, as shown in Figure 3.9-(d). It increases slightly when the number of time slots crosses 30 since the possibility of using unnecessary slots is increased.

3.5.3.4 Average energy cost for neighbor discovery

In the last set of simulation experiments, we measure the energy consumption for varying number of nodes and sectors. The graphs of Figure 3.10 show that the average energy cost per neighbor discovery increases with the growing number of nodes and sectors in all the studied systems. As the neighbor discovery rate decreases with the growing number of nodes, the energy cost increases. However, the energy cost in our proposed COND mechanism is significantly lower than those in the other two systems. This result is achieved because of efficient neighbor discovery approach used in the proposed COND.

3.6 Discussion

In this chapter, we investigated distributed solutions to the problem of neighbor discovery in DSNs and introduced indirect neighbor discovery through collaboration among the already discovered nodes. We also introduced dynamic polling period in each sector following the number of already discovered nodes in it. The joint employment of the above strategies helped the proposed COND system to achieve excellent performances in neighbor discovery. Our in-depth look into the simulation trace files depicts that the collaboration-based indirect neighbor discovery helped to reduce the discovery latency significantly while the utilization of time slots in each frame was greatly enhanced due to the use of dynamic polling periods. The results from simulation experiments, carried out in NS-3, showed the achievements of as high as 80% and 75% performance gains in neighbor discovery latency and discovery ratio, respectively, compared to SAND, a leading work in the literature.

Chapter 4

Duty-Cycle Medium Access Control

In the previous chapter, we have discussed on the formulation of the directional neighbor discovery algorithm for Directional Wireless Sensor Networks and found that, fast neighbor positioning reduces the network initialization overhead and protocol execution delay. In this chapter, we will discuss a low duty-cycle MAC protocol that can effectively schedules and transfers the data packets from the sensor nodes towards the sink. Here, we also present the detail performance evaluation results.

4.1 Introduction

Latest researches have drawn a great attention in Wireless Sensor Networks (WSNs) because of its evolving applications in many fields like - smart spaces, robotic exploration, battlefield monitoring, disaster monitoring and response, emergency health care, structural and precision agricultural system, etc. These types of applications are bandwidth hungry and demand novel mechanisms that can enhance the network performance [1]. Contrasting to WSNs that use omni-directional nodes, the DSNs with directional sensor nodes can attain greater transmission range and throughput with minimum interferences and reduced energy consumption, etc [95, 24]. Recently, numerous coverage and surveillance applications are using directional antennas like multimedia and smart camera sensors [1, 2, 90, 25, 96]. Furthermore, a Directional Wireless Sensor Network (DSN) has better energy efficiency and improved target coverage compared with a traditional

WSN.

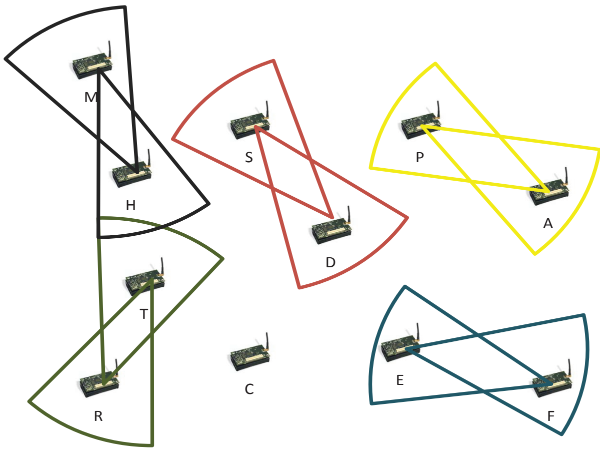


Figure 4.1: Spectrum reuse in directional communication

A sensor node with omni-directional antenna in WSNs generates interference in the neighborhood [97], which bounds spatial reusability of network [24]. On the other hand, directional antenna emphases on transmitting signal into one particular direction which leads less interference and improved spectrum utilization in the network. Thus, higher spatial reusability can be achieved with directional antennas by reducing the interference. Some directional nodes in a neighborhood are shown in Fig. 4.1; neighboring nodes can communicate to each other while particular source (S) and destination (D) nodes are transferring data in the identical channel, that is quite difficult in omni-directional case.

At present, the obtainability of lower cost sensor nodes and the advancement of novel algorithms for processing signals have facilitated a conducive situation for WSNs with smart directional antennas [1]. Unfortunately, some new problems also introduce in DSNs like - *hidden terminal*, *exposed terminal*, *deafness* and *asymmetry-in-gain* problems. A lot of duty-cycle based medium access control (MAC) protocols for WSNs are already proposed in literature. However, most existing MAC protocols, R-MAC [43], S-MAC [44], B-MAC [45], [46] etc. are designed for omni-directional WSNs, which are not applicable for DSNs because these works designed their protocols assuming that the a node can overhear the transmission signal of all its neighboring nodes.

For wireless ad hoc networks, there are a good number of medium access control protocols with directional antennas in the literature [66, 67, 68, 63, 35, 55, 98, 99]. Among them a very a limited number of works [87, 64, 65] address the MAC challenges for DSNs. In PMAC [55], a polling based directional MAC protocol is proposed for mobile wireless ad hoc networks, where one-hop neighbors are discovered. The protocol proposes a mechanism that schedules directional communications among sensor nodes so that exclusive access to the medium can be shared among them. For a dense wireless network, it fails to properly schedule all the transmissions as nodes do not give the weighted-share of transmission slots. In DU-MAC [87], the overhead of the network upsurges as a idle node constantly switch it's antenna sectors toward different directions for finding the surrounding neighbors as well as their schedules. As a result, the energy consumption of the sensor nodes is greatly increased for continuous rotations for sending the preambles prior to packet transmission. Furthermore, both protocols do not study the many-to-one data communication policy of DSNs during the selection of the transmission and reception beams of the sensors. Hence, it is hard to maintain the data transmission and reception schedule properly that results loss of data.

The WSNs has some unique characteristics for data collection from sensor nodes to the sink node. In the environment of wireless network, the directional transmission sometimes creates multifarious problems for the features of sensor networks, thus it demands a specialized MAC protocol for directional WSNs. We propose a duty-cycle medium access control protocol named DCD-MAC in this paper. The DCD-MAC cooperatively determines the transmission and reception schedules of the sensor nodes. From a periodic neighbor discovery protocol [14], each node gets the neighbor list of the network. The DCD-MAC also adopts that all the sensor nodes construct a sink-rooted tree in the WSN, where a parent node may have multiple children and a child has only one parent. DCD-MAC presents a novel frame structure for transmitting data. The frame of DCD-MAC is separated into multiple slots and each data transmission slot of child nodes is cooperatively determined by their parent node according to the transmission requirements. Only at the beginning of each time frame synchronization is carried out by the parent-child pair. The prime benefit is that, neither the parent nor the child nodes need to continuously rotate their beams. Hence, a sensor in the network need not to be active when it is not scheduled to receive or transmit any data packets. The proposed protocol is fully distributed and the scheduling mechanism exploits sensor mote's local information only which made DCD-MAC highly scalable. In this work, we have consolidated the equations for protocol operation and developed the synchronization and slot allocation algorithm, lemma for proving the protocol and also performed a theoretical analysis for the synchronization between parent-child pair. It is also mentionable that, we've done extensive simulation work in this work to validate the protocol performances. What follows next are the summarization of the key contributions of this work:

- A low duty-cycle MAC protocol for multi-hop DSNs called DCD-MAC is proposed.
- To facilitate a synchronized energy-efficient and collision-free data transmission and reception among the nodes, a novel data transmission a novel frame has been proposed.
- The DCD-MAC greatly reduces the medium access challenges caused by directional transmission(discussed in Section 4.2).
- The DCD-MAC upsurges the network lifetime significantly by keeping nodes in *sleep* state excluding the periods when they are scheduled for data or control packet transmission.
- The DCD-MAC is designed for multi hop data transmission approach of wireless sensor networks. Consequently, it reduces data delivery delay and as well as ensures

higher throughput and higher reliability.

- Lastly, we simulate our proposed DCD-MAC in NS-3 [91] and the simulation results illustrate that the recommended DCD-MAC protocol achieves as much as 40% performance improvement in terms of reliability and throughput compared to PMAC and DU-MAC protocol.

The rest of this chapter is organized as follows. The Section 4.2 describes the challenges of Directional MAC protocol, in Section 4.3, we define the assumptions and the system model of MAC design using directional antennas. The proposed DCD-MAC is introduced in Section 4.4. A theoretical analysis for the protocol is presented in Section 4.5. The performance analysis and simulation results are presented in Section 4.6, and concluding remarks are given in Section 4.7.

4.2 Challenges of Medium Access in DSNs

The directional antennas allow simultaneous transmissions from nodes in the network which increase the network bandwidth utilization. Nevertheless, the directional transmission and reception introduce supplementary problems in wireless medium access. Specifically, directional antennas increase the chance of packet collisions due to new type of *hidden terminal*, *deafness*, *asymmetry-in-gain* and *conflict of interest* problems for DSNs.

