Broadcasting, Coverage, Energy Efficiency and Network Capacity in Wireless Networks

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by

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Declaration

This submission is my own work done under supervision of Prof. Thomas Erlebach in the Department of Computer Science, University of Leicester. To the best of my knowledge, the material of this submission has not been previously published for the award of any other degree or diploma at any other university or institute. The contents of this thesis are the result of my own research except where due acknowledgement has been made. Chapter 3 is based on publications [65] and [64], and Chapter 5 is based on publication [63].

BROADCASTING, COVERAGE, ENERGY EFFICIENCY AND NETWORK CAPACITY IN WIRELESS NETWORKS

Shagufta Henna

ABSTRACT

Broadcasting, coverage, duty cycling, and capacity improvement are some of the important areas of interest in Wireless Networks. We address different problems related with broadcasting, duty cycling, and capacity improvement by sensing different network conditions and dynamically adapting to them. We propose two cross layer broadcasting protocols called CASBA and CMAB which dynamically adapt to network conditions of congestion and mobility. We also propose a broadcasting protocol called DASBA which dynamically adapts to local node density. CASBA, CMAB, and DASBA improve the reachability while minimizing the broadcast cost. Duty cycling is an efficient mechanism to conserve energy in Wireless Sensor Networks (WSNs). Existing duty cycling techniques are unable to handle the contention under dynamic traffic loads. Our proposed protocol called SA-RI-MAC handles traffic contention much more efficiently than RI-MAC without sacrificing the energy efficiency. It improves the delivery ratio with a significant reduction in the latency and energy consumption. Due to limited battery life and fault tolerance issues posed by WSNs, efficient methods which ensure reliable coverage are highly desirable. One solution is to use disjoint set covers to cover the targets. We formulate a problem called MDC which addresses the maximum coverage by using disjoint set covers S_1 and S_2. We prove that MDC is $\mathcal{NP}$-complete and propose a $\sqrt{n}$-approximation algorithm for the MDC problem to cover n targets. The use of multi-channel MAC protocols improves the capacity of wireless networks. Efficient multi-channel MAC protocols aim to utilize multiple channels effectively. Our proposed multi-channel MAC protocol called LCV-MMAC effectively utilizes the multiple channels by handling the control channel saturation. LCV-MMAC demonstrates significantly better throughput and fairness compared to DCA, MMAC, and AMCP in different network scenarios.

DEDICATION

To my parents

for letting me pursue my dream

for so long

so far away from home

&

To my son Umar Gull

for giving me

new dreams to pursue

ACKNOWLEDGMENTS

First and foremost, I am thankful to *Allah Subhanahu wa-taala* that by His grace and bounty, I am able to write my PhD thesis. Every success in my life is one reflection of his love and blessings for me. I ask sincerity in all my actions from *Allah Subhanahu wa-taala* and I quote the verse from the *Holy Quran* Say, *My prayer, my offering, my life and my death are for Allah, the Lord of all the world (Surat Al-Anam, verse 162).*

If we knew what we were doing, it wouldn't be called research (A. Einstein). Like all parts of life, this PhD has been an incredible journey. There have been monumental highs and devastating lows but it has reached its completion. I must thank those who have made it possible. I would like to thank my advisor, *Prof. Thomas Erlebach*, for supporting me over the years, and for giving me so much freedom to explore and discover new areas of Wireless Networks. It was an extraordinary piece of good fortune that led to my becoming his student. Thomas has long been an inspiration to me. His weekly meetings have proved to be one of my best learning experiences at *University of Leicester.* My other committee members including my co-supervisor *Prof. Rick Thomas* and *Dr. Fer-Jan de Vries* have also been very supportive in the thesis committee meetings and provided useful feedback on my progress.

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List of Acronyms / Abbreviations

A list of the most frequently used abbreviations appears below.

- **ACK** Acknowledgement
- **AHBP** Ad Hoc Broadcasting Protocol
- **AMCP** Asynchronous Multi-channel Co-ordination Protocol
- **AODV** Ad Hoc On-Demand Distance Vector
- **ATIM** Ad hoc Traffic Indication Message
- **BEB** Binary Exponential Back off
- **BS** Base Station
- **BW** Backoff Window
- **Bi-MMAC** Bidirectional Multi-channel MAC
- **CASBA** Congestion Adaptive Broadcasting Algorithm
- **CCA** Clear Channel Assessment
- **CCTS** Confirmation Clear To Send
- **CDMA** Code Division Multiple Access
- **CFI** Contention Free Interval
- **CMAB** Cross Layer Mobility Adaptive Broadcasting
- **CRI** Contention Reservation Interval
- **CRN** Channel Reservation Notification
- **CSMA** Carrier Sense Multiple Access
- **CSMA/CA** Carrier Sense Multiple Access/Collision Avoidance
- **CTS** Clear To Send
- **DASBA** Density Adaptive Broadcasting Algorithm
- **DC** Disjoint Coverage
- **DCA** Dynamic Channel Assignment
- **DCA-PC** Dynamic Channel Assignment with Power Control

- **DCF** Distributed Coordinated Function
- **DIFS** Distributed Inter-frame Spacing
- **DPC** Dynamic Private Channel
- **DSC** Disjoint Set Covers
- **DSC-MDC** Disjoint Set Covers for Maximum Disjoint Coverage
- **DSR** Dynamic Source Routing
- **EIFS** Extended Inter-frame Spacing
- **FDMA** Frequency Division Multiple Access
- **GPS** Global Positioning System
- **HOL** Head Of Line
- **HRMA** Hope Reservation Multiple Access
- **IEEE** Institute of Electrical and Electronics Engineers
- **LAR** Location Aided Routing
- **LCM-MAC** Local Coordination-based Multichannel MAC
- **LCV-MMAC** Least Channel Variation Multi-channel MAC
- **LPL** Low Power Listening
- **MAC** Medium Access Control
- **MANET** Mobile Ad hoc Network
- **MAP** Mulit-channel Access Protocol
- **MCBCAST** Multiple Criteria Broadcasting
- **MDC** Maximum Disjoint Coverage
- **MMAC** Multi-channel MAC
- **MPR** Multipoint Relaying
- **MSC** Maximum Set Covers
- **NAV** Network Allocation Vector
- **PLCP** Physical Layer Convergence Protocol
- **PSM** Power Saving Mechanism

- **RCE** Random Correlated Event
- **RCTS** Reject Clear To Send
- **RDT** Receiver Directed Transmission
- **RTS** Request To Send
- **SBA** Scalable Broadcasting Algorithm
- **SIFS** Short Inter-frame Spacing
- **SINR** Signal to Interference plus Noise Ratio
- **SSCH** Slotted Seeded Channel Hopping
- **TCP** Target Coverage Problem
- **TDMA** Time Division Multiple Access
- **TORA** Temporally-Ordered Routing Algorithm
- **UPMA** Unified Power Management Architecture
- **VANET** Vehicular Ad hoc Network
- **WMN** Wireless Mesh Network
- **WSN** Wireless Sensor Network
- **ZRP** Zone Routing Protocol
- **xRDT** Extended Receiver Directed Transmission

Chapter 1

Introduction

In Mobile Ad hoc Networks (MANETs) mobile users are able to communicate with each other in areas where existing infrastructure is inconvenient to use or does not exist at all. These networks do not need any centralized administration or support services. In such a network, each mobile node works not only like a host but also acts as a router. The applications of ad hoc wireless networks range from disaster rescue, tactical communication for military, to interactive conferences where it is hard or expensive to maintain a fixed communication infrastructure. Wireless Sensor Networks (WSNs) are a special type of ad hoc network and one of the recent trends in the networking research. They have extensive applications in environmental monitoring and surveillance. The ubiquitous nature of wireless networks, in combination with high bandwidth demands in multimedia streaming, disaster rescue, and emergency response has put a tremendous emphasis on improving the capacity of wireless networks. Also, efficient broadcast in wireless networks with high reachability, low broadcast latency, and low broadcast cost is desirable under different network conditions of mobility, node density, and congestion.

While problems in wireless networks are manyfold, some of these problems need more attention from research perspective. First, most of the sensor-based applications are battery-powered which eases the deployment but at the same time has constraints due to limited capacity of batteries. Limited capacity of battery puts limitations on the network lifetime. Idle listening is one of the significant sources of energy consumption in WSNs, where a node keeps its radio on without receiving or transmitting any packets, which reduces the network lifetime. One of the important problems in WSNs is the coverage problem. The coverage problem [92] includes two subtypes including target coverage and area coverage. The main objective of the area coverage problem is to monitor or cover some particular area in a WSN, whereas the main objective of target coverage is to cover a particular set of targets. As WSNs have limited battery capacity, and are prone to hardware and software failures, solutions to both the target coverage and area coverage problem focus on maximizing the limited network lifetime and increasing coverage.

In this dissertation, we look at all the above four problems, i.e., capacity improvement, efficient broadcasting, energy efficiency, and target coverage and propose different techniques to solve them. Multi-hop wireless networks suffer in terms of capacity due to interference. The majority of the IEEE 802.11 Medium Access Control (MAC) techniques are Carrier Sense Multiple Access (CSMA) based, where parallel transmissions used to achieve spatial reuse can immensely affect the capacity achieved by multi-hop wireless networks. With an increase in the demand of highly bandwidth intensive applications including Voice over IP (VoIP) and multimedia streaming, multi-hop networks are in need of huge capacity. Therefore, one of the main research problems is to investigate different solutions to increase the capacity of multi-hop networks.

Existing broadcasting schemes are not suitable under dynamics of wireless networks. Several performance studies have shown that existing broadcasting schemes are unlikely to operate well under different network conditions with respect to node density, node mobility, and congestion. These broadcasting techniques have shown poor adaptation to the varying network conditions. Therefore, there is a recent trend in broadcast research to investigate broadcast approaches to broaden their operating range of conditions in MANETs.

Different synchronous and asynchronous duty cycling approaches are optimized for light traffic loads in a WSN which is more prone to bursty and high traffic loads. Examples of such applications include convergecast [103] and broadcast [109]. Network wide broadcast is widely used to disseminate queries and updates, and convergecast is used to report an event after aggregation to the sink upon detecting it. Both these events can generate high traffic loads in WSNs. Existing duty cycling approaches become less efficient in terms of power consumption, packet delivery ratio, and latency under high traffic loads. Due to dynamic traffic loads in WSNs, an ideal MAC protocol should be able to perform well under bursty and high traffic loads.

Network lifetime and energy efficiency are the main objectives of various applications of WSNs. Set covers are used to model the coverage in WSNs [17], and the main objective of most of the coverage approaches is to provide reliable coverage and energy efficiency by using a set of covering sensors or set covers. However, these approaches do not prolong the network life time as covering sensors to cover the targets may deplete their energy. One approach to alternate among different set covers or covering sensors is to use disjoint set covers. Disjoint set covers can prolong network life time where they can be alternatively activated to cover particular targets or area. The problem to compute disjoint set covers is a well known $\mathcal{NP}$-complete problem [16].

1.1 Research Issues

Existing broadcasting, duty cycle, and multi-channel MAC protocols are not efficient under dynamic network conditions and lack any mechanism which can deduce the information about different network conditions and can dynamically adapt to them. We are interested to look problems related with efficient broadcasting, energy efficiency, and capacity improvement by sensing different network conditions and then dynamically adapting to them. In particular, in this dissertation, we consider the above mentioned problems in the following contexts.

1.1.1 Efficient Broadcasting in Mobile Ad hoc Networks

Various applications of MANETs in different scenarios have exhibited a wide range of operating conditions. MANETs are subject to network congestion which can be due to synchronization and coordination control messages. Even in a simple network with periodic traffic, congestion may occur due to limited capacity of radio channels due to concurrent transmissions. Congestion is considered as a dominant reason for degradation of broadcast performance. Broadcast protocols are more prone to congestion due to retransmissions in the network. Flooding [119] is the simplest broadcasting technique in which each node forwards a packet exactly once after receiving it for the first time. Blind flooding causes redundant transmissions, and if not controlled properly, it may result in the broadcast storm problem devastating the network resources enormously. If broadcasting techniques do not adapt to network congestion dynamically, it may result in low delivery ratio, high latency, and increased overhead affecting the quality of broadcast.

One of the network conditions is varying node density which is due to spatial distribution, mobility and number of nodes in the network. Node density plays a significant role in the network connectivity varying from sparser network scenarios to denser ones. Due to a change in the node density, a MANET may experience network partitioning which can split the network into connected and isolated disjoint groups which are not able to communicate with each other. This situation may have an adverse affect on the performance of broadcast protocols, where it is not possible to approach all the nodes in the network. An example of a large network with different node densities in different parts of the network is shown in Figure 1.1. Mobility is inherent to MANETs and causes rapid changes in the network affecting the distribution of nodes and in turn their connectivity in the network. Different nodes may have different speeds and movement patterns allowing the connectivity to evolve in an arbitrary way. Continuous mobility may change the local node density which may lead to the network partitioning problem. Therefore, mobility has significant impact on the performance of broadcasting protocols.

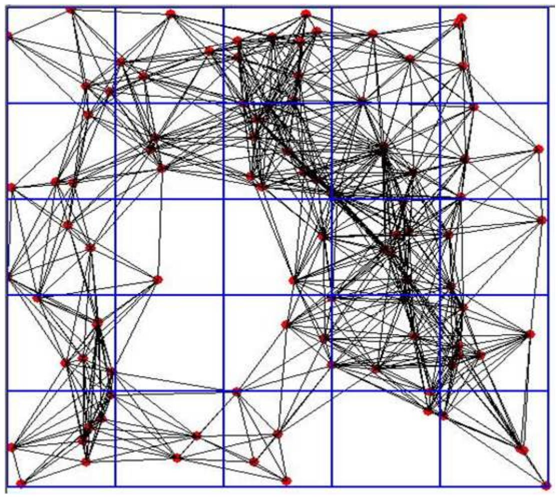


Figure 1.1: A large network with broadcasting [36]

With an increase in range of MANET operating conditions, there is a need for broadcast protocols to adapt to these conditions. The dynamics of these operating conditions require broadcast protocols which can tune dynamically according to current conditions. There is a need to broaden the scenarios with optimized broadcast including highly connected to sparser scenarios, static to mobile scenarios, and low congestion to highly congested scenarios.

1.1.2 Maximum Disjoint Coverage

The coverage problem is one of the recent research trends in wireless sensor networks. Deployment of a set of sensor nodes to cover a particular area or targets is called coverage problem. Sensor nodes are equipped with limited capacity batteries. If the coverage of the target nodes is achieved by a single set of covering nodes, they may soon deplete their energy affecting the network life time. Recently, it has been investigated whether it is possible to conserve energy by using duty cycle protocols, where nodes sleep and wake up periodically which can prolong the network life time. Further, sensor hardware or software may fail due to weather, or other physical conditions in a wireless sensor network affecting the coverage of target nodes. It is important for a WSN to use redundant or disjoint covering sensors to cover particular area or targets to construct a fault-tolerant network which can still cover the targets despite of the failure of some covering sensors.

1.1.3 Energy Efficiency in Contention-based Duty Cycle MAC Protocols

Two of the main causes of energy consumption in wireless networks are overhearing and idle listening even when there is no transmission or reception of packets. Duty cycling [111] is an efficient mechanism to conserve energy at sensor nodes. Duty cycle refers to the percentage of time a node spends in active state. A WSN can exhibit dynamic traffic loads depending on the nature of event sensed. Existing duty cycle MAC protocols are optimized for light traffic loads and their efficiency degrades as the load in the network increases on sensing an event. Therefore, these approaches achieve low or medium utilization due to high contention or traffic loads. Further, these approaches tend to consume energy without any improvement in performance. Most of the existing duty cycle MAC approaches overlook the wastage of energy during high traffic loads due to limited channel capacity, and have no mechanism to optimize channel utilization and energy consumption. Therefore, most of the approaches consider the problem of energy conservation during light traffic loads, and throughput improvement during high traffic loads. A WSN application should be able to handle both situations of high traffic as well as low traffic loads efficiently in terms of energy conservation as well as throughput improvement. To the best of our knowledge, MAC protocols which are able to deal with both situations remain un-addressed.

1.1.4 Capacity Improvement in Single-hop and Multi-hop Networks

Wireless communication requires access to the wireless medium. Most of the popular MAC protocols [37] called single-channel MAC protocols assume a common shared channel to communicate over the network. IEEE 802.11 MAC is one of the most popular single-channel based MAC protocols [15]. IEEE 802.11 MAC performs well in single-hop scenarios; however, its performance is detrimental in multi-hop network scenarios due to its CSMA-based approach. WSN MAC protocols must be capable to operate under different challenges posed by shared access to wireless channel. Examples include collisions caused by the hidden node terminals, and the local contention caused by heavy channel access which degrades the performance of sensor nodes. Time Division Multiple Access (TDMA) protocols have been used to solve these problems but they are too conservative to handle interference. They assume interference is binary in nature, i.e., it exists or not, however in reality it is probabilistic and is calculated according to the Signal to Interference plus Noise Ratio (SINR) model [85].

It is possible to exploit the channel diversity and capacity of the wireless networks by using multi-channel MAC. Performance of both single-hop and multi-hop wireless networks can be improved by dividing the available bandwidth into multiple channels, and providing access to these channels with the help of multiple access protocols. If a node is allowed to switch over multiple channels, a tremendous increase in throughput is possible immediately. The use of multiple channels reduces the probability of collisions. One more benefit which can be achieved by using multiple channels is the fairness. Due to hidden/exposed node problems in IEEE 802.11 MAC protocols, some flows are at a disadvantage due to topology design resulting in unfairness. Multi-channel MAC can alleviate this unfairness by shifting the disadvantaged flow to a different channel. In IEEE 802.11 devices equipped with half duplex transceivers, it is a challenge to design multi-channel MAC protocols which can fully exploit the

channel diversity. In half duplex transceivers, a node is able to transmit or receive at a time. Due to this problem a node is not able to listen on a channel when it is transmitting or receiving on a different channel causing a problem we refer to as multi-channel hidden terminal problem.
Further, in multi-channel MAC protocols three important issues considered are channel assignment, medium access, and channel coordination. Channel assignment is concerned with the selection of channel to be used by a node, while medium access is handling the contention or collisions experienced during a specific channel access. In order to communicate successfully, it is important to negotiate/coordinate the channels effectively to avoid the multi-channel hidden terminal problem. If channel assignment and coordination is perfect, the capacity of the networks can be fully exploited.

In particular existing broadcasting, duty cycling, and multi-channel MAC protocols lack any mechanism which is based on the deduction of the network information. Therefore, these schemes cannot dynamically adapting varying network conditions.

1.2 Contributions

In this thesis, we make four main contributions to solve the above mentioned four issues. In our work, we propose different broadcasting, duty cycle, and multi-channel MAC protocols which deduce the information about different network conditions and then dynamically adapt to them. In particular we propose three broadcasting protocols called CASBA, DASBA, and CMAB which sense the network conditions of congestion, node density, and mobility and dynamically adapts to them. Our duty cycle MAC protocol called SA-RI-MAC senses the local contention in the network and triggers sender assisted contention resolution mechanism based on this information. Our multi-channel MAC protocol called LCV-MMAC deduces the busyness ratio of control channel and based on this information devise an efficient channel assignment technique. Our main contributions can be listed as follows:

1.2.1 Context Adaptive Broadcasting Protocols

We make four contributions for research issues related with broadcasting. First we show via extensive ns-2 [138] simulations that popular broadcasting protocols are very inefficient under a wide range of network conditions including network congestion, node density, and mobility, and adaptiveness to these conditions can improve the performance of these protocols. Further, we propose three broadcasting Protocols called CASBA, DASBA, and CMAB to adapt dynamically according to network conditions of congestion, node density, and mobility. Our first protocol called Congestion Adaptive Scalable Broadcasting Algorithm (CASBA) is based on a well known broadcasting protocol called Scalable Broadcasting Algorithm (SBA). CASBA controls its retransmissions according to the congestion level in the network. In highly congestive scenarios it cancels more retransmissions by delaying the retransmission, and therefore minimizes the chance of the broadcast storm problem. On the other hand, under low congestion it triggers more retransmissions to achieve high reachability.

We also propose a solution called Density Adaptive Scalable Broadcasting Algorithm (DASBA). DASBA adapts according to the local node density and new link information, and performs well in sparser network scenarios. With the help of simulations, we demonstrate the effectiveness of both CASBA and DASBA over two other well known broadcasting protocols—Flooding and SBA—under different network scenarios with varying node density, congestion, and mobility.

We propose a protocol called Cross Layer Mobility Adaptive Broadcasting (CMAB) which follows a cross layer approach to detect the mobility, and uses this information to effectively control the number of retransmissions in the network to improve reachability under highly mobile and dynamic network scenarios. With the help of simulations, we show the effectiveness of CMAB over two other well known broadcasting protocols—AHBP and AHBP-EX—under different network scenarios with varying node density and mobility.

1.2.2 Maximum Disjoint Coverage for Target Coverage Problem

In this work, we consider the target coverage problem. We formulate a variation of the target coverage problem called Maximum Disjoint Coverage (MDC) which addresses the maximum coverage using disjoint set covers. We prove that the MDC problem is $\mathcal{NP}$-complete by reducing it from the NOT-ALL-EQUAL-3SAT problem. Further, we present an approximation algorithm called DSC-MDC to compute two disjoint set covers S_1 and S_2, where S_1 covers all the targets completely and S_2 covers a maximum number of them. An approximation analysis of the algorithm DSC-MDC shows that the algorithm can obtain approximation ratio $\sqrt{n}$, where n represents the number of targets.

1.2.3 Energy Efficient Duty Cycle MAC Protocol

We present a sender-assisted asynchronous duty cycling MAC protocol, called Sender-Assisted Receiver-Initiated MAC (SA-RI-MAC). SA-RI-MAC attempts to resolve the contention among the senders with a common intended receiver and helps them to find a rendezvous time to communicate with the receiver. SA-RI-MAC differs from previous asynchronous duty cycling protocols in the way different contending senders resolve the contention at the receiver by cooperating with each other. Another improvement is achieved by prioritizing the transmissions of the senders which have been starved longer for the channel occupancy.

We believe this is the first attempt which combines the idea of receiver initiated transmissions with the sender assisted contention resolution. This sender assisted coordination adaptively increases the channel utilization, thus improving the delivery ratio and power efficiency under dynamic traffic loads. We present simulation results to evaluate the performance of SA-RI-MAC in different network scenarios including clique, grid, and random under dynamic traffic loads. The experiments demonstrate clearly superior performance for SA-RI-MAC over other duty cycle MAC protocols.

1.2.4 Multi-Channel MAC Protocol for Control Channel Saturation Problem

In this work, we introduce a Least Channel Variation Multiple Channel Medium Access Control (LCV-MMAC) protocol which uses a limited number of channels and a half-duplex transceiver. Frequent exchange of control messages due to frequent channel switching results in control channel saturation problem which builds up queues at the control channel for retransmissions in order to negotiate data channels. LCV-MMAC mitigates the control channel saturation and channel switching delay improving the aggregate throughput. LCV-MMAC is simple and does not need any network wide periodic synchronization. It avoids frequent channel switching and channel contention, if there is no significant performance gain.

We explore the properties of LCV-MMAC through extensive simulations with the help of ns-2, and compare it with popular existing multiple channel MAC protocols. Experimental results validate that LCV-MMAC outperforms other single channel and multi-channel MAC protocols in highly congested single-hop and multi-hop network scenarios. LCV-MMAC achieves better aggregate throughput, latency and fairness index.

1.3 Thesis Outline

The rest of this thesis is organized as follows. The use of multiple channels and other forms of diversity in wireless protocols including duty cycling, broadcasting, and coverage is discussed in Chapter 2. The next four chapters present our work on CASBA, DASBA, CMAB, MDC problem, SA-RI-MAC, and LCV-MMAC. In particular, first, Chapter 3 describes the three broadcasting protocols CASBA, DASBA, and CMAB. Following this in Chapter 4, we formulate the MDC problem, present its $\mathcal{NP}$-completeness proof, and present a $\sqrt{n}$-approximation algorithm called MDC-DSC to compute disjoint set covers to achieve maximum disjoint coverage. Chapter 5 discusses the detailed design of SA-RI-MAC, and presents a comparative evaluation of

SA-RI-MAC with a representative asynchronous duty cycle MAC protocol. Chapter 6 describes the detailed design of LCV-MMAC, and presents its comparative evaluation with representative multi-channel MAC protocols. Finally, Chapter 7 presents conclusions and future works.

Chapter 2

Background and Related Work

As described in Chapter 1, our work focuses on efficient broadcasting by adapting to different network conditions, maximum disjoint coverage using disjoint set covers, energy efficiency using duty cycle MAC protocols, and capacity improvement by using multiple channels.

In this chapter, we discuss the general concepts related with the work we studied in our thesis, and the remaining chapters discuss the existing work specific to the topics studied. The organization of the chapter is as follows: In Section 2.1, we give a brief discussion about the broadcasting in wireless sensor networks. We present a general overview of coverage problems in WSNs in Section 2.2. Section 2.3 presents work related with energy efficient MAC and different duty cycle MAC protocols and their limitations. In Section 2.4, we discuss the capacity of WSNs, and different constraints on it. Further in Section 2.4, we discuss existing solutions to alleviate these constraints, the use of multi-channel communication, its classification, and different performance issues related with it.

2.1 Broadcasting in Mobile Ad hoc Networks

Broadcasting is an information propagation process of distributing a message from a source node to all other nodes within a network. Broadcasting is a major communication primitive for many applications in a MANET. It provides middleware functionalities to different applications and network protocols such as consensus [142], multicast [97], and replication [8]. It is one of the major paradigms underlying different route discovery protocols such as Location Aided Routing (LAR) [83], Zone Routing Protocol (ZRP) [60], Dynamic Source Routing (DSR) [76] and Ad hoc On Demand Distance Vector (AODV) [116]. Broadcasting is frequently used to distribute network-wide messages such as alarm signals and advertisement messages. It acts as a reliable communication primitive over multicast in highly mobile networks. It is a well studied topic in MANETs, Vehicular Ad Hoc Networks (VANETs), Wireless Mesh Networks (WMNs), and WSNs. The main objective of broadcasting is to disseminate the message to a maximum number of nodes in a network without any route establishment or maintenance. Figure 2.1 shows an example graph with broadcasting from a source node to all nodes in the network.

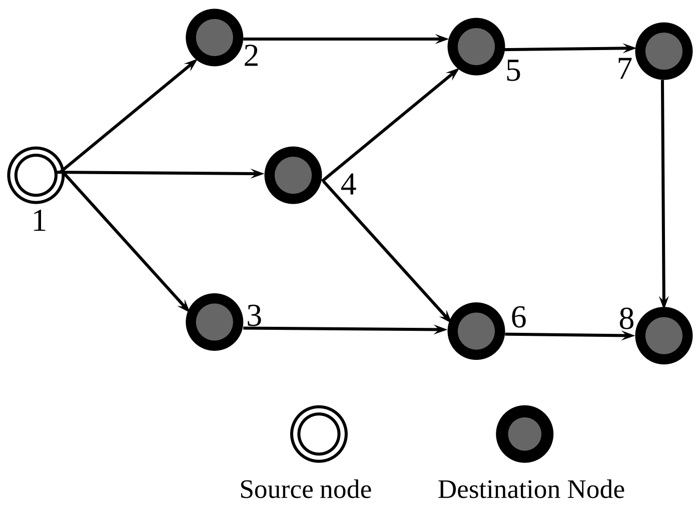


Figure 2.1: A graph with broadcast from source to destination nodes

In a VANET, one application of broadcasting is to disseminate emergency messages to vehicles in some particular area and guarantee that the message is received by all the vehicles to avoid any traffic jams [37]. In WMNs, broadcasting is used to disseminate emergency messages from source nodes to a static or mobile sink or multiple sinks

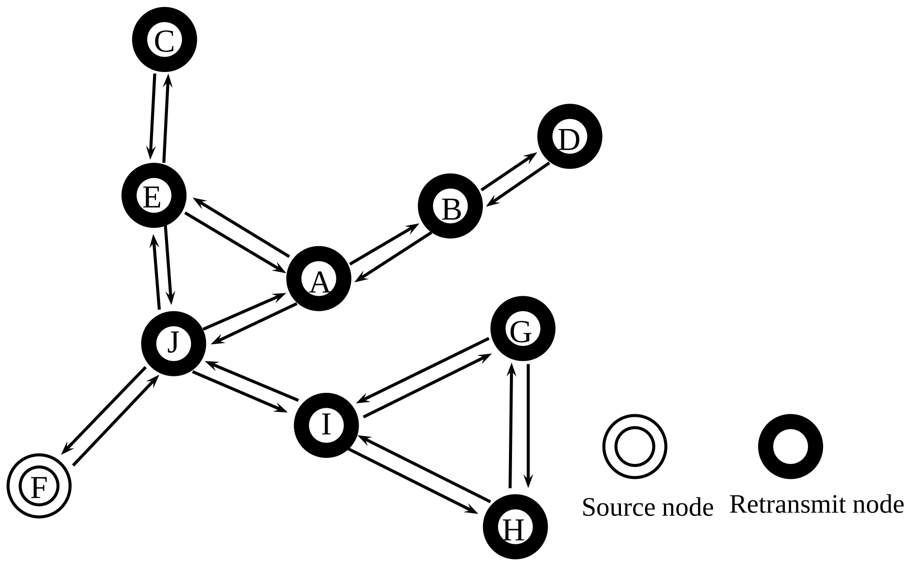


Figure 2.2: Example network with blind flooding

[47]. In [141], a proactive density-adaptive broadcasting protocol has been proposed for WSNs with uncontrolled mobility of the sink.

2.1.1 Classification of Broadcasting Protocols

Broadcasting protocols can be classified into two main categories, i.e., probabilistic and deterministic. Except Section 2.1.1.2, all broadcasting protocols discussed in this section are deterministic.

2.1.1.1 Blind Flooding

One of the earliest broadcasting schemes in both wireless and wired networks is blind flooding. In blind flooding a source node starts broadcasting to all of its neighbours. Each neighbour rebroadcasts the packet exactly once after receiving it for the first time. This process continues until all the nodes in the network have received the broadcast message. Although blind flooding is simple and easy to implement, it may lead to a serious problem known as the broadcast storm problem [109] which is characterized by the contention and collisions in the network. An example network with blind flooding is shown in Figure 2.2, with 9 rebroadcasting nodes and a large number of redundant retransmissions.

2.1.1.2 Probabilistic Broadcasting Protocols

In probabilistic broadcasting protocols [124] nodes forward the broadcast packet with a predetermined probability p after receiving it for the first time. Probabilistic approaches significantly reduce the number of forwarding or retransmitting nodes, however these approaches do not guarantee the full coverage. 100% probability to broadcast a message in the network is equivalent to blind flooding. The main objective of probabilistic broadcasting protocols is to mitigate the network congestion and collisions due to uncontrolled retransmissions of flooding. More efficient probabilistic broadcasting protocols reduce p in dense networks to minimize retransmissions, and increase it in sparse networks to increase coverage.

In counter-based broadcast schemes [109], the rebroadcast decision is made according to the number of times k, a broadcast message is received by a node and comparing it to a predefined threshold K. The value of k is incremented every time a broadcast packet is received by a node during a Random Assessment Delay (RAD) time which is randomly chosen in the interval $[0, T_{max}]$. After the RAD expires, a node evaluates if the value of k exceeds K. If it does, the packet is dropped and otherwise it is rebroadcasted. This scheme minimizes the retransmissions in a dense network because more retransmissions can be cancelled due to a large number of packets being received during a RAD interval. However in a sparse network most of the nodes rebroadcast because only few broadcast packets are received during the RAD interval and thus more retransmissions occur in the network.

2.1.1.3 Area Based Broadcasting Protocols

Area based broadcasting approaches include both distance and location based broadcast approaches. These approaches target the particular area coverage during the

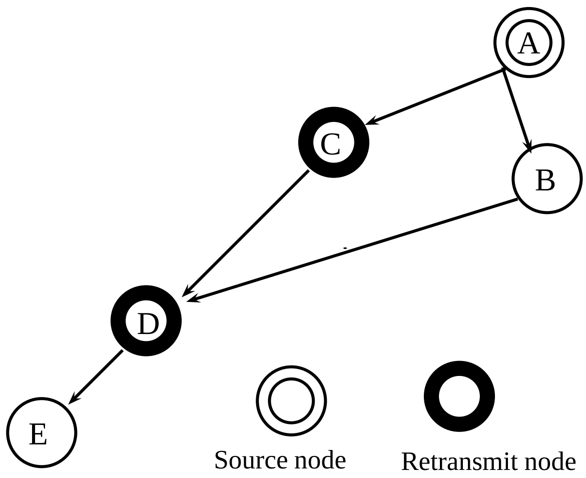


Figure 2.3: Node C provides additional coverage for rebroadcast compared to B so it rebroadcasts

broadcast process, and do not consider if nodes exist within that area or not.

In contrast to the counter-based broadcast approach, in the distance based broadcast [14] approach a receiving node decides to rebroadcast a packet according to the distance between itself and its neighbouring nodes. During the RAD period, the receiving node receives the redundant transmissions from the neighbouring nodes, and compares the distance of these neighbouring nodes with its predetermined distance threshold D. If any of these neighbour's distances is less than a threshold D, it cancels the transmission, otherwise it rebroadcasts it. The distance between a node and its neighbours can be computed by using the signal strength information from the physical layer.

Location based broadcast approaches rely on precise location information to establish an estimate about the additional coverage. Global Positioning System (GPS) [79] can be used to estimate the location information. Source node piggybacks the location information in the packet header before rebroadcasting it. Receiving nodes calculate the additional coverage by retrieving this location information from the packet header. If the additional coverage is less than a predefined threshold, the packet is dropped and rebroadcast otherwise. An example of the location based broadcast approach is shown in Figure 2.3, where node C and B receive the broadcast packet from the source node A, node C provides additional coverage above the threshold therefore C retransmits, whereas B discards the packet.

2.1.1.4 Neighbour Knowledge Based Broadcasting Protocols

The most popular approach in neighbour knowledge based broadcasting protocols is flooding with self-pruning. This approach requires the neighbourhood information for any rebroadcast decision which can be obtained by exchanging periodic HELLO messages. From the neighbourhood information, a receiving node computes the number of additional nodes covered, and rebroadcasts only if any additional neighbours can be covered. In Figure 2.4, node B receives a packet from node A. Node B is a neighbour of node A, therefore it has all the information about neighbours of A, i.e., C,D, E, and G , and about its own neighbours, i.e., F and G which are already covered by A and its 1-hop neighbour C. All the neighbours of B have already been covered by A and its 1-hop neighbour C therefore B will not retransmit the packet.

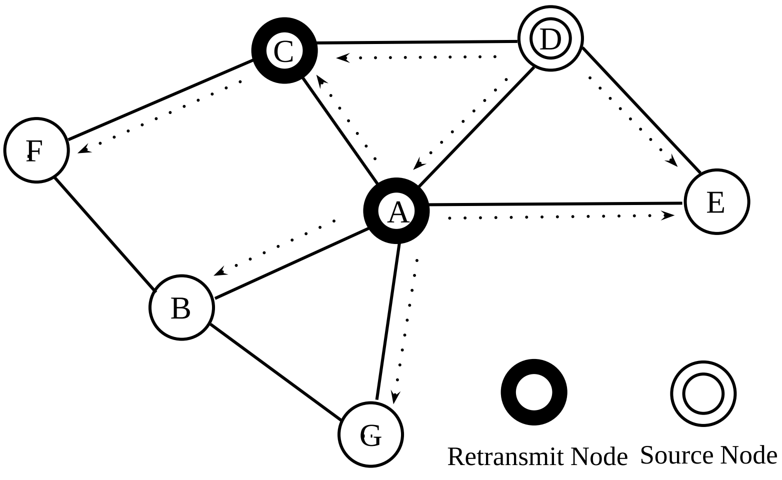


Figure 2.4: SBA: An example of flooding with self-pruning

SBA [114] is an example of flooding with self pruning and is shown in Figure 2.4. AHBP [147] is an example of dominant pruning and is illustrated in Figure 2.5. As shown in Figure 2.5, source node B pro-actively selects A among its 1-hop neighbours as a retransmitting node. Only node A which is selected as a retransmitting node by B will retransmit the packet. The detailed operation of these approaches is discussed in Chapter 3.

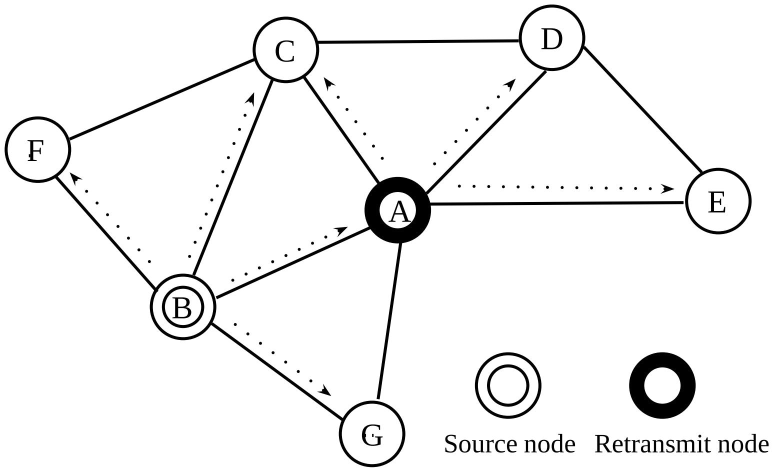


Figure 2.5: AHBP: An example of dominant pruning

2.1.2 Drawbacks of Existing Broadcasting Protocols

- Probabilistic broadcasting and area based broadcasting protocols depend on the number of retransmissions in the network. In sparser networks most of the nodes do not receive redundant transmissions and as a result the number of retransmissions does not exceed the predefined threshold and therefore these nodes most likely retransmit a packet. This results in high number of retransmissions in the network [109].

- Broadcasting approaches which depend on RAD suffer in highly dense MANETs if the value of RAD is not adapted to network congestion.

- Broadcasting approaches which depend on neighbourhood information for rebroadcast suffer in highly mobile networks, where it is difficult to get up-to-date neighbourhood information.

Different comparative studies on broadcasting protocols have shown that existing broadcasting protocols are not suitable under dynamic network conditions. In our work, we propose three broadcasting approaches called CASBA, DASBA, and CMAB which adapt dynamically to different network conditions of congestion, network density, and mobility.

2.2 Coverage in WSNs

A sensor is a device with the capability to respond to different physical stimuli including sound, heat, smoke, pressure, and any other event, and transforms it into corresponding electrical or mechanical signal [146]. These signals are mapped to sensor information. A sensor node consists of one or more sensing units, battery, memory, data processing unit, and data transmission unit. A sensor network consists of different sensor nodes deployed in a geographical region to detect or monitor certain activity. One of the most recent trends in WSNs research is the coverage question which reflects how well a particular area is monitored. Coverage problems in WSNs can arise during the network design, deployment, or operation. During the design of the network, coverage questions can be addressed by deciding the number of sensors to cover a particular area. In deployment, sensors are deployed to achieve the coverage of desired targets or areas in a geographical region. During the operational phase of a sensor network, a schedule is decided to conserve energy and increase network life time. Sensor coverage problems can be divided into two categories:

Area Coverage: [144, 134, 19, 126] where the main objective is to monitor or cover some particular area or whole sensor field.

Target Coverage: [80], where the main objective is to cover some particular points also termed as targets.

Table 2.1 summarises different coverage approaches with type of coverage and objectives in WSNs. Our work in this dissertation is related with target coverage, therefore we discuss different problems related with the target coverage only.