4.2.1 Hidden Terminal Problem

Generally, the *hidden terminal problem* is initiated by the simultaneous transmissions of two or more nodes that cannot hear each other but they transmit to the same receiver [64]. In DSNs hidden terminal problem arises because transmitter and receiver unhears DRTS/DCTS frames because of directional transmission which doesn't happen in omnidirectional transmission. Suppose, in Fig. 4.2, nodes D and E have data to send to node A and D first sends an RTS. Unlike in omnidirectional case, here the node E is not aware

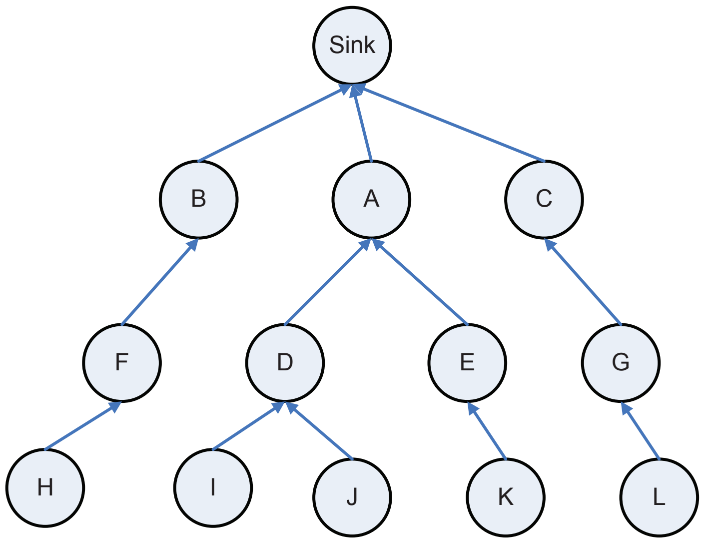


Figure 4.2: Network model

of D's transmission and might send the RTS, causing a collision at A. Thus, the problem is more acute in DSNs than in WSNs because the collision domain due to hidden terminal problem is increased.

4.2.2 Deafness Problem

In DSNs, when the intended receiver of a sender is beam forming its antenna in a different direction *deafness problem* happens. Suppose in Fig. 4.2, the parent node A receives packets from its two children D and E using two different beams. Although D is sending data packets to A, the node E is unaware about that and it's RTS packet to A will not be replied. If the transmission from D to A prolongates, E experiences many retries and thus it may wrongly regard A as unreachable whenever the retry limit exceeds.

4.2.3 Asymmetry-in-gain Problem

In the literature, many existing MAC protocols [67, 100, 66] have used the combination of directional and omni-directional antennas for communication. Most of the works have used omni-directional transmissions/receptions for control packet exchanges and directional transmissions for data packets. As a result, it introduces a heterogeneous transmission environment in terms of transmission ranges of sender nodes and received signal strengths at the receivers, which leads to *asymmetry-in-gain problem* [68]. Consequently, all the desired nodes might not be informed about RTS/CTS transmissions of communicating nodes and accordingly the number of mutually interfering nodes might be increased, which in turn degrades the protocol performance.

4.2.4 Conflict of Interest

A key problem in DSNs is to schedule the time at which a parent node gathers data from one of its child nodes and for how long it points a particular beam to that child. When more than one child nodes want to transmit their data packets at the same time slots to the same parent node the *conflict of interest problem* arises. The problem is further intensified if the parent itself has data to send to its higher level at the same time. Hence, a good level of synchronization is compulsory among all communicating pairs centered each parent node.

4.3 Network Model and Assumption

We consider a tree based Directional Wireless Sensor Netwroks (DSNs), as shown in Fig. 4.2. The deployed sensor nodes are homogeneous. The sensor nodes monitor different events and forward the collected data to the sink node in a multi-hop manner. A neighbor discovery protocol [14] is performed periodically to update the neighbor table of each node. We also assume that all nodes know their next hop routing paths toward the

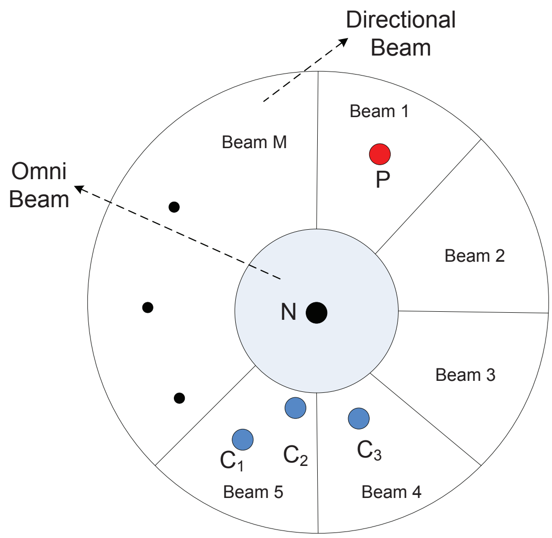


Figure 4.3: Antenna pattern of a node consisting of M beams

sink using a static or dynamic routing protocol. At a particular time, each node can directionally transmit or receive to another node but can't do both at the same time.

For the proposed DCD-MAC, we use the switched beam antenna system, which consists of fixed, pre-defined and highly directive beams for data transmission and each node for each transmission uses only one of the beams. The directional antenna consists of fixed beam width θ, and it can be activated in M fixed directions where $M = 2\pi/\theta$. A node may need to switch it's antenna to many sequential beam switches as there are many antenna beams, which is called sweeping [87]. The received DOA (Direction of Arrival) from a neighboring node is used for tracking it's position. For this protocol, we considered only the main lobe of the antenna and other side lobes are negligible [67, 68].

Every single sensor node in the network is equipped with smart directional antennas and a node N is shown in Fig. 4.3 which covers the area around it by M non-overlapping directional beams. The node has one parent node P in beam 1 and it has three children in Beam 4 and 5. All the sensors sent and receive their data and control packets using

Table 4.1: List of notations for DCD-MAC protocol

Symbol	**Definition**
$\mathcal{N}$	Set of all sensor nodes
θ	Beam width of antenna
M	Number of sectors/directions of each sensor
Ψ_i	Set of free slots for node i in Allocation phase
Ψ_{ij}	Set of matched free slots for i and j in allocation phase
φ_i	Set of free slots for node i in Data transfer phase
φ_{ij}	Set of matched free slots for i and j in Data transfer phase
K_i	Number of requsted slots by node i for sending packets
t_p	Set of scheduled slots from the parent in Allocation phase
t_c	Set of scheduled slots for the child in Allocation phase
S_p	Set of scheduled slots for sending data in Data transfer phase
S_c	Set of scheduled slots for receiving data in Data transfer phase
N_j	Number of allocated slots for each child node for Data transfer

same radio frequency channel.

In the duty cycling period, all the sensors remain in *Active* state and *Sleep* state periodically. To extend the network lifetime, in active mode a node transmits or receives data according to their schedule. In the allocation and data transfer phase the sensors that are not scheduled for any data communication remain in sleep state and completely turn off their radio to save energy.

4.4 The DCD-MAC Design

In this section, we present the details operation of DCD-MAC that contains a new frame structure. The proposed frame structure addresses the challenges in directional transmission/reception addressed in Section 4.2. DCD-MAC presents a collision aware data transfer mechanism where each parent-child nodes in the network synchronize with each other prior to any data communication and a in the frame a schedule is maintained

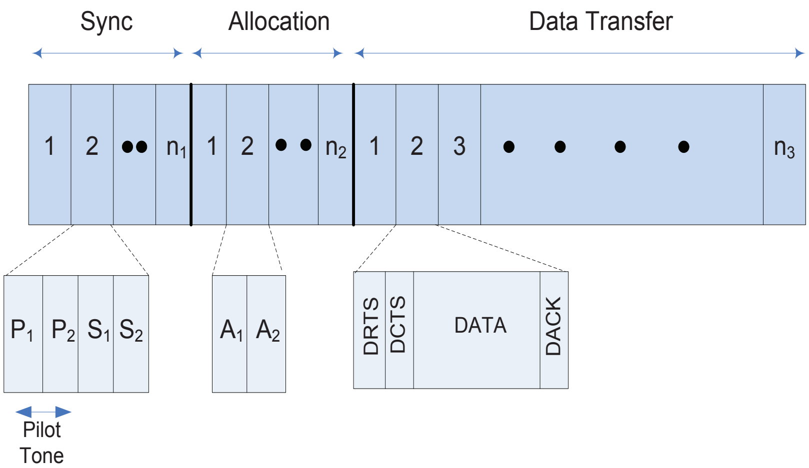


Figure 4.4: Frame Structure in DCD-MAC

for data transmission and reception. Thus the proposed protocol present a novel low-overhead duty-cycle medium access control protocol where the nodes in the network wake up and sleep dynamically contingent to their schedules. The detail mechanism of the constituents of DCD-MAC is presented in the following subsections. The terms, notations, and their semantics are given in Table 4.1.

4.4.1 The Frame Structure

Each frame in DCD-MAC is divided into adjacent time slots and the frame is divided into three phases: *Synchronization*, *Allocation* and *Data Transfer*, as shown in Fig. 4.4. The *Synchronization*, *Allocation* and *Data Transfer* phases has n_1, n_2, and n_3 number of slots and guard time is kept among the slots. The main objective of the synchronization and allocation phases is to schedule the data communication in the data transfer slots. The data transfer part is kept much greater than the synchronization and allocation parts to minimize the control overhead; typically, $n_1 = n_2$ and $n_3 >> n_1, n_2$.

Each node tries to synchronize with its neighbors by changing the antenna sectors in different directions in *Sync* phase. Control messages are interchange with each other after the synchronization among them. Each child node sends transmission request (i.e., the number of packets it wants to transmit) to its parent node. The details of mechanism is discussed in Section 4.4.2.