Method	Type of Coverage	Main Objectives
Disjoint dominating sets [17]	Area coverage	Maximize network lifetime and energy efficiency
Coverage Configuration Protocol (CCP) [144]	Area coverage	Improve connectivity and energy efficiency
Coverage based on CDS [149]	Area Coverage	Maximize network lifetime and energy efficiency
Placement algorithm for nodes [80]	Area coverage and Target coverage	Coverage and connectivity
Disjoint set cover algorithm [16]	Target coverage	Coverage using maximum number of set covers and energy efficiency
Density control algorithm based on probing [156]	Area coverage	Coverage using maximum number of set covers and energy efficiency
Optimal Geographical Density Control (OGDC) Algorithm [165]	Area coverage	Coverage using maximum number of set covers, energy efficiency, and connectivity
Self scheduling algorithm for nodes [134]	Area coverage	Coverage using maximum number of set covers and energy efficiency

Table 2.1: Coverage approaches used in WSNs

2.2.1 Target Coverage Problems

In the target coverage problem, the objective is to cover some particular set of points or targets in a sensor field, for example, missile launchers in a battlefield. These targets can be covered by using a random or deterministic deployment of sensor nodes.

2.2.1.1 Optimal Placement of Sensor Nodes

In the deterministic approach to node placement, nodes are placed at pre-determined locations to cover targets. The deterministic approach to node placement is convenient to use for reachable and friendly sensor fields. The main objective of this approach is to cover optimal locations by using a minimum number of covering nodes. In this approach, it is assumed that the locations of targets to be monitored are known, and limited. In some cases, coverage of all the targets is not necessary, when the number of covering sensors are limited or it is expensive to cover them. Most of the problems related to sensor placement are optimization problems, and it is possible to formulate them as mathematical programming problems. However, greedy solutions may not produce the best possible placement. The problem to compute a minimum number of covering sensors to cover targets is equivalent to the set cover problem [33]. Covering sensors can be represented as set covers to cover particular targets or area. To place a covering sensor, it must be placed on a location to cover at least one target, and it is possible to cover all the targets if the covering sensors are deployed on all the available locations. Different variants of the greedy approach for set cover have been proposed in the literature to solve various problems related with node placement [39, 40, 167, 48]. Apart from greedy algorithms, several approximation solutions have also been proposed for node placement [93, 94].

2.2.1.2 Coverage Lifetime Maximization

In a random deployment of sensor nodes, sensor nodes are randomly scattered to cover targets. In random deployment, a single sensor may cover more than one target, and a target may be covered by more than one sensors. Deployment of sensors in random placement may be dense. The coverage lifetime maximization problem which is a variation of the target coverage problem is to partition the sensors into more than one set covers subject to certain coverage requirements, and to activate these set covers alternately to increase the network lifetime. An example of target coverage is illustrated in Figure 2.6a, where 6 sensors are deployed to cover 4 targets in a random setting. In Figure 2.6a the T_2 and T_4 targets are covered by two sensors, and T_1 and T_3 are covered by three sensors. The coverage relationship between the sensors and targets can be represented by a bipartite graph as shown in Figure 2.6b.

In order to achieve the target coverage, all the sensors can be activated which is not an energy efficient solution and reduces the network lifetime. However alternatively activating the sensors may prolong the network lifetime. Assume that if all the sensors are activated for one unit of time, it will result in a network lifetime of one time unit. In Figure 2.6, we can have two disjoint set covers $S_1 = \{s_1, s_3, s_6\}$, and $S_2 = \{s_2, s_4, s_5\}$ to cover all the targets. For one time unit set S_1 can be activated, and for the other S_2, increasing the network lifetime to two time units. Using an optimal number of set covers and alternatively activating them may maximize the network lifetime.

Another variation of the target coverage problem is Maximum Set Cover (MSC), in which the main objective is to cover all the targets at all times. The MSC problem is known to be $\mathcal{NP}$-complete [18]. Target coverage at all times is a strict requirement for the coverage. The k-set cover for minimum coverage breach problem allows coverage breach and relaxes the strict coverage requirement [25]. A breached target is not covered by any sensor, or in other words breach coverage requires partial target coverage only. In this problem, set covers are computed to cover a fraction of targets only, and are activated alternatively for short duration. The main objective of the k-set cover problem is to maximize the network lifetime by computing maximum number of k set covers [25, 1, 38]. In [25], a problem called Disjoint Set Covers (DSC) has been proposed for complete target coverage which is similar to the MSC problem with disjointness constraints. Energy efficiency using disjoint set covers to alternatively perform the coverage task has been discussed in [18] and [126].

Slijepcevic and Potkonjak [126] address the area coverage problem, where points enclosed in a particular area called fields are covered by the same set of sensors. The algorithm [126] covers the most critical targets by using a maximum number of set covers. In this algorithm, the set covers which can cover a high number of uncovered fields are given priority. This algorithm also avoids field coverage redundancy. There exist several distributed solutions which can achieve 1-coverage, i.e., can cover the target or area by using only one set cover. In [134], a pruning method has been proposed, where each node turns its radio off if its area can be covered by some of its neighbours. In [126], a centralized solution to achieve k-coverage by using k disjoint set covers has been proposed. A distributed solution for the same problem has been proposed in [1].

In our work, we formulate a variation of the target coverage problem called MDC. MDC problem is to achieve the maximum disjoint coverage using two disjoint set covers S_1 and S_2. Our problem aims to find a set cover S_2 to maximize the target coverage in such a way that disjoint set cover S_1 still completely covers all the targets.

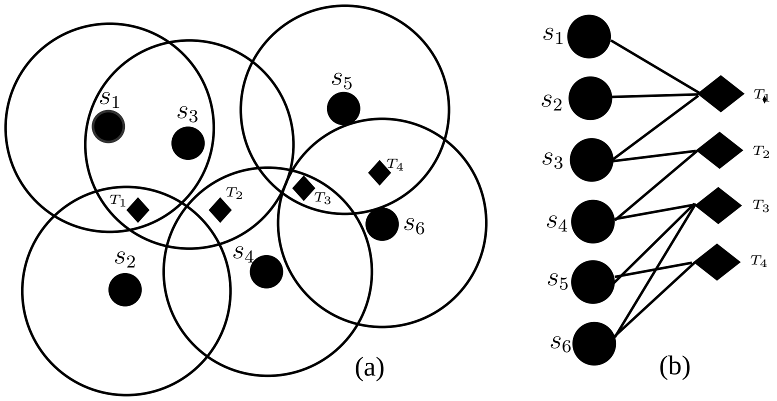


Figure 2.6: (a) Random deployment of sensor nodes (b) Corresponding bipartite graph for (a)

2.3 Energy Efficient MAC Protocols for WSN

Idle listening is one of the major sources of energy consumption in WSNs. Duty cycling is one of the efficient mechanisms to reduce idle listening.

2.3.1 Duty Cycling

In duty cycling, the radio of a node alternates between active and sleep states periodically to conserve energy [21, 35, 111, 77, 155]. A cycle consists of a listening and a sleep period called sleep/wake-up periods as shown in Figure 2.7. The ratio of listening period to sleep/wake-up period is known as the duty cycle and indicates the fraction of time of a node spends listening. A low duty cycle indicates that most of the time a node is in the sleep state to avoid overhearing and listening.

With a 10% duty cycle, a MAC protocol turns its radio on only 10% of the time to conserve energy. During the active state, a node transmits or receives data while during the sleep state a node turns its radio off completely. The choice of an appropriate duty cycle is very critical to avoid higher delays and higher energy consumption. Low duty cycle MAC protocols with duty cycles of $1 - 10\%$ are typical to conserve energy in WSNs.

The main objective of low duty cycle MAC protocols is to minimize the idle listening, and unnecessary overhearing by turning a node's radio off. These protocols target a condition, where a node is in the sleep state most of the time and wakes up to transmit and receive packets only. In order to detect any activity on the channel, a node wakes up periodically. If no activity is detected, it turns its radio off.

Duty cycle protocols vary with respect to the number of channels used, synchronization, and sender or receiver initiated approach. Further, duty cycle protocols can be classified into two major categories: asynchronous and synchronous approaches. Asynchronous approaches can be receiver-initiated or transmitter-initiated. In the transmitter-initiated approach, the transmitter frequently prompts the receiver until it hits its listening period, whereas in the receiver-initiated approach, it is the receiver who informs the sender nodes when it will be ready to receive the packets.

In the synchronous approach to low duty cycle MAC protocols, all nodes share the same wake-up phase. In this scheme, nodes frequently exchange beacon frames to inform the neighbouring nodes about their sleep/wake-up cycle schedule, and any pending data. Other nodes schedule their transmission and reception according to the schedule information obtained from the beacon frames. Synchronous approaches require frequent resynchronization with the neighbouring nodes which results in significant amount of energy consumption. In the following sections, we discuss both synchronous and asynchronous low duty cycle MAC approaches.

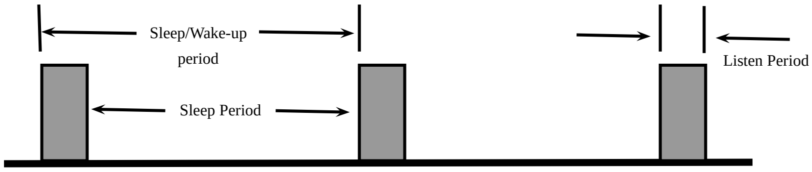


Figure 2.7: A duty cycle scheme with periodic sleep/wake-up

2.3.1.1 Synchronous Low Duty Cycle MAC Approaches

Synchronous low duty cycle MAC approaches are based on a predetermined periodic wake-up schedule which consists of an active period T_{active} and a sleep period T_{sleep}. Nodes periodically broadcast this schedule information to the neighbouring nodes. Neighbouring nodes use this schedule information to align their active and sleep periods. During the active time T_{active}, nodes wake up to transmit any data, and sleep during T_{sleep}. Synchronous low duty cycle MAC approaches reduce idle listening significantly but require synchronization which adds complexity in their implementation. In large scale networks, where global synchronization is difficult to achieve, small groups/clusters are used to achieve the synchronization. S-MAC [157] is a popular synchronous duty cycle MAC protocol which reduces idle listening significantly, however, if nodes are in the sleep mode, a transmission has to be deferred until the nodes are active for the next time which adds significant latency in the packet delivery. In order to improve the delivery latency of S-MAC, the authors of S-MAC proposed a modification to S-MAC with adaptive listening [145], where nodes overhearing a Request To Send (RTS) or Clear To Send (CTS) packet remains awake for a short interval, and can forward the packet to the next hop without delaying it for the next operational cycle. S-MAC with adaptive listening is able to forward the packet up to 2-hop neighbours only as beyond 2-hop neighbours, nodes are unlikely awake to overhear communication. S-MAC with adaptive listening may result in significant energy consumption, where multiple neighbours may overhear RTS/CTS packets, and only one will forward it to the next hop.

T-MAC [100] extends or shortens the data periods according to the traffic around the nodes to conserve more energy. It shortens data periods if there is no traffic around the node, and extends them to accommodate multiple transmissions. Similar to S-MAC with adaptive listening, T-MAC can forward the packets up to 2-hop neighbours only. This scheme also results in significant amount of energy consumption as many nodes remain awake other than the intended next hop. DMAC [100] reduces the latency of data gathering from the source nodes to the sink node in a tree based topology. On the other hand, DW-MAC [131] supports in-network processing of data in arbitrary topologies. RMAC [42] reduces the latency of packet delivery in multi-hop network scenarios. However, during an operational cycle, the number of forwarding hops is limited and depends on the size of the data period.

2.3.1.2 Asynchronous Low Duty Cycle MAC Approaches

Asynchronous approaches [45, 117, 13] to low duty cycle MAC allow nodes to maintain their own duty cycle schedule independently. Asynchronous approaches rely on frequent channel sampling to detect the activity of the neighbouring nodes. Low Power Listening (LPL) is one of the channel sampling approaches used to detect the activity of neighbouring nodes. In LPL, the sender transmits a preamble packet lasting for a duration equal to the sleep period of the receiver prior to any transmission. Upon detecting the preamble, the receiver stays awake to receive data. Asynchronous approaches do not require global knowledge about the neighbouring node's schedule, and therefore reduce memory consumption. However long preambles cause high transmission energy. In order to reduce this transmission energy consumption on the sender side, receiver initiated duty cycle MAC approaches are used.

X-MAC [13] and B-MAC [117] are the first asynchronous approaches to low duty cycle in sensor networks. In B-MAC, upon detecting channel activity a node remain awake to receive any incoming packet. On the other hand, the sender sends a long preamble to prompt the receiver. B-MAC may result in significant amount of energy consumption because nodes may stay awake periodically to detect any channel activity even if the DATA is not destined for them. X-MAC [13] uses a strobed preamble consisting of a sequence of small preambles prior to any transmission to avoid unnecessary overhearing of preambles with long duration. After receiving a packet, the receiver stays awake for a duration equal to the maximum backoff window size to receive any queued packets. Another variation of X-MAC known as Unified Power Management Architecture (UPMA) for WSNs [154] uses the DATA frame itself to act as a preamble. If the receiver sends an acknowledgement back to the sender, it continues with its transmission.

Both X-MAC and B-MAC are optimized for power efficiency for light traffic loads, but for contending flows these schemes become less efficient as long preambles used by them occupy the medium for a long time. RI-MAC [132] avoids these preambles by using receiver initiated transmissions. WiseMAC [44] computes the length of the preamble by sampling the schedules of its neighbours, which significantly reduces the length of the preamble. However, hidden nodes may cause collisions due to the same sampling schedules.

The concept of receiver-initiated transmissions in duty cycle MAC protocols is not new, but to our best knowledge, our proposed approach SA-RI-MAC represents the first attempt to combine the idea of receiver-initiated transmissions with sender assisted contention resolution in duty cycling in the context of MAC approaches for WSNs, where energy efficiency is a major issue.

2.4 Delivery Capacity of WSNs

Gupta and Kumar [59] established the asymptotic capacity to transport point-to-point traffic in a random deployment of sensor nodes in the network. Accordingly, the achievable throughput per node in a wireless network with n randomly located nodes and randomly chosen destinations is bounded by:

$$throughput/node = \Theta(W/\sqrt{n \log n}) \tag{2.1}$$

where n denotes the number of nodes in the network, W represents the transmission capacity and Θ is an asymptotic notation and represents that the throughput/node is bounded both above and below by $W/\sqrt{n \log n}$ up to constant factors. For optimal placement of nodes in a disk of unit area with optimal transmission range, they have given the bound for achievable throughput to each node for a distance of the order of $1m$ away as follows:

$$throughput/node = \Theta(W/\sqrt{n}) \tag{2.2}$$

Grossglauser et al. [58] extended Gupta and Kumar's work and proved that it is possible to improve the achievable capacity in mobile networks, where mobility can help to reduce the number of hops between the source and destination, and therefore reduces the contention in the network. [56] achieved an improved bound on the achievable capacity by introducing relay nodes, which act only as forwarding nodes to assist delivering the data to the destination without generating any traffic. The majority of the WSN applications are event based and therefore involve the reporting of the event to the sink following a many-to-one communication pattern. [43] investigates the capacity of WSNs in such scenarios, and presented a trivial upper bound on per node throughput as W/n. They assume that the sink is equipped with a half-duplex transceiver. The bound W/n follows because the sink is busy 100% of the time in receiving data from n nodes with same data rates in the network. However, this bound is achievable only in scenarios, where the nodes in the network can send data directly to the sink, and therefore it is not applicable in multi-hop scenarios.

2.4.1 Limiting Factors on the Capacity of Wireless Networks

Half duplex transceivers, limited bandwidth capacity, contention, and interference are major limiting factors on the capacity of wireless networks. Wireless nodes are equipped with radios which have channels with limited bandwidth. The data rate of these channels is limited to kilobits per second. Radios like $CC2420$ with a data rate improvement of $250kbps$ were introduced where each channel is allocated $5MHz$ of spread spectrum band [26]. Recently, IEEE 802.11g Wireless LAN (WLAN) standard has been introduced with a data rate of $54Mbps$ [29].

The half duplex nature of transceivers allow nodes to transmit or receive data at a time, and nodes are not able to receive transmissions from more than one senders. This causes a problem known as the "Destination Bottleneck", where the capacity of the network is constrained according to the receiving capacity of the destination node [89]. In order to improve the limited receiving capacity of the destination nodes, one viable solution is to equip the wireless nodes with more than one radio, however this solution is expensive due to energy constraints [88, 6, 101].

Due to the shared and broadcast nature of wireless medium, simultaneous transmissions cause interference where parallel transmissions may conflict with each other. However, if interference weakens the signal significantly and it is not possible to decode the signal correctly at the receiver, it results in a collision. One of the recent research trends is to increase the interference free spatial reuse. Several MAC protocols have been proposed to alleviate the interference by using different methods. Examples include TDMA, Frequency Division Multiple Access (FDMA), CSMA, and Code Division Multiple Access (CDMA). TDMA mitigates the interference by scheduling the transmissions in different time slots, on the other hand FDMA schedules them on different frequencies. CDMA allows simultaneous access to the shared medium by assigning unique spreading codes to these transmissions. CSMA is a probabilistic technique which senses the medium for its availability prior to any transmission. A detailed discussion about these medium access techniques can be found in [37, 90, 88]. Transmission power control is also one of the mechanisms to alleviate interference in wireless networks [46, 87, 128, 161]. In transmission power control, it is possible to alleviate the interference by limiting the transmission power of radios. According to Moscibroda [107], it is possible to achieve unbounded improvement in asymptotic capacity by using non-linear power assignment in data aggregation applications in WSNs [106]. The use of directional antennas in place of omnidirectional antennas is also a solution which can be used to improve the spatial resuse, where parallel transmissions are possible depending on the direction of antennas [159].

Different from the previous work, we consider the use of multiple channels to mitigate the effects of interference and therefore improve the capacity of wireless networks.

2.4.2 Use of Multiple Channels in Wireless Networks

A MAC protocol is used to resolve the contention and collisions while accessing the medium. The majority of the MAC protocols use a common shared channel based on the IEEE 802.11 standard known as single channel MAC protocols [50, 9, 96, 95, 82, 81]. However, the performance of these protocols degrades with an increase in contention or collisions in the network. There is a potential in the IEEE 802.11 standard to exploit multiple frequencies to relieve contention and collisions by enabling transmissions on different non-conflicting frequencies. Kysanur et al. [89] have extended the capacity analysis of Gupta and Kumar [59] to investigate the capacity of multi-channel wireless networks. In their analysis, they showed that multi-channel communication can significantly increase the capacity of wireless networks, even if the number of transceivers is less than the number of channels.

2.4.3 Classification of Multi-Channel MAC Protocols

Multi-channel MAC protocols can be classified according to different channel assignment techniques. A brief discussion on these techniques is given below.

2.4.3.1 Static Channel Assignment

In static channel assignment, radio interfaces are assigned a fixed frequency for the communication. A radio can be tuned to a different frequency, however during the communication channel switching is not supported. The main objective of static channel assignment is to use multiple radios, each of which is tuned to a different channel to support concurrent transmissions. Channels are assigned to different radios to minimize the interference. Several approaches based on static channel assignment are discussed in [121, 122, 2, 104, 3, 84]. Such approaches are often graph-theoretic, and are based on interference models. Further, the static assignment of channels reduces the effectiveness of these approaches.

2.4.3.2 Dynamic Channel Assignment

In dynamic channel assignment, a radio is able to switch over a set of channels dynamically with negligible switching delay. Channel selection or switching can be performed prior to every data transmission. Compared to static channel assignment, this approach has a significant performance improvement even with a single radio interface. This approach can utilize the interference information prior to channel selection. Multi-channel MAC approaches based on dynamic channel assignment suffer from problems of multi-channel hidden terminal, deafness, channel switching delay, and control channel saturation. Dynamic channel assignment approaches can be further classified into three more categories according to the methods of coordination as discussed below.

Split Phase

Split phase divides the access to the channel into two phases: a data exchange phase and a control phase. During the control phase, nodes complete their channel negotiation by switching to the common control channel and reserve the data channel to be used during the data exchange phase. Access to the channel during the control phase is contention-based. During the data exchange phase, both sender and receiver tune to the channel selected during the control phase, and transfer data. Different channel access mechanisms can be used during the data exchange phase and can vary from sender or receiver's own schedule to contention-based. MMAC is an example of a contention-based protocol [127]. On the other hand, TMMAC [164] and Multi-channel Access Protocol (MAP) [23] are examples of protocols using scheduled access. Split phase provides benefits by eliminating hidden terminal and deafness problem. However, this approach requires time synchronization among the nodes, has high channel switching delay and suffers from underutilization of data channels during the control phase. Operation of split phase is illustrated in Figure 2.8a. In the Figure 2.8a both sender and receiver exchange the channel information to be used for the data phase by exchanging RTS and CTS packets during the control phase. During the data phase both sender and receiver tune to the selected data channel, and complete the transmission.

Common Frequency Hopping

In multi-channel MAC approaches based on frequency hopping, nodes switch over a set of available channels. Two different variations of frequency hopping exist: independent hopping and common hopping. In the independent frequency hopping, nodes hop according to their own hopping frequency sequence. In order to exchange the hopping sequence with the source node, nodes switch to a common channel after following their frequency sequence. The source node hops according to the destination's hopping sequence to transmit data. Slotted Seeded Channel Hopping (SSCH) [7] and McMAC [105] are examples of multi-channel MAC approaches based on independent hopping sequence. On the other hand, in common frequency hopping approaches, the same frequency hopping sequence is negotiated to transmit data. In this approach nodes stay switched on the same channel for the transmission, and afterwards resume from the negotiated frequency hopping sequence. HRMA [133] and CHMA [136] are examples of common frequency hopping approaches. One of the main advantages of frequency hopping over dedicated control channel, and split phase is the elimination of negotiation overhead to exchange channel information. Once the hopping sequence has been negotiated, nodes can hop according to the hopping sequence.

On the downside, these approaches require tight synchronization and have significant channel switching overhead. The operation of common frequency hopping is shown in Figure 2.8c. In order to transmit data both sender and receiver exchange RTS/CTS and after successful RTS/CTS exchange both sender and receiver stay on the same channel. However, other nodes continue to hop during this time. After DATA transmission, both sender and receiver resume with the common hopping sequence of all other idle nodes. Nodes can wrap around the hopping sequence, and refrain from transmitting on a channel if it is busy.

Dedicated Control Channel

Multi-channel MAC approaches based on dedicated control channel use a common control channel to exchange the control packets and to negotiate the channel information. DCA is an example of a multi-channel MAC protocol based on dedicated control channel. DCA utilizes two interfaces, one of which is permanently tuned to the control channel which is used to negotiate and exchange channel usage information with the neighbouring nodes. DCA [152] keeps up-to-date channel usage information due to a dedicated interface for the control channel, however this technique requires an extra resource and therefore adds expense. Other examples of dedicated control channel based approaches include Dynamic Channel Assignment with Power Control (DCA-PC) [153] and Dynamic Private Channel (DPC) [69]. One of the major advantages of dedicated control channel based approaches is that they do not need any synchronization and therefore they are easy to implement. However, these techniques are prone to the control channel saturation problem [74]. Other drawbacks of this approach include the multi-channel hidden terminal problem and deafness. The operation of dedicated control channel based approaches is shown in Figure 2.8b. In the Figure 2.8b, channel 0 is selected as a control channel, and the other 3 are selected as data channels. When the sender wants to send data to a receiver, the sender sends an RTS packet to the receiver and also appends the preferred channel information to it.

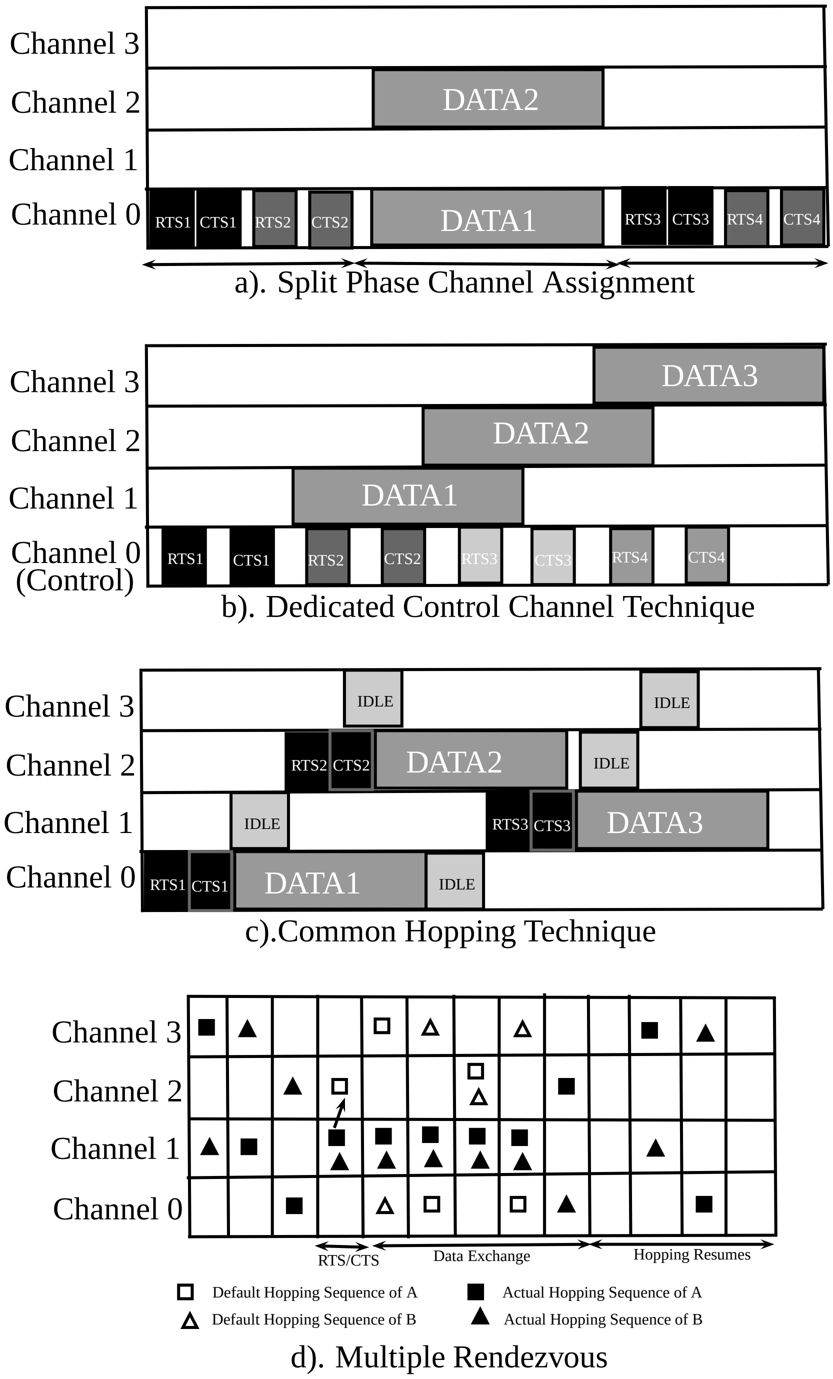


Figure 2.8: Different Multi-channel MAC Approaches

The receiver responds with a CTS packet upon receiving RTS packet, and confirms the channel selected by the sender. Similar to 802.11, the sender appends a Network Allocation Vector (NAV), which is equal to the duration for which both sender and receiver will be busy during the transmission on the selected data channel. The use of dedicated control channel keeps neighbouring nodes informed about the status of channels, and therefore neighbouring nodes can avoid selecting the busy channel for transmissions.

Multiple Rendezvous Approach or Independent Frequency Hopping

The multiple rendezvous approach or independent frequency hopping is a variation of frequency hopping and is based on the motivation to control channel bottleneck problem. In this approach, different nodes can make an agreement to use distinct channels. Since this approach utilizes multiple channels, to rendezvous on different channels, special coordination is required among the nodes. McMAC is an example of frequency hopping with multiple rendezvous. Its operation is shown in Figure 2.8d, where each node generates an independent hopping sequence by using a pseudo-random number. Nodes share this seed with the neighbouring nodes to help them know about their hopping sequence. Node A transmits to node B with probability p during each time slot. To transmit data, A tunes to B's current channel and sends an RTS. If no CTS is received from B for a specified amount of time, B tries to retransmit with probability p. Upon receiving CTS from B, both A and B stop hopping and exchange the data. The transfer of data may take several slots to complete the transmission. After completing, both A and B resume their original hopping sequence.

Further work related with different channel assignment techniques in multi-channel MAC protocols is presented in Chapter 6. In our work, we present a dedicated control channel based MAC approach called LCV-MMAC which increases the capacity of wireless networks in different network scenarios by mitigating channel switching delay and the control channel saturation problem. Our approach allows nodes to avoid unnecessary channel switching and channel contention during the control channel saturation, and mitigates the control channel saturation problem.

2.4.4 Performance Issues in Multi-Channel Communication

Multi-Channel Hidden Terminal Problem

In multi-channel wireless network scenarios, the multi-channel hidden terminal problem is an inborn problem [74]. This problem arises when a node is not able to listen to the handshake procedure on the control channel while it was busy on the data channel for transmission. This node has no information about the channel being reserved by the other nodes during the handshake procedure and therefore may inadvertently select the same data channel for the next transmission, thus causing a collision. Dynamic Channel Assignment (DCA) [152] solves the multi-channel hidden terminal problem by using two transceivers, one of which is permanently tuned to the control channel and a node is able to listen on the control and data channel simultaneously, however this solution is expensive. Multi-channel MAC (MMAC) [127] solves this problem by using a split phase approach where handshake occurs during the control phase, and therefore neighboring nodes have information about the channel usage. Another possible solution to reduce the multi-channel hidden terminal problem is careful channel selection.

Missing Receiver Problem or Deafness

Another common problem in multi-channel MAC protocols is the missing receiver or deafness problem, which occurs when a receiver is not able to receive the control packets because it was busy in transmission on some other channel and therefore is not able to respond. Missing receiver problem persists in the protocols, where a dedicated control channel is used to exchange the control messages. This problem induces an increased number of retries resulting in congestion, delay and unfairness [52]. DCA [152] avoids this problem by using multiple transceivers, one of which is always tuned to the control channel, and therefore the receiver cannot miss any control packet. MMAC [127] uses the control phase to exchange any channel information, and therefore the receiver cannot miss the channel information.

Channel Switching Delay Problem

Multi-channel MAC methods based on dynamic channel assignment require unnecessary switching of the radio on different channels without any performance gains, which adds delay, and increases the overhead of channel negotiation and coordination. In IEEE 802.11b, the time required to switch from one channel to another is $224\mu s$ [4] , and in Chipcon $CC2420$ radio it is $300\mu s$ [26].

Control Channel Saturation Problem

In dedicated control channel based MAC approaches, the control channel has significant impact on the aggregated throughput of the data channels. Compared to the three other categories of multi-channel MAC protocols, i.e., split phase, frequency hopping, and multiple rendezvous, dedicated control channel based approaches do not need any synchronization and therefore are simple to implement. However, one of the drawbacks of such approaches is the control channel saturation problem due to channel negotiations. This may result in underutilization of data channels. This problem has been discussed in detail in [105] and [143]. DCA [152] is an example of a multi-channel MAC protocol which is prone to the control channel saturation problem. Certain dedicated control channel approaches based on the IEEE 802.11 MAC standard have been proposed with improved performance. In [153], the original MAC design has been improved in terms of energy efficiency, however the control channel saturation problem has not been addressed. In [49], an approach is proposed to reduce the underutilization of data channels due to the control channel reservation process. This scheme improves the aggregated throughput of data channels when the control channel is not saturated.

Chapter 3

Cross Layer Broadcasting in Mobile Ad hoc Networks

3.1 Introduction

Broadcasting is a fundamental operation in MANETs where a source node disseminates the same message to all the nodes in the network. Broadcasting to all nodes is used extensively in MANETs, such as to discover routes in several routing protocols [75, 113, 115], error reporting [112], or as a building block for reliable multicast in fast moving ad hoc networks [67]. The simplest broadcasting approach is blind flooding, in which each node is obligated to forward the broadcast packet exactly once in the network whenever it receives the packet for the first time. Blind flooding causes redundancy that may lead to broadcast storm problem which results in high bandwidth and energy consumption devastating network performance enormously. This problem can be alleviated by reducing the number of redundant transmissions. Therefore, the main objective of efficient broadcasting techniques is to reduce the broadcast redundancy while reaching to a maximum number of nodes in the network, which minimizes the bandwidth wastage and computational overhead.

In mobile ad hoc networks, mobility, network congestion, and link transmission errors are major causes of data loss [62]. Designing reliable, efficient, and robust broadcasting protocols in MANETs is challenging. A broadcast protocol must be bandwidth efficient, reliable, and should give the maximum coverage under different network conditions of mobility, network congestion, and node density. In a mobile network, congestion may occur at time intervals when the incoming traffic exceeds the capacity of the network. This can adversely increase the packet loss and delay, and significantly degrades the network throughput. The main objective of congestion adaptive broadcasting schemes is to lower the end to end delay, and the packet loss in the network, thus offering better network performance. In broadcasting, congestion may take place at any intermediate nodes when the packets are traversing from source to destination. Recent research on different broadcasting techniques [110, 120] reveals that it is indeed possible to decrease the broadcast redundancy. Keeping this fact in consideration, several efficient broadcasting schemes have been proposed which ensure improved performance of these protocols. These broadcast schemes perform well when the congestion is not very high. A few of them adapt to some extent to the network congestion, but lack an efficient mechanism to distinguish packet losses due to congestion from mobility-induced losses [62].

MANETs can be classified as sparse or dense depending on the node density, which is defined as the number of nodes deployed in a fixed area. In a dense network, the same transmission range is shared by multiple nodes. This results in a highly connected network which improves the reachability but at the same time may result in a higher number of retransmissions which may lead to the broadcast storm problem [109]. On the contrary, in a sparse network the coverage area shared among the nodes is smaller; thus due to lack of connectivity some nodes may not receive some of the broadcast packets [114].

Network connectivity evolves over time due to node mobility which induces the changes in the spatial distribution of nodes in the network. In a mobile network, different nodes may follow different movement patterns with varying speeds, and therefore evolve network connectivity in an arbitrary way. More specifically, mobility can continuously change the local node density and may result in network partitioning. A relay node is not able to send the broadcast packet to a node which has link failure due to mobility, thus reducing the reachability significantly. Blind flooding is considered most reliable in highly mobile network scenarios; however it may lead to the broadcast storm. Most of the existing broadcasting schemes do not consider the mobility of the nodes and therefore do not consider the dynamics of topology. Others try to adapt to node mobility but at the expense of increased number of redundant retransmissions.

Different efficient broadcasting schemes have been proposed by different research groups while ensuring the improved performance of these protocols in different network scenarios. Some schemes perform well in congestive scenarios while suffering in highly dense networks. None of these efficient schemes adapt to both the network conditions of congestion and network density simultaneously. Furthermore, most of the existing broadcasting schemes are not mobility tolerant, and therefore under high mobility the performance of these protocols suffers.

In this chapter we present a simulation based performance analysis of some popular existing broadcasting schemes. We analyze the effect of congestion, node density, and mobility on the performance of these broadcasting schemes. Three important metrics, notably reachability (defined as the fraction of nodes that receive the broadcast message), broadcast cost (average cost to deliver a broadcast message to all the nodes in the network), and broadcast speed (delay) are used to assess the performance of these protocols. From the simulation results, it is apparent that these factors have significant impact on the performance of all the broadcasting techniques.

We propose two adaptive cross layer broadcasting protocols CASBA and CMAB. CASBA is based on a well known broadcasting protocol SBA and has significantly better performance in highly congestive network scenarios. Simulation results of CASBA have shown excellent reduction in broadcast latency and broadcast cost while improving reachability. Further, our proposed cross layer mobility adaptive broadcasting protocol CMAB handles the mobility in mobile ad hoc networks. The proposed protocol balances the retransmission redundancy by avoiding the broadcast storm problem and increases the reachability in highly mobile and denser network scenarios. We propose a third broadcasting protocol called DASBA which is also based on SBA, and it improves the reachability in sparser and mobile network scenarios. In particular, in this chapter we make the following contributions:

- We evaluate the performance of several popular broadcasting protocols under different conditions of congestion, node density, and mobility with network simulator ns-2 [138]. Our objective is to observe the efficiency (average cost to deliver a broadcast message to all the nodes), reliability (reachability) and end-to-end delay (broadcast speed) as a function of network congestion, node density, and mobility and determine if these protocols are practical in congestive, sparser, denser, and highly mobile network scenarios.

- We also present two adaptive extensions to SBA. These extensions adapt according to the network conditions of congestion and node density. Our first extension CASBA uses a cross layer mechanism for congestion detection and adapts to it. Our second extension to SBA known as DASBA improves the performance of the SBA by adapting to the local node density and link information. Simulations are performed to evaluate the performance of our proposed extensions, i.e., CASBA and DASBA. The simulation results demonstrate that CASBA can achieve better reachability while reducing the broadcast redundancy significantly. Simulation results of DASBA have shown an excellent improvement in broadcast speed and reachability in case of sparse and mobile networks.

- We point out some of the deficiencies of AHBP-EX, AHBP, and MPR protocols, which affect their reachability in highly mobile scenarios and do not eliminate frequent retransmissions. We describe a broadcasting protocol called CMAB which utilizes the 2-hop neighbourhood and cross layer mobility information to effectively control the number of rebroadcasts while achieving good reachability and broadcast speed. We conducted simulations with ns-2 to verify that CMAB outperforms other broadcast protocols under conditions of high mobility and high node density.

The remainder of the chapter is organized as follows: Section 3.2 examines some of the related work with existing broadcasting protocols. In Section 3.3, we discuss some of the preliminaries related with our work in this chapter. In Section 3.4, we discuss the motivation for the work in this chapter. Section 3.5 provides a simulation based analysis of the effect of congestion, node density, and mobility on some popular existing broadcasting protocols. Section 3.6 discusses briefly the cross layer model. In Section 3.7 , we present our proposed cross layer broadcasting protocols, i.e, CASBA and CMAB, and their experimental evaluation. In Section 3.8, we present our density adaptive broadcasting protocol DASBA and its experimental evaluation. Section 3.9 concludes the chapter.

3.2 Related Work

3.2.1 Flooding with Self-Pruning

Flooding with self pruning is the simplest neighbour knowledge based broadcast method [66, 22]. This is an effective approach to reduce the number of retransmissions in the network. This approach requires that each node has the knowledge of its 1-hop neighbours which can be achieved by exchanging periodic HELLO messages. A node decides its status as a forwarding or non-forwarding node (self-pruned) depending on the information received from the incoming broadcast message. If the receiving node can cover some additional nodes, it rebroadcasts the message otherwise it discards it. Forwarding nodes including the source of the broadcast packet form a connected dominating set (CDS) to achieve the coverage.

3.2.2 Scalable Broadcast Algorithm (SBA)

SBA [114] requires that all nodes in the network maintain knowledge of up to 2-hop neighbours by exchanging HELLO messages. The HELLO packet contains the node

ID and the list of all of its neighbours which are known. SBA is based on a self-pruning approach, where a node rebroadcasts only if it can cover some additional nodes which have not already been covered by a previous transmission. A random delay called RAD is used by each node, which denotes the time between receiving a broadcast packet from its neighbours for the first time and then rebroadcasting it. The RAD value delays the rebroadcast of message and is randomly chosen between 0 and T_{max} seconds. The value of T_{max} is uniformly distributed between 0 and a function of the degree of the neighbour with maximum degree d_{max} divided by the node's own degree d_x. This makes the node with the highest number of neighbours rebroadcast earlier to cancel more redundant retransmissions. The operation of SBA is illustrated as follows:

1. Node x receives a broadcast packet from a node s.

2. Node x chooses a random value T_{max} which is uniformly distributed between 0 and a function of the degree of the neighbour with maximum degree d_{max} divided by the node's own degree d_x, i.e., $\frac{d_{max}}{d_x}$.