Each parent including the sink node schedules the slots for data transfer for each of its children nodes and also share the allocated slots to the child nodes in *Allocation* phase.Consequently, every sensor knows its transmission and reception schedules for the data transmission phase. Section 4.4.3 presents the detailed mechanism of allocation phase.

Data transfer among all nodes in the network is done in *Data Transfer* phase. A parent node moves its antenna beam toward a specific child during the allocated slot and the child node sends its data packets to the parent. The data transfer mechanism among nodes is discussed in details in Section 4.4.4.

4.4.2 Transmitter-Receiver Synchronization

Without direction synchronization, it may happen that parent-child nodes will not activate their sectors to each other at the time of data transmission. Thus, it is very important to synchronize the active sectors of communicating nodes prior to data communication.

Each node finds the active sector of the neighboring nodes in the synchronization phase (sync). There are four sub-slots in each sync slot: P_1, P_2, S_1 and S_2, as shown in Fig. 4.4. If a node has some data packets to send, it randomly selects a slot in the *Sync* phase and a pilot tone is transmitted toward its parent node by that sender node in the first sub-slot P_1,; or else, the node listen the medium to hear any pilot tone. Each node selects a random slot to transmit pilot tone otherwise it may happen that two or more nodes will transmit pilot tone continuously toward their parent node and collision happens repetitively. After receiving a pilot tone in P_1, the node sends back a pilot tone to the child nod in P_2 sub-slot after SIFS time period (as in IEEE 802.11). A node activate its omni-directional antenna when it is not transmitting pilot tone i.e., when it is in idle mode. If a child node transmits any pilot tone, the node can hear that tone as it is in omni-directional mode. It is important that, the parent not activates its antenna in omni-directional mode in idle state, otherwise it may happen that, the child node continuously tries to synchronize with it's parent but the antenna sector of the parent node is activated toward another direction. As a result, synchronization cannot either occur at all or happen after spending so many pilot tone transfers. Therefore, DCD-MAC nodes receive pilot tones in omni-directional mode and transmit in directional mode.

The parent-child pairs interchange the prerequisite informations in S_1 and S_2 sub-slots after the successful handshaking between the nodes. A node calculated the required number of slots for sending data packets toward its child node and sends it toward its parent node in S_2 sub-slot so that they can be directed to each other in the *Allocation* phase. Accordingly, the request message structure for data transfer is $< ID, K_i, \Psi_i >$, here, ID is the node identification, K_i contains the number of slots a particular node i needs to transmit data packets to it's parent and Ψ_i represents the set of free slots in the *Allocation* phase of a particular node i so that the parent node can determine a slot number in which the child node will be directed to the parent for receiving allocated data transfer slots. To determine the slot number for the *Allocation* phase in which they can be directed to each other, the parent node in the network calculates the intersection of the free slots of own and children by using Eq. 4.1 using the message received from the child node.

$$\Psi_{pc} = \Psi_p \cap \Psi_c \tag{4.1}$$

where the set of free slots of parent is represented by Ψ_p and the set of free slots of it's child is represented by Ψ_c. If $|\Psi_{pc}| > 1$, then the first slot of the set Ψ_{pc} can be selected for *Allocation* phase. Thus, each parent node gives the slot number of the *Allocation* phase to it's child nodes so that the child can fix it's beam in that slot to its parent for

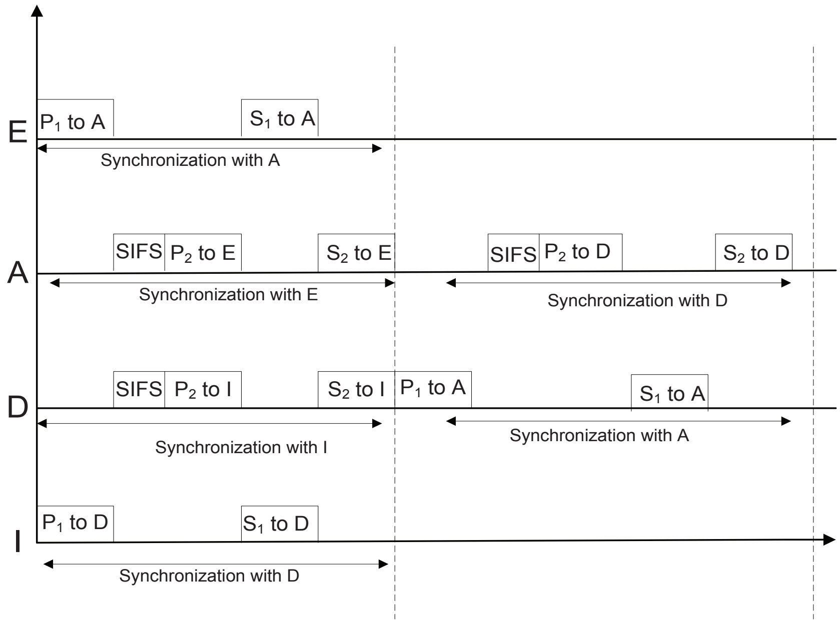


Figure 4.5: Transmitter-receiver synchronization mechanism

receiving the scheduled slots during the data transfer.

Each parent node will have knowledge about the number of requested data packets for all of it's child nodes At the end of the *Synchronization* phase. Likewise, the parent node sends the slot number of the *Allocation* phase toward its each child node when it will announce the data transfer slot to that child. An example scenario for the synchronization for the nodes A, D, E, and I, is shown in Fig 4.2.

4.4.3 Transmission Slot Allocation

Parent nodes in the network fix the number of data transfer slots in the *Allocation* phase that can be allocated for its child nodes ensuring their requirements in the *Synchronization* phase. If the number of free spaces in the buffer of a parent node i is $|\varphi_i|$, it allocates at most $|\varphi_i|$ number of slots to its child nodes since each slot in the *Data Transmission* phase is corresponding to transmission-reception of data packet. A DCD-MAC parent

Algorithm 2 Synchronization algorithm, at each parent-child pair, $(i, j) \in \mathcal{N}$

Synchronization Phase starts
while (i, j are in sync phase) **do**
if i is IDLE and has an unsynchronized child **then**
Continue listening in omni-directional mode
if i receives a pilot-tone in P_1 sub-slot from j **then**
i steers it's antenna beam towards j
i sends a pilot-tone in sub-slot P_2 to j
i receives $< j, K_j, \Psi_j >$ in sub-slot S_1 from j
i determines the slot numbers for j for Allocation Phase using Eqn 4.1
i sends the allocated slot number to j in sub-slot S_2
end if
end if
if j has data to send to it's parent i **then**
j steers it's antenna towards i
while j does not receive P_2 from i **do**
j sends a pilot-tone in P_1 of next sync slot
end while
j sends $< j, K_j, \Psi_j >$ to i in sub-slot S_1
j receives the slot number for Allocation Phase in sub-slot S_2 from i
end if
if Synchronization is not done with any node **then**
Sleep up to next sync phase starts
else
Allocation Phase starts
end if
end while

node i gives weighted-share of the total number slots to each of its n number of child nodes j using Eq. 4.2,

$$N_j = \left\lfloor \frac{K_j}{\sum_{j=1}^{n} K_j} \times |\varphi_i| \right\rfloor, \tag{4.2}$$

where, K_j is the number of slots requested by the child node j.

But, the above-mentioned mechanism might lead a *race condition* among the parent-child pairs in allocating the data transmission slots. A *race condition* is corresponding to the simultaneous attempts to multiple parent nodes to allocate the same data transmission slots to their child nodes. For example, in Fig. 4.2, the parent node D has already allocated slots {3,4,5} and {6,7} to its child nodes I and J, respectively; however, the parent node A does not know that. In such a case, the parent A might also attempt to allocate the same or overlapping slot numbers to its child nodes, leading a *race condition* for the node D.

The propagation of the slot allocation process from the sink node of the tree to the lower levels is a naive solution for the problem. With this approach each parent node induced to allocate the child nodes its free slots only. For a large scale wireless sensor networks this solution is quite impractical and also not scalable attributable to the strict requirement of clock synchronization among the all nodes. The proposed DCD-MAC mechanism provides a distributed solution to this challenge. The *Allocation* slot in each data frame is divided into two sub-slots: α_1 and α_2.

Each node in the network has a set φ, which contains the free slot numbers of that particular node in the *Data Transfer* phase. Each node allocates the required slots for data transfer to it's children from this φ. After allocating S_c slots to a particular child node, this φ of a particular node becomes,

$$\varphi = \varphi \setminus S_C \tag{4.3}$$

In sub-slot α_1, a child node j shares its free slots φ_j with its parent i. Similarly, i replies with $Alloc_j$ (set of allocated slots) to j, chosen from the slots that are free both at i and j, φ_{ij}, computed using Eq. 4.4.

$$\varphi_{ij} = \varphi_i \cap \varphi_j. \tag{4.4}$$

Consequently, the DCD-MAC proposed a distributed slot allocation process. Each parent-child nodes in the network are independent from others while allocating data transmission slots and exploits local information only. From the list of free data transmission slots the DCD-MAC parent nodes allocate slots to their child nodes serially. This scheduling process in *Allocation* phase helps the nodes to increase their *sleep* period as well as to decrease the state transition overheads. In the *Allocation* phase, all nodes will be in *sleep* state excepting the slots in which they are scheduled to transmit or receive the data transfer slots.

Algorithm 3 Transmission slot allocation algorithm, at each parent-child pair, $(i, j) \in \mathcal{N}$

```
while (i is in Allocation Phase) do
    i wakes up for t_c period in Allocation Phase
    i receives φ_j from j in α_1 sub-slot
    i computes Alloc_j using Eq. 4.2 and Eq. 4.4, ∀j
    i sends Alloc_j to j in α_2 sub-slot
end while
while (j is in Allocation phase) do
    j wakes up for t_p period in Allocation phase
    j sends φ_j in α_1 sub-slot to i
    j receives Alloc_j in α_2 sub-slot from i
end while
```

4.4.4 Data Transfer Mechanism

In the data transfer phase, the data transfer among all nodes take place. In the scheduled data transfer slots, the parent-child pair that want to communicate with each other direct their antenna beams in the direction to each other. The data packets are then sent to the parent nodes from their children nodes in the data transfer phase.

Lemma 1. *No two siblings will get the same scheduling slots in the* Data Transfer *phase. Thus transmission from sibling nodes will never collides.*

Proof. We use proof by contradiction to prove this lemma. Let P be the proposition, "No two siblings will get the same scheduling slots in the *Data Transfer* phase." Suppose $\neg P$ is true, i.e, two sibling nodes will get the same scheduling slots in the *Data Transfer* phase and their transmissions will collide with each other.

Suppose A is a parent node and D and E are two child nodes as given in Fig. 4.2. In the *Sync* phase D and E requests slots to transmit data packets to A. A gives weighted-share of total slots to each child node in such a way that transmission from it's children will never collide with each other. After the *Synch* phase A knows the data transmission requirements of D and E. Accordingly, A allocates slots to D and E in the *Allocation* phase for scheduling the data transfer. A allocates the S_D and S_E slots for data transfer to D and E from it's free slots which is maintained by Eqn 4.3.

Suppose the set of free slots available at node A is, $\varphi_A = 2, 3, 4, 5, 6, 9, 10, 11, 12, 14$. After getting the requirement of D it gives $S_D = 2, 3, 4$ slots to it's child D. Now, using Eqn 4.3 the φ_A becomes $5, 6, 9, 10, 11, 12, 14$. After allocating these slots parent A will allocate $S_E = 9, 10$ from the new φ_A.

Now we can find that,

$$S_D \cap S_E = \phi \tag{4.5}$$

So, we can see that S_D and S_E has no common slots. This is a contradiction, since we have stated that, two siblings will get the same scheduling slots.

Hence, $\neg P$ is false, so P : "No two siblings will get the same scheduling slots in the *Data Transfer* phase." is true. □

Each transmitting parent-child node is synchronized with each other prior to the data transmission. According to the schedule, data packets are sent and received in the pre-defined slots. Though, if the neighboring nodes are directed toward the same receiver a small possibility of occurring collisions still remains. Because, during the synchronization, each parent-child pair checks their own free slots but the data slots of the surrounding neighbor nodes are not checked for the scheduling. If transmission of two neighboring nodes happen at the same time then a collision can occur due to scheduling conflicts. Introduction of Directional Ready to Send (DRTS) and Directional Clear to Send (DCTS) control packets minimizes the collision in the network. The exchange of DRTS and DCTS follows the same procedure as RTS and CTS control packets, respectively, used in the IEEE 802.11 standard protocols. It reduces the collision among data transmissions from neighboring nodes.

In DSNs, the nodes could be idle for long time if there is no sensing event. Throughout this period the data rate would also be very low. Consequently, it is not required that the nodes in the network will remain active all the time. The active period of the nodes can be greatly reduced by putting the nodes into periodic sleep state. A novel low-overhead schedule based protocol is propose in this paper which permits the nodes to go to *sleep* state after and before of the operational cycle as stated in Section. 4.3. The duty-cycle of the network is calculated as,

$$Duty - Cycle = \frac{|S_c \cup S_p|}{|S|} \times 100\%. \tag{4.6}$$

Here, S is the set of all data transmission slots, S_c is the set of slots in which a node communicates with it's child nodes and S_p is the set of slots in which it communicates with the parent.

Accordingly, the nodes are allowed to go to low-power *sleep* states during the non-active slots of *Allocation* and *Data Transfer* phases except the *Synchronization* phase which lead to conserve a significant amount of energy. Fig.4.6 shows a simple scenario of data transmission between parent node A and it's child node B. After the synchronization is done, the sender and receiver set up a wakeup time for themselves for data transmission. The nodes A and B will be wake up only when they need to communicate with each other, rest of the time both nodes remain sleep to save the energy.

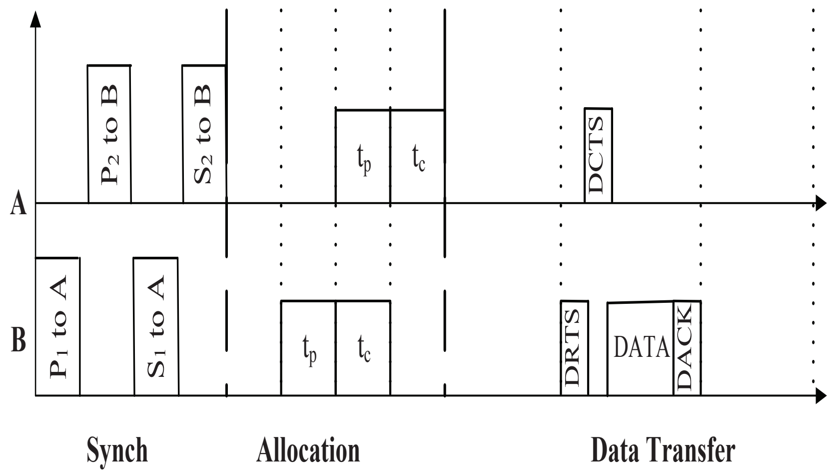


Figure 4.6: Data transmission in DCD-MAC

4.5 Theoretical Analysis

The performance of our proposed DCD-MAC greatly depends on the success probability of synchronization between each pair of parent-child nodes. In this section, we provide the statistical analysis for synchronization success probability P_s and the expected number of the synchronization slots $E[s]$ required for synchronization for a certain neighborhood in the network.

Given that, each parent has at most k child nodes, there are n synchronization slots in the frame, and each sensor node has m sectors. For data transmission and reception, a sensor node can be directed to one of m sectors for a particular time. In the *Sync* phase, a node in the network can either transmit or receive pilot tone in a slot. More specifically, a node will transmit pilot tone toward its parent node *if and only if* it has data packets in its queue. While transmitting pilot tone, the node remains in directional mode. On the other hand, there is no packet to transmit i.e, the node need not to communicate with it's parent node, it waits to receive pilot tones. For pilot tone reception, the node remains in omni-directional mode so that it can receive the pilot tone from any of its child nodes. Therefore, in *Sync phase*, the directional mode of a node is determined by its packet arrival rate. Lets consider the packet arrival rate at sensor nodes follow Poisson distribution with rate λ. Therefore, probability that no packets arrive in a particular node's queue during time duration t is calculated as,

$$P_o = \frac{(\lambda t)^0 e^{-\lambda t}}{0!} = e^{-\lambda t}. \tag{4.7}$$

Therefore, P_o is the probability that the node will remain in omni-directional mode and the probability that the node will be in directional mode is,

$$P_d = 1 - P_o \tag{4.8}$$

Now, any pair of parent-child in Fig 4.2, where the child has data to send, needs to synchronize with each other. For example, child node E requires synchronization with its parent A in a particular slot of *Sync phase*. The node A should be in receiving mode, i.e., the antenna of A should be in omni-directional mode. This event can be happened with probability P_o^A. In the same way, node E should be in transmitting mode with it's directional antenna beam forming towards A with probability $\frac{1}{m} \times P_d^E$. Additionally, we are assuming that A has k children. So, successful synchronization between E and A imposes the condition that none of the other $(k-1)$ child nodes try to synchronize with A at the same *Sync* slot. The probability of the event is $(1 - \frac{1-P_o}{m})^{k-1}$.