3. Node x chooses a random value RAD_{val} uniformly distributed between $[0, T_{max}]$ seconds.

4. x determines the set of neighbours common with itself and s which have already received the packet from s.

5. If some neighbours of x are uncovered by s, x reschedules the broadcast of m to these uncovered nodes after RAD_{val} interval.

6. Upon receiving duplicate packets x computes any new nodes which can be reached by rebroadcast of m.

7. x repeats step 4 until RAD_{val} interval expires.

8. If some neighbours of x are still uncovered, x rebroadcasts the packet.

[14] shows that in a congested network a higher value of RAD is effective to delay the retransmission of a broadcast message to cancel more redundant retransmissions thus resulting in improved reachability. Therefore it is desirable to adapt the value of $RAD\ T_{max}$ according to the congestion in the network. Adaptive SBA (ASBA) adapts the $RAD\ T_{max}$ value according to the congestion in the network. In ASBA, a node estimates the congestion in the network by calculating the number of packets received per second. The T_{max} value is adjusted to a higher value if the packet arrival rate is above a certain thresold. In ASBA, this threshold is set to 260 packet per second. If the average packet arrival rate is greater than 260 packets/second, the value of $RAD\ T_{max}$ is adjusted to 0.05 seconds otherwise to 0.01 seconds.

3.2.3 Dominant Pruning (DP)

Dominant pruning [66] is similar to SBA with the difference that only pro-actively selected 1-hop neighbouring nodes rebroadcast to cover 2-hop neighbours. If a node d has been selected as a rebroadcasting node, it uses greedy set cover algorithm to determine the next set of rebroadcasting nodes from its 1-hop neighbours to cover its 2-hop neighbours. Greedy set cover algorithm [98] selects recursively the 1-hop neighbouring nodes which can cover the maximum number of d's 2-hop neighbours. This approach also depends on the 2-hop neighbourhood information which can be obtained by exchanging HELLO messages.

3.2.4 Multipoint Relay Method (MPR)

In multipoint relaying [119], the upstream sender explicitly chooses the rebroadcasting nodes among its 1-hop neighbouring nodes. The selected rebroadcasting nodes are called Multipoint Relays (MPRs). The upstream sender selects the MPRs as follows:

1. Compute its 2-hop neighbour set covered by its 1-hop neighbours.

2. Determine the neighbours which have already received the broadcast packet from the current MPRs.

3. Select 1-hop neighbour which is covering the maximum number of 2-hop neighbours and add them into MPR set.

4. Repeat step 2 and 3 to cover all the 2-hop neighbours.

5. Broadcast the packet piggybacked with the information of MPRs.

3.2.5 Ad Hoc Broadcast Protocol (AHBP)

Similar to SBA, Ad Hoc Broadcast Protocol (AHBP) [147] is also based on 2-hop neighbourhood information. However, unlike SBA, it is the sender who decides which nodes should be designated as Broadcast Relay Gateway (BRG). Only BRGs are allowed to rebroadcast a packet. In AHBP, the sender selects the BRGs in such a way that their retransmissions can cover the 2-hop neighbours of the sender. This ensures that all the connected nodes in the network receive the broadcast message, provided that the 2-hop neighbour information is accurate. A selected BRG marks these neighbours as already covered and removes them from the list used to choose the next BRGs. We describe the operation of AHBP protocol as follows:
Suppose x receives a new broadcast packet from node s, N_x is the set of nodes traversed by packet in path P, and $N_1(x)$ and $N_2(x)$ are the set of 1-hop and 2-hop neighbours of N_x. Node x selects the BRGs from $N_1(x)$ by following the following steps:

1. Node x computes $N_1(x)$ and $N_2(x)$, and removes all nodes included in the path P and its neighbours.

2. From $N_1(x)$ selects nodes which are the only one which can cover nodes in $N_2(x)$ and designates these nodes as BRGs.

3. Compute set $C(x)$ of nodes covered by selected BRGs. Update $N_2(x)$ by excluding $C(x)$ from them and $N_1(x)$ by excluding selected BRGs.

4. From $N_1(x)$, find a node n which can cover the most number of nodes in $N_2(x)$ and designate node n as a BRG.

5. Repeat step 3 and 4 until all 2-hop neighbours of x are covered.

AHBP performs well in static networks; however mobility of the network results in outdated 2-hop neighbour information affecting the reachability. In [147] the authors have proposed an extension to AHBP known as AHBP-EX (extended AHBP) in order to cope with the mobility. In AHBP-EX, if a node receives a broadcast message from an unknown neighbour, it designates itself as a BRG and rebroadcast the packet. Suppose node x receives a broadcast message from node s, and node s is not included in the neighbour list of x, i.e., they have not exchanged any HELLO packet. In such situation, node x will designate itself as a BRG and rebroadcast the message to reach to maximum number of nodes in the network.

3.2.6 Multiple Criteria Broadcasting (MCBCAST)

Reachability, broadcast speed, and energy life-time are three important performance objectives of any broadcasting scheme. MCBCAST defines the broadcasting problem as a multi-objective problem. MCBCAST is an enhancement to SBA with an improved coverage constraint. Nodes use a constant threshold α to make a rebroadcast decision, a node rebroadcasts only if the ratio of covered nodes is less than α. In MCBCAST, the source node assigns some priority to different broadcast objectives. Neighbouring nodes use this priority information along with the neighbourhood knowledge to rebroadcast the packet [10].

3.3 Preliminaries

In this section, we describe some of the preliminaries related with the work in this chapter.

- **Broadcast Cost**: is defined as the average cost to deliver a broadcast message to all the nodes in the network. It is defined as $T_{xall}/(T_{xsrc} \times N)$, where T_{xall} denotes the total number of messages transmitted by all the nodes in the network. T_{xsrc} is the number of messages generated by all the broadcast sources in the network and N defines the total number of nodes in the network.

- **Reachability**: defines the delivery ratio of a broadcast message and is calculated as N_r/N, where N_r represents number of nodes in a network which have received the message successfully, and N is the total number of nodes in the network.

- **Broadcast Speed**: is measured as the inverse of broadcast latency which denotes end-to-end delay from the time a source originates a flooding message to the time it has been successfully received by the last node in a network.

- **Random Way Point Mobility Model**: This a popular mobility model used to model mobility in wireless networks [12]. In this model, each node moves towards a random destination, with a random speed selected uniformly from an interval $[0, V_{max}]$, where V_{max} is the maximum speed. When the node reaches the destination it waits for a predefined pause time p, and the process repeats itself.

- **Random Assessment Delay (RAD)**: Many neighbour knowledge based broadcasting techniques require to record redundant retransmissions over a short time interval. After this time interval they broadcast or discard the packet. This time interval is called RAD, and is chosen randomly between 0 and T_{max} seconds, where T_{max} denotes the maximum time interval. On the one hand it helps to cancel the redundant retransmissions, and on the other hand it prevents collisions by randomly scheduling transmissions.

- **RTS/CTS**: Request To Send/Clear To Send are control packets which are used as a virtual carrier sensing mechanism in wireless networks. These packets control access to the wireless medium. They are optional packets which can be exchanged prior to transmission in order to reduce the number of collisions.

- **R_xThreshold**: is a threshold for the successful reception of a packet and depends on whether the SINR is above or equal to a predefined threshold γ.
- **Short Retry Limit**: is a limit on the number of retries attempted by packets shorter than RTSThreshold.
- **Long Retry Limit**: is a limit on the number of retries attempted by packets longer than RTSThreshold.
- **RTSThreshold**: A threshold which indicates that the packets longer than this threshold can exchange RTS/CTS packets only prior to transmission.
- **src**: represents a short retry counter which indicates the number of retries attempted by packets shorter than RTSThreshold.
- **lrc**: represents a long retry counter which indicates the number of retries attempted by packets longer than RTSThreshold.
- **Two Ray Ground Reflection Model**: is a propagation model which takes into account the ground reflected path in addition to the direct path between the transmitter and receiver.

3.4 Motivation for Context Adaptive Broadcasting

The nature of wireless links, the mobility of the wireless nodes, contention, and node density bring some inherent issues of ad hoc networks. The links in these networks are dynamic because they are likely to break or change with the movement of the nodes. Due to the limited capacity of the shared wireless medium and channel contention, network congestion can be experienced by nodes in a MANET. In fact, the multi-hop nature of wireless ad hoc networks increases the level of local contention and results in network congestion which degrades the performance of broadcasting schemes. Further a change in the node density in MANET environment can result in sparse or dense networks which have direct impact on the performance of broadcasting protocols. Recently, there is a trend in the broadcast research to design broadcasting protocols which can support a broader range of operating conditions. Research focuses on broadcasting protocols which can dynamically tune their operation depending on the node density, congestion, and mobility. Broadcasting techniques that can deal with the continuously changing MANET characteristics without any explicit pre-configuration are desirable. Motivated by these research issues, in this chapter we investigate the performance of some existing broadcasting schemes under various network conditions of congestion, node density and mobility. Performance metrics we want to consider are reachability, broadcast speed and number of retransmitting nodes. By analyzing the impact of these conditions on the performance of broadcasting protocols, our main target is to improve their performance under wide range of network conditions. To achieve this, we propose three different broadcasting protocols called CASBA, DASBA, and CMAB which adapt to different conditions of network including congestion, node density, and mobility.

As network density, node mobility and congestion are the dynamic attributes associated with a mobile ad hoc network, by locally monitoring the state of the network, a node can establish an estimation of these variables. Therefore in our work we follow a cross layer approach to monitor the network conditions. By using cross layer design we aim to measure congestion and mobility at different layers of the protocol stack and use this information on the other layers to improve their performance.

3.5 Impact of Network Conditions on Broadcasting Schemes

The main objective of all the efficient broadcasting schemes is to reduce the number of rebroadcasts while keeping the reachability as high as possible. In this section we analyze the impact of congestion, node density and mobility on the performance of some popular broadcasting schemes. We choose to analyse blind flooding and different neighbour knowledge-based broadcasting schemes. Flooding is the simplest broadcasting approach, and the only protocol in this category so we have chosen it for evaluation. The largest category among different categories of broadcasting protocols is the neighbour knowledge-based category as discussed in Chapter 2, we have chosen SBA, ASBA, AHBP, MCBCAST, and AHBP-EX to represent this category. SBA, ASBA and MCBCAST are based on self-pruning and make a local decision to forward a packet. AHBP and AHBP-EX are representative of protocols with dominant pruning or multipoint relaying. In dominant pruning nodes are pro-actively chosen by the source or forwarding node to rebroadcast or not without any local decision.

The performance metrics we observed are the reachability, broadcast speed, and broadcast cost. In order to analyse the impact of congestion, node density and mobility on the performance of the existing broadcasting schemes we have taken an average over 10 different experiment runs. Each simulation runs for a simulation time of 1110 seconds. For the first 1000 seconds nodes exchange HELLO messages to populate their neighbour tables. For the next 100 seconds broadcast operations are initiated by different nodes in the network and messages are disseminated in the network. In order to ensure that the packets which have been broadcasted during the simulation time can successfully propagate in the network, another 10 seconds are given to complete the broadcast process. Other simulation parameters are listed in Tables 3.1 and 3.2.

Parameter Name	Parameter Value
Simulation area	$500m \times 500m$
Simulation time	$1110s$
HELLO interval	$5s$
Jitter value	$0.0001s$
Neighbor info timeout	$10s$
Number of runs	10

Table 3.1: Simulation parameters

Parameter Name	Parameter Value
Receiver sensitivity	$65dBm$
Frequency	$2.472GHz$
Transmit power	$24dBm$
Channel sensitivity	$-78dBm$

Table 3.2: Cisco aironet 350 card specifications

3.5.1 Impact of Congestion on Broadcasting Schemes

In order to congest the network, we have selected a random node which starts the broadcast process in the network and have varied the flooding rate from 1 *packet/s* to 90 *packets/s*. The payload size is 64 *bytes*. All the nodes in the network are moving with a maximum speed of 20 *m/s* with a pause time of 0 seconds following a random way point mobility model. The number of nodes we have considered is 70.

Figure 3.1 illustrates that when messages are disseminated at a rate of 15 *packets/sec* or less, the reachability achieved by ASBA, SBA and MCBCAST remains above 98%. However, with an increase in the congestion level, it reduces gradually due to larger number of collisions in the network. It can be observed from Figure 3.1 and Figure 3.2 that there is a direct relationship between the broadcast cost and reachability. A higher number of retransmissions can reach to a higher number of nodes in the network resulting in improved reachability. Collisions result in retransmissions in the network causing more contention in the network. AHBP and AHBP-EX seems less sensitive to the congestion because they have only few retransmitting nodes. Fewer number of retransmissions in AHBP and AHBP-EX result in lower reachability compared to other broadcasting protocols. The number of retransmitting nodes in flooding reduces with an increase in the network contention and therefore degrades its reachability. It is apparent from Figure 3.2 that the number of retransmitting nodes decreases with an increase in congestion. This results in fewer nodes which can receive and forward a broadcast message affecting the reachability. Flooding has 60% retransmitting nodes even in the worst congestion scenario because each node in the network tries to retransmit. This results in a substantial increase in the number of collisions in the network. It can be observed from Figure 3.2 that when the flooding rate is between 15 *packets/sec* and 45 *packets/sec*, the number of retransmissions observed by SBA and ASBA increases. This is due to the fact that a congested network does not deliver the redundant transmissions in the network during the RAD period and therefore does not help SBA and ASBA to cancel many redundant transmissions. For a highly congestive scenario, the broadcast cost of SBA, ASBA and MCBCAST remains as high as 50%. However AHBP and AHBP-EX have lower broadcast cost for all congestion levels because more retransmissions can be avoided due to the selected number of BRGs. Figure 3.3 illustrates that the broadcast speed of all the broadcasting schemes suffers with an increase in congestion level.

3.5.2 Impact of Node Density on Broadcasting Schemes

In this study we have varied the node density by increasing the number of nodes over a simulation area of $500m \times 500m$. The number of nodes has been varied from 25 to 150 in steps of 25. Each node is moving with a maximum speed of $5m/s$ with a pause time of 0 seconds. We have randomly selected one node to start the broadcast process with a sending rate of 2 *packets/s*. Figure 3.5 presents the broadcast cost of each protocol as the node density increases. Figure 3.5 illustrates that the neighbour knowledge-based schemes require fewer retransmitting nodes than flooding. AHBP performs well in denser networks and has a smaller number of retransmitting nodes than all other broadcasting schemes. For a dense network of 150 nodes, AHBP requires less than 50% of the network nodes to rebroadcast and therefore achieves less reachability compared to other protocols. Figure 3.4 shows the effects of node density on reachability. It illustrates that all the broadcasting schemes are scalable when the network region is dense. Reachability increases almost linearly from low to medium dense networks and reaches 100% for highly dense networks. It can be observed from Figure 3.4 and Figure 3.5 that AHBP and AHBP-EX have lower reachability due to selected number of retransmissions in the network. Figure 3.6 shows the results of the effects of node density on the broadcast speed of all broadcasting schemes. It verifies a strong correlation between the broadcast speed and the node density. It shows that the broadcast speed decreases with an increase in the number of nodes in the network. However AHBP and AHBP-EX have better broadcast speed than other broadcasting protocols because they do not use any RAD delay for making a rebroadcast decision. Other protocols have better broadcast speed than flooding due to fewer retransmissions.

3.5.3 Impact of Mobility on Broadcasting Schemes

To analyze the ability of each protocol to react to mobility we use the random way point mobility model to model the movement of nodes in the network. The number of network nodes we have considered is 70. The maximum speed of all the nodes in the network is varied from $5m/s$ to $30m/s$ with a pause time of 0 seconds. All nodes have fixed $250m$ transmission radius in a fixed network area of $500m \times 500m$.

Figure 3.7 shows that the performance of AHBP suffers in the dynamic topology. However, its mobility extension called AHBP-EX has better performance in highly dynamic networks but still it performs poor compared to other protocols. AHBP-EX reacts to mobility by forcing a node to act as a relay if it has received a HELLO message from a node for the first time. This results in a higher number of retransmissions for AHBP-EX than for AHBP as shown in Figure 3.8. In AHBP-EX, a BRG is not able to cover the 2-hop neighbours of the source or forwarding node when it is no

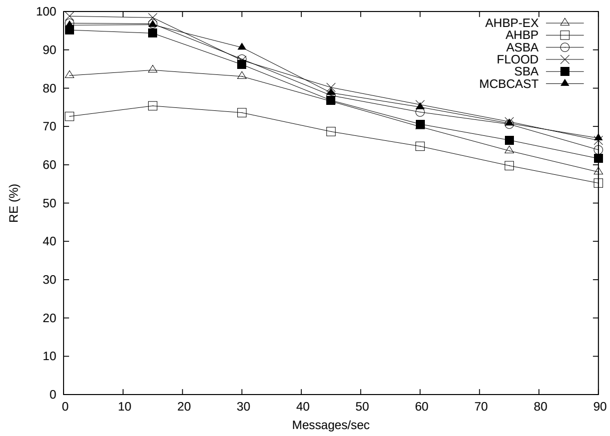


Figure 3.1: Reachability versus messages/second

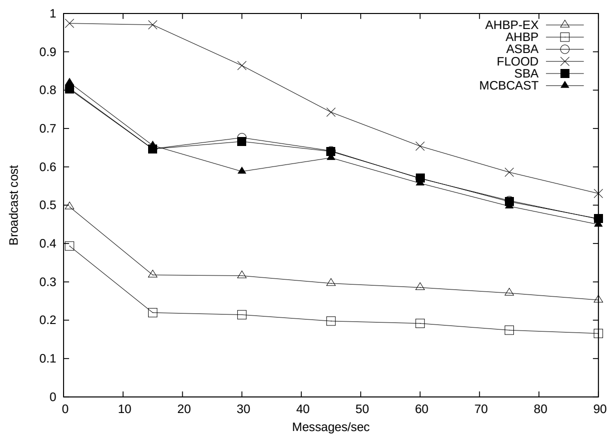


Figure 3.2: Broadcast cost versus messages/second

longer in the 2-hop neighbour's transmission range affecting the reachability. SBA is less sensitive to mobility because if a node receives a packet from an unknown neighbour, it does not know any common neighbours with that node and therefore likely it rebroadcasts. SBA adapts to mobility by requiring more nodes in the network to rebroadcast as shown in Figure 3.8. Figure 3.9 shows that flooding is less sensitive to mobility as it allows each node in the network to rebroadcast. However, its broadcast cost is higher than all other protocols as shown in Figure 3.8. Compared to other broadcast protocols AHBP and AHBP-EX have less broadcast cost as they select only few nodes in the network to retransmit which results in lower reachability.

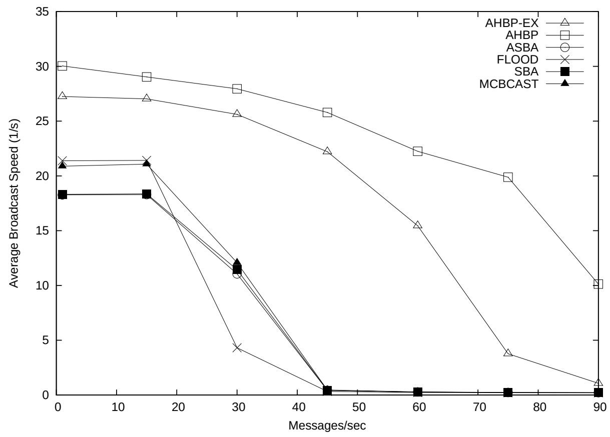


Figure 3.3: Broadcast speed versus messages/second

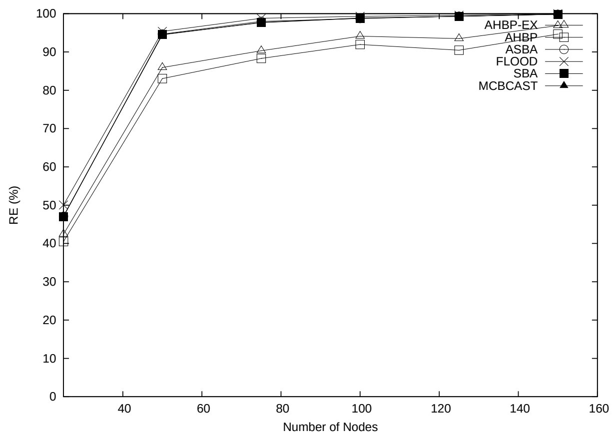


Figure 3.4: Reachability versus No. of nodes

In Figure 3.9, we observe that for most of the broadcasting schemes mobility has no effect on the broadcast speed. AHBP and AHBP-EX show better broadcast speed than all other broadcasting schemes. AHBP delivers a broadcast message to fewer nodes in the network, therefore compared to other broadcasting schemes it has better broadcast speed. It is apparent from Figure 3.9 that an increase in mobility improves the broadcast speed of AHBP.

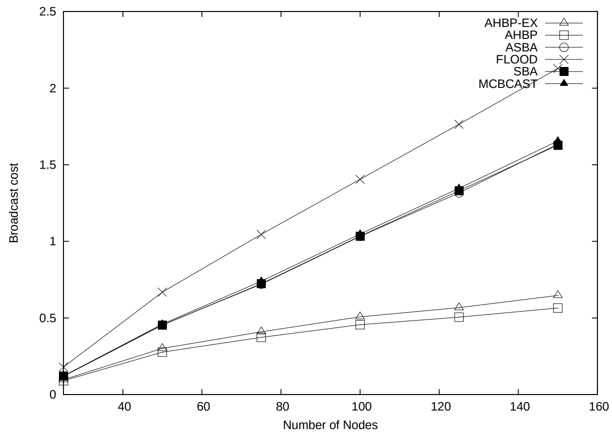


Figure 3.5: Broadcast cost versus No. of nodes

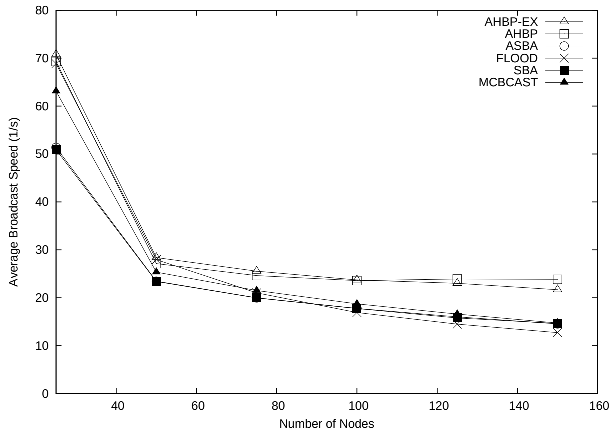


Figure 3.6: Broadcast speed versus No. of nodes

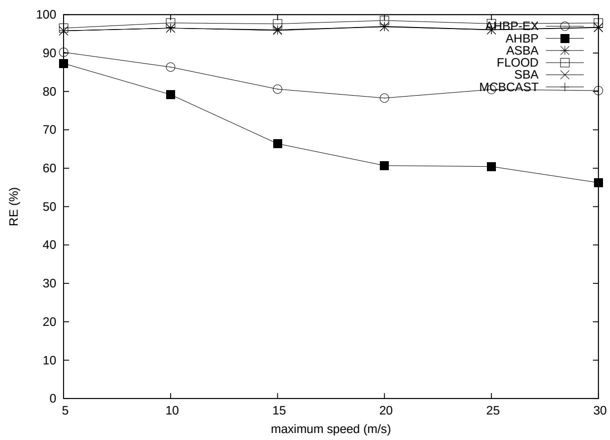


Figure 3.7: Reachability versus maximum speed (m/s)

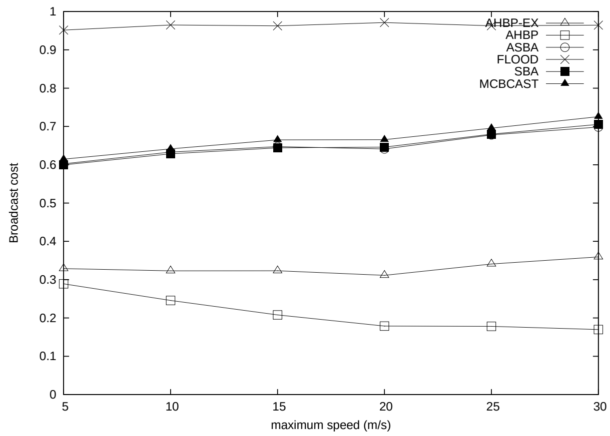


Figure 3.8: Broadcast cost versus maximum speed (m/s)

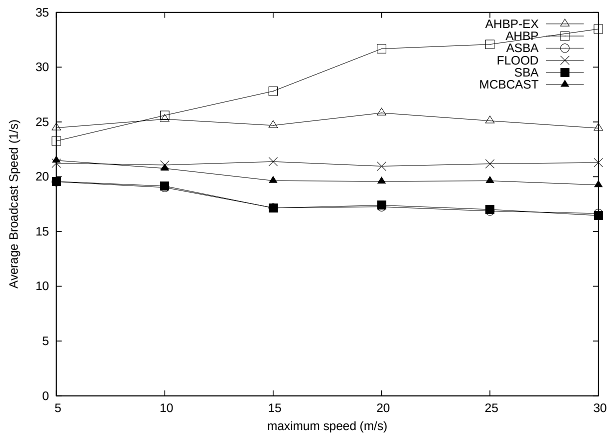


Figure 3.9: Broadcast speed versus maximum speed (m/s)

From the above analysis we conclude that neighbour knowledge-based broadcast schemes suffer in highly mobile networks in which frequent topological changes cause neighbourhood information to become stale quickly. This effect is more prominent for broadcasting schemes based on dominant pruning like AHBP, MPR and AHBP-EX in which if a relay node moves out of transmission range of the source or a forwarding node, no mechanism is provided to cover its neighbours.

3.6 Cross Layer Model

Different layers of the protocol stack are sensitive to different conditions of the network. For example, the MAC layer is considered good at measuring congestion, packet losses, and mobility in the network. The network layer can calculate the number of neighbours associated with a node, i.e., node density, and the physical layer is good at computing the link capacity. We can use the information measured on one layer of the protocol stack and may use it on another. However the layered architecture of the TCP/IP protocol stack is not flexible enough to cope with the dynamics of wireless networks. Cross layer design differs from the traditional network design, in which each layer of the protocol stack operates independently. Communication between these layers is only possible through the interfaces between them. In the cross layer design, information can be exchanged between non adjacent layers of the protocol stack. By adapting to this information the end-to-end performance of the network can be optimized. In [130] it is shown that by exploiting the cross layer design we can improve the performance of the other layers of the protocol stack. Cross layer awareness has been used to improve the performance of TCP [160]. For both CASBA and CMAB, we obtain the congestion and mobility information directly from the MAC layer following the cross layer approach. Figure 3.10 illustrates the cross layer approach.

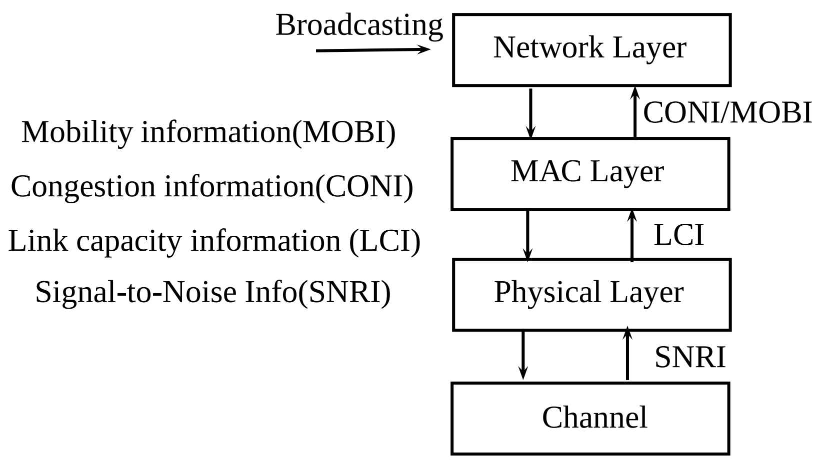


Figure 3.10: A cross layer approach example to obtain network information

3.7 Cross Layer Broadcasting Protocols

3.7.1 Congestion and Mobility Detection

Packets at the MAC layer can be discarded due to three types of reasons, i.e., duplicate packets, MAC busy and retry exceeded count. However approximately 95% of the packets are lost due to collisions and the rest due to other reasons [123]. IEEE 802.11 [57] uses a standard short retry limit and long retry limit to limit the number of retransmissions. These values represent the continuous number of packet losses occurring in the network. A packet is considered to be correctly received by a node, if its received power is greater than or equal to $R_xThreshold$. Any packet having power less than $R_xThreshold$ is considered not to be valid and is therefore discarded. Based on the observations made from the MAC layer behaviour, we use a simple scheme for distinguishing mobility-induced packet losses from congestion losses. This scheme is described in the *Retransmit(Packet)* pseudo code in Algorithm 1. Some symbols used in our approach are defined as follows:

- A_r: Average of the power P_r of the last 10 packets from $Array_{Pr}$
- $R_xThreshold$: Reception threshold to decode a received packet successfully
- T_{Rx}: Time when the last packet was received as recorded by *Recv(Packet)*
- src and lrc: Short Retry Count and Long Retry Count to indicate the number of retransmissions at the MAC layer
- V_m: Variation in received power observed by the MAC layer, i.e, decreasing or increasing
- $Array_{Pr}$: An array which records the power of the last 10 packets received from a particular destination.
- SHORT_RETRY_LIMIT, and LONG_RETRY_LIMIT: Limit imposed by MAC layer on the maximum number of retransmissions

Input:

A_r //Average of P_r of the last 10 packets received from a particular destination d

T_{Rx} //Time in seconds when the last packet was received by the *Recv(Packet)*

$R_xThreshold$ // Reception threshold

$Packet$ // Packet for the destination d

Output: $PACKET\_LOSS\_REASON$

```
if src>SHORT_RETRY_LIMIT || lrc>LONG_RETRY_LIMIT then
    Discard(Packet)
    V_m = Array_Pr[lastpacket] − Array_Pr[secondlastpacket]
            //Variation in received power
    if (A_r < R_xThreshold && V_m < 0) && (NOW − T_Rx <= 3seconds) then
        d.PACKET_LOSS_REASON= MOBILITY
    else
        d.PACKET_LOSS_REASON=CONGESTION
    end
else
    Send(Packet)
end
```

Algorithm 1: *Retransmit(Packet)* procedure to compute the reason of packet loss

In Algorithm 1, in *Retransmit(Packet)* procedure, we have used the average A_r of the received power from the last 10 packets received from a particular destination node d by using the *Recv(Packet)* procedure of MAC 802.11. Further, *Recv(Packet)* also captures/records the time T_{Rx} when a node has received the last packet from that destination d. If there is a continuous packet loss for the destination d recorded as counters src or lrc, frequent retransmissions occur. However, Short Retry Limit and Long Retry Limit are used to limit these retransmissions. If the number of retransmissions by a particular node exceeds these limits, a packet is discarded without any retries. In order to know the reason of the continuous packet loss, i.e., mobility or congestion, the average of the received powers A_r is compared with $R_xThreshold$. If A_r is less than $R_xThreshold$ and the destination d is showing a decreasing trend in the received powers indicated by V_m, we conclude that the packet has been lost due to mobility, and otherwise due to network congestion.

We assume that the Physical Layer Convergence Protocol (PLCP) header part of the PLCP frame is always interpretable. We have monitored the congestion information through simulations by using ns-2 [138] with different scenarios of mobility and congestion in the network. Simulation results have verified that not all packet losses are due to congestion but some are due to mobility, i.e., when nodes are moving with a speed of $10m/s$, approximately 2% retransmissions are due to link failures in the network.

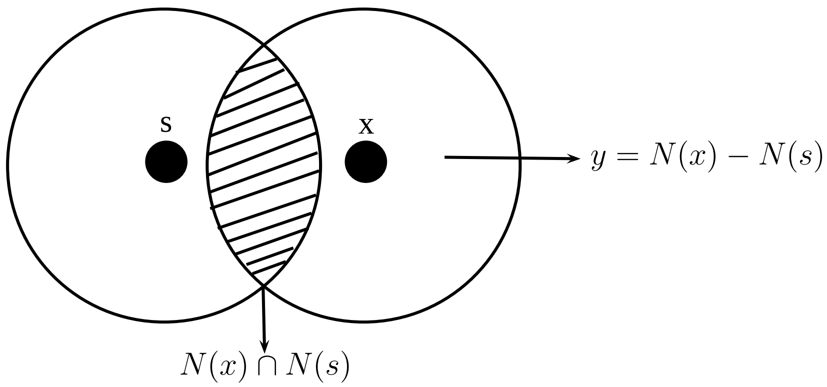


Figure 3.11: Self-pruning approach used by CASBA and DASBA

3.7.2 Congestion Adaptive SBA (CASBA)

CASBA follows the cross layer approach where congestion information computed by the MAC layer is used to improve the performance of the network layer as shown in Figure 3.10. CASBA is based on SBA [114], and uses a self-pruning approach as discussed in Section 3.2.1 and is shown in Figure 3.11. Based on the information obtained from the previous broadcast or control packets received, a node makes a local decision to forward the packet or not to forward, i.e., it is self-pruned. In Figure 3.11, it is shown that node x after receiving a broadcast packet from node s excludes its 1-hop neighbours common with 1-hop neighbours of s, i.e, $y = N(x) - N(s)$. If $y = \emptyset$, it prunes itself otherwise it broadcasts the packet. CASBA also needs to maintain

2-hop neighbourhood information which is obtained with the help of HELLO packets. It also requires the ID of the last sender. The broadcasting procedure of CASBA is shown in Algorithm 2. For our proposed approach we have used some symbols as described below:

- $N_1(s)$: 1-hop neighbours of s
- $P(s, N_1(s))$: Broadcast packet piggybacked with node ID s and its 1-hop neighbours
- d_{max}: Maximum node degree (number of neighbours) among 1-hop neighbours
- d_x: Node degree (number of neighbours) of x
- RAD_{max}: Maximum random assessment delay to schedule the retransmission of broadcast packet
- T_{max}: Time to compute the RAD_{max}.

CASBA is illustrated in Algorithm 2. As illustrated in Algorithm 2, source node s broadcasts the message to all of its 1-hop neighbouring nodes, i.e., $N_1(s)$. For any other node say, x after receiving a broadcast packet from the node s for the first time, it computes $y = N_1(x) - N_1(s)$. Node x keeps on updating y by excluding its 1-hop neighbours covered by other forwarding nodes until the timer T_{RAD} which randomly chooses a value from a uniformly distributed interval $[0, RAD_{max}]$ is expired. RAD_{max} is computed according to Equation 3.1. If $y = \emptyset$, it means that all the neighbors of x have already been covered by s or forwarding nodes, therefore x discards the broadcast packet. If $y \neq \emptyset$, it means some 1-hop neighbours of x are not covered, so x broadcasts the packet. The maximum value of RAD_{max} is computed as follows:

$$RAD_{max} = (d_{max}/d_x) \times T_{max} \tag{3.1}$$

For new *packet* start from source s

Get a list of $N_1(s)$
Piggyback $N_1(s)$ in *packet*, i.e., $P(s, N_1(s))$;
Broadcast $P(s, N_1(s))$ to $N_1(s)$

// x receives the packet from the source directly, or from a forwarding node

```
if x receives a packet P(v, N_1(v)) from a node v for the first time then
    d_max =Maximum Node degree of a node n ∈ N_1(x)
    d_x =Node degree of x
    if v.PACKET_LOSS_REASON=CONGESTION then
        T_max = 0.05s
    else
        T_max = 0.01s
    end
    RAD_max = (d_max / d_x) × T_max
        // x chooses a random value uniformly distributed from the interval
    [0, RAD_max]
    RAD_val = random(0, RAD_max)
    y = N_1(x) − N_1(v)
    Start a timer T_RAD with an initial value RAD_val
    while T_RAD has not expired do
        if x receives packet P from the forwarding node w then
            y = y − N_1(w)
        end
    end
    if y ≠ ∅ then
        Piggyback N_1(x) in packet, i.e., P(x, N_1(x))
        Broadcast P(x, N_1(x))
    else
        Discard(P)
    end
else
    Discard(P)
end
```

Algorithm 2: Congestion Adaptive Scalable Broadcasting Algorithm (CASBA)

where d_x is the degree of the node x and d_{max} is the degree of the node with maximum number of neighbours among its 1-hop neighbours. T_{max} and d_{max}/d_x control the value of RAD_{max}. T_{max} controls the length of the RAD_{max}, and d_{max}/d_x makes it more likely that nodes with higher degree rebroadcast earlier to cancel more retransmissions.

As shown in Algorithm 2, CASBA adjusts the value of RAD_{max} according to the congestion in the network. By using the congestion information from the MAC layer as computed in Algorithm 1, if node x finds PACKET_LOSS_REASON is CONGESTION, it adjusts T_{max} to $0.05s$, and therefore delays the retransmissions for a long time to mitigate the congestion, and cancel more redundant transmissions. However if it finds that PACKET_LOSS_REASON is not congestion, the value of the T_{max} is adjusted to $0.01s$ to speed up the broadcast process.

3.7.3 Performance Analysis of CASBA

We have used the ns-2 packet level simulator to conduct experiments in order to evaluate the performance behaviour of CASBA. For the physical layer configurations we have followed cisco aironet 350 specifications as shown in Table 3.2 and other simulation parameters are the same as given in Table 3.1.

3.7.3.1 Effect of congestion

In the analysis below, we have quantified the effect of congestion on four broadcasting schemes: flooding, CASBA, ASBA and SBA. We have varied the packet origination rate from 1 *packets/s* to 90 *packets/s* to congest the network. Figure 3.12 shows the reachability achieved by all protocols as the network becomes congested. In congested scenarios, we observe that the reachability achieved by CASBA is better than SBA, ASBA and flooding. Figure 3.13 shows the number of retransmitting nodes in the congested network. With an increase in the congestion level, the number of retransmitting nodes decreases given that the number of nodes and network area is constant. Reachability as shown is Figure 3.12 shows a direct relationship with the number of retransmitting nodes which are shown in Figure 3.13. CASBA has better reachability than ASBA, SBA, and flooding because it has a small number of retransmitting nodes with an increase in the network congestion. CASBA minimizes redundant retransmissions in the network as it uses a longer value of RAD to cancel more redundant retransmissions as soon as the MAC layer detects a congestion loss. It improves its performance in congested network scenarios and reduces the risk of the broadcast storm problem.

CASBA has poor broadcast speed as shown in Figure 3.14 as it adds more delay than ASBA and SBA as soon as the MAC layer detects a congestion loss. This increase in delay helps CASBA to cancel more redundant transmissions which may congest the network and can affect the reachability and broadcast cost. It can be observed from Figure 3.13 that flooding has the highest broadcast cost among all protocols which may lead to the broadcast storm problem. Broadcast speed of flooding as shown in Figure 3.14 decreases when the network becomes more congested due to high number of collisions in the network. It can be observed from Figure 3.14 that CASBA performs better than flooding in terms of broadcast speed in highly congestive scenarios.

3.7.3.2 Effect of Node Density

In order to analyze the effect of node density on the performance of CASBA, we have varied the number of nodes from 25 to 150 in steps of 25 nodes on a fixed area of $500m \times 500m$. The packet origination rate for all the nodes is 2 *packets/sec*. Other simulation parameters are the same as listed in Table 3.1. It is apparent from Figure 3.15 that the reachability observed for all the protocols increases with an increase in node density. An increase in node density increases the number of nodes covering a particular network area, resulting in improved reachability.

It can be observed from Figure 3.17 that broadcast speed is largely affected by the network density; it decreases with an increase in network density. Flooding has better broadcast speed than CASBA, SBA, and ASBA. This is due to the fact that when the network density increases, the number of retransmissions of flooding increases more rapidly compared to other protocols. As shown in Figure 3.15, reachability increases as the network becomes denser, however a significant amount of congestion also arises in the network triggering a higher number of retransmissions. CASBA outperforms

SBA and ASBA by adapting to any level of congestion in the network. CASBA has fewer retransmissions compared to SBA, ASBA, and flooding as shown in Figure 3.16, which improves its performance in denser network scenarios as well.

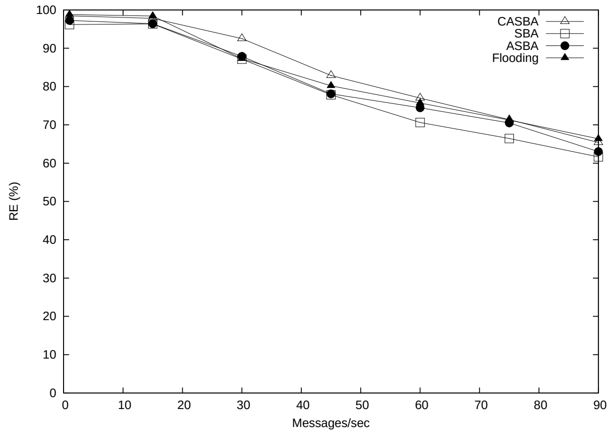


Figure 3.12: Reachability versus messages/second for CASBA

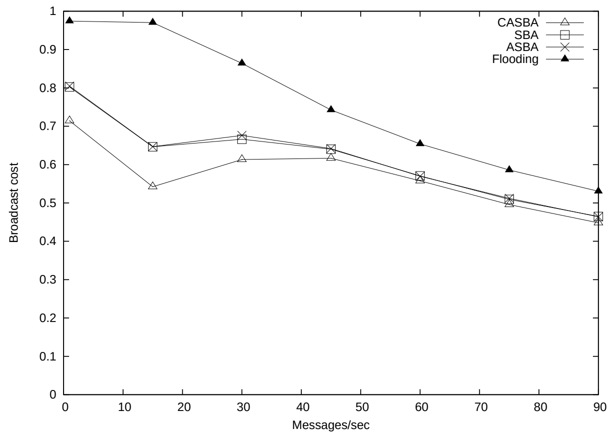


Figure 3.13: Broadcast cost versus messages/second for CASBA

3.7.3.3 Effect of Mobility

We used the random way point mobility model to model the mobility and have varied the maximum speed from $5m/s$ to $30m/s$ with pause time of 0 seconds. Other simulation parameters are listed in Table 3.1. We have measured the performance of all four

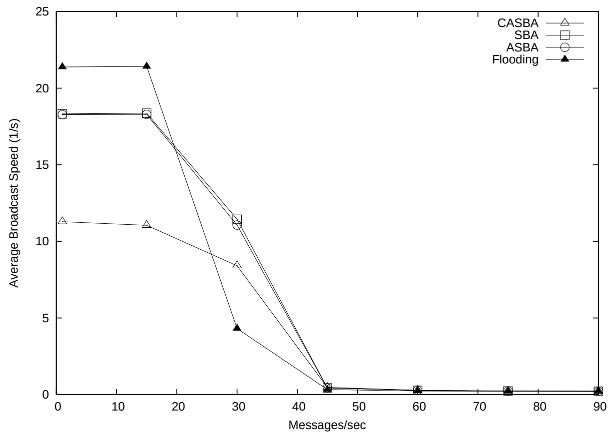


Figure 3.14: Broadcast speed versus messages/second for CASBA

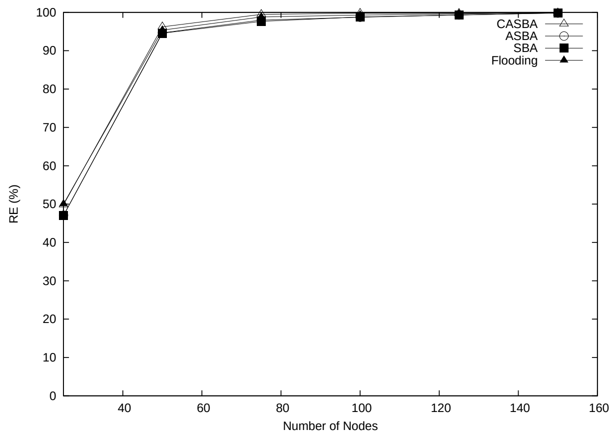


Figure 3.15: Reachability versus No. of nodes for CASBA

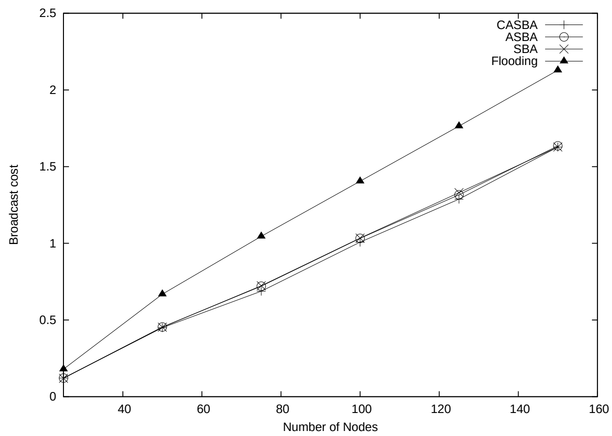


Figure 3.16: Broadcast cost versus No. of nodes for CASBA

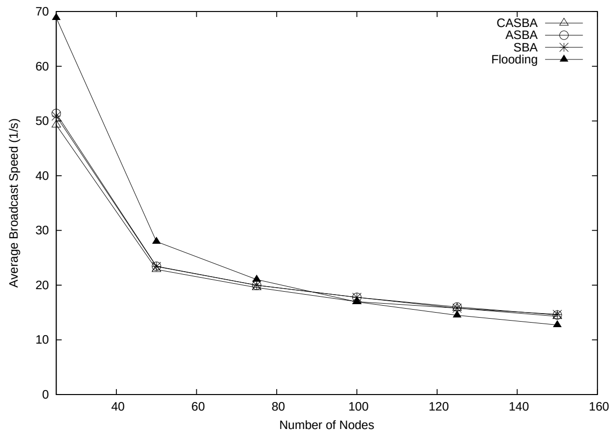


Figure 3.17: Broadcast speed versus No. of nodes for CASBA

protocols as the maximum speed increases. Figure 3.18 shows that the reachability of all broadcasting schemes is almost the same for all speeds. We have simulated a realistic scenario and have induced a significant amount of congestion in the network. The performance of CASBA is slightly better than SBA and ASBA. However the number of retransmitting nodes of CASBA is significantly less than SBA, ASBA and flooding as shown in Figure 3.19. This is because of the cross layer mechanism used to distinguish the reason of packet losses, i.e., congestion or link failures. When the MAC layer detects a retransmission due to congestion, RAD is adapted according to congestion and for link failure it improves the reachability and broadcast speed by reducing the RAD. Flooding has the highest number of retransmitting nodes as it has no mechanism to control redundant retransmissions in the network. The broadcast speed of CASBA is lower than SBA and ASBA due to its frequent congestion adaptation as shown in Figure 3.20.

It is obvious from the experiments that CASBA performs well in denser and congestive network scenarios where packet losses due to congestion are common. By using the congestion information from the MAC layer, CASBA adapts to network congestion. It is able to cancel more redundant retransmissions during the periods of congestion compared to the other three broadcasting protocols.

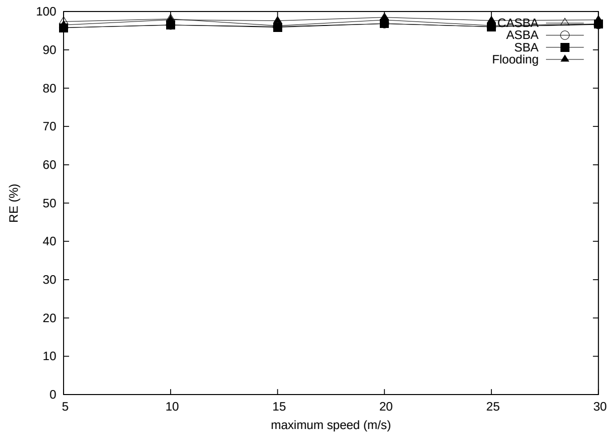


Figure 3.18: Reachability versus maximum speed (m/s) for CASBA

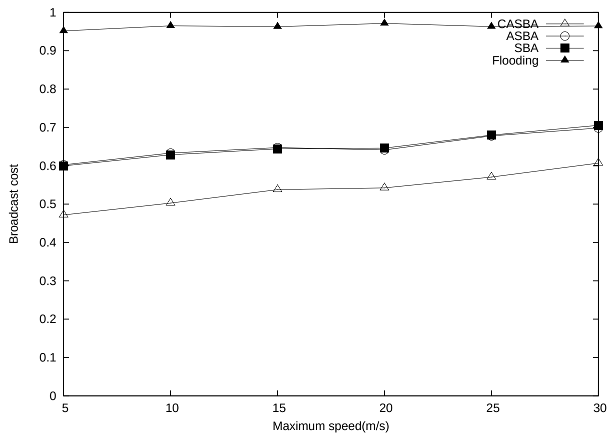


Figure 3.19: Broadcast cost versus maximum speed (m/s) for CASBA

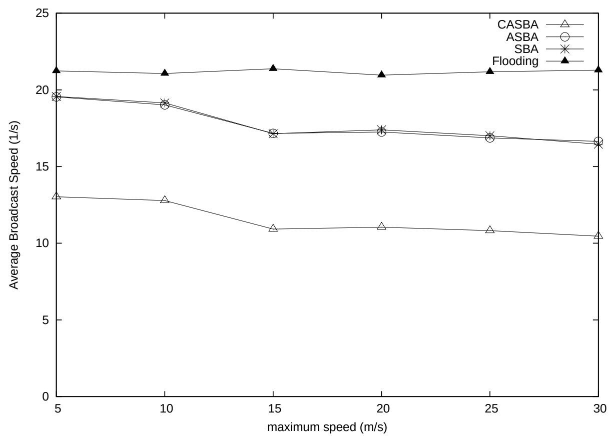


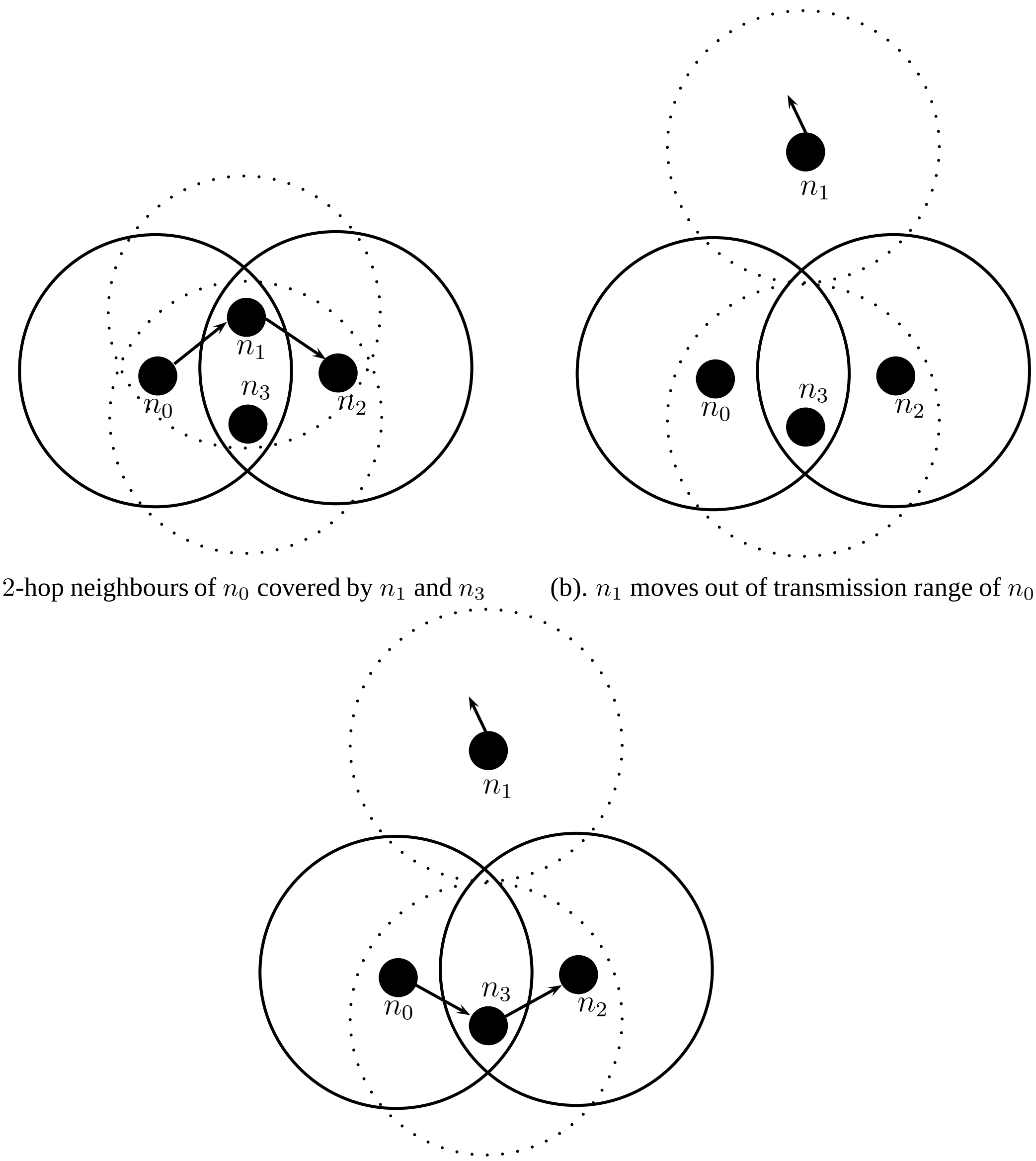
Figure 3.20: Broadcast speed versus maximum speed (m/s) for CASBA

3.7.4 Cross Layer Mobility Adaptive Broadcasting (CMAB)

The proposed approach is motivated by the scenario depicted in Figure 3.21 below and the simulation analysis given in Section 3.5. In the original AHBP protocol, AHBP-EX which is an extension to AHBP to cope with mobility, and MPR, n_1 or n_3 need to be selected as BRGs/MPRs to cover n_0's 2-hop neighbor, i.e., n_2 as shown in Figure 3.21a. However both AHBP and AHBP-EX do not handle the case when a chosen BRG/MPR is no longer within the source node or forwarding node's transmission range due to mobility and therefore cannot cover the 2-hop neighbors of the source or forwarding node. Motivated by this example, our proposed approach is based on the selection of two disjoint sets of BRGs, i.e, BRG_1 and BRG_2. The set BRG_2 is activated only in the case when the chosen BRG_1 is no longer in the transmission range of the source or forwarding node. It helps to cover the 2-hop neighbours of source or forwarding node left uncovered by BRG_1. We first give a few definitions:

Definition 1: For an upstream sender, i.e., a source node or a forwarding node v, we say a node w is covered by v if it is either its 1-hop neighbor $w \in N_1(v)$ or is a 2-hop neighbor $w \in N_2(v)$ covered indirectly by some 1-hop neighbour of v.

In our proposed approach, a node v, i.e, forwarding or source node selects two disjoint sets of $BRGs$, i.e., $BRG_1(v)$ and $BRG_2(v)$ by using 2-hop neighbourhood information. We have selected BRG_1 to cover all neighbours of v, and BRG_2 to cover a maximum number of them as illustrated in Algorithm 4. We have computed BRG_2 to provide reliable broadcasting in highly mobile network scenarios and to achieve maximum reachability. However, the rebroadcast decision by $BRG_2(v)$ depends on the maximum coverage rule. We want to achieve the maximum coverage at the expense of small increase in broadcast cost. We have the following maximum coverage rule for the $BRG_2(v)$ to activate itself for rebroadcast.



(a). 2-hop neighbours of n_0 covered by n_1 and n_3

(b). n_1 moves out of transmission range of n_0

(c). 2-hop neighbours of n_0 can still be covered by n_3

Figure 3.21: AHBP, AHBP-EX, and MPR are unable to cover 1-hop neighbours of n_1 which has moved out due to mobility, and is not able to cover its neighbours any more. Its 1-hop neighbours still can be covered by n_3

Maximum Coverage Rule: node v is an active node to rebroadcast if v:

1. Has been selected as BRG_2 by a node s which is a forwarding or source node
2. Among 1-hop neighbours of s is covering the maximum number of 2-hop neighbours of s

Our maximum coverage rule is explained in Figure 3.22, where n_0 elects n_1 as a BRG_1 and n_3 and n_2 as BRG_2s to cover n_0's 2-hop neigbours, i.e., n_4, n_5, and n_6. If n_1 moves out of transmission range of n_0, it is not able to cover n_0's 2-hop neighbours. In that case, both n_3 and n_2 will compute locally by using 2-hop neighbour information which one is covering a maximum number of 2-hop neighbours of n_0 among their 1-hop neighbours. In Figure 3.22, n_2 is covering the maximum number of n_0's 2-hop neighbours among its 1-hop neighbours. Therefore n_2 will rebroadcast the packet, and n_3 will discard it. We want the maximum coverage rule to be source-independent so that each node can locally evaluate its coverage with respect to other neighbors. Our maximum coverage rule is computed and verified locally and is based on the reason that due to high mobility there is frequent change in the local node density of a node. If decision for the maximum coverage rule, i.e., which BRG_2 should be activated upon detecting the mobility of a node is taken at the source or forwarding node, the maximum coverage is not possible with small number of retransmissions. The activation of BRG_2 also depends on range sensing rule and is defined as follows:
Range Sensing Rule: Node v will sense the transmission position of any node $n \in BRG_1(s)$ if v:

1. Has been elected as BRG_2 by forwarding or source node s
2. Node n is its 1-hop neighbor

For the range sensing rule, we use a simple cross layer mechanism for mobility detection as described in Algorithm 1. After the number of retries to transmit a packet to a particular node $n \in BRG_1(s)$ exceeds the maximum limit allowed a packet is dropped.

In order to detect the reason of the packet loss, node $v \in BRG_2(s)$ calculates the average received power A_r of the most recently received packets from $n \in BRG_1(s)$. A variable V_m which shows the trend of the $n \in BRG_1(s)$ movement either moving away or moving towards the node is also maintained. With the help of the average received power A_r and V_m, reason about the packet loss is detected. If the A_r is less than the $R_xThreshold$ and V_m is showing a trend of moving away from the node $v \in BRG_2(s)$, the MAC layer infers that node $n \in BRG_1(s)$ is no more in its transmission range, and detects the reason of the packet loss to $n \in BRG_1(s)$ as a result of mobility. Range sensing rule is illustrated in Figure 3.21b where $n_3 \in BRG_2(n_0)$ senses the mobility of a node $n_1 \in BRG_1(n_0)$ which is also its 1-hop neighbour.

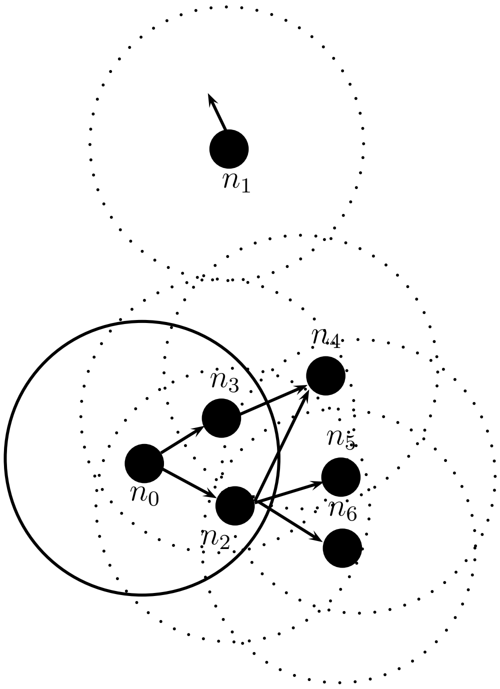


Figure 3.22: 1-hop neighbours of n_1 can be covered by n_2 and n_3, however n_2 covers a larger number of 2-hop neighbours of n_0 than n_3

3.7.5 CMAB Description

CMAB is distributed protocol which works on demand and thus does not need any virtual backbone for its operation. In CMAB, a node s selects two disjoint sets of $BRGs$ from its 1-hop neighbor set $N_1(s)$ which can cover its 2-hop neighbors $N_2(s)$. Assuming that the network is connected, two disjoint sets of $BRGs$ will constitute two disjoint set covers in the network. The procedure to compute two disjoint BRGs has been described in Algorithm 4. The operation of CMAB has been illustrated in Algorithm 3. For our proposed approach CMAB we have used some symbols as described below:

- $BRG_1(v)$: denotes the first forwarding set computed by v, a source/forwarding node
- $BRG_2(v)$: denotes the second forwarding set computed by v, a source/forwarding node
- $N_1(v)$: denotes the 1-hop neighbour set for source/forwarding node v
- $N_2(v)$: denotes the 2-hop neighbour set for source/forwarding node v
- $P(v, BRG_1(v), BRG_2(v))$: Broadcast packet piggybacked with node ID v with disjoint forwarding sets, i.e., $BRG_1(v)$ and $BRG_2(v)$

We assume a broadcast process starts from source node s, s uses the Disjoint Broadcast Relay Gateways (DBRGs) as described in Algorithm 4 to select its two disjoint forward node sets, i.e., $BRG_1(s)$ and $BRG_2(s)$ to cover the 2-hop neigbours of s, i.e., $N_2(s)$, and then piggybacks $BRG_1(s)$ and $BRG_2(s)$ with its ID with the packet and broadcasts the packet among its 1-hop neighbour set, i.e., $N_1(s)$.

For a node v that receives a new broadcast packet from an upstream sender s, if $v \in BRG_1(s)$, it uses the DBRGs algorithm to select its two disjoint forwarding node sets, i.e., $BRG_1(v)$ and $BRG_2(v)$ to cover its 2-hop neigbours, and appends this information in the broadcast packet and broadcasts it to its 1-hop neighbours, i.e., $N_1(v)$. However, if $v \in BRG_2(s)$ and it satisfies two event driven rules, i.e., range sensing rule and maximum coverage rule, it computes two disjoint forwarding node sets, i.e., $BRG_1(v)$ and $BRG_2(v)$ using DBRGs to cover its 2-hop neigbours, and broadcasts the packet among $N_1(v)$. If $v \notin BRG_2(s)$, or it violates range sensing rule or maximum coverage rule, it discards the packet. Note if v is not selected either for $BRG_1(v)$ and $BRG_2(v)$, it discards the packet without any processing.

For new *packet* start from source s
    s uses DBRGs to find $BRG_1(s)$, $BRG_2(s)$ to cover $N_2(s)$
    Piggyback $BRG_1(s)$, $BRG_2(s)$ in *packet*, i.e., $P(s, BRG_1(s), BRG_2(s))$
    Broadcast$P(s, BRG_1(s), BRG_2(s))$ to $N_1(s)$
if v *receives a packet* $P(s, BRG_1(s), BRG_2(s))$ *from* s *for the first time* **then**
    if $v \in BRG_1(s)$ **then**
        v uses DBRGs to find $BRG_1(v)$, $BRG_2(v)$ to cover $N_2(v)$
        Piggyback $BRG_1(v)$, $BRG_2(v)$ in *packet*, i.e., $P(v, BRG_1(v), BRG_2(v))$
        Broadcast$P(v, BRG_1(v), BRG_2(v))$ to $N_1(v)$
    end
    if $v \in BRG_2(s)$ **then**
        if v *fullfills Range Sensing Rule* && *Maximum Coverage Rule* **then**
            v uses DBRGs to find $BRG_1(v)$, $BRG_2(v)$ to cover $N_2(v)$
            Piggyback $BRG_1(v)$, $BRG_2(v)$ in *packet*, i.e.,
            $P(v, BRG_1(v), BRG_2(v))$
            Broadcast$P(v, BRG_1(v), BRG_2(v))$ to $N_1(v)$
        else
            Discard(P)
        end
    else
        Discard(P)
    end
else
    Discard(P)
end

Algorithm 3: Cross Layer Mobility Adaptive Broadcasting (CMAB)

Input: $N_1(s)$, $N_2(s)$, s

Output: $BRG_1(s)$, $BRG_2(s)$

1. $S = N_2(s)$
2. The Relay node set $BRG_1(s)$ is initialized to be empty, i.e., $BRG_1(s) = \emptyset$
3. Add in $BRG_1(s)$ the node $n \in N_1(s)$ that covers the largest number of $N_2(s)$ neighbors that are not yet covered by the current $BRG_1(s)$, a tie is broken by node ID
4. $S = S \setminus N_1(n)$
5. $N_1(s) = N_1(s) - \{n\}$
6. Repeat steps 3, 4, and 5 until all nodes in S are covered by $BRG_1(s)$
7. The Relay node set $BRG_2(s)$ is initialized to be empty, i.e., $BRG_2(s) = \emptyset$
8. Add in $BRG_2(s)$ the node $n \in N_1(s)$ that covers the largest number of $N_2(s)$ neighbors that are not yet covered by current $BRG_2(s)$, a tie is broken by node ID
9. $N_2(s) = N_2(s) \setminus N_1(n)$
10. $N_1(s) = N_1(s) - \{n\}$
11. Repeat steps 8, 9, and 10 until all nodes in $N_2(s)$ are covered by $BRG_2(s)$ or there is no node in $N_1(s)$ left that covers additional nodes in $N_2(s)$

Algorithm 4: Disjoint Broadcast Relay Gateways (DBRGs)

3.7.6 Performance Evaluation of CMAB

We ran the simulation under ns-2 [138] testbed with CMU wireless extension. The simulation parameters used for our experiments are listed in Tablel 3.1. We used cisco aironet 350 card specifications to simulate CMAB as shown in Table 3.2. The network area used for our simulations is confined within $500m \times 500m$. The radio propagation model used for our experiments is two ray ground reflection model. The transmission range of each node in the network is $250m$. We have used the random way point mobility model to model the mobility in our simulations. We have chosen a random node in the network to start the broadcast process. We are interested in analyzing the effect of mobility and node density on the performance of CMAB. Each simulation run lasts for 1110 seconds. For the first 1000 seconds all the nodes in the network exchange HELLO packets and populate their neighbour tables. For the next 100 seconds broadcast operations are initiated by different nodes in the network and messages are disseminated in the network. In order to ensure that the packets which have already been broadcasted during the simulation time can successfully propagate in the network, another 10 seconds are given to complete the broadcast process. We have taken an average over 10 experiments to ensure a confidence interval of 95% that the actual mean is within the said interval for the final results.

3.7.6.1 Performance Metrics and Chosen Protocols

We compare the performance of our proposed protocol CMAB with two other popular broadcast protocols known as AHBP and its extension AHBP-EX. We compare the performance of all protocols in terms of reachability, broadcast cost, and broadcast speed. For our simulations we consider the following parameters that affect the performance of CMAB:

1. **Mobility of the Node** (S_{max}): The mobility of the nodes in the network affects the performance of all broadcast protocols. If the nodes are moving with high speed, the possibility to lose a broadcast packet is high.

2. **Hello Interval** (T_{hello}): CMAB, AHBP, and AHBP-EX rely on 2-hop neighborhood information which is maintained by exchanging of HELLO messages periodically. The HELLO interval determines the accuracy of the 2-hop neighborhood information. A larger HELLO interval T_{hello} causes the 2-hop information to become stale. A too frequent exchange of HELLO messages increases the protocol overhead leading to network congestion as well as causes information to expire quickly.

3. **Node Density** (d_n): Increasing the number of nodes in a fixed simulation area increases the node density. A dense network increases network connectivity as well as causes collisions and contention in the network.

3.7.6.2 Results and Analysis

Sensitivity to Mobility

The analysis below show the effect of mobility on the performance of CMAB. The number of nodes used is 70. We vary the maximum speed of each node from $5m/s$ to $30m/s$. Each node broadcasts a packet with a rate of 15 *packets/second*. Figure 3.23 shows the effect of mobility on the reachability of CMAB. The performance of CMAB is significantly better than AHBP when the node speed increases but not better than AHBP-EX. The performance difference between CMAB and AHBP-EX is due to inherent mobility adaptation mechanism of CMAB which is based on mobility detection technique illustrated in Algorithm 1. Mobility adaptation mechanism based on mobility detection need not to always yield the improved or anticipated results due to frequent topological changes induced by high mobility resulting in link failures [31]. Figure 3.24 shows that the broadcast cost decreases with an increase in mobility for both AHBP and CMAB, however for AHBP-EX the broadcast cost shows an increase. From Figure 3.24 it is clear that for all mobility values the broadcast cost of CMAB is higher than AHBP but is significantly less than AHBP-EX. This is due to the fact that unlike the controlled event driven retransmission mechanism used by CMAB in highly mobile scenarios, AHBP-EX shows aggressive retransmission. Figure 3.25 shows the broadcast speed for all three protocols. The broadcast speed of CMAB and AHBP shows an increase with an increase in mobility. It is clear from Figure 3.25 that the speed of CMAB is more or less the same as that of AHBP. However, the broadcast speed of AHBP-EX is less than both AHBP and CMAB and seems to be less affected by mobility.

Sensitivity to Node Density

In order to investigate the effect of node density on CMAB, we have varied the node density by increasing the number of nodes over a simulation area of $500m \times 500m$. The number of nodes has been varied from 25 to 150 in steps of 25. The network has high mobility with each node moving with a maximum speed of $20m/sec$ with a pause time of 0 seconds. We select one node randomly to start the broadcast process with a sending rate of 2 packets/s. We analyze the effect of node density on each metrics described in Section 3.7.6.1. As the packet rate is 2 *packets/second*, most of the packet losses are result of link failures due to mobility.

Figure 3.26 shows the reachability. We can see that under a denser and mobile network scenario, AHBP-EX and CMAB have good reachability, i.e., $> 90\%$. For the dense network, the reachability achieved by CMAB is slightly higher than AHBP-EX, as a denser network has a high chance to have disjoint broadcast relay gateways which improves its reachability. This slight increase in reachability suggests that in a dense network, a controlled retransmission mechanism is better than an aggressive retransmission. AHBP-EX due to its aggressive retransmission mechanism for mobile networks causes some losses due to incipient congestion. When the node density is small, the chance of having two disjoint broadcast relay gateways is less which leads to reachability of CMAB lower than AHBP-EX but still higher than AHBP. Figure 3.27 shows the broadcast cost. AHBP-EX for the denser network, i.e., $n \geq 150$ and mobile network has more than 80% total nodes forwarding a broadcast packet. AHBP has the less forwarding nodes than CMAB and AHBP-EX. When the network density is not very high, the broadcast cost achieved by CMAB is slightly higher than AHBP but the gap becomes higher when the network size increases. AHBP and CMAB have similar broadcast speed, while AHBP-EX has lower broadcast speed as shown in Figure 3.28. It is clear from the Figure 3.28 that for all three protocols, the broadcast speed is less sensitive to node density.

From these simulations, we can observe that all protocols have a remarkable increase in reachability for denser network scenarios. CMAB and AHBP-EX have comparable performance in terms of reachability, while CMAB has comparable performance with AHBP in terms of broadcast speed and broadcast cost. The performance difference between CMAB and AHBP-EX is due to explicit mobility adaptation mechanism of CMAB which is based on mobility detection scheme as described in Algorithm 1. On the other hand, in AHBP-EX rebroadcasts decision is made on the discovery of a new link with another node without any mobility detection and adaptation mechanism and therefore it has improved performance. CMAB is suitable for network scenarios where maximum coverage is desirable but at the limited budget of retransmitting nodes. In such scenarios, CMAB provides better broadcast coverage and broadcast speed than AHBP at the expense of small increase in the broadcast cost.

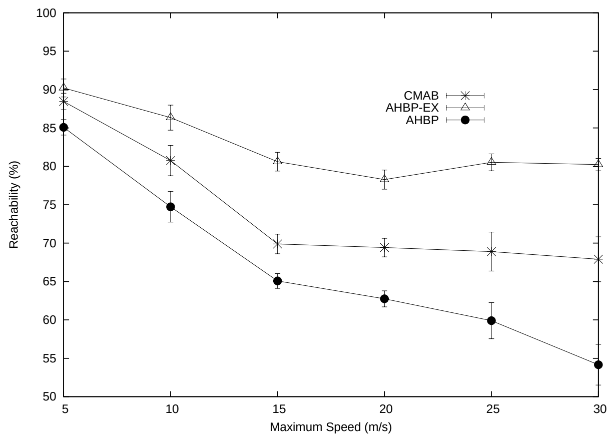


Figure 3.23: Reachability versus maximum speed (m/s) for CMAB

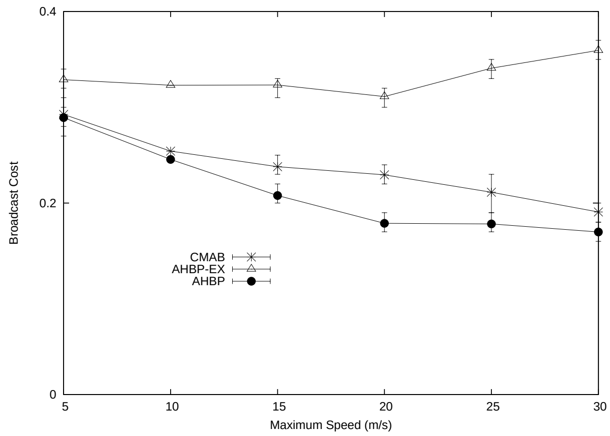


Figure 3.24: Broadcast cost versus maximum speed (m/s) for CMAB

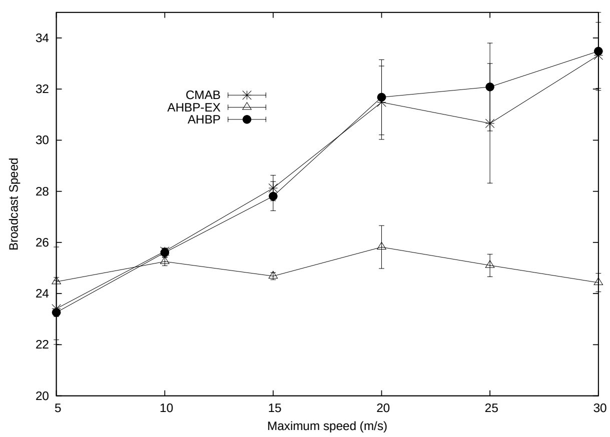


Figure 3.25: Broadcast speed versus maximum speed (m/s) for CMAB

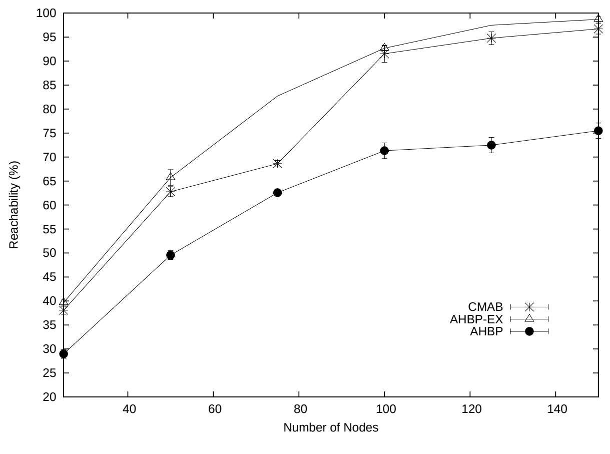


Figure 3.26: Reachability versus No. of nodes for CMAB

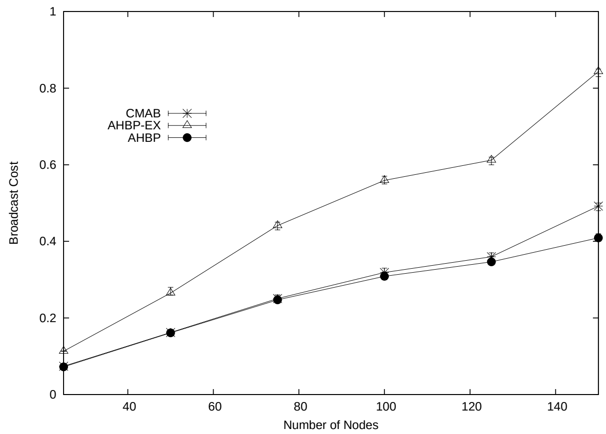


Figure 3.27: Broadcast cost versus No. of nodes for CMAB

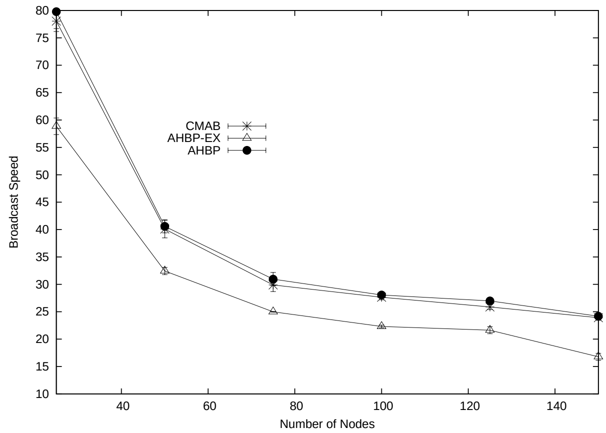


Figure 3.28: Broadcast speed versus No. of nodes for CMAB

Sensitivity to Hello Interval

We analyze the effect of the HELLO interval on the performance of CMAB, in order to investigate its effect we set the value of the HELLO-Interval T_{hello} at $0.2s$, $5s$, and $1s$. The other simulation parameters we have used are $n = 70$ and all the nodes in the network follow a random way point mobility model with a maximum speed varied from $5m/s$ to $30m/s$ with a pause time of 0 seconds. We have selected a random node which starts the broadcast process with a sending rate of 2 *packets/second*. Figure 3.29 shows that the reachability achieved by CMAB decreases as the maximum speed of the nodes increases. This decrease in reachability is more prominent for T_{hello} $5s$ as compared to $0.2s$.

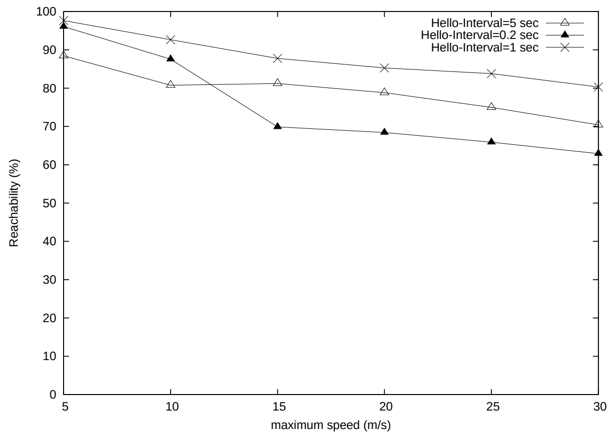


Figure 3.29: Reachability versus maximum speed (m/s) for CMAB

This is due to the fact that an increase in the mobility of the nodes causes more rapid topological changes, so the neighborhood information becomes outdated more quickly. In such dynamic scenarios, a T_{hello} of $0.2s$ keeps the neighborhood information more updated and accurate as compared to a long interval of $5s$. It can be observed from the Figure 3.29 that a very frequent exchange of the HELLO messages with $0.2s$ decrease the reachability as compared to T_{hello} value of $1s$. A more frequent exchange of neighborhood information causes the information to expire quickly. It can be observed from the Figure 3.29 that neither a too small value of the T_{hello} improves the performance of CMAB nor a too large value. A preferable value seems close to 1 second to increase the performance of CMAB.