Henceforth, the probability that nodes A and E synchronize with each other in a particular slot of *Sync* phase is given by,

$$P_s = P_o^A \times \frac{1}{m} \times P_d^E \times (1 - \frac{1 - P_o}{m})^{k-1}. \tag{4.9}$$

Now, the probability that A and E synchronize with each other in any of the N slots of *Sync* phase in a frame is calculated as,

$$P_f = 1 - (1 - P_s)^N. \tag{4.10}$$

Note that the number of slots required for E to get synchronized with A is a Geometric random variable Y, and we find the probability that E finds A in exactly nth slot is:

$$P(Y = n) = P_s(1 - P_s)^{n-1}, \qquad 1 \leq s \leq Y \tag{4.11}$$

The average number of time slots that the node E has to wait before synchronization is given by,

$$\begin{aligned} E[n] &= \sum_{n=0}^{\infty} n \times P(Y = n) \\ &= \sum_{i=1}^{\infty} n \times P_s(1 - P_s)^{(n-1)} \\ &= \frac{P_s(1 - P_s)}{(1 - P_s)^2} \\ &= \frac{P_s}{(1 - P_s)} \end{aligned} \tag{4.12}$$

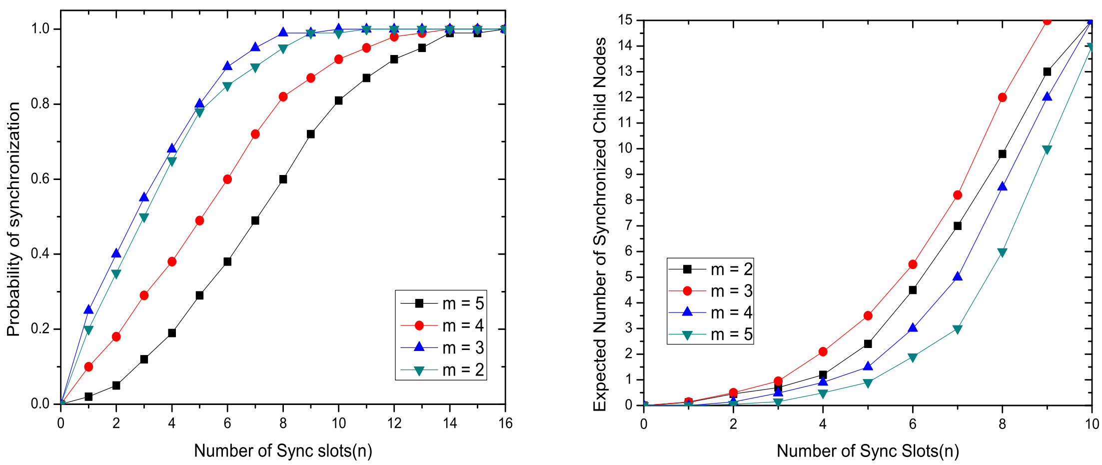
For a parent node synchronization with each of its child nodes is independent of each other, i.e., the number of children nodes that will be synchronized in the *Sync phase* of a frame is a binomial random variable. Therefore, the probability that c nodes are synchronized nodes is given by,

$$P_{c,N} = \binom{k}{c} (P_f)^c (1 - P_f))^{k-c}. \tag{4.13}$$

Then, the expected number of child nodes that would be synchronize with their parent node within K number of slots is given by,

$$E[C] = \sum_{k=1}^{K} k \times P_{c,N} \tag{4.14}$$

We plot the probability of synchronization of a node in a network with it's child nodes within a particular frame for an example topology in Fig. 4.7. We know, for different antenna beamwidths, m varies. For this experiment, we vary the beam width from 72^0 to 180^0, ranging m from 2 to 5. In addition, we vary the number of sync slots from 0 to 16. We also plot the expected number of child nodes that have been synchronized in synchronization slots for varying beam width.



(a) Probability of synchronization between parent-child nodes

(b) Expected number of synchronized child

Figure 4.7: Statistical analysis of parent-child synchronization during sync Phase

From the graph of Fig. 4.7-a, we observe that the larger the antenna beam width and the larger the number of sync slots, the higher the probability that a particular child synchronize with by it's parent within a specified number of slots in a frame. However, when the antenna beam width is 180^0, a particular parent node may have more child nodes than that of bigger beamwidth. Hence, the collision between the child nodes increase at that time. From the graph of Fig. 4.7-b, we also observe that with the increasing number of synchronization slots the number of expected child nodes that synchronize with their parent node also increase.

4.6 Performance Evaluation

The performance of the proposed DCD-MAC protocol is evaluated and a comparative study is done among the performances of DCD-MAC, DU-MAC [87] and PMAC [55]in this section. The DU-MAC operates in a distributed manner and targets to achieve the same objectives as in DCD-MAC and PMAC is a directional MAC protocol where neighbors are synchronized with each other before data transmission in ad-hoc fashion.

4.6.1 Simulation Environment

We implement the studied MAC protocols using ns-3 [91], a discrete-event network simulator. The wifiSimpleAdhoc model is used for the simulation. For the simulation, a tree structured directional wireless sensor network with a sink node is deployed, where a neighbor discovery protocol is run in periodic basis which allows each node to perform neighbor discovery within a bounded time. To compare the performance of our proposed protocol, we run COND [14] and SAND [41] before our MAC protocol to discover the neighboring nodes in the network. Each node relays its neighborhood information to the surroundings and makes a neighbor table for a certain interval. SAND performs neighbor discovery in a serialized fashion allowing individual nodes to discover all potential

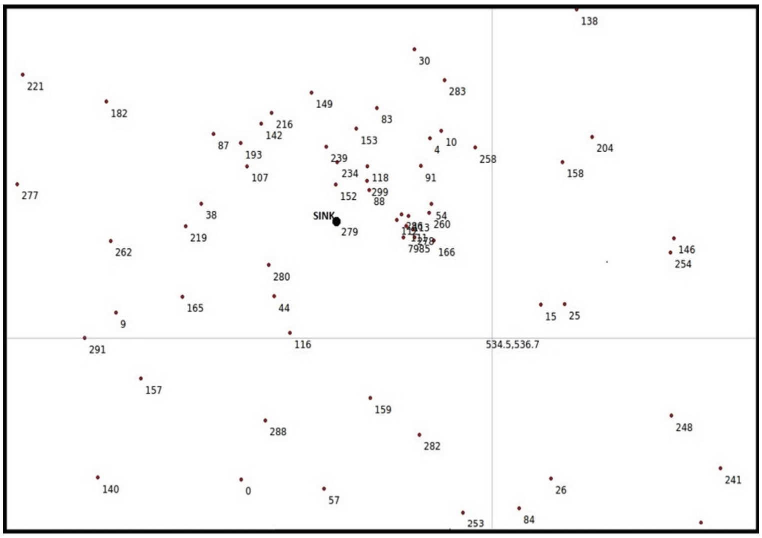


Figure 4.8: An example scenario for random node deployment in simulation environment

neighbors within a predetermined time, whereas COND performs neighbor discovery distributedly with collaborative update of neighbor table. After neighbor discovery each node have a knowledge about its surrounding neighbors and starts data communication in the direction to the sink in multi-hop manner using a dynamic routing protocol. We have used the Friis Propagation Loss Model to calculate the available energy at the receiving and transmitting antenna and fragmentation is enabled for the large packets. For defining the channel characteristics and channel properties the YansWifiPhy model is used.

The network configuration parameters are shown in Table 4.2 and an example scenario of the implemented topology in simulation environment is given in Fig. 4.8. We deploy the sensors with uniform random distribution in a region of $500 \times 500m^2$. Runtime of the simulation is 1000 seconds. We run the simulation experiments 30 times, with different seed values, and take the average for each graph data points. Three events are generated randomly for the simulation and the event description is given in Table 4.3.

Table 4.2: Simulation parameters for DCD-MAC protocol

Parameters	Value
Area deployment	$500m \times 500m$
Type of deployment	Uniform random
Number of nodes deployed	$100 \sim 1000$
Number of sectors	$2 \sim 6$
Transmission range	$100m$
Sensing range	$50m$
Initial node energy	$5J$
Synchronization phase slots	15
Allocation phase slots	10
Data transfer phase slots	75
Slot duration	5 ms
Packet size in sync phase	$20Bytes$
Packet size in allocation phase	$20Bytes$
Data packet size	$512Bytes$
Data transmission rate	$1Mbps$
Routing protocol	AODV
Channel model	Yans WiFi Model
Propagation model	Friis Propagation Loss Model
Application type	Event-driven
Simulation time	1000 Seconds

4.6.2 Performance Metrics

- *Data delivery throughput* of the network is computed in the simulation period from the number of data bytes received by the sink per second. The MAC protocol performance is better for the higher value of throughput.

- *Reliability* is calculated as the ratio of the total number of unique packets received by the sink within the delay-deadline to the number of packets generated by all the source nodes. The transmission efficiency will be better with the higher value.

- *Average end-to-end packet delay* for a particular packet is measured by the time difference between receiving time at the sink and packet generation time at the

Table 4.3: Events and bursts description

	Event A	**Event B**	**Event C**
Burst 1	20s - 40s	30s - 60s	50s - 100s
Burst 2	140s - 160s	150s - 180s	100s - 300s
Burst 3	700s - 750s	740s - 790s	800s - 850s

source. These delays are averaged in respect of total number packets received by the sink. Lower value of averaged end-to-end delay indicates better performance of the protocol.

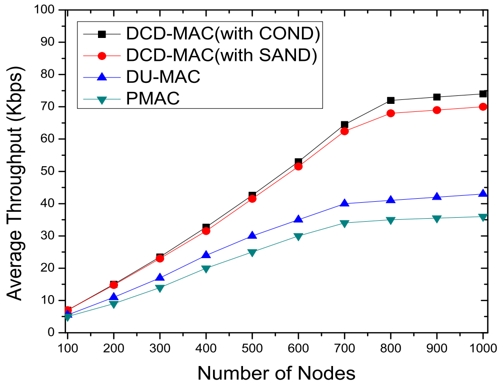
- *Network lifetime* is defined in several approaches in the literatures. In this paper, *Network lifetime* is considered when the first node dies out of energy in the network. This is a reasonable measurement, used in the literature, since it is expected that the rest of the nodes would also exhaust their energy soon after the first one. Better performance corresponds to the higher amount of time.
- *Protocol overhead* is measures as the amount of control messages sent for a successful data delivery. It is calculated as the ratio of control message bytes transmitted to the data packet bytes delivered to the sink during the simulation period.