3.8 Density Adaptive SBA (DASBA)

In a sparser network there is less chance of congestion and redundant retransmission cancellations as few nodes are involved in the retransmission of the broadcast message. Local node density is defined as the number of 1-hop neighbours of a node. If local node density of a node is ≤ 4, it indicates a sparser network scenario. Delaying the retransmissions of broadcast packets in such scenarios adds delay and affects the reachability significantly. Our proposed DASBA protocol improves the reachability

For new *packet* start from source s

Get a list of $N_1(s)$
Piggyback $N_1(s)$ in *packet*, i.e., $P(s, N_1(s))$
Broadcast $P(s, N_1(s))$ to $N_1(s)$

// x receives the packet from the source directly

```
if x receives a packet P(v, N_1(v)) from a node v for the first time then
    d_max = Maximum Node degree of a node n ∈ N_1(x)
    d_x = Node degree of x
    if Low Local Density Rule && New Link Rule then
        T_max = 0s
    else
        T_max = 0.01s
    end
    RAD_max = (d_max / d_x) × T_max
        // x chooses a random value uniformly distributed from the interval
        [0, RAD_max]
    RAD_val = random(0, RAD_max)
    y = N_1(x) − N_1(v)
    Start a timer T_RAD with an initial value RAD_val
    while T_RAD has not expired do
        if x receives packet P from the forwarding node w then
            y = y − N_1(w)
        end
    end
    if y ≠ ∅ then
        Piggyback N_1(x) in packet, i.e., P(x, N_1(x))
        Broadcast P(x, N_1(x))
    else
        Discard(P)
    end
else
    Discard(P)
end
```

Algorithm 5: Density Adaptive Scalable Broadcasting Algorithm (DASBA) by rebroadcasting the broadcast packet immediately. An immediate rebroadcast also improves broadcast speed in sparser network scenarios. The procedure for DASBA is similar to CASBA, however DASBA uses the local density and a new link information to delay the retransmission of a packet. The local density can be computed by using the low local density rule, if it is true it indicates a sparser network scenario. The new link information can be computed according to the new link rule. Both of these rules are defined as follows:

Low Local Density Rule: A value of $d_x \leq 4$ indicates a low local node density, where d_x denotes the number of neighbours of node x.

New Link Rule: When x receives a broadcast message transmitted by v, if node v is not a neighbour of x, or x is not in the neighbour list of v, it is likely that there exists a new link between them.

The operation of DASBA is illustrated in Algorithm 5.

3.8.1 Performance Analysis of DASBA

We have conducted experiments by using ns-2 to evaluate the performance of DASBA in different network scenarios. For physical layer specification, parameters are listed in Table 3.2, the other parameters are the same as Table 3.1.

3.8.1.1 Effect of Node Density

In this section we evaluate the performance of DASBA with varying node densities. We have used the random way point mobility model and all nodes are moving with a maximum speed of $5m/s$ with pause time of 0 seconds. It is apparent from the Figure 3.30 that the reachability achieved by DASBA is better than SBA. This improvement is due to the fact that in sparser network scenarios, there is a small number of nodes in the network so instead of waiting for a RAD time to delay the transmission, a node rebroadcasts immediately increasing the chance of a packet to be received by neighbouring nodes. It is clear from the Figure 3.32 that immediate rebroadcast in DASBA results in an excellent improvement in broadcast speed compared to SBA.

However DASBA as shown in Figure 3.31 has slightly higher broadcast cost than SBA because as a result of immediate rebroadcast fewer redundant retransmissions can be cancelled. In a sparser network the number of redundant retransmissions cancelled is smaller than in a dense network, thus an excellent improvement in broadcast speed and improved reachability seems reasonable at the slight expense of broadcast cost.

3.8.1.2 Effect of Mobility

We used the random way point mobility model to model the mobility and have varied the maximum speed from $5m/s$ to $30m/s$ with pause time of 0 seconds. The other simulation parameters are listed in Table 3.2. The maximum number of nodes we have considered is 20. It is apparent from Figure 3.33 that the reachability achieved by DASBA is better than SBA for all speeds. A highly mobile network may result in a sparser network due to variations in spatial distribution of nodes in the network which may change the local node density; therefore an immediate rebroadcast can reach more nodes compared to a delayed rebroadcast. In highly mobile networks, DASBA rebroadcasts earlier than SBA, improving its performance.

It is apparent from Figure 3.35 that DASBA has much better broadcast speed than SBA due to immediate rebroadcast compared to delayed rebroadcast in SBA. However, as shown in Figure 3.34, high mobility results in a sparser network resulting in immediate rebroadcast, and therefore DASBA is able to cancel only few redundant retransmissions resulting in higher broadcast cost than SBA.

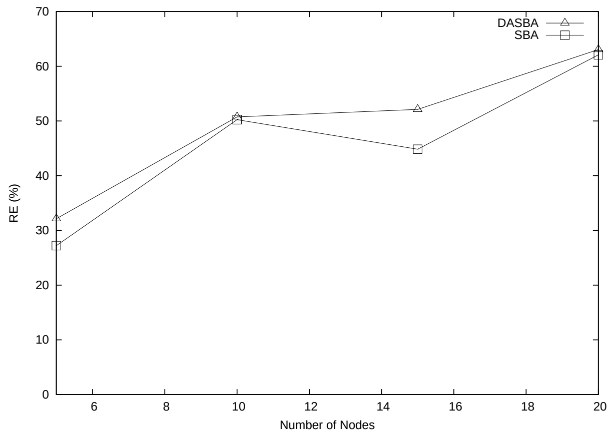


Figure 3.30: Reachability versus No. of nodes for DASBA

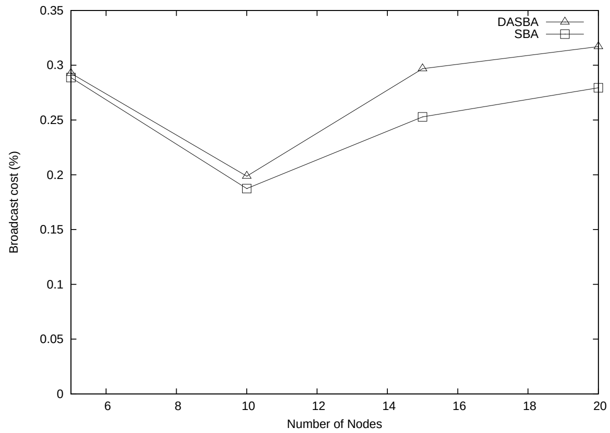


Figure 3.31: Broadcast cost versus No. of nodes for DASBA

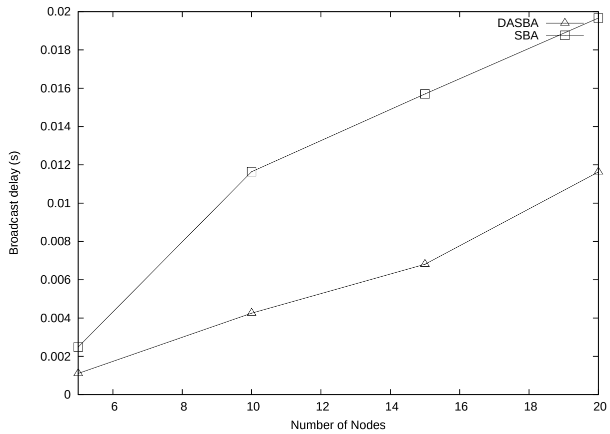


Figure 3.32: Broadcast delay versus No. of nodes for DASBA

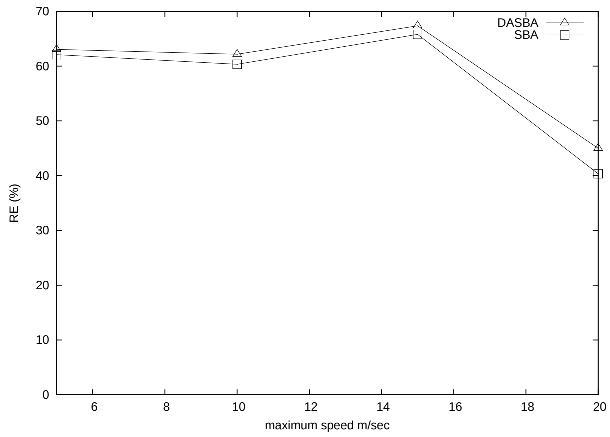


Figure 3.33: Reachability versus maximum speed (m/s) for DASBA

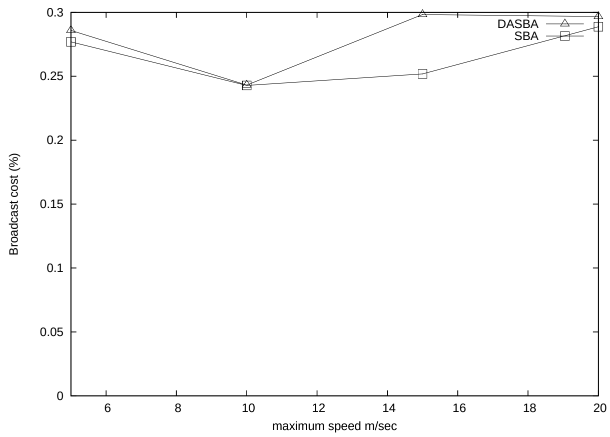


Figure 3.34: Broadcast cost versus maximum speed (m/s) for DASBA

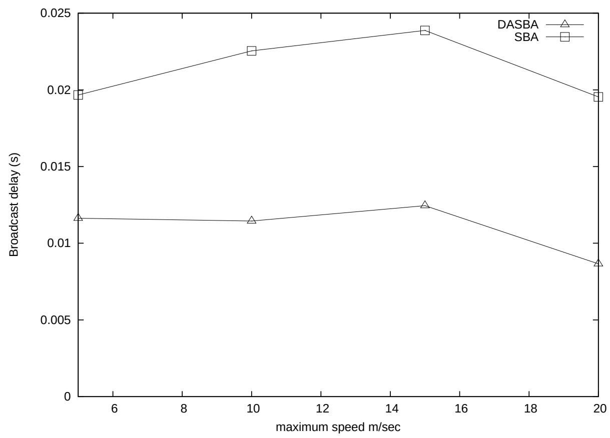


Figure 3.35: Broadcast delay versus maximum speed (m/s) for DASBA

3.9 Conclusion

In this chapter we present a comprehensive analysis of the impact of network conditions on existing popular broadcasting schemes. This analysis provides an insight into different broadcasting schemes and how they work under different conditions of network congestion, node density, and mobility. We also propose two extensions to SBA which improve its performance in sparse and congested network scenarios. In our congestion adaptive extension to SBA known as CASBA, the RAD value is adjusted by the MAC layer according to the estimated reason of the packet loss in the network. CASBA reduces the broadcast redundancy significantly. It controls the number of retransmissions to achieve a balance between broadcast cost and broadcast speed according to congestion in the network. Our other extension to SBA known as DASBA uses local density and new link information to adjust the value of the RAD which improves its broadcast speed and reachability in mobile and sparser network scenarios. Further, we propose a cross layer mobility adaptive broadcast protocol CMAB that provides high reachability while reducing the broadcast redundancy in highly mobile networks. This reduction is achieved by activating extra retransmissions only in case of high mobility for increased coverage. Simulation results show that cross layer mobility adaptive broadcast has high reachability, low broadcast cost and high broadcast speed in highly mobile and denser network scenarios compared to AHBP. However, mobility adaptation mechanism of CMAB does not yield anticipated outcomes compared to AHBP-EX due to frequent mobility-induced topological changes in the network.

Chapter 4

Approximating Maximum Disjoint Coverage in WSNs

4.1 Introduction

Wireless sensor networks support a variety of applications, such as environmental monitoring and battle surveillance. More often WSNs comprise of thousands of sensors randomly deployed in some particular area to cover some particular targets. Due to random deployment of sensor nodes in a particular area, the only better way to achieve adequate target coverage is to use more sensors than the optimal number. If a target is in the sensing range of a sensor, we say that the sensor provides coverage to that particular target. Sensors which can cover targets can be divided into sets, called set covers, where each set cover can monitor the specified targets. The coverage problem as discussed in Chapter 2 is one of the important research issues in WSNs, and reflects how well a set of targets is monitored by a set of deployed sensors. Coverage problems can be classified into area coverage and target coverage as discussed in Chapter 2. However, our work in this chapter is related with the target coverage problem only.

Sensors are small devices with limited battery for which it may not be possible to replace or recharge them. Further, sensors are prone to software and hardware failures. Sometimes harsh weather or physical environment may contribute to the failure of sensors. It is therefore critical to provide a fault-tolerant coverage that may still continuously monitor the critical targets despite some sensor failures. Coverage problems in sensor networks can be categorized into single coverage and multiple coverage. In single coverage, a target is monitored by at least a single sensor, whereas in multiple coverage, a target is monitored by k different sensors [51].

The problem of coverage in WSNs has been studied in various applications. In [130, 92] coverage problems have been discussed to achieve an objective related with the quality of service of a sensor network. Coverage problems have also been discussed in various studies to maintain connectivity. In [61], improved coverage has been discussed for multi-hop ad hoc networks considering the constraint of limited path length. In order to achieve fault-tolerant coverage, the initial studies focus on the problem of finding a maximum number of set covers to cover some targets. Cardei and Du [18] prove that the problem to find maximum set covers to cover some targets is a $\mathcal{NP}$-complete problem, where a sensor may participate in more than one set covers. Cardei et al. [166] have proposed a breadth first search algorithm for the computation of connected set covers from a Base Station (BS) to particular targets. In the same work, they propose a distributed minimum spanning tree algorithm to address the same problem. Jaggi et al. [70] propose a set cover algorithm to maximize the network lifetime. In their problem, they try to maximize the number of disjoint set covers. They use the shortest path algorithm to select the sensors to maintain the connectivity in the network.

The work most relevant to our approach is [16] and [18]. In [16] the target coverage problem maps disjoint sensor sets to disjoint set covers. These disjoint set covers monitor all the targets. They give a lower bound of 2 for any polynomial time approximation algorithm for disjoint set covers such that every set cover can monitor all the targets. In [126] a heuristic known as constrained least coverage is proposed to find a maximum number of disjoint set covers.

MSC [18] for complete target coverage computes non-disjoint set covers where each set cover can cover all the targets. The main objective of MSC is to determine a number of set covers where each set cover covers all the targets such that the network lifetime is maximized by alternating among these set covers. The MSC problem is a well known $\mathcal{NP}$-complete problem. However, this solution does not guarantee fault tolerance because a covering sensor may participate in more than one set covers, and therefore may deplete energy. Cheng et al. [24] have discussed that the MSC problem and similar problems which aim to achieve complete coverage by using non-disjoint set covers assume unlimited number of covering sensors to cover targets. These techniques do not consider the bandwidth constraints. They propose the use of disjoint set covers to solve this problem. In their work they compute disjoint set covers such that a set can cover no more than an assigned number of targets and their main objective is to maximize the number of disjoint set covers. Another variation of the MSC problem is MSC with disjointness constraints [25] for complete target coverage by using disjoint set covers and the main objective is to maximize the number of disjoint set covers. In [1] Abrams et al. discuss a variation of the k-set cover problem. In their problem, they relax the coverage constraint where each node may cover only partial targets, and their main objective is to increase the number of set covers to cover some targets. In order to solve this problem, they have proposed three algorithms. The first algorithm computes k-set covers with a fraction of $1-1/e$ of the optimum solution. The second algorithm is based on a greedy approach and gives a solution with $\frac{1}{2}$-approximation ratio. The third algorithm computes a solution with $(1-1/e)$-approximation ratio.

In this chapter, we consider a variation of the target coverage problem of computing two disjoint set covers S_1 and S_2 such that the first set cover S_1 achieves complete target coverage, whereas the second set cover S_2 can achieve maximum coverage. In other words, our problem relates to both MSC and MSC with disjointness constraints. In particular for the first set cover S_1 our problem is based on MSC, whereas the second set cover tries to achieve the maximum coverage while holding the disjointness constraint. Our problem called Maximum Disjoint Coverage (MDC) computes two set covers S_1 and S_2 such that S_1 achieves complete target coverage and the coverage of the second disjoint set cover S_2 is maximized. In our work, first we reduce the NOT-ALL-EQUAL-3SAT problem to MDC problem. Further, we present an approximation algorithm called Disjoint Set Covers for Maximum Disjoint Coverage (DSC-MDC) to compute two disjoint set covers S_1 and S_2 for the MDC problem. We also show that DSC-MDC achieves approximation ratio $\sqrt{n}$, where n denotes the number of targets.

The remainder of the Chapter is organized as follows. In Section 4.2, we present some preliminaries that are necessary for our work in this chapter. In Section 4.3, we formulate the MDC problem, and prove its $\mathcal{NP}$-completeness. In Section 4.4, we present a $\sqrt{n}$-approximation algorithm DSC-MDC to compute two disjoint set covers for MDC problem. Finally Section 4.6 concludes the chapter.

4.2 Preliminaries

In this section we discuss some of the preliminaries related with MDC problem.

Set Cover problem

Given a universal set of elements U and a collection C of subsets of U, the set cover problem is to choose a minimum number of sets from C such that the union of all the sets covers all elements in U. Basically, the main aim of the set cover problem is to cover all the elements of the U. The set cover problem is illustrated below with the help of an example.

Let $U = \{a, b, c, d\}$ be the universal set. Given the following collection of sets S. $S = \{S_1, S_2, S_3, S_4\}$, where $S_1 = \{a, b\}$, $S_2 = \{b, c\}$, $S_3 = \{c, d\}$, and $S_4 = \{d, a\}$. Both S_1 and S_3 together form a minimum set cover, i.e., $Set\_cover_1 = \{S_1, S_3\}$. Another possible minimum set cover is $Set\_cover_2 = \{S_2, S_4\}$. Both minimum set covers have size 2.

Target Coverage Problem (TCP)

Given T targets with known locations, and n sensors with known energy constraints deployed in a wireless sensor network, The Target Coverage Problem (TCP) is to schedule the activity of sensors S such that all the targets are continuously monitored and the overall network lifetime is maximized [18]. For every target $t_j \in T$, there is at least one sensor $s_i \in S$ that covers t_j, and each $s_i \in S$ may cover several targets. In order to maximize the network lifetime, activity among the sensors can be scheduled as follows:

- Based on the information of the sensor nodes S, BS uses some scheduling algorithm and broadcasts this schedule information to the sensor nodes.
- According to the schedule information received from the BS, sensor nodes S follow sleep or active intervals.

The main objective of TCP is to maximize network lifetime and at the same time continuously observe all the targets, so one viable solution is to compute a number of set covers to cover the targets. Each set cover $S_i \subset S$ covers all the targets T. The BS can schedule the activity among these set covers to adjust their sleep or active intervals in order to maximize the network lifetime.

Figure 4.1 shows an example of a sensor network, where base station BS has to cover targets t_0, and t_1. Assume that each of the sensors s_0, s_1, r_0, and r_1 has a battery life of one time unit. If BS uses all the sensors S to cover all the targets, it may result in network lifetime of one time unit. However, BS may select two set covers $S_1 = \{s_0, s_1\}$ and $S_2 = \{r_0, r_1\}$ to cover all the targets. BS can schedule the activity among S_1 and S_2 such that at time $t = 1$ set cover S_1 can be activated and at time interval $t = 2$ S_2 can be activated resulting in a network lifetime of two time units.

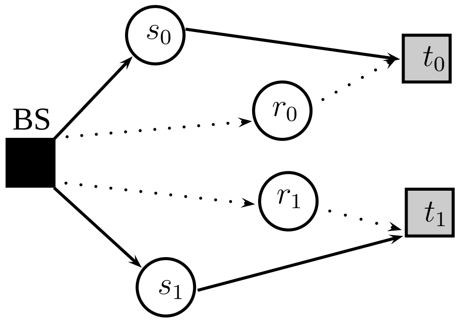


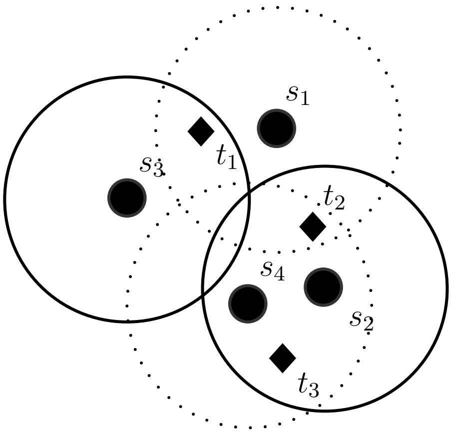
Figure 4.1: Two disjoint set covers to cover targets selected by the BS

Maximum Set Covers (MSC)

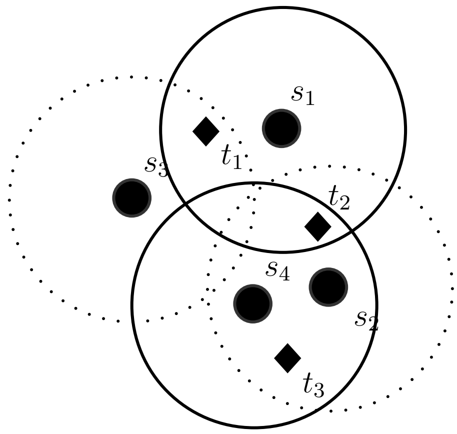
The target coverage problem can be formally modelled as the combinatorial optimization problem called MSC and is described below. Given a collection S of subsets of a finite set T, compute set covers $S_1, \ldots, S_m$ and weights $w_1, \ldots, w_m$ in $[0, 1]$ such that the total weight $w_1 + \ldots + w_m$ is maximized, and for each sensor $s_i \in S$, s appears among set covers $S_1, \ldots, S_m$ with weight w_i such that $\sum_{s \in S_i} w_i \leq 1$, where 1 denotes the lifetime of each sensor [18].

In the MSC problem definition, S denotes the set of sensors, and T denotes the set of targets, where each sensor monitors a subset of targets. For set covers $S_1, \ldots, S_m$, each set cover S_i, where $i = 1, \ldots, m$ completely monitors all the targets. The objective of MSC is to maximize the network lifetime represented as $w_1 + \ldots + w_m$, where w_j is in $[0, 1]$ and $j = 1, \ldots, m$. w_j denotes the length of the time interval while set cover S_j is active. A sensor can participate in more than one set covers, but the sum of active time intervals of those set covers cannot be more than 1. An example illustrating the MSC problem is shown in Figure 4.2.

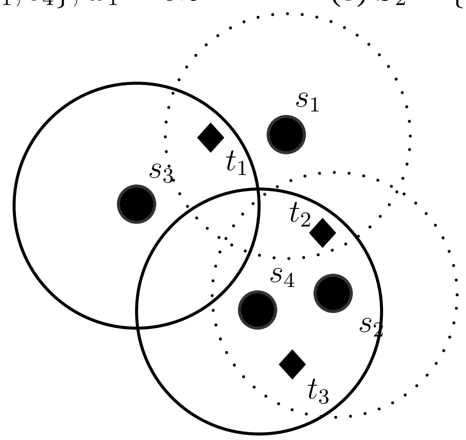
The MSC problem can be further illustrated with the help of Figure 4.2, where the three set covers computed are: $S_1 = \{s_1, s_4\}$, $S_2 = \{s_2, s_3\}$, and $S_3 = \{s_1, s_2\}$. Network lifetime can be maximized by allowing different sets to be operational at different time intervals. In this case S_1 can be active for $W_1 = 0.5$ time, S_2 for $W_2 = 0.5$ time, and S_3 for $W_3 = 0.5$ time resulting in a total network lifetime of 1.5.



(a) $S_1 = \{s_1, s_4\}, w_1 = 0.5$



(b) $S_2 = \{s_2, s_3\}, w_2 = 0.5$



(c) $S_3 = \{s_1, s_2\}, w_3 = 0.5$

Figure 4.2: Three set covers S_1, S_2, and S_3 to cover all the targets

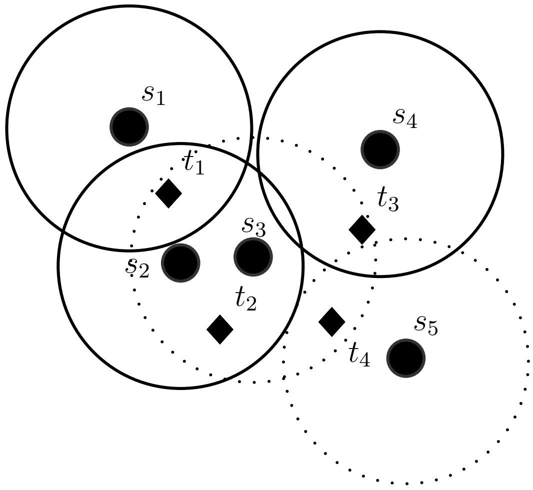


Figure 4.3: Randomly deployed sensors with overlapping sensing ranges to cover targets

Disjoint Set Covers (DSC)

Given a collection S of subsets of a finite set T, the objective of the DSC problem is to compute the maximum number of disjoint set covers for T [16]. Each set cover $S_i \subset S$ must be such that every element $t_j \in T$ can be covered by at least one element of S_i, and for any two set covers S_i and S_k, $S_i \cap S_k = \emptyset$. In DSC, all the set covers to cover all the targets should be disjoint, therefore one sensor can contribute to one set cover only. As shown in Figure 4.3, it is possible to cover all the targets by using two disjoint set covers $S_1 = \{s_1, s_3\}$ and $S_2 = \{s_2, s_4, s_5\}$, according to DSC problem. Both S_1 and S_2 can be activated alternatively resulting in a total network lifetime of 2 time units.

Bipartite Graphs

The vertices of a bipartite graph can be divided into two sets, and there exists no edge between the vertices of the same set [11]. An example of a bipartite graph is shown in Figure 4.4. A bipartite graph can be used to model the coverage relation between the sensors and targets, where the sensors are part of the set S and targets

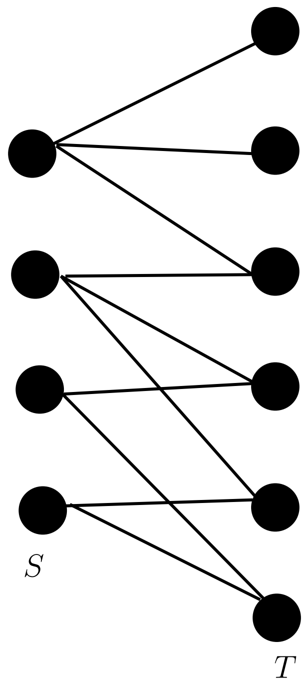


Figure 4.4: A bipartite graph with two disjoint sets S and T

of T, and the coverage relationship from a sensor to a target is represented by an edge.

Approximation Algorithm

Unless $\mathcal{P} = \mathcal{NP}$, for many combinatorial optimization problems, it is unlikely that a polynomial time algorithm exists that always computes optimal solutions [32, 30]. Such problems are known as $\mathcal{NP}$-hard problems. Although no polynomial time solution exists for such problems, near optimal solutions in polynomial time are possible [32, 30, 55, 73]. An approximation algorithm is an algorithm which runs in polynomial time and computes a near optimal solution [32]. Let $\mathcal{OPT}$ denote an arbitrary optimal solution. In case of maximization problems, the approximation ratio of an approximation algorithm is the ratio of the value of $\mathcal{OPT}$ to the value of the solution computed by the approximation algorithm in the worst case. On the other hand, for minimization problems the approximation ratio is the ratio of the value of the approximate solution to the value of $\mathcal{OPT}$ in the worst case.

4.3 Maximum Disjoint Coverage (MDC) Problem

In this section, we define the MDC problem. It can be seen as a variation of the minimum set cover problem [55] and we prove its $\mathcal{NP}$-completeness.

4.3.1 Problem Description

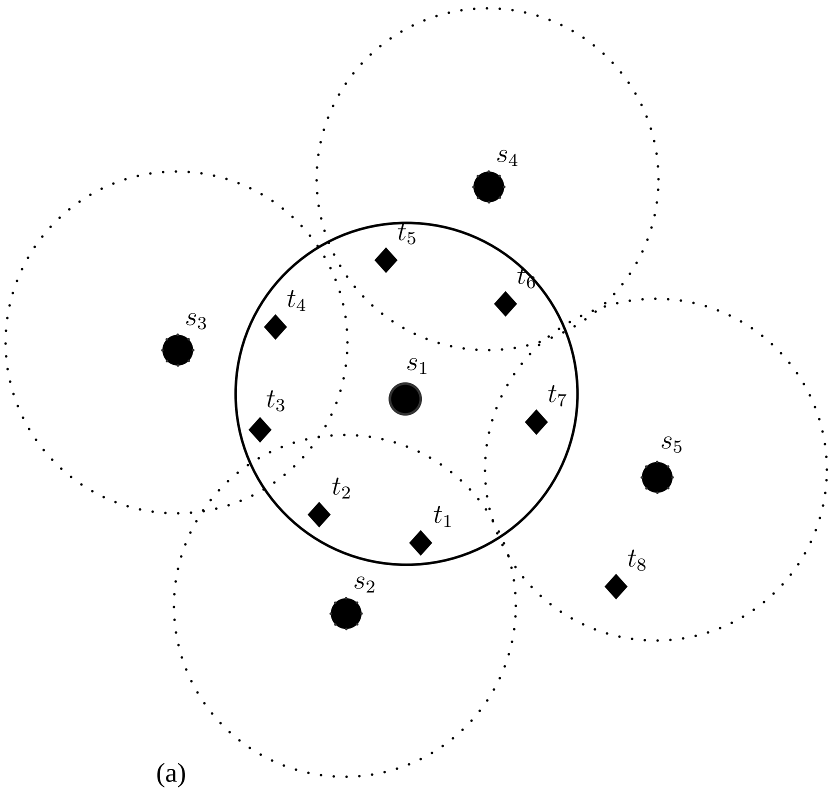
Let us assume that there is a set of n sensors $s_i, i = 1, \ldots, n$ to cover m targets t_k, $k = 1, \ldots, m$. The goal is to divide the sensors into two disjoint set covers S_1 and S_2, such that S_1 completely covers all the targets and S_2 covers a maximum number of targets. A target is covered by a sensor if it lies within the sensing range of that sensor. Next we formally define the MDC problem which can be modelled as the combinatorial optimization problem of the target coverage problem.

Definition 1. MDC Problem: Given a collection S of subsets of a finite set T, find two disjoint set covers S_1 and S_2 for T. Both set covers are subsets of S, i.e., $S_1 \subset S$ and $S_2 \subset S$, such that every element of T belongs to at least one member of S_1, and a maximum number of elements of T belong to members of S_2, and for the set covers S_1 and S_2, $S_1 \cap S_2 = \emptyset$.

The decision version of the MDC problem called Disjoint Coverage (DC) is stated as follows:

Disjoint Coverage (DC): Given a set of targets T and a collection S of subsets of T, find out whether S can be partitioned into two disjoint set covers that cover all elements of T or not.

Given a collection S of subsets of a finite set T, where S denotes the set of sensors and T denotes the set of targets, and each sensor monitors a subset of targets. An



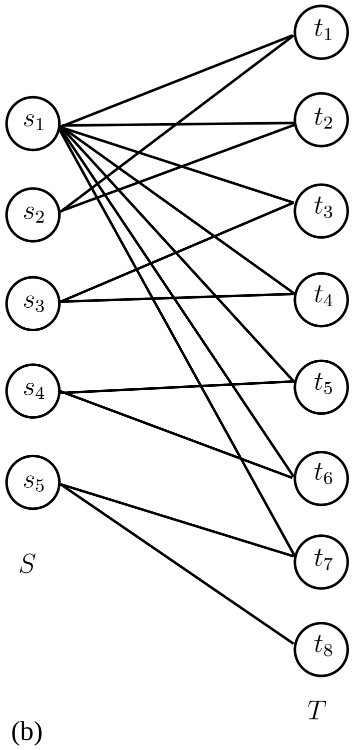


Figure 4.5: (a). Example of a sensor network with 8 targets and 5 covering sensors (b). Corresponding bipartite graph for (a)

instance of the DC problem can be represented as a bipartite graph, where the set of sensors S represents the set of S-vertices and the set of targets T represents the set of T-vertices in the bipartite graph. For every target represented as vertex $t_j \in T$-vertices, there is at least one sensor represented as vertex $s_i \in S$-vertices, where $i = 1, \ldots, m$ and where $j = 1, \ldots, n$. The coverage of target t_j by some sensor s_i is represented by an edge between $t_j \in T$-vertices and $s_i \in S$-vertices in the bipartite graph. The DC problem is to compute two disjoint set covers S_1 and S_2 from S-vertices, such that both S_1 and S_2 cover all the elements of T-vertices in the bipartite graph. An instance of the DC is represented as a bipartite graph G with S-vertices and T-vertices in Figure 4.5.

Figure 4.5(a) shows an example of a sensor network where 5 sensors $s_1, \ldots, s_5$ are deployed to cover 8 targets $t_1, \ldots, t_8$. Figure 4.5(b) shows the corresponding bipartite graph for the sensor to target coverage for the sensor network in Figure 4.5(a). One solution to the MDC problem in Figure 4.5 is two disjoint set covers using $S_2 = \{s_1\}$ to cover 7 targets $t_1, \ldots, t_7$ and $S_1 = \{s_2, s_3, s_4, s_5\}$ to cover all the 8 targets $t_1, \ldots, t_8$.

4.3.2 DC is $\mathcal{NP}$-complete

It can be proved that DC$\in \mathcal{NP}$ because a non-deterministic solution can partition the collection C into two disjoint sub-collections and it is verifiable in polynomial time if both sub-collections S_1 and S_2 cover T completely.

We reduce the NOT-ALL-EQUAL-3SAT problem, which is known to be $\mathcal{NP}$-complete, to DC in polynomial time. The NOT-ALL-EQUAL-3SAT problem appears in Garey and Johnson [55] and is defined below:

Definition 2. NOT-ALL-EQUAL-3SAT problem: Given a set U of variables, and a collection C of clauses over U, such that each clause $c_i \in C$ has size $|c_i| = 3$. The decision problem is to find out, if there is a truth assignment of U such that each clause $c_i \in C$ has at least one literal true and at least one literal false.

Theorem 4.3.1. *DC is $\mathcal{NP}$-complete.*

Proof. Let $U = \{x_1, x_2, x_3, \ldots, x_n\}$ be a given set of variables. Let $C = c_1 \wedge c_2 \wedge \ldots \wedge c_m$ be a collection of clauses given over U, where each clause $c_i \in C$ takes variables from U, i.e., $c_i = (u_{i1} \vee u_{i2} \vee u_{i3})$, where each u_{ij} denotes x_h, or $\bar{x_h}$ for some variables in U where $h = 1, \ldots, n$. We show how to construct a bipartite graph G in polynomial time such that U has a NOT-ALL-EQUAL-3SAT truth assignment for clauses C, if and only if G has two disjoint set covers that cover all elements of T.

We first define graph H as it can be seen in Figure 4.6 as a bipartite graph with the sensors S_H in one set of the bipartition, and T_H in the other, where $S_H = \{x_i, \bar{x_i}\}$ and $T_H = \{y_i\}$, where T_H denotes the set of targets. The only vertices from the H sub-graph which will be adjacent to other vertices of G will be from the set S_H, i.e., x_i and $\bar{x_i}$. So, every copy of sub-graph H in graph G will be represented by x_i and $\bar{x_i}$.

We can construct a graph G for the set C of clauses as illustrated in Figure 4.7 and explained below. In the construction of the graph G we have n copies of the sub-graph H as shown in Figure 4.6. In the example the copies are H_1, H_2, and H_3, where H_1 is represented by vertices x_1 and $\bar{x_1}$, H_2 by vertices x_2 and $\bar{x_2}$, and H_3 by vertices x_3 and $\bar{x_3}$. We also add one vertex for each clause in C to G. These vertices are called clause vertices. In graph G each vertex c_i representing a clause $c_i = (u_{i1} \vee u_{i2} \vee u_{i3})$ is connected to x_{i1} if $u_{i1} = x_{i1}$, to $\bar{x_{i1}}$ if $u_{i1} = \bar{x_{i1}}$, to x_{i2} if $u_{i2} = x_{i2}$, to $\bar{x_{i2}}$ if $u_{i2} = \bar{x_{i2}}$, to x_{i3} if $u_{i3} = x_{i3}$, to $\bar{x_{i3}}$ if $u_{i3} = \bar{x_{i3}}$. The vertices x_h and $\bar{x_h}$ for $h = 1, \ldots, n$ are the S-vertices of G and the remaining vertices are the T-vertices. Figure 4.7 shows the construction of graph G for three clauses $c_1 = \{\bar{x_1} \vee x_2 \vee x_3\}$, $c_2 = \{x_1 \vee \bar{x_2} \vee \bar{x_3}\}$, and $c_3 = \{x_1 \vee \bar{x_2} \vee x_3\}$.

Given a satisfying assignment to the NOT-ALL-EQUAL-3-SAT instance, let $D_1 =$ variables x_h in U that are true, and $D_2 = U - D_1$ constitute variables x_h in U that are false. We can construct two disjoint set covers S_1 and S_2 as follows: for each x_h in G, if $x_h \in D_1$ then place x_h in S_1, and place $\bar{x_h}$ into S_2, and if $x_h \in D_2$, then place x_h in S_2, and $\bar{x_h}$ into S_1. For example in Figure 4.7 for $C = \{\bar{x_1} \vee x_2 \vee x_3\} \wedge \{x_1 \vee$

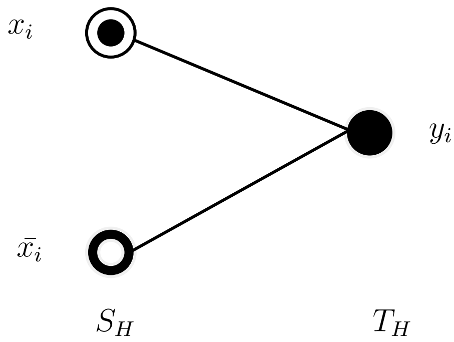


Figure 4.6: Graph H, building block for graph G

$\bar{x_2} \vee \bar{x_3}\} \wedge \{x_1 \vee \bar{x_2} \vee x_3\}$, one NOT-ALL-EQUAL-3-SAT truth assignment is to let $D_1 = \{x_2, x_1, x_3\}$, then for each $x_k \in D_1$, place the literal in S_1, and place $\bar{x_k}$ in S_2. So, we have $S_1 = \{x_2, x_1, x_3\}$ and $S_2 = \{\bar{x_2}, \bar{x_1}, \bar{x_3}\}$ two disjoint set covers because both sets S_1 and S_2 cannot contain x_h and $\bar{x_h}$ in the same set cover. Therefore both S_1 and S_2 disjointly cover all T-vertices of G.

Conversely, suppose graph G has disjoint set covers S_1 and S_2. For every variable x_i, S_1 must contain one literal and S_2 its opposite. If both literals, i.e., x_i and $\bar{x_i}$ are in S_1 then y_i cannot be covered by S_2 because y_i is covered by x_i and $\bar{x_i}$ only and therefore S_2 cannot be a set cover. We may define a truth assignment by assigning true values to literal x_h if and only if its corresponding vertex in S_1, i.e., for each $x_h \in U$, if $x_h \in S_1$, set x_h to true, and if $x_h \in S_2$ then set x_h to false. Then every clause c_i is satisfied since S_1 covers the clause vertices and S_2 covers the clause vertices thus providing the disjoint coverage DC which is also a NOT-ALL-EQUAL-3SAT assignment. Finally, the reduction from NOT-ALL-EQUAL-3SAT to DC is polynomial-time computable.

□

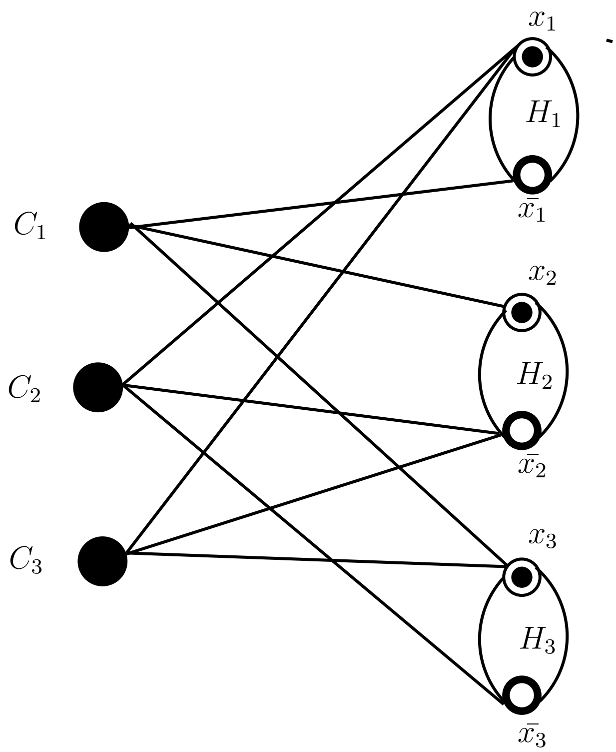


Figure 4.7: Graph G for $C = \{\bar{x_1} \vee x_2 \vee x_3\} \wedge \{x_1 \vee \bar{x_2} \vee \bar{x_3}\} \wedge \{x_1 \vee \bar{x_2} \vee x_3\}$

4.4 Approximation Algorithm for Maximum Disjoint Coverage (DSC-MDC)

In this section, we present an approximation algorithm Disjoint Set Covers for Maximum Disjoint Coverage (DSC-MDC) for the MDC problem. Given a collection S of subsets of a finite set T we want to determine two disjoint set covers S_1 and S_2 such that S_1 covers T completely and S_2 covers a maximum number of elements of T. DSC-MDC takes as an input a collection of subsets $S = \{s_1, s_2, \ldots, s_m\}$ and $T = \{t_1, t_2, \ldots, t_n\}$ where every set s_i for $1 \leq i \leq m$ denotes a set of elements in T.

DSC-MDC uses a greedy approach and selects a subset s_i from S which can cover a maximum number of elements of T. DSC-MDC evaluates if the elements of s_i can still be covered by other subsets in S, if it is true it adds s_i into set cover S_2. The algorithm DSC-MDC repeats until it has added all the possible subsets from S into set cover S_2 while ensuring that all elements of T can be still covered by subsets of

S. From the remaining subsets in S, i.e., $S \setminus S_2$, a simple greedy algorithm is used to compute a disjoint set cover S_1 which can cover all the elements of set T. Finally, DSC-MDC returns two disjoint set covers S_1 and S_2 where S_1 covers all the elements of T and S_2 covers as many as possible. The algorithm is shown in pseudo-code in Algorithm 6 and Algorithm 7.

```
Data: Collection of subsets S = {s_1, s_2, ..., s_m}
Result: Two Disjoint Set Covers S_1, and S_2
X ⇐ S
S_2 ⇐ ∅
while X ≠ ∅ do
    Let s_i ∈ X be a set that increases the coverage of S_2 by as much as possible
    if all elements of s_i can still be covered by some other sets in S then
        S_2 ⇐ S_2 ∪ {s_i}
        S ⇐ S \ {s_i}
    end
    X ⇐ X \ {s_i}
end
S_1 ⇐ Greedy(S)
Output Disjoint Set Covers S_1 and S_2
```

Algorithm 6: $\sqrt{n}$-approximation algorithm for computing disjoint set covers for maximum disjoint coverage (DSC-MDC)

We can explain the operation of Algorithm 6 with the help of an example given in Figure 4.8. Figure 4.8 shows a bipartite graph with two sets S and T. S is a covering set which can cover the elements in set T. The coverage relationship between the elements of set S and T is illustrated with the help of an edge. From the bipartite graph given in Figure 4.8, Algorithm 6 and Algorithm 7 can compute two disjoint set covers S_1 and S_2 as follows:

Data: Collection of subsets $S = \{s_1, s_2, \ldots, s_m\}$
Result: Set Cover S_1
$S_1 \Leftarrow \emptyset$
while S_1 *does not cover all targets* **do**
  Let $s_i \in S$ be a set that increases the coverage of S_1 by as much as possible
  $S_1 \Leftarrow S_1 \cup \{s_i\}$
  $S \Leftarrow S \setminus \{s_i\}$
end
Return S_1

Algorithm 7: A greedy algorithm to compute set cover S_1 ($Greedy(S)$)

Algorithm 6 computes S_2 to cover the set of targets T as follows

1. DSC-MDC chooses s_2 greedily which covers a maximum number of targets, i.e., $\{t_1, t_2, t_3, t_4\}$ such that still it is possible to cover these targets by s_3 and s_5, and adds s_2 to S_2.

$$S_2 = \{s_2\}$$

2. DSC-MDC chooses s_6 greedily which covers a maximum number of targets, i.e., $\{t_4, t_5, t_6\}$ such that still it is possible to cover these targets by s_1 and s_5, and adds s_6 to S_2.

$$S_2 = \{s_2, s_6\}$$

3. DSC-MDC chooses s_4 greedily which covers a maximum number of targets, i.e., $\{t_2, t_5, t_7\}$ such that still it is possible to cover these targets by s_1 and s_5, and adds s_4 to S_2. DSC-MDC does not select s_3 or s_1 because then t_3 or t_4 cannot be covered by S_1.

$$S_2 = \{s_2, s_6, s_4\}$$

Targets covered by set cover S_2

$$T = \{t_1, t_2, t_3, t_4\} \cup \{t_4, t_5, t_6\} \cup \{t_2, t_5, t_7\}$$

$$= \{t_1, t_2, t_3, t_4, t_5, t_6, t_7\}$$

From the remaining sets, i.e., $\{s_1, s_2, s_3\}$, Algorithm 7 computes S_1 greedily to cover the set of targets T as follows:

$$S_1 = \{s_1, s_5, s_3\}$$

Targets covered by set cover S_1

$$\begin{aligned} T &= \{t_2, t_4, t_7, t_8\} \cup \{t_1, t_5, t_6\} \cup \{t_3, t_7, t_8\} \\ &= \{t_1, t_2, t_3, t_4, t_5, t_6, t_7, t_8\} \end{aligned}$$

In this example, S_1 and S_2 are two disjoint set covers. By using Algorithm 6 and Algorithm 7, S_1 achieves the complete coverage of set T, and S_2 covers a maximum number of the elements of set T.

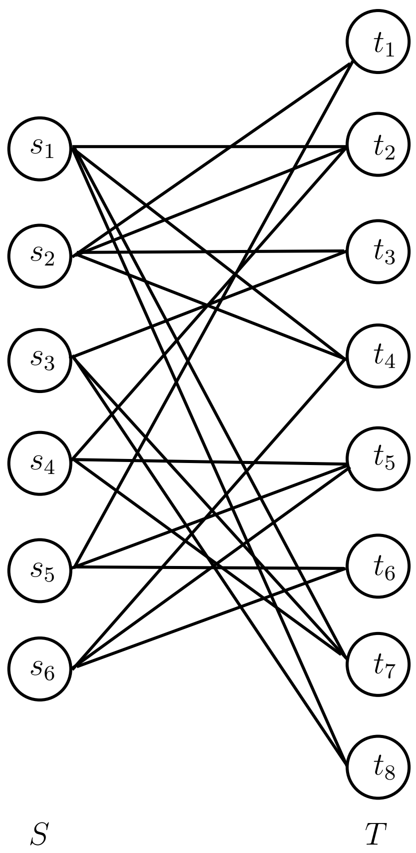


Figure 4.8: A bipartite graph with two disjoint set covers

4.5 Approximation Analysis

Theorem 4.5.1. *The approximation ratio of DSC-MDC is at most* $\sqrt{n}$ *where* n *is the number of elements of* T.

Proof. Let us have a collection of subsets $S = \{s_1, s_2, \ldots, s_m\}$ such that all the subsets in S can cover all n elements of T. Let us say set s_i is selected by DSC-MDC to add it into S_2 and s_i covers k_i elements in the i^{th} iteration, where $1 \leq i \leq A$, where A is the number of sets the Algorithm 6 adds to S_2. In A iterations the total number of elements covered by S_2 denoted by $Coverage_{DSC\_MDC}$ is given as follows:

$$|Coverage_{DSC\_MDC}| = k_1 + k_2 + k_3 + \ldots + k_A \tag{4.1}$$

Let $\mathcal{OPT}$ denote an optimal solution to compute S_2 to cover targets T. We describe two cases below to show that in the worst case compared to the optimum $\mathcal{OPT}$ DSC-MDC is a $\sqrt{n}$-approximation algorithm.

Case 1:

Let us assume that in the A iterations, the total number of elements covered by S_2 with DSC-MDC is greater than or equal to $\sqrt{n}$. $\mathcal{OPT}$ can cover at most n elements. So we can compare the coverage of elements of T using S_2 by both DSC-MDC and $\mathcal{OPT}$ as follows:

$$k_1 + k_2 + k_3 + \ldots + k_A \geq \sqrt{n}$$
$$C(\mathcal{OPT}) \leq n$$
$$\Rightarrow \frac{C(\mathcal{OPT})}{k_1 + k_2 + k_3 + \ldots + k_A} \leq \sqrt{n}$$
$$\Rightarrow \sqrt{n} - Approximation$$

Case 2:

Let us assume that the total number of elements of S covered by DSC-MDC using S_2 in A iterations is less than or equal to $\sqrt{n}$. Let us say for each iteration, DSC-MDC covers k_i elements and the other sets covering these elements are the last available sets in S, each covering $k_i - 1$ other elements. It means for these k_i elements, DSC-MDC loses at most $k_i(k_i - 1)$ elements in the i^{th} iteration, where $1 \leq i \leq A$. So, the total loss of elements for DSC-MDC for A iterations, denoted by $|Loss_{DSC\_MDC}|$, is at most $k_1(k_1 - 1) + k_2(k_2 - 1) + k_3(k_3 - 1) + \ldots + k_A(k_A - 1)$, i.e.,

$$|Loss_{DSC\_MDC}| \leq \sum_{i=1}^{A} k_i(k_i - 1) \tag{4.2}$$

On the other hand, every element covered by $\mathcal{OPT}$ is either covered by DSC-MDC or belongs to $Loss_{DSC\_MDC}$. So the total number of elements covered by $\mathcal{OPT}$ for A iterations is given as follows:

$$\begin{aligned} |\mathcal{OPT}| &\leq |Loss_{DSC\_MDC}| + |Coverage_{DSC\_MDC}| \\ &\leq \sum_{i=1}^{A} k_i(k_i - 1) + \sum_{i=1}^{A} k_i \end{aligned}$$

We can compare the number of elements of T covered by DSC-MDC using S_2 to the total elements of T covered by S_2 computed by $\mathcal{OPT}$, i.e., $C(\mathcal{OPT})$ as follows:

$$k_1 + k_2 + k_3 + \ldots + k_A \leq \sqrt{n}$$

$$\begin{aligned} C(\mathcal{OPT}) &\leq k_1^2 + k_2^2 + k_3^2 + \ldots + k_A^2 \\ &\leq (k_1 + k_2 + k_3 + \ldots + k_A)^2 \\ &\leq (k_1 + k_2 + k_3 + \ldots + k_A).\sqrt{n} \\ &\Rightarrow \frac{C(\mathcal{OPT})}{k_1 + k_2 + k_3 + \ldots + k_A} \leq \sqrt{n} \\ &\Rightarrow \sqrt{n} - Approximation \end{aligned}$$

From both cases, we can conclude that DSC-MDC is a $\sqrt{n}$-approximation algorithm.

□

4.6 Conclusion

Due to several limitations including limited battery life and fault tolerance issues posed by wireless sensor networks, efficient methods which can ensure reliable coverage of targets are highly desirable. One solution to provide reliable coverage to targets is to organize the sensors in set covers. These set covers can monitor the targets completely. However, one sensor may participate in more than one set covers to monitor the targets which is not a very energy efficient and fault-tolerant solution. Another solution is to divide the sensor into disjoint set covers which can completely cover the targets. However, sometimes it is not possible to achieve complete target coverage while keeping the disjointness constraint. In our work we formulate a problem called MDC which is a variation of the target coverage problem. The MDC problem is to use two set covers S_1 and S_2 to maximize the target coverage while holding the disjointness constraint. We proved that the decision version of MDC problem called DC is $\mathcal{NP}$-complete and proposed a $\sqrt{n}$-approximation algorithm DSC-MDC for the MDC problem. Our algorithm computes disjoint set covers S_1 and S_2 in such a way that computation of S_2 maximizes the target coverage whereas S_1 gives the complete coverage.

Chapter 5

SA-RI-MAC: Sender-Assisted Receiver-Initiated Asynchronous Duty Cycle MAC Protocol for Dynamic Traffic Loads in Wireless Sensor Networks

5.1 Introduction

One of the major limitations considered in wireless sensor networks is scarcity of energy. In order to conserve energy, power efficient protocols are desirable. These protocols try to mitigate energy consumption by devising different clever mechanisms at different layers of the protocol stack. Due to direct access to wireless medium, MAC layer mechanisms are more power efficient. Generally, a wireless radio has four power levels depending on its state: idle, sleeping, receiving and transmitting. During the active state a node is able to transmit and receive data but in sleep state it completely turns its radio off. Idle listening is one of the main reasons of energy consumption as it requires nearly the same amount of energy as to transmit and receive. This consumption can be saved by turning the radio of a sensor off as frequently as possible. Duty cycling is an efficient mechanism to handle the problem of idle listening [118, 157]. In duty cycling, wireless nodes periodically turn their radios on and off to reduce the idle listening time.

As discussed in Chapter 2, different approaches to duty cycling MAC can be categorized as synchronous and asynchronous. Synchronous approaches include RMAC [42], T-MAC [140], DW-MAC [131] and S-MAC [157]. In these approaches, neighbouring nodes synchronize their active and sleep schedules by using some synchronizing protocol. These approaches greatly reduce idle listening but are complex and need extra overhead to synchronize different neighbours with different sleep and active schedules. On the other hand, asynchronous approaches such as WiseMAC[44], X-MAC [13], B-MAC [117] and RI-MAC [132] allow nodes to have their own sleep and active schedules independent of the schedule of any neighbouring nodes. Asynchronous schemes work efficiently for light traffic loads but become less efficient in terms of latency, energy consumption, and delivery ratio under high traffic loads. In some applications of wireless sensor networks such as convergecast [164] and correlated-event workload traffic [68] where sensors are used for event monitoring, communication demand may suddenly increase in a burst. For example, in the event of fire several sensors report this event to some common sink. If contention caused by such events is not handled well, the data sent to the sink may experience longer delays or may be lost. Under such dynamic traffic loads, MAC layer protocols should be able to handle the contention at the sink.

In this chapter, we present a sender-assisted asynchronous duty cycling MAC protocol, called Sender-Assisted-Receiver-Initiated MAC (SA-RI-MAC). SA-RI-MAC attempts to resolve the contention among the senders with a common intended receiver and helps them to find a rendezvous time to communicate with the receiver. SA-RI-MAC differs from RI-MAC and previous asynchronous duty cycling protocols in the way different contending senders resolve the contention at the receiver by cooperating with each other. In SA-RI-MAC, a sender waits for an explicit beacon from the receiver to initiate the transmissions. An explicit beacon containing the value of channel access failure is exchanged among the neighbours having a common intended receiver. This value of channel access failure is used to resolve the contention among the senders for the medium access. Another improvement is achieved by prioritizing the transmissions of the senders which have been starved longer for the channel occupancy.

We believe this is the first attempt which combines the idea of receiver initiated transmissions with the sender assisted contention resolution. This sender assisted coordination adaptively increases the channel utilization; thus improving the delivery ratio and power efficiency under dynamic traffic loads. More importantly, the sender assisted contention resolution mechanism used by SA-RI-MAC increases fairness among the contending senders, gives priority to starved senders, and is more energy efficient. We have implemented SA-RI-MAC in ns-2 [138] simulator for evaluation in different network scenarios under dynamic traffic loads.

The rest of the Chapter is organized as follows. Section 5.2 gives a literature review of some popular duty cycling protocols. Section 5.3 discusses the contention resolution mechanism in RI-MAC and main problem in this protocol. Section 5.4 presents the details of SA-RI-MAC design. Section 5.5 reports the performance evaluation of SA-RI-MAC using ns-2 simulation. Finally in Section 5.6, we present our conclusions.

5.2 Related Work

In wireless sensor networks where energy is a scarce resource, transmissions between sender and receiver can be classified as sender initiated or receiver initiated. The idea of receiver initiated transmissions in a MAC protocol has been recently introduced in [132]. Receiver initiated collisions avoidance schemes for general wireless networks have been proposed in [54]. These schemes put more emphasis on collision avoidance than energy efficiency. However under high traffic loads when the degree of contention rises, these approaches are not able to resolve the contention. Low power probing (LPP) is an asynchronous receiver initiated transmission mechanism used in Koala systems [108]. In koala systems, downloads of the bulk data are initiated by the gateway nodes which allows other nodes to sleep most of the time to conserve energy. In LPP, each node broadcasts a preamble periodically. Upon receiving the preamble, nodes send an acknowledgement. Once an acknowledgement has been received, a node stays awake and starts acknowledging the probes of other nodes. LPP approach triggers useless wake-ups and sleep periods affecting the throughput and energy efficiency. B-MAC [118] and X-MAC [13] are asynchronous duty cycling MAC protocols in which transmissions are initiated by the senders. Prior to transmission, the sender sends a wake-up signal to the receiver by using a long preamble. The length of the preamble is longer than the sleep interval of a node to ensure that the node will wake up at least once during this duration. B-MAC is optimized under light traffic loads for energy consumption. However, an increase in the traffic load causes a significant amount of energy consumption, as the node spends most of the time in active state, even though the packet is meant for other nodes. The X-MAC solves this problem by sending the preamble as a series of short preambles prior to any transmission and waits for an acknowledgement from the receiver thus reducing the channel occupancy significantly. X-MAC preamble contains the target address which allows the irrelevant nodes to turn off their radio to conserve energy. Further, in this approach the receiver sends an acknowledgement to the sender to stop probing the channel. Once a DATA packet has been received, the receiver stays awake for the duration of the maximum back-off window size. This time interval is termed as dwell time and is used by the sender to send any queued packets.

RI-MAC [132] uses the concept of receiver initiated transmissions. In RI-MAC, the receiver initiates the transmissions by sending beacons at regular intervals. The sender wakes up asynchronously at regular intervals to receive any invitation from the receiver. The sender responds to the invitation by sending a DATA frame. In RI-MAC collisions are handled by the receiver dynamically. Under high contention, the receiver sends an explicit beacon by increasing the value of the contention window to the senders to reduce the contention at the receiver. In RI-MAC medium access among senders is controlled by the receiver, however this mechanism is not very power efficient and reliable under dynamic traffic loads. Senders back off according to the back off value specified by the receiver, however under dynamic traffic loads an increased value of back offs affects the energy efficiency and delivery ratio significantly.

Previous synchronous and asynchronous duty cycling approaches such as X-MAC, B-MAC, and RI-MAC achieve greater energy efficiency under light traffic loads. These approaches use sender initiated or receiver initiated transmissions. We make the first attempt to combine the idea of receiver initiated transmissions with the sender assisted contention resolution in wireless sensor networks. SA-RI-MAC differs from these approaches by dynamically triggering the coordination among the senders to handle the contention under high traffic loads. Other asynchronous duty cycling approaches give no preference to starving nodes waiting longer for channel occupancy. On the other hand, after resolving contention SA-RI-MAC prioritizes the transmissions from the most starved nodes.

5.3 Contention Resolution Mechanism in RI-MAC

In RI-MAC, the receiver coordinates the DATA transmissions from the contending senders by exchanging an explicit beacon. In the beacon frame, the receiver appends the Back off Window (BW) size which senders should use to contend the channel. Depending on the network conditions, the receiver adjusts the value of BW with the help of Binary Exponential Back off (BEB). In the BEB procedure, the BW value is uniformly chosen in $[0, CW]$, where CW denotes the current contention window size. In the first transmission attempt CW is set to CW_{min} and is doubled each time the receiver detects the channel busy. The CW value is doubled up to a predefined CW_{max} value. Clear channel assessment (CCA) is used to detect any channel activity. If CCA detects channel busy, the receiver assumes a collision and generates another beacon with an increased value of BW. On detecting continuous collisions, or if the value of BW exceeds the maximum back off window size, the receiver turns its radio off.

Under high contention, senders can potentially miss the beacon frame with the accurate and exact value of BW specified by the receiver. If no beacon frame has been received from the receiver for a duration equal to three times the sleep interval, the sender increments its retry count. Further, if no acknowledgement has been received from the receiver for a DATA transmission within the maximum backoff window time, the sender also increments the retry count. If the value of retry count exceeds a predefined retry limit, the sender cancels the further transmission of the DATA frame, and discards the packet. The contention resolution mechanism in RI-MAC does not involve the senders to resolve the contention at the receiver. RI-MAC tries to handle the contention by using the BW value as specified by the receiver. However, the BW value specified by the receiver is not sufficient to handle the contention at the receiver. An increased value of the BW value increases the number of back offs at the senders, which results in throughput degradation and high latency. Further, increased back offs at senders do not help to conserve any energy as the sender is not able to access the medium. If senders are not well coordinated during the high contention, it results in increased latency and unfairness. A high number of back offs causes some of the senders to starve to transmit data to the receiver if the contention is not handled properly.

Figure 5.1 shows the contention resolution mechanism of RI-MAC under high traffic loads. It can be observed from the figure that contending sender S_1 and S_2 cause continuous collisions at the receiver and as a result increased backoffs because they are not well coordinated to control the contention at the receiver. During continuous collisions and backoffs both S_1 and S_2 have their radio on without any significant improvement in throughput.

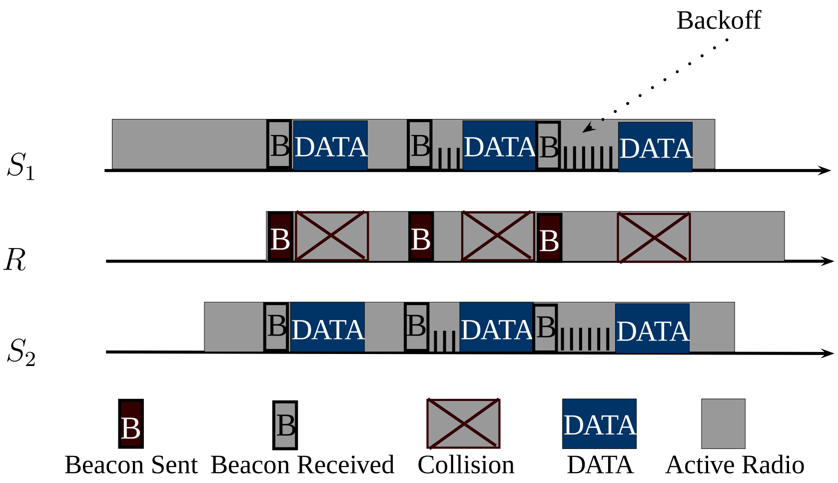


Figure 5.1: RI-MAC: DATA frame transmissions from contending senders. Simultaneous transmissions from the contending senders can cause continuous collisions at the receiver

5.4 SA-RI-MAC Design Overview

In SA-RI-MAC, the sender keeps track of the number of failures to access the channel while trying to transmit to the receiver. A counter `CHANNEL_ACCESS_FAILURE` is maintained to record the channel access failures. Each time, the retry limit exceeds the maximum retry limit threshold, `CHANNEL_ACCESS_FAILURE` is updated. Contending senders exchange an explicit beacon B containing the value of `CHANNEL_ACCESS_FAILURE` with each other at regular intervals.

Prior to transmission, the sender estimates the contention level at the receiver with the help of the BW value specified by the receiver. If this BW value exceeds the maximum contention window size, the sender considers it as an indication of high contention. However, under high traffic loads, the possibility to drop the beacon containing the BW value increases. In this case, the value of `CHANNEL_ACCESS_FAILURE` is compared with the `CHANNEL_ACCESS_FAILURE_THRESHOLD`. If `CHANNEL_ACCESS_FAILURE` exceeds `CHANNEL_ACCESS_FAILURE_THRESHOLD`; this indicates the high contention at the receiver.

If a sender detects the contention at the receiver by using the above procedure, it evaluates if any of its neighbours has a value of `CHANNEL_ACCESS_FAILURE`

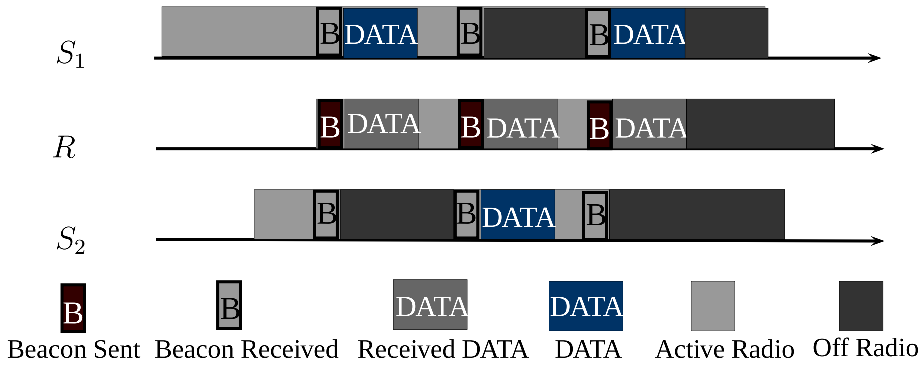


Figure 5.2: SA-RI-MAC: DATA frame transmissions from contending senders. Transmissions from the contending senders are well coordinated to avoid continuous collisions at the receiver

higher than its own value. If there is such a contending neighbour who has been starving longer, i.e., has higher `CHANNEL_ACCESS_FAILURE` value, it turns its radio off immediately to conserve energy and to minimize further contention at the receiver and wakes up asynchronously. Compared to RI-MAC, SA-RI-MAC introduces extra overhead due to the need of periodic beacons which are required to exchange the value of `CHANNEL_ACCESS_FAILURE`.

Figure 5.2 shows how SA-RI-MAC avoids collisions at the receiver. It shows that under high contention after making a number of retry attempts to send DATA to the receiver, both contending senders S_1 and S_2 exchange the `CHANNEL_ACCESS_FAILURE` counter with each other. In Figure 5.2, S_1 has value of `CHANNEL_ACCESS_FAILURE` greater than `CHANNEL ACCESS FAILURE` value of S_2, therefore S_1 starts transmissions to the receiver R. In order to avoid further collisions and to conserve energy, S_2 turns its radio off and gives the chance to S_1 and increments `CHANNEL_ACCESS_FAILURE`. S_2 wakes up asynchronously and exchanges `CHANNEL_ACCESS_FAILURE` with the contending senders, if still contention at the receiver is high, once again sender S_2 compares the `CHANNEL_ACCESS_FAILURE` with the neighbouring nodes. In Figure 5.2, the second time S_2 has `CHANNEL_ACCESS_FAILURE` value higher than `CHANNEL_ACCESS_FAILURE` value of S_1, therefore S_2 starts the transmission and

S_1 turns its radio off to conserve energy. It can be observed from Figure 5.2 that S_1 and S_2 coordinate with each other and resolve the contention at the receiver while conserving energy. This design choice also improves the delivery ratio compared to RI-MAC.

5.4.1 Beacon Frame in SA-RI-MAC

In SA-RI-MAC, when a receiver wakes up it sends a base beacon containing the value of source id. Base beacon can have two optional fields, destination field and BW size. If destination field is set in the base beacon, it means beacon frame is an acknowledgement to the sender with the destination field and other senders can consider this as a request to send data. The BW value is specified by the receiver according to the contention level at the receiver. In RI-MAC, this BW value is used by the contending senders to back off before transmission in order to reduce the chance of collision at the receiver. However, in SA-RI-MAC this value is used as an indication of the contention at the receiver and triggers the coordination among the contending senders before any further transmissions. It is a better design choice compared to continuous back offs at the sender which are not very energy efficient and do not improve delivery ratio. Further these back off increase the latency of the transmissions significantly. After receiving a beacon from the receiver, a sender always makes a CCA before transmission in order to avoid collisions at the receiver. CCA must indicate the medium idle for at least Short Inter-Frame Spaces (SIFS) plus maximum propagation delay time. If no activity is detected during this time, receiver R turns its radio off.

5.4.2 Collisions in SA-RI-MAC

By coordinating the senders to transmit data at the receiver, SA-RI-MAC reduces collisions significantly at the receiver and thus cuts down unnecessary retransmissions. As data transmissions among contending senders are explicitly controlled and coordinated based on the contention level at the receiver, contending senders know when not to send the data and thus can turn their radio off to conserve energy. In RI-MAC, if the back off value reaches the maximum back off window and the receiver keeps detecting collisions, it turns its radio off. On the other hand, SA-RI-MAC tries to reduce the continuous collisions at the receiver and thus prevents unnecessary back offs forced by the collisions. Reduction in unnecessary backoffs decreases the latency and increases the delivery ratio significantly.

5.5 Performance Evaluation

We evaluated SA-RI-MAC in ns-2 [138] simulations and compared its performance with the RI-MAC. We simulated SA-RI-MAC under different network scenarios with dynamic traffic loads.

5.5.1 Simulation Evaluation

We have used the two ray ground reflection radio propagation model for all the scenarios. Other simulation parameters used are shown in Table 5.1. These parameters are similar to $CC2420$ radio [26] used in MICAz motes. The CCA check is performed by sampling RSSI delay as reported by Ye et al. [158]. This check is performed every $20ms$ longer than the interval between two short preambles. Transmission and sensing range are modelled according to 914 MHz lucent WaveLAN radio, as similar ranges have been observed in some sensor nodes [5]. In both RIMAC and SA-RI-MAC, BW value is adjusted based on BEB which takes value of $0, 31, 63, 127$ and 255. We have used a value of 31 for minimum contention window CW_{min} which is a default value used in the UPMA package distributed as TinyOS [99]. Dwell time for both RI-MAC and SA-RI-MAC is dynamically adjusted based on the BW specified by the receiver plus propagation delay and SIFS. Initial wake up for both the protocols is randomized and a value of 1 second is used for the sleep interval. We compared the performance of SA-RI-MAC with RI-MAC in random, clique, and a 49 node 7×7 grid network.

5.5.1.1 Clique Networks

We compare the performance of SA-RI-MAC and RI-MAC in clique networks. In a clique network all the nodes are within the transmission range of each other. We varied the number of flows in the network to vary the traffic load in the network. We allow flows to share the same destination to cause contention. A simple clique network is shown in the Figure 5.3.

Table 5.1: Simulation parameters for radio

Transmission range	$250m$
Slot time	$320\mu s$
SIFS	$192\mu s$
Bandwidth	$250Kbps$
CCA check Delay	$128\mu s$
Carrier sensing range	$550m$
Duty cycle	1 %
CW_{min}	$32ms$
Transmission power	$31.2mW$
Receive power	$22.2mW$
idle power	$22.2mW$
`CHANNEL_ACCESS_FAILURE_THRESHOLD`	5

For the clique network, the number of nodes in the network is twice the number of flows. Each source node generates packets 10 seconds after the start of the simulation. The interval between two packets is uniformly distributed between 0.5 and 1.5 seconds. Next wakeup time for each node in the network is randomly chosen between 0 and 10 seconds. A packet is not considered delivered if it is in the queue. Each simulation run lasts for 100 seconds. We have taken an average on three random clique network scenarios.

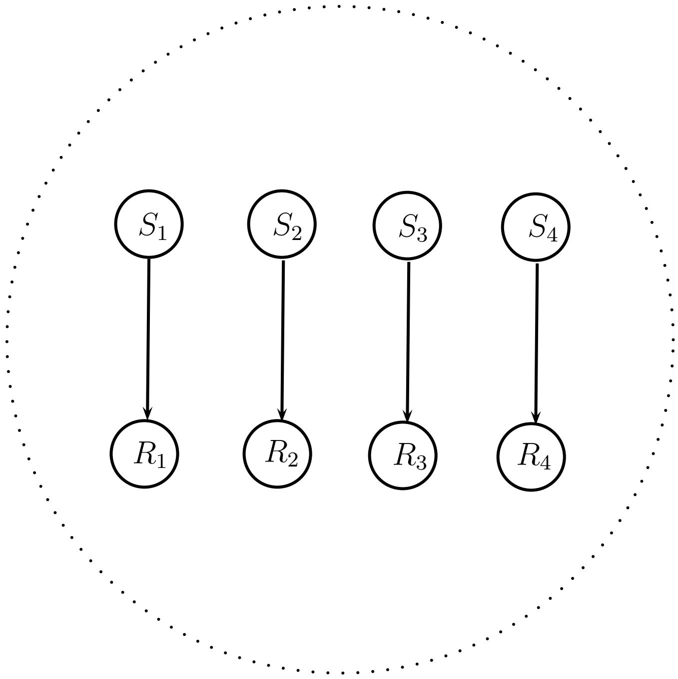


Figure 5.3: An example of a clique network

Figure 5.4 shows the delivery ratio of SA-RI-MAC for a clique network with an increase in the number of contending flows. Both RI-MAC and SA-RI-MAC achieve delivery ratio close to 100% when the number of flows are fewer than 15. However, as the number of flows exceed 15, the delivery ratio of RI-MAC drops significantly due to an increase in the contention level at the receiver. The delivery ratio of SA-RI-MAC does not drop significantly as an immediate coordination will be triggered among the contending senders to resolve the contention at the receiver.

The overall duty cycle of the nodes is shown in Figure 5.5. In addition to an improved delivery ratio, SA-RI-MAC conserves much more energy than RI-MAC. It can be observed from the Figure 5.5 that for all contending flows the energy consumption of SA-RI-MAC is less than RI-MAC. For all flows, SA-RI-MAC saves more than 75% energy compared to RI-MAC. SA-RI-MAC conserves much more energy during high traffic loads by triggering coordination among the senders giving them a chance to conserve energy by turning their radio off compared to the back off mechanism used by RI-MAC.

In addition to having a high duty cycle, RI-MAC also has higher latency compared to SA-RI-MAC as shown in Figure 5.6. This increase in latency is due to an increased value of back off by the receiver to handle the contention. However, SA-RI-MAC avoids collisions at the receiver by coordinating the transmissions from the senders under high traffic loads which reduces unnecessary back offs and helps to conserve the energy.

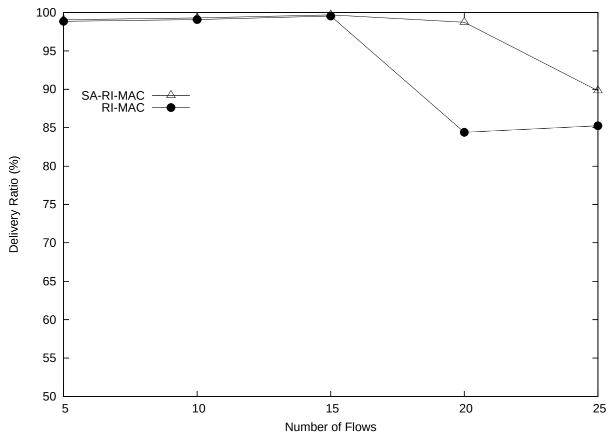


Figure 5.4: Delivery ratio versus No. of flows for clique network

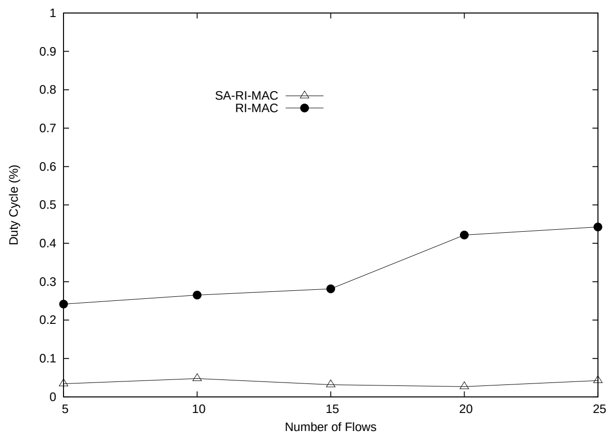


Figure 5.5: Duty cycle versus No. of flows for clique network

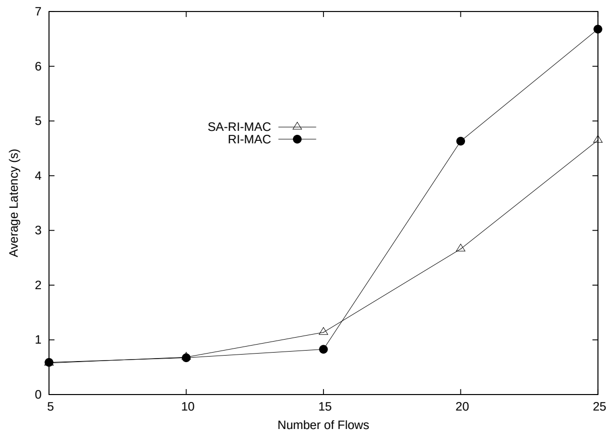


Figure 5.6: Average latency versus No. of flows for clique network

5.5.1.2 Grid Network under Correlated Event Workload

We compare the performance of SA-RI-MAC with RI-MAC in a grid network with 49 nodes. The maximum distance between two neighbouring nodes is $200m$. A sink node which can receive the event notifications is at the centre of the grid. We used a Random Correlated Event (RCE) model to generate traffic in the grid network [131]. RCE is based on the correlated-event workload which simulates spatially-correlated events in a sensor networks. This model simulates a synchronized triggered traffic load in the network which is a common case for tracking and detection applications. A grid network with correlated event workload is shown in Figure 5.7.

In RCE, an event is generated on some randomly selected location (x, y) in the network. A node in the network can sense and report an event if it is in the radius R centred at (x, y) as shown in Figure 5.7. We generated a new event once every 200 seconds. Each node within radius R senses the event and reports it to the sink. In a 7×7 grid network, the path traversed by each packet varies from 1 to 6 hops and is on average 3.05 hops. We perform each simulation for 3 random runs for a series of 48 events triggered from random locations. Unicast packets are transmitted by the nodes within the radius R to notify the sink. Each simulation run lasts for $10,000$ seconds. The performance comparison of RI-MAC and SA-RI-MAC is shown in Figure 5.8. Figure 5.8 shows the packet delivery ratio. When the traffic load in the network is not very high RI-MAC and SA-RI-MAC maintain packet delivery ratio up to 100%. However, with an increase in sensing range high contention is caused for medium access as more nodes try to report the event to the sink, therefore the performance of RI-MAC and SA-RI-MAC drops. However, SA-RI-MAC is augmented with sender assisted coordination which maintains its delivery ratio higher than RI-MAC in high traffic loads.