4.6.3 Simulation Results

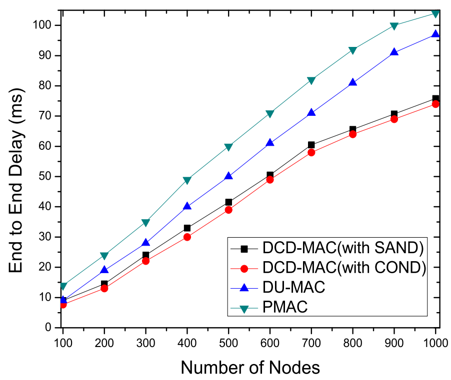
We study the performance of the DCD-MAC protocol for varying number of sensor nodes and the data traffic rate deployed in the network . We examine the performances of two versions of the proposed DCD-MAC protocol - neighbor discovery with SAND [41] and with COND [14].

4.6.3.1 Impact of number of sensor nodes

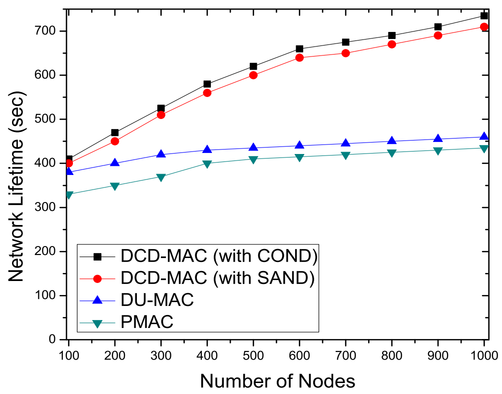
The protocol performance is measured for varying number of directional sensor nodes ranging from 100 to 1000 and the number of sectors of each sensor is fixed at 4. The



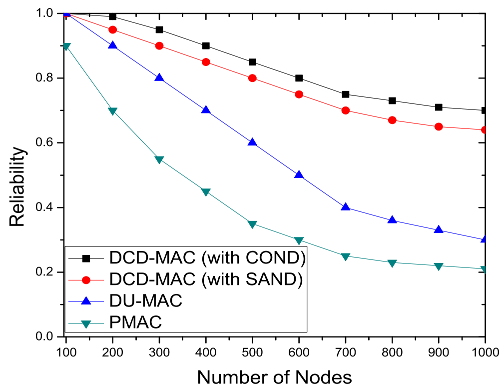
(a) Data delivery throughput



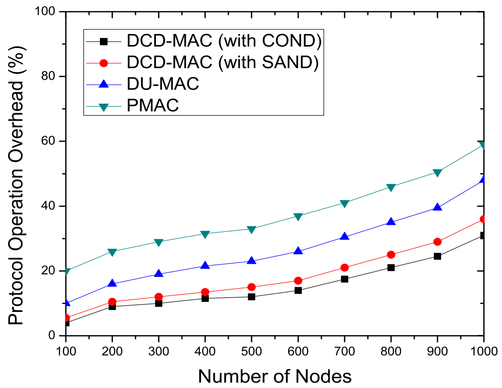
(b) Average end-to-end packet delay



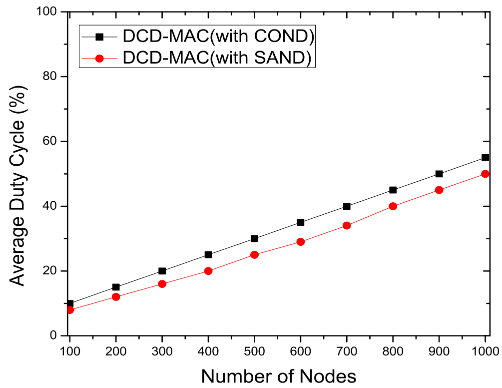
(c) Network Lifetime



(d) Reliability



(e) Protocol operation overhead



(f) Average duty-cycle

Figure 4.9: Impacts of number of sensor nodes on performances of the studied MAC protocols.

packet generation rate during the simulation time is 1.5 packets per second.

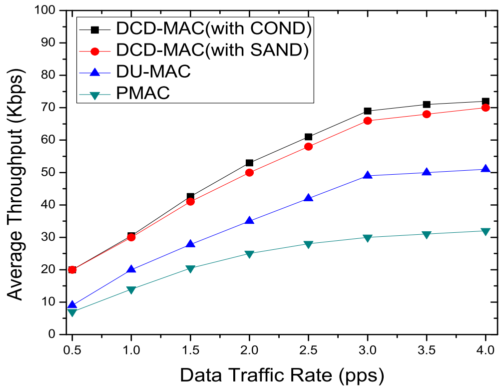
The graph in Fig 4.9(a) and (b) shows that the average data delivery throughput and the average end to end delay are increased with the growing number of sensing nodes in the protocols. However, our DCD-MAC has more throughput and least delay compared to DU-MAC and PMAC as it schedules the data transfer before transmitting data. Again, DU-MAC has an extra overhead for maintaining the neighbors location and beam locking, unlocking and as PMAC is designed for wireless ad-hoc network, it doesn't perform well in wireless sensor network scenario. Both the protocols are unable to synchronize properly with growing number of sensor nodes.

As shown in Fig 4.9(c), the reliability is decreased in both protocols as the network becomes dense, because with the growing number of nodes the probability of collision in the network increases. The performance of DCD-MAC (with COND) gives better lifetime with the growing number of nodes, as neighbors are discovered using less energy and overhead compared to the performance of DCD-MAC (with SAND). The DCD-MAC (with COND) also achieves more throughput and reliability. Fig 4.9 (d) shows that, the reliability of the network in DCD-MAC increase with the growing number of nodes, whereas in DU-MAC, it remains almost in a stable state and it decreases in PMAC.

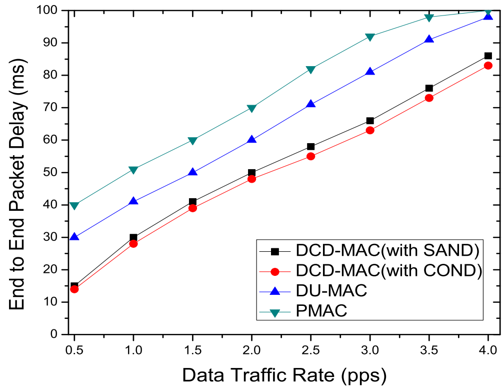
4.6.3.2 Impact of increasing data traffic

The number of deployed sensor nodes in the network is 500 and antenna of each node has four sectors. We also assume that all data packets are homogeneous.

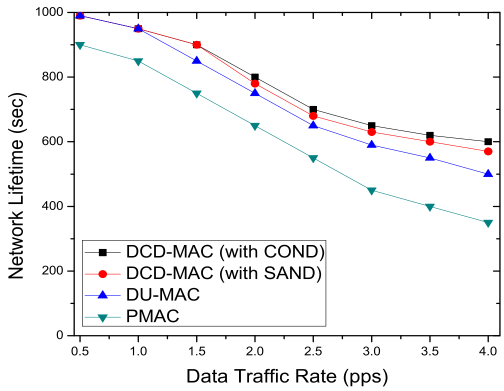
The graphs in Fig 4.10(a) and (b) show that the average data delivery throughput and the average end-to-end delay is increased with the increasing data traffic rate in all protocols. We observe that our DCD-MAC has more throughput and least delay compared to DU-MAC and PMAC. As the data rate increases the network nodes have to carry more traffic, the additional traffic causes congestion in the network and the reliability decreases as shown in Fig 4.10(c). Similarly, the increasing traffic puts energy



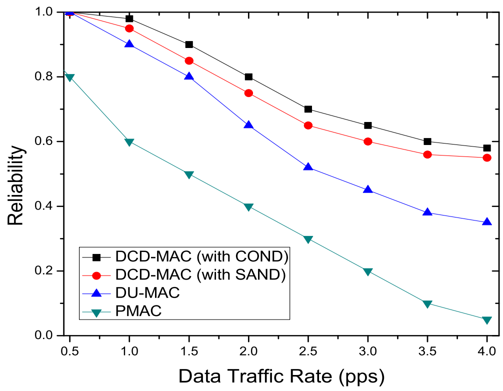
(a) Data delivery throughput



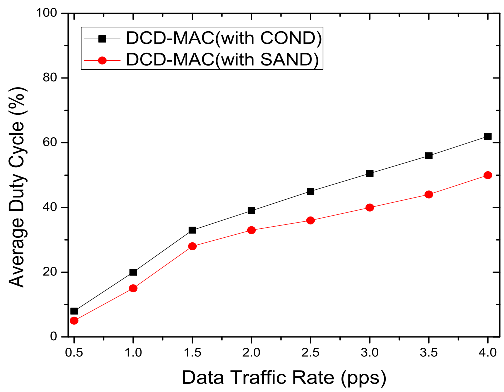
(b) Average end-to-end packet delay



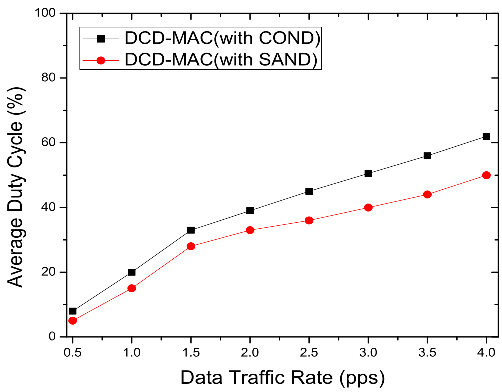
(c) Network Lifetime



(d) Reliability



(e) Protocol operation overhead



(f) Average duty-cycle

Figure 4.10: Impacts of increasing data traffic on performances of the studied MAC protocols.

burden on to the nodes, because of fast exhaustion of node energy which reduces the network lifetime.