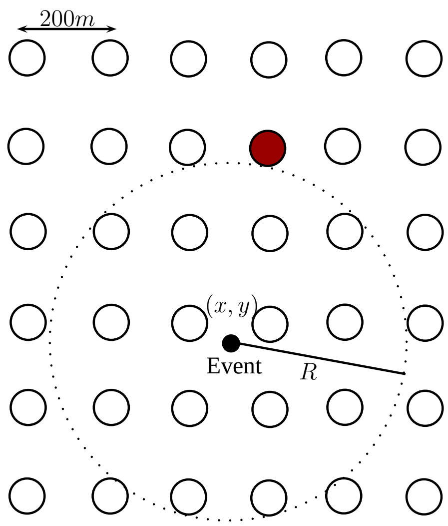


Figure 5.7: A grid network with correlated event workload

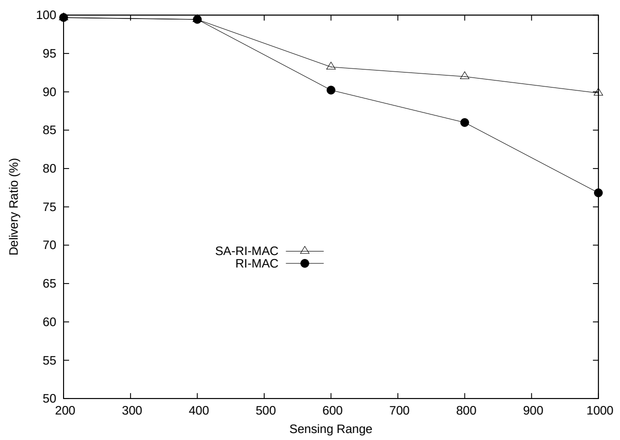


Figure 5.8: Delivery ratio versus sensing range (m) for grid network

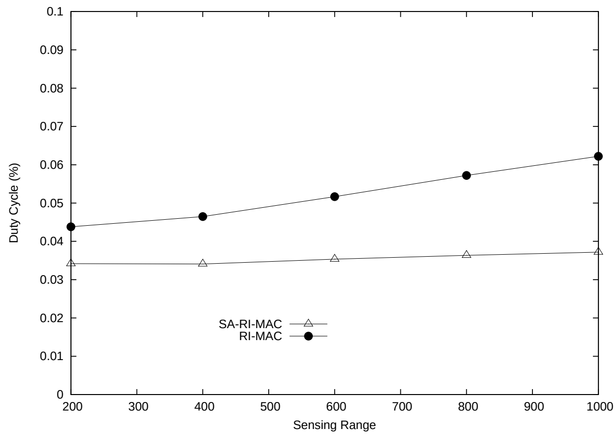


Figure 5.9: Duty cycle versus sensing range (m) for grid network

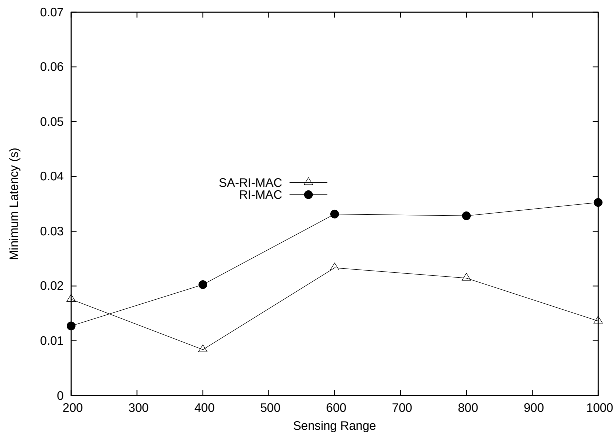


Figure 5.10: Minimum latency versus sensing range (m) for grid network

SA-RI-MAC as shown in Figure 5.9 in addition to achieving the better delivery ratio than RI-MAC also achieves lower duty cycles. In RI-MAC, contention is handled at the receiver end only which increases the value of back offs for senders. These unnecessary back offs do not conserve any energy. On the other hand, in SA-RI-MAC, sender coordination allows contended sender to turn off their radio to conserve energy and reduce contention at the receiver. For all the sensing ranges, the duty cycle for SA-RI-MAC is significantly lower than RI-MAC. For example, for a sensing range of 1000m, the duty cycle of SA-RI-MAC is better than the duty cycle of RI-MAC at 200m.

Figure 5.10 shows the minimum end to end latency for packets reported to a sink for RCE model as the sensing range increases in the grid network. It is apparent from the figure that, in SA-RI-MAC an event notification is received earlier than in the RI-MAC. This event reporting is faster than RI-MAC for most of the sensing ranges. Sender coordinated contention resolution conserves energy and at the same time allows contending senders to deliver packets without collisions at the receiver. For the RCE model, how fast an event has been notified to a sink is more important than the average latency of all the packets received at the receiver.

5.5.1.3 Random Networks

We have compared the performance of SA-RI-MAC and RI-MAC in three different random network scenarios with 40 nodes randomly located in $1000m \times 1000m$ simulation area. Flows are generated between a random source and a randomly selected sink node. The interval between two consecutive packets is 1 second. Each simulation run lasts for 100 seconds. Figure 5.11 shows the delivery ratio achieved by SA-RI-MAC and RI-MAC. For the random network scenario, with flows between random source and destination pairs, SA-RI-MAC outperforms RI-MAC. SA-RI-MAC shows a substantial improvement over RI-MAC in terms of delivery ratio as the traffic load in the network increases. SA-RI-MAC maintains delivery ratio above 90% for all the traffic loads.

SA-RI-MAC conserves much more energy than RI-MAC by turning off the radio of a contended sender under high traffic loads as shown in Figure 5.12. Figure 5.13 shows that for light traffic loads, RI-MAC has lower latency than SA-RI-MAC. It can be observed from Figure 5.11, Figure 5.12, and Figure 5.13 that for 15 and less flows in the network, both SA-RI-MAC and RI-MAC achieves similar performance in terms of latency and delivery ratio due to low contention in the network. However SA-RI-MAC still resolves any contention in the network by allowing senders to turn off their radios instead of longer backoffs in RI-MAC and therefore it conserves much more energy than RI-MAC. As the contention in the network increases, RI-MAC triggers

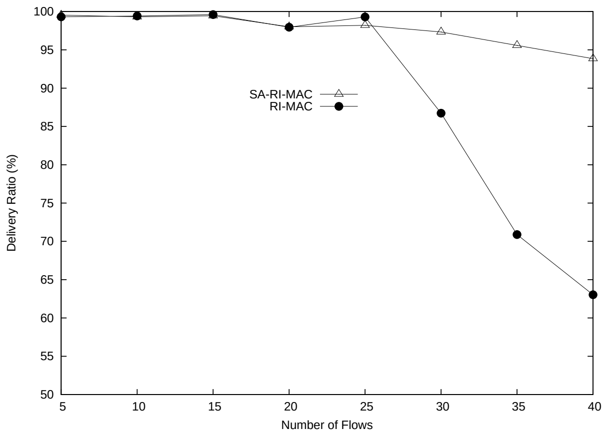


Figure 5.11: Delivery ratio versus No. of flows for random network

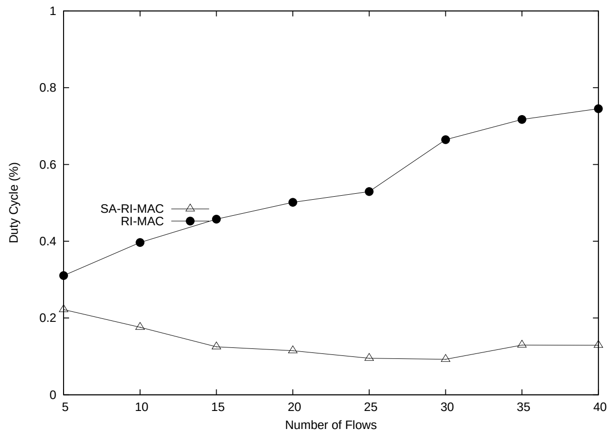


Figure 5.12: Duty cycle versus. No. of flows for random network

increased back offs at the senders which causes an increase in the latency. On the other hand, senders in SA-RI-MAC resolves contention by turning their radio off by giving chance to transmit most starved senders. This conserves energy compared to longer backoffs in RI-MAC.

It can be observed from Figure 5.11, Figure 5.12, and Figure 5.13 that for flows greater than 15 and less than 25, RI-MAC performs better compared to SA-RI-MAC in terms of latency and delivery ratio. It is not clear why SA-RI-MAC performs worse than RI-MAC. However when the number of flows increase 25, there is a sudden degradation observed by RI-MAC in terms of latency and delivery ratio. This degradation is due

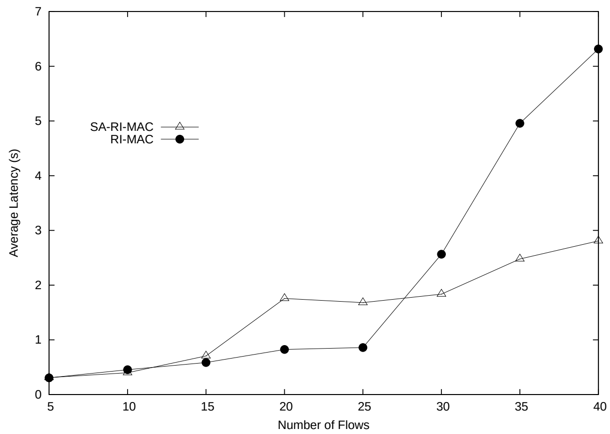


Figure 5.13: Average latency versus No. of flows for random Network

to increased contention at the receiver resulting in increased backoffs at the senders with no improvement in delivery ratio and latency. Further, these increased backoffs do not conserve any energy at the contending senders. On the other hand, SA-RI-MAC triggers sender assisted coordination among the contending senders to avoid collisions at the receiver which results in improved delivery ratio, latency, and duty cycle compared to RI-MAC.

5.6 Conclusion

In this chapter, we have presented a sender assisted receiver initiated asynchronous duty cycling MAC protocol for wireless sensor networks. SA-RI-MAC adaptively resolves the contention at the senders as traffic load increases, allowing SA-RI-MAC to achieve higher delivery ratio, lower delivery latency, and less energy consumption under dynamic traffic loads. To achieve this, SA-RI-MAC turns off the radio of the contending senders to minimize the collisions at the intended receiver while still decoupling sender and receiver clocks. However it adds extra overhead by requiring periodic exchange of beacons in order to exchange channel access failure information. SA-RI-MAC significantly improves fairness among the contending senders by prioritizing the transmissions from the starved senders. We have compared SA-RI-MAC with RI-MAC through extensive simulations. Our evaluation shows that SA-RI-MAC significantly outperforms RI-MAC, with higher delivery ratio, lower delivery latency, and higher power efficiency under high traffic loads. For example, under high traffic loads in clique networks, SA-RI-MAC conserves more than 75% more energy than RI-MAC. In addition, SA-RI-MAC improves delivery ratio and latency in grid and random network scenarios as well.

Chapter 6

Least Channel Variation Multi-Channel MAC (LCV-MMAC)

6.1 Introduction

As discussed in Chapter 2, the half-duplex nature of transceivers [28, 41], limited bandwidth, interference [107, 129] and topology [27] of wireless networks are the fundamental constraints on the capacity of wireless networks. There exist different solutions to enable spatial reuse by mitigating interference, including different MAC methods [37, 90, 88], transmission power control [46, 87, 128, 161] protocols, and use of directional antennas [159] instead of omnidirectional antennas.

The capacity of wireless networks by using multi-channel communication is well studied by Kyasanur et al. [89], in their work they extend the analysis of Gupta and Kumar [59]. Their study investigates the impact of the number of radios and multiple channels on the capacity of wireless networks. Their results show that it is possible to improve the capacity of wireless networks even if the number of radios is smaller than the number of channels.

Several techniques [89] have been proposed to challenge the scalability limitations established by Gupta and Kumar as discussed in Chapter 2, with a notable example by Glossglauser and Tse [58], who show that a constant improvement in throughput is achievable with an increase in the number of nodes in a mobile network. Recently, several multi-packet transmission/reception techniques [53] have been proposed to increase the capacity of wireless networks with an increase in the number of nodes. However, these techniques are expensive to deploy as they require multiple radios at each node.

A low cost, yet attractive solution is to use multiple channels offered by the IEEE 802.11 PHY. Its Distributed Coordination Function (DCF) originally uses a single common channel for transmissions, however it has the capability to support multiple channels. Significant capacity improvement is possible by using multiple channels for simultaneous transmissions. Capacity improvement through multiple channels is a well studied research area in WMNs [34], and radio networks [78]. Another potential benefit of using multiple channels is fairness. In IEEE 802.11 MAC, the hidden terminal problem causes unfairness in some network scenarios where some flows get less opportunity to transmit compared to other flows and therefore starve. However, with the use of multiple channels these flows can better compete for transmission resulting in better fairness.

As discussed in Chapter 2, the use of multiple channels for transmissions has raised several challenges, for example, multi-channel hidden terminal problem, channel switching delay, and control channel saturation problem. As discussed in Chapter 2, dedicated control channel techniques simplify channel coordination by eliminating the need for synchronization, however the control channel may become the bottleneck for the performance of the network. A better trade off which can solve the coordination problem, and can mitigate the control channel bottleneck is desirable. Further, dynamic channel assignment techniques as discussed in Chapter 2 may induce significant channel switching delay, which if not controlled properly may result in significant increase in latency.

In this chapter, we propose a protocol called LCV-MMAC based on IEEE 802.11 MAC. The novel part of this protocol is the channel assignment technique, where a mechanism to avoid unnecessary channel assignment and thus channel switching is used. Further, LCV-MMAC avoids channel contention when the control channel is highly saturated. Channel assignment in LCV-MMAC provides efficient utilization of data channels resulting in improved aggregated throughput. Our solution helps to mitigate the channel switching and channel contention overhead, and as a consequence reduces the control channel saturation. LCV-MMAC is based on a generic model of multiple channels from the literature, and uses $K > 1$ physical layer channels, one channel of which acts as the control channel and the remaining $K - 1$ channels are used for data transmission. Further, each node is equipped with a half-duplex single transceiver which is tunable to any of the physical channels. All the channels have identical transmission, bit error rate, and signal-to-noise ratio.

The main highlights of our work in this chapter are the following:

- We devise a multi-channel MAC protocol LCV-MMAC which uses an efficient channel selection technique. In particular LCV-MMAC mitigates the control channel saturation and improves the aggregated throughput, with a reasonable fairness in different network scenarios. LCV-MMAC avoids control channel contention if the control channel is saturated thus utilizing both the control and data channels effectively.

- We explore the properties of LCV-MMAC through extensive simulations with the help of ns-2, and compare it with popular existing multi-channel MAC protocols. Experimental results validate that LCV-MMAC achieves better aggregated throughput, and fairness index than other multi-channel MAC protocols in highly congested single hop and multi-hop network scenarios. In particular, the performance of LCV-MMAC is significantly better than other multi-channel MAC protocols in random network topologies.

The remainder of the chapter is organized as follows: Section 6.2 presents the related work. In Section 6.3, we discuss the motivation for the design of LCV-MMAC. Section 6.4 introduce the technique for control channel detection, and in Section 6.5

we introduce LCV-MMAC. In Section 6.6, we evaluate the performance of LCV-MMAC in terms of aggregated throughput, latency and fairness for different network topologies including both the single hop and multi-hop. Section 6.7 concludes the chapter.

6.2 Related Work

In this section, we review some existing multi-channel MAC protocols which suffer from the control channel saturation problem.

Vaidya and Jungmin [127] propose Multi-channel MAC (MMAC) which is a well known time multiplexed (split phase) multi- channel MAC protocol. MMAC periodically transmits beacons with a beacon period of $100ms$, which is further subdivided into an Ad hoc Traffic Indication Message (ATIM) window of $20ms$ and a DATA window of $80ms$. MMAC exploits ATIM windows of IEEE 802.11's Power Saving Mechanism (PSM) and extends it for channel reservations. During the ATIM window, all nodes listen on the common control channel and contend for the free channels. After channel reservation, data transmissions take place on all the available data channels during the DATA window. For data transmission, both sender and receiver switch to the reserved channel. In order to handle the hidden terminal problem, MMAC also uses RTS, CTS, and Reservation (RES) packets to negotiate the data channels during the ATIM window. These messages also help to update the information about the reserved channels. Although MMAC requires only one transceiver at each node, the use of synchronizing beacons adds complexity in its implementation. Further, periodic exchange of RTS/CTS, ATIM, ATIM Acknowledgement (ATIM-ACK), and ATIM Reservation (ATIM-RES) packets during the ATIM window negatively impact the efficiency of the control channel resulting in reduced scheduling capacity. In MMAC, during highly congestive scenarios, how to solve the control channel saturation problem remains open.

DCA [151] is a multi-radio multi-channel MAC protocol and requires two radio interfaces. One interface is permanently tuned to the control channel to facilitate the channel negotiation process. The second interface is able to dynamically switch to a reserved data channel to transmit or receive data. In DCA, access to the control channel is similar to IEEE 802.11 MAC. The use of a dedicated control channel eliminates the need for synchronization. Further, the RTS/CTS mechanism on the control channel tuned to the dedicated radio interface makes DCA more immune to the hidden terminal problem. However, one of its major limitations is the control channel saturation, where the control channel may become a bottleneck for the network performance. The right bandwidth for the control channel is tightly coupled with the traffic; a wide control channel results in bandwidth wastage and a narrow channel may become a bottleneck to network performance. This control channel saturation problem has been discussed in [150]. Further, DCA requires an extra radio interface and therefore is an expensive solution.

Asynchronous Multi-channel Coordination Protocol (AMCP) [74] uses a dedicated control channel and n data channels. Nodes exchange control messages on the control channel in order to negotiate and reserve the data channel. Each node is equipped with a half duplex transceiver where a node can transmit or receive at a time. Each node maintains a table, where each table entry records a *channel*, a *bit* indicating its availability and a *timer* indicating the duration of the time a channel is being used by other neighbouring nodes. Further, AMCP uses a $prefer$ variable to decrease the probability of collisions which in turn increases the aggregated throughput and fairness among the flows. Nodes in AMCP defer the channel availability for a duration equal to Distributed Inter-frame Spacing (DIFS) plus channel switching duration which negatively impacts the capacity of the control channel. The DIFS is the amount of time a node must wait for a clear channel before starting a new transmission. High contention or queues at the control channel may result in underutilization of data channels.

Bi-directional Multi-channel MAC protocol (Bi-MMAC) [86] is an extension to

MMAC with bidirectional flow of data. Bi-MMAC uses the RTS/CTS handshake mechanism complemented with Channel Reservation Notification (CRN). A sender explicitly sends CRN to its neighbours about the channel reservation and its duration. Similar to MMAC, Bi-MMAC uses K channels where one channel is used as the control, and the remaining $K - 1$ as the data channels. However, Bi-MMAC differs from other multi-channel MAC protocols by facilitating the DATA frame exchange in both directions. In particular Bi-MMAC improves the performance of TCP, where both the DATA and ACK packets traverse in opposite directions in a network. The Bi-MMAC protocol is named as bidirectional as the receiver may append any data to the acknowledgement and send it back to the sender. This bidirectional flow of data saves the handshake procedure for sending data from receiver to sender. Specifically, this approach improves the performance of TCP transfers, where TCP DATA and TCP ACKs packets traverse in opposite directions. However, the exchange of RTS/CTS/CRN on the control channel may result in a bottleneck in heavily loaded network scenarios and can adversely affect the performance of Bi-MMAC.

Receiver Directed Transmission (RDT) [125] is one of the popular works for dynamic channel selection. In RDT, each node is equipped with a half duplex transceiver and each node assigns itself a quiescent channel to which a node stays tuned whenever it is idle. In order to transmit data to a receiver, the transmitter must switch its interface to the quiescent channel of the receiver. The rest of the transmission mechanism is similar to the 802.11 MAC protocol with RTS/CTS enabled. After the successful data transmission,the transmitter tunes back to its quiescent channel. RDT assumes a separate mechanism for the assignment of the quiescent channel, and for the distribution of selected quiescent channel information to the neighboring nodes. These mechanism can be implemented by using a cross layer approach. In highly contended network scenarios, the performance of RDT may be even poorer compared to single channel IEEE 802.11 MAC due to deafness and hidden node terminal problems. Extended Receiver Directed Transmission (xRDT) protocol [102] extends RDT, in which different nodes can use possibly different quiescent channels complemented with a busy tone radio to inform the neighboring nodes about the ongoing reception. The additional busy tone radio mitigates the multi-channel hidden node and deafness problems inherent to RDT. However, the need for an extra radio adds cost and complexity in its implementation. Further, this scheme results in wastage of bandwidth for the control channel used to send busy signals only.

Local Coordination-based Multichannel MAC (LCM-MAC) [102] needs a single interface compared to xRDT, and provides multi-channel support by using coordinated channel negotiation and channel switching. Local coordination in LCM-MAC helps to schedule transmissions without the need for any time synchronization. The transmission schedule of LCM-MAC consists of two phases: control window and data window. During the control window phase, all nodes are tuned to the same channel to transmit or receive control packets. In contrast to xRDT, nodes use a common channel to negotiate and reserve the channel during the control window. This common channel also acts as a data channel during the data window. Access to the control channel is similar to 802.11 MAC. After negotiating the channel during the control window, nodes use the reserved channel for transmission during the data window. After transmission the nodes switch back to the default channel to listen/negotiate any channel reservations. Additional signaling packets for channel reservation during the control phase increase the signaling payload similar to [127] resulting in wastage of bandwidth for the control, and data channel.

The multi-channel MAC approach proposed in [37] employs a dedicated control channel. Similar to LCM-MAC, the control channel in this approach acts both as a signaling as well as data channel. The protocol works in two phases: Contention Free Interval (CFI) and Contention Reservation Interval (CRI). During the CRI, nodes contend for the data channel and defer their transmission until the start of CFI. The deferment of the transmission results in underutilization of data channels and also degrades the capacity of the control channel.

Several other multi-channel MAC protocols including receiver initiated channel hopping with dual polling [137, 136, 135] and Hop Reservation Multiple Access (HRMA) [133] are well known frequency hopping spread spectrum techniques and are worth to mention here. [137] is based on a dedicated control channel approach where nodes listen to the control channel in order to synchronize their hopping sequence. Frequent channel hopping results in longer channel switching delays degrading the performance of the protocol.

Other popular techniques include multi-radio multi-channel MAC approaches [139, 71, 91, 125, 91] with static and dynamic channel selection and target improved network throughput by reducing the number of collisions. The multi-channel approach in [71] implements N data channels and a dedicated control channel. The RTS/CTS used in this scheme is not sufficient to cope with the hidden node problem and therefore triggers numerous retransmissions degrading the capacity of the control channel. This technique assumes that a node is able to sense and receive on all the channels simultaneously, which incurs high overhead cost due to frequent channel switching.

In this chapter, we propose a multi-channel MAC protocol called LCV-MMAC which is based on the dedicated control channel approach similar to DCA, AMCP, and Bi-MMAC. Similar to AMCP and Bi-MMAC , LCV-MMAC uses a dedicated control channel and n data channels. LCV-MMAC share the design similarity with AMCP by using a channel table to record channel availability and the timer which indicates the time a channel is being used by neighbouring nodes. LCV-MMAC uses RTS/CTS handshake mechanism to share channel information complemented with CRN which is similar to Bi-MMAC.

All the above multi-channel MAC protocols suffer from control channel saturation or channel switching problems. Both these problems degrade the performance of these protocols significantly. LCV-MMAC mitigates the control channel saturation and channel switching delay problems which improves the network capacity significantly.

In comparison to the previous multi-channel MAC approaches like MMAC, LCV-MMAC is simple, and does not require periodic network wide synchronization. LCV-MMAC avoids frequent channel switching if there is no significant performance gain. As we will show later through extensive simulations in ns-2, LCV-MMAC improves the aggregated throughput significantly by incorporating both the channel switching gain, and mitigating the control channel saturation.

6.3 Motivation for Design of LCV-MMAC

Multi-channel MAC protocols have the potential to exploit channel diversity which can significantly increase the capacity of wireless networks. However, in order to fully exploit the potential of channel diversity, proper channel selection and control channel saturation problems need to be addressed. Below, we describe both problems in multi-channel MAC protocols. Further, we discuss briefly about channel usage information, and how it can be collected.

6.3.1 Channel Assignment and Channel Usage Information

Channel assignment in multi-channel MAC protocols causes overhead, which negatively impacts the throughput. Protocols which can efficiently utilize the available channels in order to improve the aggregated throughput are desirable. It is possible to have zero channel switching overhead, if a dedicated transceiver is used for each channel. However, this is an expensive solution and for most devices the number of transceivers is usually smaller than the number of channels. The main objective of channel assignment is to switch a limited number of transceivers to available channels in order to transmit data. An efficient multi-channel technique requires channel usage information for channel assignment in order to avoid collisions. The majority of dynamic channel assignment techniques rely on a dedicated control channel to collect channel usage information. An efficient channel selection strategy can be designed in line with the re-usability of channels in order to avoid degradation in the throughput. Since most of the time transceivers are fewer than channels, frequent channel switching is required among the available channels. An efficient multi-channel MAC protocol should be designed by considering two issues: acquiring channel usage information and channel switching delay. For the second problem, a per-packet channel assignment technique is not preferred, instead a channel assignment technique which is valid for long time should be preferred.

6.3.2 Control Channel Saturation Problem

Several existing multi-channel MAC approaches assume that the channel switching delay is low and have small switching penalty [127, 7, 74]. However, practical measurements on IEEE 802.11 MAC [20, 121, 148] show that the channel switching penalty is rather high (in several milliseconds) which adds delay. Furthermore, channel switching requires channel co-ordination among the nodes in order to transmit and receive data. In order to co-ordinate and reserve the channel, both the sender and receiver need to exchange the control messages for which they have to contend the control channel. The control channel is able to accommodate a limited number of data channels or contentions. Frequent exchange of control messages due to frequent channel switching without any significant increase in the capacity results in high control channel saturation. A highly saturated control channel builds up queues at the control channel for retransmissions in order to negotiate data channels. These queues result in bandwidth wastage of data as well as control channels. If too many nodes frequently contend the control channel in order to exchange control messages, the control channel would become a bottleneck of the overall aggregated throughput. An efficient channel assignment technique which can avoid the channel switching and channel contention during control channel saturation may result in efficient use of both the control and data channels, and therefore may improve the aggregated throughput. We propose a multi-channel MAC protocol called LCV-MMAC which utilizes an effective channel assignment technique and avoids unnecessary channel assignment and control channel contention when the control channel is highly saturated.

6.4 Detection of Control Channel Saturation

In this section, first we characterize how to measure the control channel status. Based on the estimate of the busyness of the control channel we propose a novel channel assignment technique. Then LCV-MMAC, a multi- channel MAC protocol based on this channel assignment technique, is proposed.

6.4.1 Channel Busyness Ratio: An Accurate Measure of Channel Saturation

An efficient channel assignment technique which can mitigate control channel saturation and can avoid unnecessary channel switching delay needs to be able to measure contention on the control channel in a timely and easy manner. Access to the control channel is tightly coupled with the contention on the channel. A control channel saturation detection technique should reflect the condition of contention and collisions on the channel.

In the current IEEE 802.11 MAC standard which is a CSMA-based MAC protocol with the capability to use both the physical, and virtual carrier sensing, the function which can measure the status of the channel, i.e., busy or idle is already available. The channel busyness ratio R_{busy} [162] is defined as the ratio of time intervals a channel is busy due to collisions or transmission to the total time. The channel busyness ratio provides a good early sign of control channel saturation.

Let T_{suc}, and T_{col} be the time periods associated with the successful transmission, and a transmission resulting in collision respectively. Then with the RTS/CTS enabled [162]:

$$T_{suc} = rts + ccts + crn + data + ack + 3sifs + difs \tag{6.1}$$

$$T_{col} = rts + cts\_timeout + difs = rts + eifs \tag{6.2}$$

Where rts denotes time to send an RTS, and $ccts$ denotes time to receive a successful CTS packet from the receiver. The time to send a control channel reservation notification to inform neighbouring nodes about the channel reservation is denoted by crn in Equation 6.1. The $data$ denotes the average length of the data packet in seconds for successful transmission. Both $sifs$, and $difs$ denote short inter-frame spacing, and distributed inter-frame spacing. Short inter-frame spacing is the time a node must wait before transmitting a data packet or receiving a rts, $ccts$ or ack packet. The $difs$ is the amount of time a node must sense a clear channel before starting a new transmission. When a node experiences a collision it adjusts its NAV with an extended inter-frame spacing $eifs$ period as shown in Equation 6.2. It is equal to the duration of the time a node waited for cts, i.e., $cts\_timeout + difs$, where $cts\_timeout$ denotes the time, a node waits for a CTS packet from the receiver.

The channel busyness ratio R_{busy} of the control channel can be computed as follows:

$$R_{busy} = \frac{T_{suc} + T_{col}}{T_{tot}} \tag{6.3}$$

Equation 6.3 defines the R_{busy} as the ratio of the total lengths of busy periods due to collisions or successful transmissions to the total time T_{tot} during a time interval.

The channel busyness ratio provides a good sign of early control channel saturation, we can use the observed channel busyness ratio at a node for efficient channel assignment. In order to avoid control channel saturation, we take R_{busy} as an inception of control channel saturation and compare it with a predefined threshold Th_{busy}. A detailed discussion on how to choose Th_{busy} can be found in [163]. For MANETs, a payload size of $1000 - 1500$ bytes is commonly used so according to [163], setting Th_{busy} to 92% is a good way to detect that the control channel has entered into saturation. In [162] channel busyness ratio has been used for a call admission control algorithm to provide best effort traffic. In [163], a wireless congestion control algorithm based on the channel busyness ratio has been proposed which improves the performance of TCP for multi hop ad hoc networks.

6.5 Protocol Description of LCV-MMAC

6.5.1 Structures and Variables

In our protocol, we have one control channel and N data channels. Each node is equipped with a half-duplex transceiver, and therefore can listen or transmit at a time only. Further, a node can listen or transmit on a single channel at a time only. Other data structures and variables used for LCV-MMAC are defined below.

- *Channel Table:* Each node maintains a channel table. Each entry of the table records a data channel, the neighbour who is using it, and the timer when the channel will be released by the neighbour. The timer is set to expire after a data transmission duration or upon hearing updated time duration from the control packets. Each table entry also has an availability called avail bit which indicates that the channel is available or not. When the timer associated with a particular data channel gets expired, its availability bit is set to zero. Similar concepts have been used in [74] and introduced in [152].

- *Data Channel Usage Counter (U_i):* A channel usage counter U_i is computed by counting the number of times a particular channel i is used by the neighbouring nodes.

- $prefer_c$: The variable $prefer_c$ indicates the preferable channel selected by the node.

6.5.2 Basic Protocol Operation

Channel selection is not needed for every transmission. If a neighbour already knows the receiver's channel, it selects the same channel for transmission. Further, every node detects the control channel saturation by using the channel busyness ratio R_{busy} as discussed in Section 6.4. If the control channel is saturated, a node continues with the last known data channel to transmit to the receiver without any channel switching. It is likely that the receiver stays switched on the same channel. If a node has no knowledge about the receiver's last known channel and the control channel is saturated or not saturated, the procedure below is followed for channel selection.

6.5.2.1 Channel Selection

Node x iterates through the channel table, and looks for the available channels in the table. Node x compares the current data channel usage U_c of channel c with the data channel usage U_i of all the available channels, where i denotes the ith available channel. If no data channel with lower channel usage than U_c is found, the node prefers to use the current data channel c as the preferable channel $prefer_c$ and does not switch the transceiver to any other channel. If a data channel U_i with lower channel usage than U_c is found, the node selects U_i as the preferable channel $prefer_c$. If the control channel saturation is detected by using channel busyness ratio R_{busy} as discussed in Section 6.4, the transceiver stays switched on the last known data channel with the particular receiver. Further, in case of control channel saturation, the node will not contend the control channel for channel negotiation, and will directly go on to the Data Transmission stage.

6.5.2.2 Channel Contention

Node x contends the control channel only if the node wants to switch to another channel as discussed in Section 6.5.2.1. If no control channel saturation is detected then $prefer_c$ is the preferable channel selected by x node. Node x inserts the $prefer_c$ to its RTS packet and contends on the control channel using the IEEE 802.11 DCF CSMA/CA mechanism.

6.5.2.3 Channel Negotiation/Reservation

When a node receives the RTS packet, it checks the status of channel $prefer_c$ in its channel table. If channel $prefer_c$ is available, the node replies to x with a Confirming

CTS (CCTS) packet containing $prefer_c$. Then, it switches to data channel $prefer_c$ and waits for a DATA packet. However if data channel $prefer_c$ is not available, the node replies to the sender x with a Rejecting CTS (RCTS) and includes its available data channels in it, and stays switched on the control channel.

If sender x receives a CCTS, it broadcasts a CRN on the control channel. If a RCTS is received, the sender randomly selects a common channel among its and the receiver's preferable channels. If a match is found, the sender contends the control channel for RTS/CTS. If no match is found, the sender selects another preferable channel $prefer_c$ with minimum channel usage, and appends it in the RTS to begin a new contention cycle on the control channel. The sender retries to send RTS up to a maximum number of retries, and afterwards discards the packet.

6.5.2.4 Data Transmission

A node responds with an acknowledgement ACK packet after receiving a DATA packet on the $prefer_c$ channel, and then switches back to the control channel. Node x after receiving the ACK packet also switches to the control channel. However, if the control channel is still saturated, x will continue on the same data channel instead of switching to the control channel.

6.5.2.5 Deferral of Transmission for the Neighbouring Nodes

Upon overhearing a CCTS, neighbouring nodes update their channel table. Further these nodes adjust NAV according to the channel reservation duration from the CCTS. Initially the neighbouring nodes of sender x which are hidden for the receiver adjust the initial value of NAV according to the channel reservation duration from the RTS, and defer the transmission. However, after receiving a CRN from the sender, they update their NAV based on the channel reservation duration from CRN, and defer their transmission accordingly on that channel. Other than the channel listened from CRN/CCTS, neighbouring nodes can compete for other preferable channels according to the channel usage information. If neighbouring nodes overhear RCTS, no deferring rule is applied and nodes can contend for their preferable channels.

6.5.2.6 Updating Channel Usage Information/Channel Preferences

Neighbouring nodes update their channel usage information according to the information received from the overheard RTS/CCTS/CRN packets by switching to the control channel.

Figure 6.1 shows an example of control channel saturation. Figure 6.1 shows that with an increase in the number of flows more nodes contend the control channel to negotiate data channels for the transmissions. This results in control channel saturation problem. For example, Figure 6.1 shows nodes $A, \ldots, I$ contend the control channel in order to negotiate data channels. It is apparent from the Figure that all the data channels are being underutilized.

It is shown in Figure 6.2 that in LCV-MMAC, if control channel saturation is detected, nodes avoid control channel contention. Instead, they use the last known data channel to transmit the data to the receiver. It can be seen from the Figure 6.2, upon detecting control channel saturation node A, B, C stop contending the control channel and start transmissions on the last known data channels chan 01, chan 02, and chan 03. It can be observed from the Figure 6.2, LCV-MMAC mitigates the control channel saturation and at the same time utilizes the data channels effectively. Gradually the control channel saturation mitigates, and nodes can contend the control channel to negotiate any preferable channels.

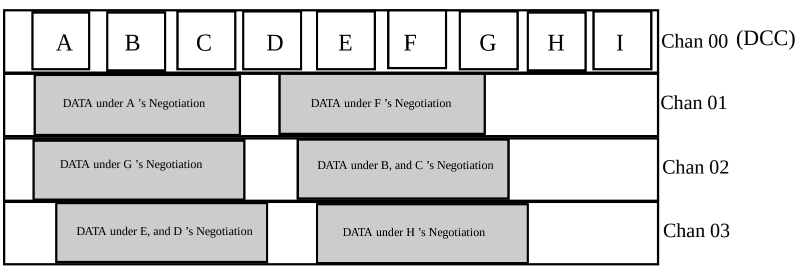


Figure 6.1: Control channel saturation example

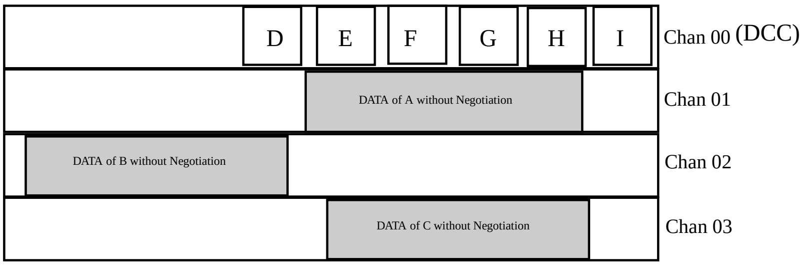


Figure 6.2: Operation of LCV-MMAC under control channel saturation

6.6 Performance Evaluation

We evaluate the performance of LCV-MMAC with the help of extensive simulations by using ns-2. We compare the performance of LCV-MMAC with MMAC, AMCP, DCA, and single channel 802.11 in different network topologies namely grid, chain, and random. DCA, and AMCP are well known multi-channel MAC protocols based on dedicated control channel. DCA is a well known representative of multi-channel MAC protocols which suffer from the control channel saturation problem. MMAC is a representative of multi-channel MAC protocols based on the split-phase approach, and finally we also compare the performance of LCV-MMAC with single channel standard 802.11 MAC.

We run all experiments for a simulation time of 300 seconds. For all the experiments we have used the AODV routing protocol. Unless stated otherwise, the distance between the nodes is $250m$. We have used 4 channels for LCV-MMAC, 1 for the control and the other 3 as the data channels. Other IEEE 802.11 simulation parameters are listed in the Table 6.1. In order to evaluate the performance of LCV-MMAC in low contention scenarios, we have selected a chain topology, as in a chain scenario a node has maximum two neighbours. To investigate the performance of LCV-MMAC

Table 6.1: IEEE 802.11 system parameters

Parameter Name	Parameter Value
SIFS	$10\mu s$
DIFS	$50\mu s$
Long Retry Limit	7
Short Retry Limit	4
CW_{min}	31
CW_{max}	1023
EIFS	$364\mu s$
DATA packet	8000 bits
Bit rate for DATA packets	2 Mbps
MMAC ATIM window	$20ms$
MMAC Beacon interval	$100ms$
Channel switching delay	$224\mu s$
RTS packet	160 bits + Phy header + MAC header
CCTS/RCTS,ACK packet	112 bits + Phy header
CRN packet	160 bits + Phy header + MAC header

in low density topologies, we have selected a grid network, where a node has maximum four neighbours. A random topology with area $250m \times 250m$ has been simulated to analyze the effect of high density on the performance of LCV-MMAC; in a random topology a node can have varying number of neighbours. Further, we have simulated a random network with mobility to analyze the effect of mobility on the performance of LCV-MMAC and on other multi-channel MAC protocols.

The sections below illustrate the results for all the three topologies including chain, grid, random, and random topology with mobility respectively.

6.6.1 Chain Topology

The chain topology used for our experiments is shown in Figure 6.3. In our simulations, the distance between nodes is $250m$. At any instant of time, two TCP connections traverse the chain. The first connection was established from the first to the last node in the chain, and the second connection from the second node to the second last node in the chain. Each TCP connection can send an infinite amount of data. We repeat each experiment 10 times. For each repetition, the seed for the random number generator of the MAC layer's backoff timer is changed.

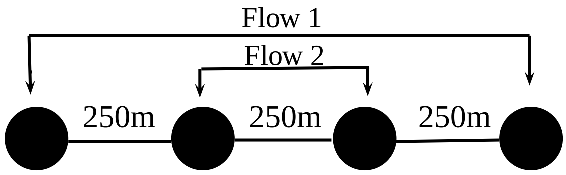


Figure 6.3: A chain topology with 4 nodes

Figure 6.4 below shows the results of aggregated throughput for two TCP NewReno connections as a function of network size. For all the protocols, the aggregated throughput is good for a 4-node topology. However, it drops sharply as further nodes are added to the chain. Beyond 6 nodes, the dropoff in the aggregated throughput is gradual. For a 4-node network, LCV-MMAC has comparable aggregated throughput with DCA, and better than MMAC, AMCP, and 802.11 MAC. LCV-MMAC avoids control channel contention and thus negotiation if control channel saturation is detected while still using data channels, thus resulting in maximum utilization of data and control channel.

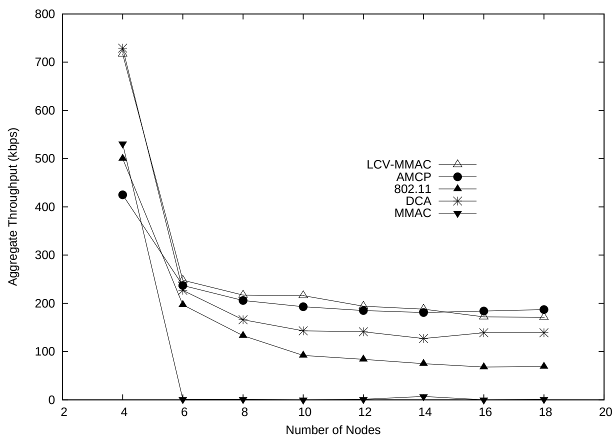


Figure 6.4: Aggregated throughput versus No. of nodes in chain topology

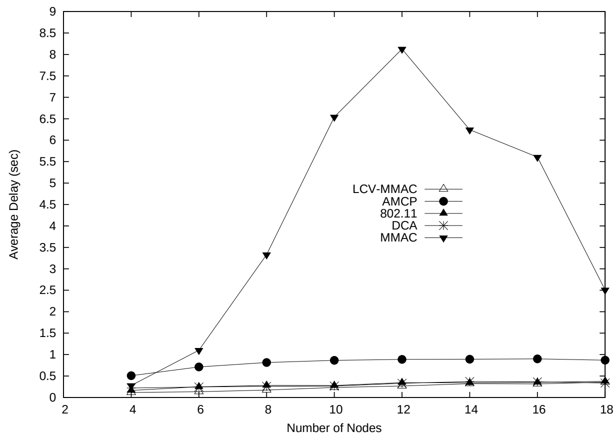


Figure 6.5: Average delay versus No. of nodes in chain topology

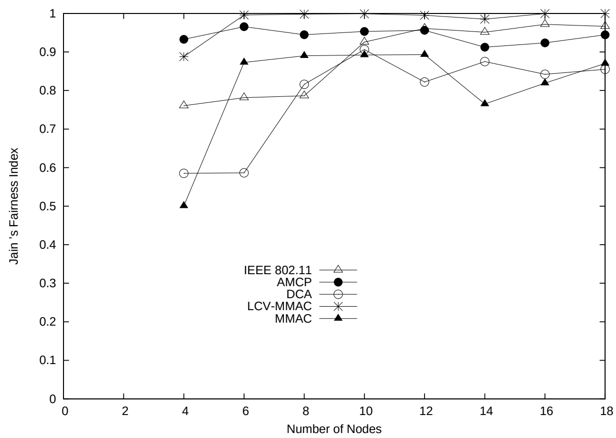


Figure 6.6: Fairness index versus No. of nodes in chain topology

As the number of nodes in the chain increases, the control channel contention increases as more nodes contend the channel to exchange control packets for channel negotiations. This effect coupled with other possible collisions on the data channels results in throughput degradation. Among all the MAC protocols evaluated, LCV-MMAC, and AMCP mitigates both effects, providing better aggregated throughput than others.

The IEEE 802.11 MAC protocol has poor performance as it is not able to cope with the contention and collisions in the network. MMAC has the worst performance when the number of nodes in the chain exceeds 4. This degradation in throughput is due to the fact that each node intends to send packets to multiple outgoing destinations. In the 20ms control window, each node tries to contend for the link resulting in a Head of Line (HOL) in its queue. In the HOL blocking problem, if a packet on the top of the queue finds the channel busy for a particular destination, while waiting for the channel to be free this packet unnecessarily blocks other packets in the queue for other destinations. After a successful contention, the node transmits on the reserved channel for one neighbour only. An effective use of the 80ms DATA window frame is possible only if a significantly high number of packets can be transmitted during the DATA window. In multihop scenarios, this is likely the case as nodes in the network intend to transmit packets to multiple neighbours which may result in HOL blocking. However, both LCV-MMAC and AMCP do not have HOL problem because channel contention occurs on per packet basis.

Figure 6.4 shows that compared to IEEE 802.11 MAC, the average aggregated throughput advantage of LCV-MMAC on a large chain network (more than 14 nodes) is 59.64%. The DCA protocol provides only 50.35% aggregated throughput advantage over IEEE 802.11 MAC for large chain networks. This result indicates that appropriate channel selection, and contention while considering control channel saturation optimization is an important feature of LCV-MMAC.

MMAC provides better connectivity comparable to 802.11 MAC, and overcomes the multi-channel hidden terminal problem for single hop network scenarios. In other words, MMAC cannot handle multi-hop scenarios. In MMAC, only nodes which are involved in communication can exchange ATIM messages during the ATIM window. However MMAC is not able to handle the hidden terminal problem in multihop scenarios because all transmissions cannot be overheard. Therefore, as shown in Figure 6.4, MMAC performs poorly compared to other MAC protocols in the chain network.

It can be seen from Figure 6.5, as the number of nodes in the chain increase, the average delay experienced by 802.11 MAC increases which is due to increased contention along the route. Multi-channel MAC protocols alleviate both contentions and collisions, which can significantly reduce the delay due to backoffs and retransmissions. LCV-MMAC and other multi-channel protocols have almost constant average delay with an increase in the number of nodes in the chain. MMAC requires nodes to align their handshake and channel negotiations with the ATIM phase and therefore induces additional delay in the chain network. When the number of nodes exceeds 10, nodes in the network are not able to synchronize their schedule with each other beyond 10 nodes therefore they schedule their transmissions without aligning ATIM phase which reduces the delay experienced by MMAC significantly.

In order to analyze how effectively channel capacity is shared among all the flows, we have used Jain's Fairness Index [72]. This is defined in Equation 6.4.

$$\text{Fairness index } (FI) = \frac{(\sum_{i=1}^{m} x_i)^2}{m \sum_{i=1}^{m} x_i^2} \tag{6.4}$$

Where m denotes the number of contending flows in the network, x_i is the throughput achieved by flow i. Absolute fairness is achieved when $FI = 1$. The worst case unfairness occurs when $FI = \frac{1}{m}$.

As shown in Figure 6.6 in the chain topology, both DCA and MMAC do not have good FI with value ranging from 0.45 to 0.85. 802.11 MAC also suffers in terms of fairness performance. The reason is the capture behaviour of these protocols which is contention based and the control channel saturation problem. LCV-MMAC and AMCP solve these problems and therefore have better fairness with $FI = 1$.

6.6.2 Grid Topology

Grid topology is shown in Figure 6.7, where 100 nodes are placed in rows and columns in a 10×10 grid and the distance between these nodes is $250m$. We established a varying number of TCP NewReno connections between randomly chosen source and destination nodes from 2 to 16 in steps of 2. In order to mitigate the periodic congestion effects, TCP connections were randomly started between 0 and $1000ms$. Each experiment is simulated for a period of 300 seconds, and each experiment is repeated 10 times with different seed for MAC backoff timer and with different randomly generated connections. We have used a different seed for the random source/destination generator for each repetition. A total of 10 different scenarios with different randomly generated connections were tested for each repetition.

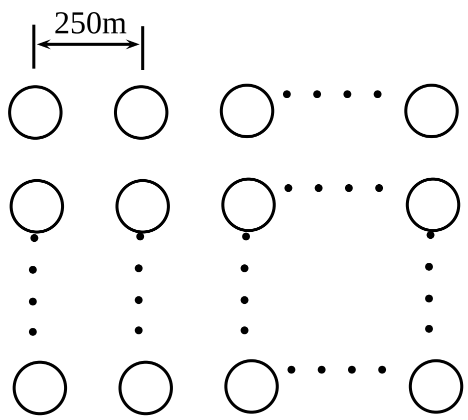


Figure 6.7: The grid topology

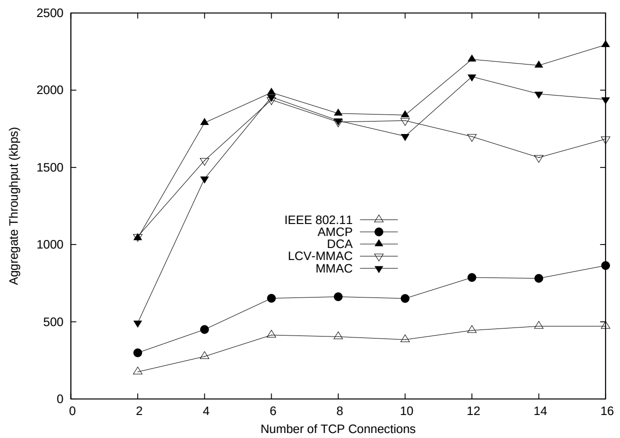


Figure 6.8: Aggregated throughput versus No. of connections in grid topology

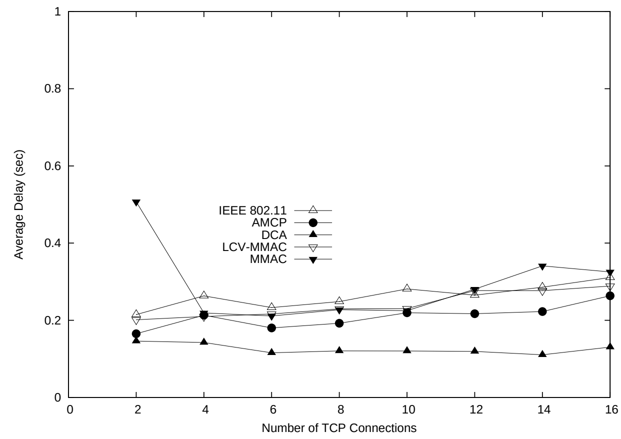


Figure 6.9: Average delay versus No. of connections in grid topology

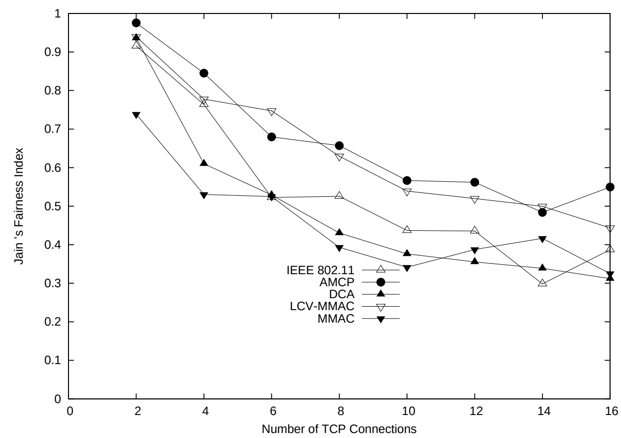


Figure 6.10: Fairness index versus No. of connections in grid topology

Figure 6.8 shows that multi-channel MAC protocols have significantly better aggregated throughput compared to 802.11 MAC. This is due to the use of multiple channels giving a significant bandwidth increase. With an increase in the number of flows, contention in the network increases and therefore degrades the aggregated throughput. Multi-channel MAC protocols try to resolve this contention by allowing more concurrent transmission on multiple channels and therefore have significant performance gain. LCV-MMAC provides higher aggregated throughput compared to both 802.11 MAC and AMCP under low as well as high loads. It achieves comparable performance with DCA and MMAC under moderate traffic load. DCA uses two transceivers, one of which is constantly tuned to the control channel, where a node can always listen for control messages. This helps to alleviate the hidden terminal problem, and improves its performance in the grid topology compared to other multi-channel MAC protocols. The average improvement of the AMCP protocol over 802.11 MAC is about 41% for 10 connections. On the other hand, the LCV-MMAC protocol improves the aggregated throughput for 10 connections which is comparable with both DCA and MMAC protocols.

As shown in Figure 6.9 with an increase in the number of flows, the average delay experienced by 802.11 MAC increases due to increased contention. The average packet delay of multi-channel protocols is significantly smaller as there are fewer packet collisions and hence fewer retransmissions, in particular under high traffic loads. However, multi-channel MAC protocols show no significant advantage under lower traffic loads. LCV-MMAC shows comparable average delay with DCA and AMCP by avoiding control channel contention, and therefore channel negotiation procedure when it detects the control channel saturation.

Figure 6.10 shows that with an increase in the number of connections, the fairness index of all multi-channel and single channel MAC protocols degrades. When the number of flows in the network is small, different flows are not likely to compete with each other. When the number of flows in the network increases, contention among the flows increases resulting in continuous backoffs and retransmission attempts. The increase in the number of backoffs and retransmissions increases unfairness among the contending flows. LCV-MMAC achieves fairness comparable to AMCP. Under high contention LCV-MMAC avoids channel contention and therefore avoids frequent backoffs and retransmission which provides fair competition for data channels.

6.6.3 Random Topology

We simulated two kinds of random topologies. In the first random topology, in a flat area of $500m \times 500m$, 100 nodes are placed randomly (uniformly). The second topology is the same as the first topology; however, the area is reduced to $250m \times$

$250m$ to simulate a denser scenario. In the second scenario, most of the nodes are within each other's transmission range due to a maximum transmission range of $250m$. We varied the seed for both random topology generators and the random source/destination. For 10 random TCP connections, we tested 10 random topologies yielding a total of $10 \times 10 = 100$ topologies/scenarios.

6.6.3.1 Low Density

In the random topology, the number of neighbours of a node can be high compared to grid, and chain networks. In this network, more nodes in the network are likely to have traffic to send, causing more contention. LCV-MMAC performs approximately 6 times better than 802.11 MAC. It can be seen in Figure 6.11 that LCV-MMAC achieves 50% improvement over DCA which uses two transceivers. However, with an increase in the number of flows, the control channel in DCA gets saturated, which degrades its performance significantly. LCV-MMAC solves the control channel saturation problem by avoiding control channel contention during control channel saturation.

With an increase in the number of flows, local contention increases. High contention saturates the control channel resulting in an increased number of retransmissions and backoffs, which causes an increase in average delay. It can be seen from Figure 6.12 that by avoiding channel switching during the control channel saturation, LCV-MMAC achieves significantly lower average delay than 802.11, and AMCP.

It is apparent from Figure 6.13 that the fairness index of all MAC protocols drops with an increase in the number of flows in the network, when more flows compete for the channels. In the low density random network scenario, the fairness index of LCV-MMAC is comparable with AMCP and IEEE 802.11.

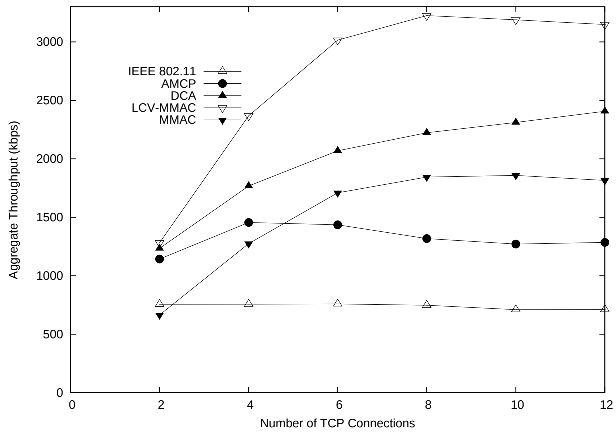


Figure 6.11: Aggregated throughput versus No. of connections in low density topology

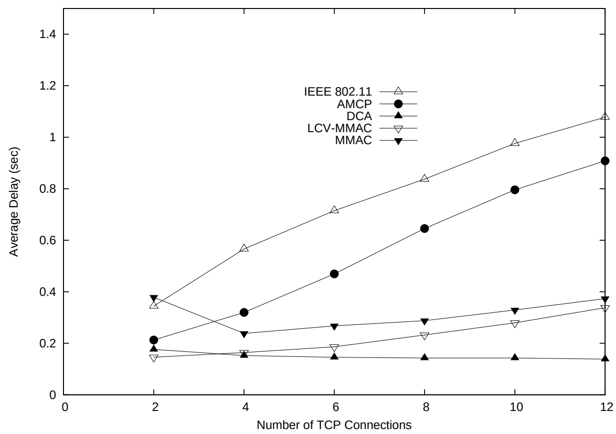


Figure 6.12: Average delay versus No. of connections in low density topology

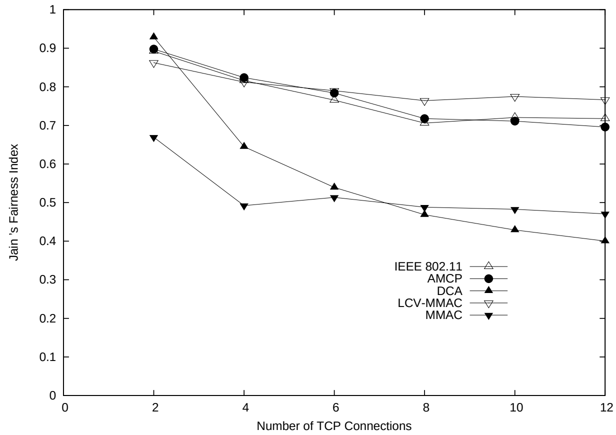


Figure 6.13: Fairness index versus. No. of connections in low density topology

6.6.3.2 High Density

Since a $250m \times 250m$ topology is almost a single cell topology, all 100 nodes share the same control channel. When the number of flows increases in the network, the control channel becomes saturated. High control channel saturation results in control messages being lost due to collisions. As 802.11 MAC cannot support simultaneous transmissions, it has the worst aggregated throughput in denser network scenarios as shown in Figure 6.14. Control channel saturation in DCA does not exploit the effective use of available data channels for simultaneous transmissions, therefore its performance degrades. It is apparent from Figure 6.14 that by avoiding channel switching and therefore channel contention if the control channel is saturated, LCV-MMAC achieves more than 100% aggregated throughput improvement over all MAC protocols. Control channel saturation can result in a loss of broadcast and route request messages which are required to establish a route. It means some TCP connections will be established late. Those flows which start later, have to compete against established flows. Some disadvantaged flows may have zero throughput.

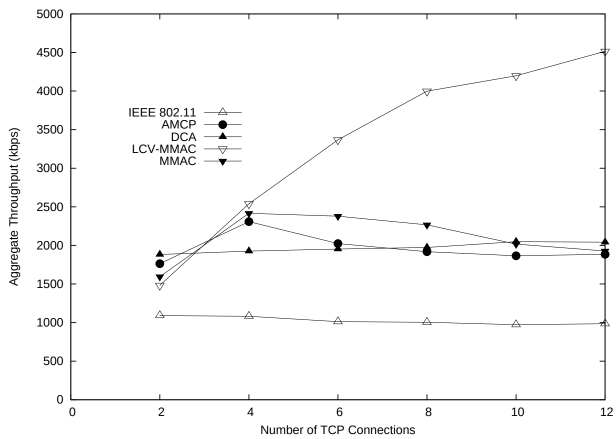


Figure 6.14: Aggregated throughput versus No. of connections in high density topology

The average improvement of LCV-MMAC over the 802.11 MAC protocol for the $500m \times 500m$ topology, and the $250m \times 250m$ topology are 76%, and 75% respectively

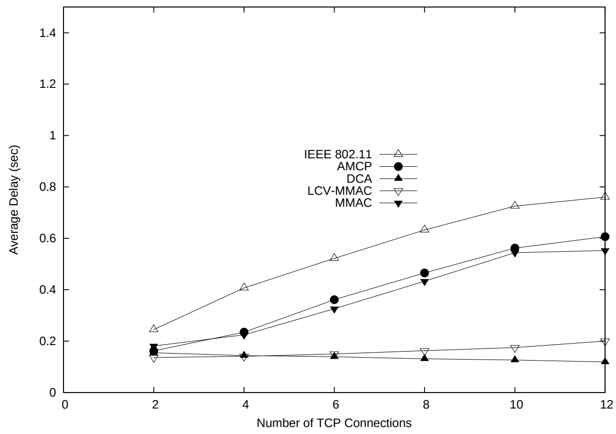


Figure 6.15: Average delay versus No. of connections in high density topology

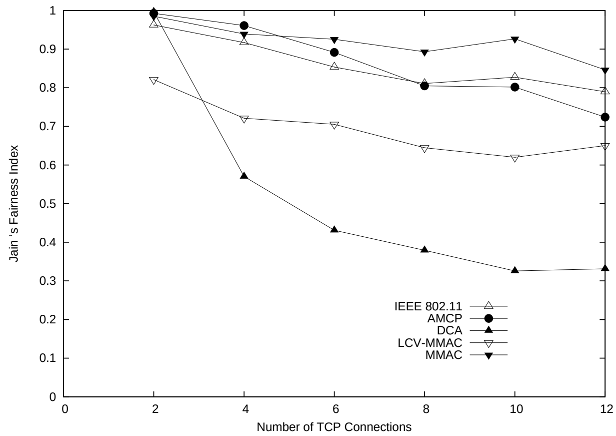


Figure 6.16: Fairness index versus No. of connections in high density topology

as shown in Figure 6.11, and Figure 6.14. LCV-MMAC improves the throughput over MMAC by 47% and 60% for both topologies. Figure 6.14 and Figure 6.11 also show that for both topologies all the protocols achieve almost constant aggregated throughput, however LCV-MMAC in high density topologies shows an increase in the trend for aggregated throughput with an increase in number of flows. Comparing the results, it is clear that when the node density increases, the multi-channel protocols in particular LCV-MMAC has greater advantage. LCV-MMAC alleviates the control channel saturation problem in high density random topologies, and therefore avoids excessive retransmissions, and backoffs. The average delay achieved by LCV-MMAC is significantly lower than 802.11, AMCP, and MMAC as shown in Figure 6.15. It is apparent from Figure 6.16 that the control channel saturation degrades the fairness index of DCA significantly. For more than 4 flows, its fairness index drops below 0.5. LCV-MMAC, however, tries to reduce the control channel saturation by avoiding channel switching and channel contention, and has better fairness index than DCA.

6.6.4 Static Random Topology Vs. Mobile Random Topology

In order to analyse the effect of mobility on multi-channel protocols we have deployed 100 nodes in a simulation area of $1000m \times 1000m$ compared to the $500m \times 500m$ simulation area in Section 6.6.3. We have compared the performance of LCV-MMAC with other multi-channel protocols in both static and mobile network topologies. Further, we simulate the mobility of the nodes by using the random way point mobility model, where nodes can move with a maximum speed of $10m/s$ with $0s$ pause time. We varied the seed for both random topology generator and the random source/destination. For 10 random TCP connections, we tested 10 random topologies yielding a total of $10 \times 10 = 100$ topologies/scenarios. Each simulation run lasts for 300 seconds.

LCV-MMAC outperforms 802.11 MAC and all other multi-channel protocols in both static and mobile random topologies. We demonstrate the mobility in the network which makes the situation somewhat more challenging for channel access and therefore use of multiple channels. In a network with mobility, a single flow may traverse through multiple routes throughout the simulation and therefore may choose the best route at different intervals offering different degrees of channel diversity. The full benefit of multiple channels can be realized when there is an increase in the number of flows in the network. LCV-MMAC leverages this benefit better compared to other multi-channel protocols, and therefore demonstrates significant performance improvement over 802.11 MAC, and other multi-channel protocols. In a random network due to dynamics of control channel contention LCV-MMAC mitigates control channel saturation and effectively utilizes the data and control channels.

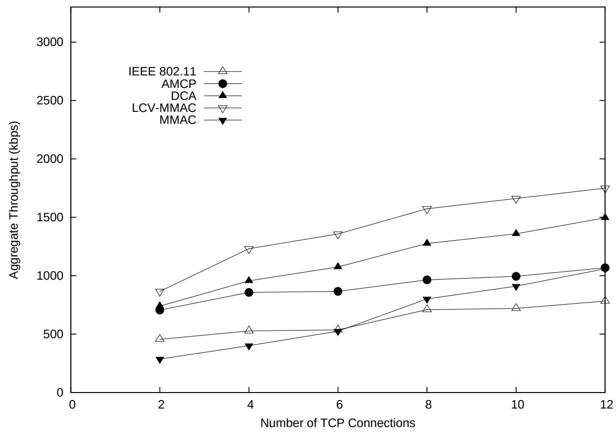


Figure 6.17: Aggregated throughput versus. No. of connections in static toplogy

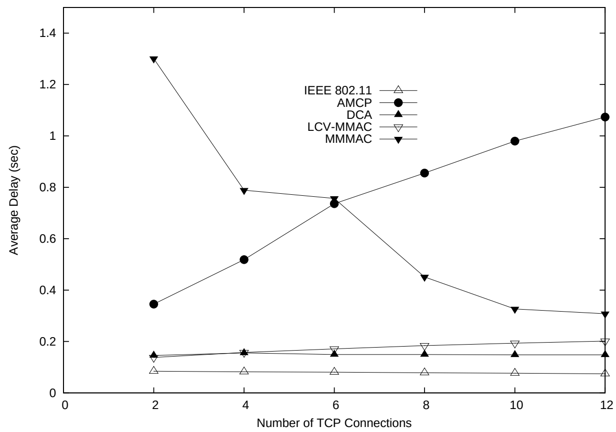


Figure 6.18: Average delay versus No. of connections in static toplogy

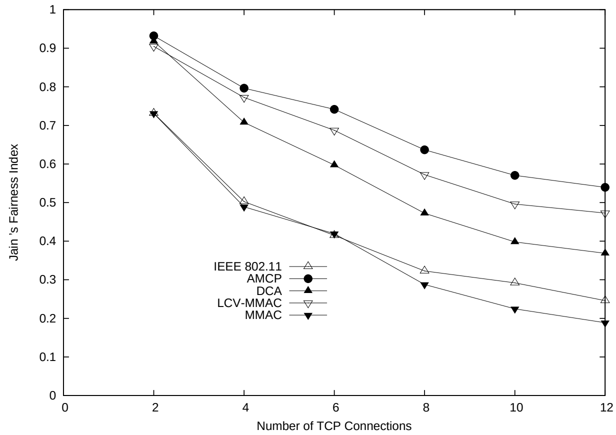


Figure 6.19: Fairness index versus No. of connections in static toplogy

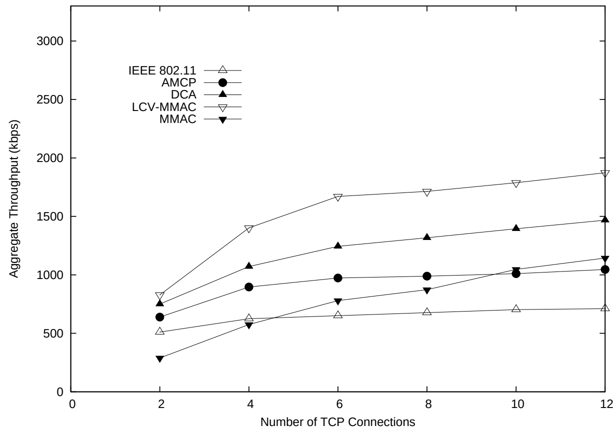


Figure 6.20: Aggregated throughput versus. No. of connections in mobile toplogy

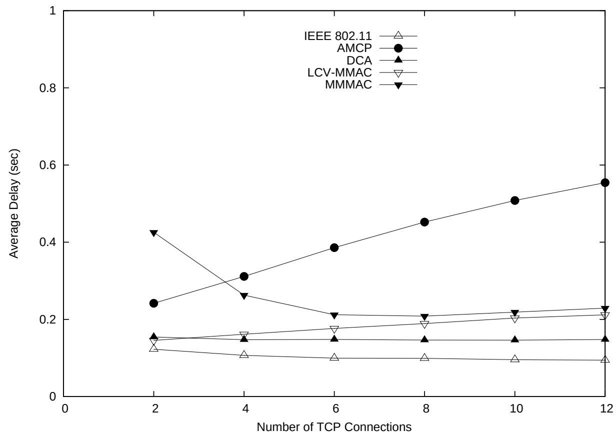


Figure 6.21: Average delay versus No. of connections in mobile toplogy

As shown in Figure 6.17 and Figure 6.20, the aggregated throughput of MMAC for both static and mobile topologies is poor compared to other multi-channel protocols due to the need of synchronization. In multi hop scenarios, it is very difficult to achieve synchronization as only nodes which are involved in communication can exchange ATIM messages during the ATIM window. Mobility in a network results in increased route discoveries which increase the packet delay. Multi-channel diversity in mobile networks mitigates this effect and the use of extra channels always results in lower

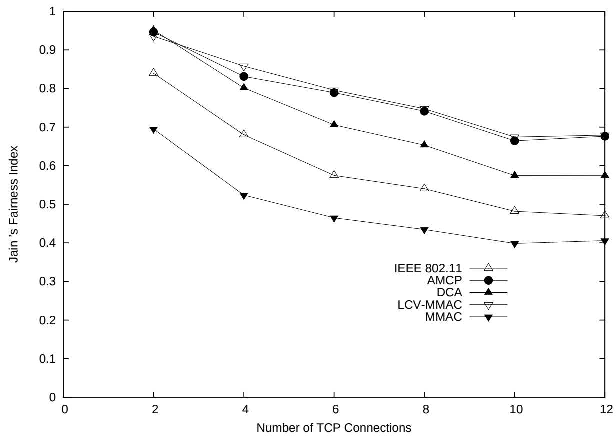


Figure 6.22: Fairness index versus No. of connections in mobile toplogy

delays. From the Figure 6.18 and Figure 6.21 it is clear that most of the multi-channel protocols have almost the same delay performance in both the static and mobile networks. However, the delay experienced by MMAC significantly reduces in mobile networks.

In both the static and mobile random networks, Jain's fairness index as shown in Figure 6.19 and Figure 6.22 reduces for almost all the MAC protocols due to increased competition among the flows. LCV-MMAC has better fairness compared with other MAC protocols for all the traffic loads.

6.7 Conclusion

The use of multi-channel MAC protocols improves the performance of wireless networks, in particular throughput and fairness. The main objective of most of the research in multi-channel MAC protocols is to find out ways which can use multiple channels in an efficient way, thus further improving the aggregated throughput and fairness.

LCV-MMAC improves the aggregated throughput in different network scenarios including random topologies compared to single channel and some other multi-channel MAC protocols. When the number of flows in the network is large, this scheme is relatively more effective compared to other multi-channel and single channel techniques by mitigating the control channel saturation problem. LCV-MMAC uses an efficient channel selection technique according to the control channel saturation and avoids unnecessary channel contention. This results in an efficient use of both the control channel and data channels.

Results obtained by conducting experiments reveal that LCV-MMAC demonstrates significantly better aggregated throughput performance compared to MMAC and AMCP in chain, grid and random network scenarios under high traffic load. It shows significant performance improvement over DCA which is a multi-radio multi-channel MAC protocol in both chain and random network. Future work includes a detailed fairness analysis for individual flows and further optimization in the channel assignment to enhance the fairness in different network scenarios.

Chapter 7

Conclusions and Future Work

In this dissertation we address different issues related with broadcasting, coverage, energy efficiency, and capacity improvement in wireless networks. To effectively tackle these issues we have proposed different MAC and network layer protocols.

The first problem we have addressed is the performance issues of broadcasting under dynamic network conditions of congestion, node density, and mobility. As a part of this work, we evaluated the performance of some popular broadcasting protocols including SBA, ASBA, AHBP, AHBP-EX, MCBCAST, and flooding under different network conditions of congestion, node density, and mobility. The simulation results show that broadcasting approaches like SBA which depend on RAD suffer in highly dense networks if the value of RAD is not adapted to network congestion. Broadcasting protocols which depend on neighbourhood information like AHBP suffer in highly mobile networks, where it is difficult to get up-to-date neighbourhood information. Experimental studies show that existing broadcasting protocols are not suitable under dynamic network conditions. This initial simulation study provided the background and motivation to propose different broadcasting techniques which can dynamically adapt according to the current network conditions.

In this thesis, we have presented three broadcasting protocols called CASBA, DASBA, and CMAB. CASBA, and CMAB are broadcasting protocols which use a cross layer approach to obtain information about the network congestion and mobility and dynamically adapt to it. CASBA reduces the broadcast redundancy significantly.

It controls the retransmissions to achieve a balance between broadcast cost and broadcast speed according to the congestion in the network. DASBA uses local density and new link information to adjust the value of the RAD which improves its broadcast speed and reachability in mobile and sparser network scenarios. CMAB provides high reachability while reducing the broadcast redundancy in highly mobile networks. This reduction is achieved by activating extra retransmissions only in case of high mobility for increased coverage.

We also address the issue of target coverage. Due to limited batter power and fault tolerance issues in WSNs, reliable coverage of targets is desirable. As a part of our dissertation we formulate the problem of Maximum Disjoint Coverage (MDC) using Disjoint Set Covers. We prove that this problem is an $\mathcal{NP}$-complete problem by a reduction from the NOT-ALL-EQUAL-3SAT problem. Further, we propose a $\sqrt{n}$-approximation algorithm to compute two disjoint set covers S_1 and S_2, where n denotes the number of targets. Our algorithm computes disjoint set covers S_1 and S_2 in such a way that S_2 maximizes the coverage whereas S_1 gives complete coverage.

In order to improve energy efficiency in duty cycle MAC protocols, as a part of our dissertation we have presented a sender-assisted receiver-initiated asynchronous duty cycling MAC protocol for wireless sensor networks. SA-RI-MAC uses receiver initiated data transmission in order to efficiently and effectively operate over a wide range of traffic loads. In addition to receiver initiated transmissions, SA-RI-MAC uses a sender-assisted contention resolution mechanism to resolve the contention at the receiver. SA-RI-MAC decouples the sender and receiver's duty cycle schedules while minimizing the time contended senders occupy the wireless medium to find a rendezvous time for the transfer of data. SA-RI-MAC adaptively resolves the contention at the senders as the traffic load increases, allowing SA-RI-MAC to achieve higher delivery ratio, lower delivery latency and less energy consumption under dynamic traffic loads. We compared SA-RI-MAC with RI-MAC through extensive simulations. We found through the evaluation that SA-RI-MAC significantly outperforms RI-MAC, with higher delivery ratio, lower delivery latency and higher power efficiency under high traffic loads. For example, under high traffic loads in clique networks, SA-RI-MAC conserves more than 75% more energy than RI-MAC. In addition, SA-RIMAC improves delivery ratio and latency under all scenarios in our simulations. Even under light traffic load SA-RI-MAC achieves comparable performance to RI-MAC.

As a part of our thesis, we have designed a multi-channel MAC protocol, LCV-LMAC, which is a dedicated control channel based multi-channel MAC protocol. LCV-MMAC uses an efficient channel assignment and channel access technique based on the control channel saturation. Upon detecting control channel saturation, LCV-MMAC avoids unnecessary channel contention and uses the data and control channels effectively. It provides higher aggregated throughput compared to DCA, MMAC, and AMCP in most of the network scenarios under high traffic load.

Future Directions

- In the future, we aim to propose a heterogeneous broadcasting solution which can cope with all the network conditions of congestion, node density, and mobility based on a cross layer approach. We aim to study the interoperability of the proposed broadcasting protocols as a base of different routing protocols for route discovery.

- One of the future research directions can be to extend the broadcasting protocols under error-prone conditions, i.e., location errors and message losses. One possibility is to use redundant broadcast retransmissions to mitigate the effect of errors.

- In our thesis we have studied one-to- many broadcasting only. It would be interesting to analyse the impact of cross layer mechanisms on all-to-all broadcasting for improved reachability and reduction of redundant transmissions.

- We aim to analyse the effects of using multi-channel communication at the upper layers. Information about the local channel contention and interference on the control channel can be utilized to devise TCP congestion control or rate control algorithms that utilize multi-channel communication in wireless networks.

- Multi-channel communication can help to reduce the energy consumption in WSNs. One of the major research issues can be to evaluate the energy consumption of existing multi-channel protocols and analyse the impact of channel switching by using single and multiple transceivers.

- An interesting research question can be to analyse the impact of multi-channel communication on individual flows in a network and to devise channel assignment and channel coordination techniques which can improve the fairness among the individual flows.

- To investigate the impact of channel errors on the energy efficiency and Quality of Service (QoS) performance of dedicated and split phase multi-channel MAC protocols and to devise multi-channel MAC protocols to improve the energy efficiency and QoS will be another interesting research question.

- In our dissertation we have studied the maximum disjoint coverage using two disjoint set covers. The computation of k disjoint set covers to provide maximum disjoint coverage for both the target coverage as well as area coverage problems can be a future research direction. As part of our future work, we will investigate the impact of MDC-DSC on the network lifetime.

- In this thesis we have studied the SA-RI-MAC protocol under the RCE model. However, in a real sensing field the events might have varying event distributions. So it would be interesting to analyse the impact of non-uniform node deployment according to different event distributions on SA-RI-MAC. Further, it will be interesting to study the performance of SA-RI-MAC in large static sensor network systems where the node density for some region is too large to perform planned deployment.

Appendix A

Notations

A summary of the most frequently used notations for Chapter 3, Chapter 4, Chapter 5, and Chapter 6 appears in the tables below. We also adopt the standard convention that random variables are denoted as capital letters, and instantiations of random variables (values) are denoted as lower-case letters.

Symbol	Meaning
d_x	Degree of a node
d_{max}	Maximum degree of a node
$N_1(s)$	1-hop neighbours of s
$N_2(s)$	2-hop neighbours of s
V_m	Variation in received powers
A_r	Average of the powers received
T_{max}	Maximum time interval to compute RAD
T_{Rx}	Time when the last packet is received
$BRG_1(s)$	Forwarding set 1 selected by s
$BRG_2(s)$	Forwarding set 2 selected by s
$Array_{Pr}$	An array which records received powers
RAD_{max}	Maximum value of random assessment delay
$R_xThreshold$	Reception threshold to receive a packet
src	Short retry count for packets less than RTSThreshold
lrc	Long retry count for packets larger than RTSThreshold
$P(s, N_1(s))$	Packet piggybacked with node id s,$N_1(s)$
$P(s, BRG_1(s), BRG_2(s))$	Packet piggybacked with node id s, $BRG_1(s)$, and $BRG_2(s)$

Table A.1: Notations for cross layer broadcasting (Chapter 3)

Symbol	Meaning
t_i	Target i
s_i	Sensor i
S	Set of sensors
T	Set of targets
U	A set of variables
S_1	First set cover
x_h	A variable in U
C	A collection of clauses
c_i	i_{th} clause in C
S_2	Second disjoint set cover
$\mathcal{OPT}$	An optimal solution
T_H	Set of targets in sub-graph H
S_H	Set of sensors in sub-graph H
D_1	Set of variables with true value
D_2	Set of variables with false value
k_i	Number of elements covered in i^{th} iteration
$C(\mathcal{OPT})$	Coverage achieved by the optimal solution
W_j	Denotes the time interval S_j set cover is active

Table A.2: Notations for approximating maximum disjoint coverage in WSNs (Chapter 4)

Symbol	Meaning
T_x Power	Transmit power
$RSSI$	Received signal strength indicator
BW	Back off window to delay the next transmission
CW_{min}	Minimum contention window to start backoff timer
CW_{max}	Maximum contention window to limit backoff Timer
`CHANNEL_ACCESS_FAILURE`	Counter to record channel access failures
`CHANNEL_ACCESS_FAILURE_Threshold`	Threshold to indicate contention at receiver

Table A.3: Notations for SA-RI-MAC (Chapter 5)

Symbol	Meaning
R_{busy}	Busyness ratio
FI	Jain's fairness index
m	Number of contending flows
$eifs$	Time equal to $cts\_timeout + difs$
x_i	Throughput achieved by flow i
$prefer_c$	Preferable channel selected
T_{suc}	Time for successful transmission
T_{col}	Time for a colliding transmission
T_{total}	Total time a node spent for transmission
$sifs$	Time a node must wait prior to transmit or receiving a packet
$cts_{timeout}$	Time a node waits for a CTS packet from the receiver
$difs$	Time a node should sense a clear channel prior to a new transmission

Table A.4: Notations for LCV-MMAC (Chapter 6)

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