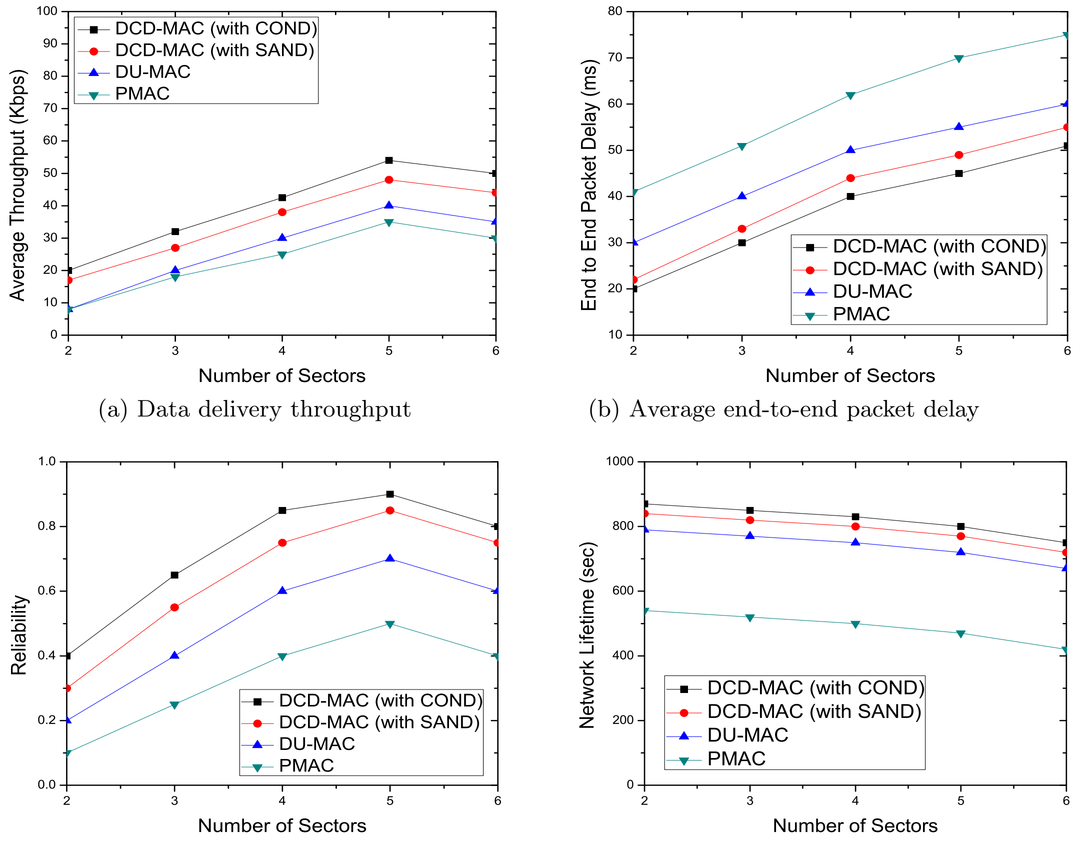
4.6.3.3 Protocol operation overhead

The protocol operation overhead of DCD-MAC protocol is compared with the studied protocols as shown in Fig 4.9(e) for varying number of sensor nodes. Our proposed protocol has less overhead than the DU-MAC as in DU-MAC during the simulation runtime active scanning is applied to each individual sectors sequentially. With the increasing number of sensor nodes, DU-MAC has higher throughput as in DCD-MAC only the parent-child nodes are synchronized with each other. Again, PMAC has also more overhead than both the other protocols because synchronization is done among all the neighbors of a node.

In Fig 4.10(e), we have shown the protocol operation overhead for varying number of data traffic. Naturally, with the increasing number of data packets, the protocol overhead increases as it takes more control messages to synchronize with each other.

4.6.3.4 Average duty-cycle of DCD-MAC

The average duty-cycles of the network for varying number of sensors and data traffic are shown in Fig. 4.9-(f) and Fig. 4.10-(f), respectively. From the Fig. 4.9-(f) we observe that, the duty-cycle of proposed DCD-MAC protocol linearly increases with the growing number of sensor nodes. All over again, the duty-cycle of DCD-MAC slightly increases with varying data traffic, and after a certain interval it becomes flat as shown in Fig. 4.10-(f). In DUMAC and PMAC, the sensor nodes always remain awake and do idle listening for synchronization and node discovery. Consequently, the duty-cycle of DCD-MAC is always lower than the studied protocols and it remains from 20% to 50% with varying number of sensor nodes and data traffic. The duty-cycle of DCD-MAC with SAND mechanism increases as with growing number of data packets the congestion among the



(a) Data delivery throughput (b) Average end-to-end packet delay

(c) Reliability (d) Network lifetime

Figure 4.11: Impacts of increasing number of sectors on performances of the studied MAC protocols.

neighborhood also increases and a sender with it's pending data must wait for next data frame when the medium is congested and has to awake longer.

4.6.3.5 Impact of varying number of sectors

For this simulation, sensor nodes are equipped with directional antenna of 2 to 6 sectors, resulting in a 180^0 to 60^0 beamwidth respectively. Here, we assume fixed number of 650 sensor nodes and the traffic load is also fixed at 1.5 pps. The graph of Fig 4.11, shows that when we are increasing the beam width the network performance is increasing gradually.

Again, when the sector is 6, the performance degrades than the situation when the sector is 5. This is not surprising, because it requires more slots for synchronization and also causes greater collision among the transmissions from the sensor nodes. Similarly, the energy consumption of node increases with the higher number of sectors for additional coordination activities among the nodes of the network and thus the network lifetime in the studied protocol also slightly decreases as shown in Fig 4.11(d).

4.7 Discussion

In this chapter, a low duty-cycle distributed MAC protocol DCD-MAC is described for Directional Wireless Sensor Networks as traditional MAC protocols do not perform well in DSNs. The proposed mechanism ensures synchronized transmission-reception between all parent-child pairs. In the network all the nodes distributedly schedules the collision free data transmission slots for their child nodes. Each parent determines collision-free scheduling slots proportionately for it's child nodes. Thus, an energy-efficient and highly scalable protocol is proposed that allows a sensor node to switch into *sleep* state whenever it is not scheduled to receive or transmit any data packets. We have also presented an analytical model for the synchronization among nodes in the network. The performance evaluation of the proposed DCD-MAC protocol depicts the effectiveness in achieving reduced delay and higher throughput, reliability, and network lifetime performances.

Chapter 5

Conclusion

In this chapter, we summarize the research results presented in this thesis and state few directions for future works.

5.1 Summary of Research

The human need for real-time information collection, monitoring, and tracking applications on the physical environment has driven the evolution of many technologies and applications in recent years. The wireless sensor network satisfies that need, and the technology is growing exponentially. The use of directional antennas in wireless networks can bring numerous benefits, such as the reduced interference, the extended communication range, and the improved spatial reusability and network capacity. However, the self-limitations of directional antennas restrict the wide applications. Our advanced study on DSN attributes shows that there are a number of concerns which stand as vulnerabilities for DSNs, including self configuration difficulties, sector synchronization, idle listening, energy wastage etc. In this thesis, we have concentrated on neighbor discovery and medium access control in DSNs. The different approaches designed in the literature have considered as motivations and inspirations for proposing the solutions of such problems.

In this thesis, we have proposed a collaborative neighbor discovery mechanism named as COND. We introduced dynamic polling period in each sector following the number of already discovered nodes in it. The COND mechanism introduced indirect neighbor discovery along with direct neighbor discovery through collaboration among the already discovered nodes. The joint employment of the above strategies helped the proposed COND system to achieve excellent performances in neighbor discovery. The developed Markov-chain model proves that the proposed indirect neighbor discovery reduces the neighbor discovery latency significantly in the network. Finally, the simulation results evaluated in NS-3 depict that the collaboration-based indirect neighbor discovery helped to reduce the discovery latency significantly while the utilization of time slots in each frame was greatly enhanced due to the use of dynamic polling periods.

Furthermore, in this thesis, a low duty-cycle distributed MAC protocol DCD-MAC is proposed for Directional Wireless Sensor Networks. The schemes proposed in this thesis are based on the duty-cycle mechanism, in which nodes are synchronised together into schedules. The proposed MAC protocol ensures synchronized transmission-reception between all parent-child pairs. All the nodes in the network distributedly schedule the number of collision free data transmission slots for their child nodes. Each parent determines collision-free scheduling slots proportionately for its child nodes. Thus, the DCD-MAC is an energy-efficient and highly scalable protocol that allows a sensor node to switch into *sleep* state whenever it is not scheduled to receive or transmit any data packets. We have also presented an analytical model for the synchronization among nodes in the network. The performance evaluation of the proposed DCD-MAC protocol depicts the effectiveness in achieving reduced delay and higher throughput, reliability, and network lifetime performances.

5.2 Discussion

From few years, interest in wireless sensor networks has been in potential use where, sensors are deployed in wide area to operate autonomously for long time in unattended environment. Sensor networks have the promise of revolutionizing many areas of science, industry, and government. We have also explored the applications of these sensor nodes as well as the issues in the application, transport, network, datalink and physical layers. We found that, the current challenges for next-generation sensor networks are scalability, decentralization, resource scarcity and dynamicity. These requirements and challenges cannot be fully fulfilled by traditional Wireless Sensor Networks. We have reconnoitered that, the introduction of directional antennas in sensor networks reduces interference, transmission delay and flooding and consequently improves the network performances. We investigate the network connectivity of wireless sensor networks with directional antennas and found that with the additional advantages directional communication also introduces some challenges in sensor network.

In this thesis, we have studied the design requirements of energy efficient MAC protocols in sensor networks and found that, the MAC protocols for traditional Wireless Sensor Networks are not fully applicable for Directional Wireless Sensor Networks. Thus, a specialized MAC protocol for directional WSNs is needed to develop. While developing a MAC protocol, we found that, each node must know its surrounding neighbors before any communication protocol. Hence, the core function of Directional Sensor Network lies in the neighbor discovery design as the other design issues are dependent on neighbor discovery. Consequently, the aim of this thesis was to develop and evaluate a medium access control protocol along with neighbor discovery mechanism. We opt to develop MAC protocol with neighbor discovery mechanism that would be energy-efficient, reliable, scalable and deployable without incurring much overhead. In this thesis, we have developed a collaborative neighbor discovery mechanism and with the knowledge of neighboring nodes a MAC protocol is designed for Directional Sensor Networks.

In my PhD academic program, I took three theory courses. One of those courses was *Network Performance and Analysis*, which help me in developing theoretical model (Probability-based and Markov chain based model) to analyze the performances of the developed algorithms theoretically. After the theoretical analysis, we had to go for simulation to examine the performance of the network. Since we do not have the enough facility to develop a real-time prototype network, we have to choose the option of doing experiments using a simulation tool. As NS-3 is a very popular simulation tool in this arena and many leading works in the literature have done their simulation studies using this, we have also chosen NS-3 for the simulation. However, as we did not get enough resources about NS-3, therefore we had to go through a lot of difficulties to simulate our network in NS-3. Finally, after spending plenty of hours in the lab, we had been able to implement our developed systems, compared with a good number of literature works and finally got satisfactory results. Thanks to the co-workers of our laboratory to extend all supports wherever and whenever necessary.

5.3 Future Works

In this thesis, we have presented the approaches for an improved architecture of DSN applications. The purpose of the developed schemes is building sensor networks that take into account the synchronization errors, self-configuration, system capacity and scheduling of transmission and reception of data packets. NS-3 simulator was used for implementing and investigating the performances of the proposed schemes separately. While the preliminary simulation results from the above schemes looked promising, there are still several interesting issues and open challenges that require further investigation.

The simulation results help us to study the behavior of proposed solution mechanisms and to compare with other systems with diverse topologies, traffic patterns, environmental parameters, etc. It is difficult to predict how these protocols perform in real-time applications with a simulation tool. The next step research, therefore, is to experiment with the approaches presented in this thesis in a real test-bed implementation.

In this work, we have considered single channel bandwidth resource only; however, multi-channel environment would enhance the network performance significantly if a suitable MAC protocol can be designed for multi-channel Directional Sensor Networks. The sensors in our proposed scheme are assumed to be static and battery driven. This work can also be extended to the case where the sensor nodes are mobile and also assumed to be equipped with energy harvesting solar cells. A cross-layer approach is also needed to design a complete solution of energy-efficient communication in a DSN.

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Appendix A

List of Notations

$\mathcal{S}$	Set of all sensor nodes
$\mathcal{M}$	Set of sectors of directional antenna
P_t	Transmission probability
r	Communication radius of each sensor
$\mathcal{K}$	Delay tuning parameter
A	Deployment area of the network
ρ	Network density
$\mathcal{T}_a$	Neighbor table of node $a \in \mathcal{S}$
E_n	Expected number of nodes in the neighborhood
$\mathcal{N}_e^m$	Number of expected neighbor nodes in a sector $m \in \mathcal{M}$
$\mathcal{N}_d^m$	Number of discovered neighbor nodes after an iteration
$\mathcal{F}$	Flag indicating a neighbor is discovered directly or indirectly
$\mathcal{R}$	Iteration for neighbor discovery
x'	Mini sub-slot of a slot x
δ_m	Parameter that tunes $\mathcal{K}$
α, β, γ	Threshold values for tuning parameter δ_m
θ	Beam width of antenna
Ψ_i	Set of free slots for node i in Allocation phase
Ψ_{ij}	Set of matched free slots for i and j in allocation phase
φ_i	Set of free slots for node i in Data transfer phase

φ_{ij}	Set of matched free slots for i and j in Data transfer phase
K_i	Number of requsted slots by node i for sending packets
t_p	Set of scheduled slots from the parent in Allocation phase
t_c	Set of scheduled slots for the child in Allocation phase
S_p	Set of scheduled slots for sending data in Data transfer phase
S_c	Set of scheduled slots for receiving data in Data transfer phase
N_j	Number of allocated slots for each child node for Data transfer

Appendix B

List of Acronyms

ACK	Acknowledgment
COND	Collaborative Neighbor Discovery
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear To Send
CW	Contention Window
DCD-MAC	Duty Cycle Directional MAC
DCF	Distributed Coordination Function
DCTS	Directional Clear To Send
DOA	Direction of Arrival
DRTS	Directional Ready To Send
DIFS	Distributed Inter Frame Space
DSN	Directional Wireless Sensor Network
DUMAC	Dirctional Ultra wide band MAC
GPS	Global Positioning System
MAC	Medium Access Control Protocol
NS-3	Network Simulator - version 3
PMAC	Polling based MAC
RTS	Request To Send
SAND	Sectored Antenna based Neighbor Discovery

S-MAC	Sensor MAC Protocol
SIFS	Short Inter Frame Space
SYNC	Synchronization packets
TDMA	Time Division Multiple Access
TTL	Time To Live
WSN	Wireless Sensor Network

Appendix C

List of Publications

International Journal Papers (SCI-indexed)

1. ——-. "Collaborative Neighbor Discovery in Directional Wireless Sensor Networks: Algorithm and Analysis", EURASIP Journal on Wireless Communications and Networking (2017), pp.119. doi:10.1186/s13638-017-0903-6.

2. ——-. "A Low Duty Cycle MAC Protocol for Directional Wireless Sensor Networks.", Wireless Personal Communications, Springer, Volume 96, Issue 4, pp.5035-5059, Oct 2017.

3. ——-. "α-Overlapping Area Coverage for Clustered Directional Sensor Networks", Computer Communication (Elsevier), Volume 109, September 2017, pp.89–103, ISSN 0140-3664.

4. ——-. "Tradeoff Between Sensing Quality and Network Lifetime for Heterogeneous Target Coverage Using Directional Sensor Nodes", IEEE Access, vol. no.99, pp.15490-15504, doi: 10.1109/ACCESS.2017.2718548.

International Conference Papers

5. ——-. “Quality-aware Directional MAC Protocol for Multi-channel Wireless Sensor Networks” In 15th IEEE International Symposium on Parallel and Distributed Processing with Applications (ISPA) 2017, 12 - 15 December, Guangzhow, China. [Accepted].

6. ——-. “Target Coverage-Aware Clustering for Directional Sensor Networks” In 15th IEEE International Symposium on Parallel and Distributed Processing with Applications (ISPA) 2017 , 12 - 15 December, Guangzhow, China. [Accepted].

7. ——-. “Collaborative Neighbor Discovery in Directional Wireless Sensor Networks.” In IEEE Region 10 Conference (TENCON) 2016 - Technologies for Smart Nation, pp. 1097-1100, 22 - 25 November 2016, Marina Bay Sands, Singapore.

8. ——-. “Network Lifetime Aware Coverage Quality Maximization for Heterogeneous Targets in DSNs.” In IEEE Region 10 Conference (TENCON) 2016 - Technologies for Smart Nation, pp. 3030 - 3033, 22 - 25 November 2016, Marina Bay Sands, Singapore.

9. ——-. “Starfish Routing for Wireless Sensor Networks with a Mobile Sink.” In IEEE Region 10 Conference (TENCON) 2016 - Technologies for Smart Nation, pp. 1093 - 1096, 22 - 25 November 2016, Marina Bay Sands, Singapore.

10. ——-. “A duty cycle directional mac protocol for wireless sensor networks.” In International Conference on Networking Systems and Security (NSysS), 2015, pp. 1-9, 5 - 7 January 2015, BUET, Dhaka, Bangladesh.

11. ——-. “Network lifetime aware area coverage for clustered directional sensor networks.” In International Conference on Networking Systems and Security (NSysS), 2015 International Conference on, pp. 1-9, 5 - 7 January 2015, BUET, Dhaka, Bangladesh.

12. ——–. "Area coverage for clustered directional sensor networks using Voronoi diagram." In IEEE International WIE Conference on Electrical and Computer Engineering (WIECON-ECE), pp. 370-373, 19 - 20 December, 2015, BUET, Dhaka, Bangladesh.

13. ——–. "Congestion Aware Fair Data Delivery in Wireless Multimedia Sensor Networks", 8th World Scientific and Engineering Academy and Society (WSEAS) International Conference on Computer Engineering and Applications, 10-12 Jan, 2014, Tenerife, Spain.