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**HIGH-PERFORMANCE BROADCAST AND MULTICAST
PROTOCOLS FOR MULTI-RADIO MULTI-CHANNEL
WIRELESS MESH NETWORKS**

by

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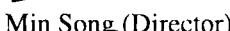
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ABSTRACT

HIGH-PERFORMANCE BROADCAST AND MULTICAST PROTOCOLS FOR MULTI-RADIO MULTI-CHANNEL WIRELESS MESH NETWORKS

Jun Wang

Old Dominion University, 2009

Director: Dr. Min Song

Recently, wireless mesh networks (WMNs) have attracted much attention. A vast amount of unicast, multicast and broadcast protocols has been developed for WMNs or mobile ad hoc networks (MANETs). First of all, broadcast and multicast in wireless networks are fundamentally different from the way in which wired networks function due to the well-known wireless broadcast/multicast advantage. Moreover, most broadcast and multicast protocols in wireless networks assume a single-radio single-channel and single-rate network model, or a generalized physical model, which does not take into account the impact of interference. This dissertation focuses on high-performance broadcast and multicast protocols designed for multi-radio multi-channel (MRMC) WMNs. MRMC increases the capacity of the network from different aspects. Multi-radio allows mesh nodes to simultaneously send and receive through different radios to its neighbors. Multi-channel allows channels to be reused across the network, which expands the available spectrum and reduces the interference. Unlike MANETs, WMNs are assumed to be static or with minimal mobility. Therefore, the main design goal in WMNs is to achieve high throughput rather than to maintain connectivity. The capacity of WMNs is constrained by the interference caused by the neighbor nodes. One direct design objective is to minimize or reduce the interference in broadcast and multicast. This dissertation presents a set of broadcast and multicast protocols and mathematical formulations to achieve the design goal in MRMC WMNs. First, the broadcast problem is addressed with full consideration of both inter-node and intra-node interference to achieve efficient broadcast. The interference-aware broadcast protocol simultaneously achieves full reliability, minimum broadcast or multicast latency, minimum redundant transmissions, and high throughput. With an MRMC WMN model, new link and channel quality metrics are defined and are suitable for the design of broadcast and multicast protocols. Second, the minimum cost broadcast problem (MCBP), or minimum number of transmissions problem, is studied for MRMC WMNs. Minimum

cost broadcast potentially allows more effective and efficient schedule algorithms to be designed. The proposed protocol with joint consideration of channel assignment reduces the interference to improve the throughput in the MCBP. Minimum cost broadcast in MRMC WMNs is very different from that in the single radio single channel scenario. The channel assignment in MRMC WMNs is used to assign multiple radios of every node to different channels. It determines the actual network connectivity since adjacent nodes have to be assigned to a common channel. Transmission on different channels makes different groups of neighboring nodes, and leads to different interference. Moreover, the selection of channels by the forward nodes impacts on the number of radios needed for broadcasting. Finally, the interference optimization multicast problem in WMNs with directional antennas is discussed. Directional transmissions can greatly reduce radio interference and increase spatial reuse. The interference with directional transmissions is defined for multicast algorithm design. Multicast routing found by the interference-aware algorithm tends to have fewer channel collisions. The research work presented in this dissertation concludes that (1) new and practical link and channel metrics are required for designing broadcast and multicast in MRMC WMNs; (2) a small number of radios is sufficient to significantly improve throughput of broadcast and multicast in WMNs; (3) the number of channels has more impact on almost all performance metrics, such as the throughput, the number of transmission, and interference, in WMNs.

To my parents,
Shengying and Jibai,
my wife, Lei,
my daughter, Megan,
and my son, David.

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CHAPTER I

INTRODUCTION

A vast amount of multicast and broadcast protocols has been developed for WMNs or MANETs. Unlike MANETs, WMNs are assumed to be static or with minimal mobility. Therefore, the main design goal of high-performance broadcast and multicast protocols is to minimize or reduce the interference in broadcast and multicast, since the capacity of WMNs is constrained by the interference caused by neighbor nodes. However, most broadcast and multicast protocols in wireless networks assume a single-radio single-channel and single-rate network model, which does not take into account the impact of interference. This Chapter introduces the background, motivation, problem statement, and outline of this dissertation.

This Chapter is organized as follows. Section I.1 discusses the background and motivation of the research work. Section I.2 states the main goals that are going to be achieved. Finally, Section I.3 summarizes the outlines of this dissertation.

I.1 BACKGROUND AND MOTIVATION

WMNs are viewed as a promising broadband access infrastructure in both urban and rural areas. In WMNs, there are two types of nodes, mesh routers and mesh clients [1]. A mesh router has routing capability for gateway functions similar to a conventional wireless router. Conventional wireless networks, such as wireless local area networks, cellular networks, and sensor networks, can connect directly to mesh routers. A small set of routers is attached to the Internet and functions as gateways connecting to the wired network. Mesh routers also contain additional routing functions to support mesh networking. Unlike MANETs, mesh routers in WMNs are assumed to be static or have minimal mobility. Only the mobile mesh clients may result in dynamic topology change; thus topology change is less of a concern in WMNs. As a consequence, the main design goal is shifted from maintaining connectivity to achieving high throughput.

This dissertation follows the style of *IEEE Transactions*.

Compared to unicast, broadcast and multicast are two other fundamental routing services in WMNs. Both broadcast and multicast provide bandwidth efficient communications between a source and a group of nodes, and help to reduce the bandwidth consumptions of many applications and services. It is especially appropriate in wireless environments where bandwidth is scarce and many users are sharing the wireless medium. Broadcast can be used for data dissemination, resource discovery, network coordination and control among the nodes, as well as a primitive operation in on-demand unicast protocols such as DSDV [2], DSR [3], and AODV [4]. Multicast supports collaborative applications such as video conferencing, webcast, distance learning, and distributed gaming, etc. Broadcast and multicast in wireless networks are fundamentally different from the way in wired networks due to the well-known *Wireless Broadcast Advantage* (WBA) [5]. In WMNs, multiple users can receive the same data through one transmission, which represents a huge enhancement of the network capacity. Typically, in order to leverage WBA, MAC layer broadcasts a message once as opposed to unicast messages multiple times. Although both broadcast and multicast are common for communication among a group of nodes, designing multicast has more technical challenges than designing broadcast. Several routing algorithms proposed for multicast [6, 7, 8, 9, 10, 11] use minimum-hop-count as the routing metric. Routing metrics other than the hop-count metric for unicast have been proposed [12, 13, 14, 15]. Due to the difference of MAC layer handling broadcast/multicast and unicast, directly using the link-quality-based metrics proposed for unicast is not appropriate.

Typical deployments of WMNs utilize mesh routers equipped with only one IEEE 802.11 radio, and broadcast and multicast are performed at the lowest possible rate. Research has shown that single-radio single-channel mesh networks suffer from serious capacity degradation [16], and that broadcast protocols developed under the implicit assumption of single transmission rate always lead to sub-optimal performance in multi-rate mesh networks [17]. A promising approach to improve the capacity of mesh networks is to provide each node with MRMC and allow MAC protocols to adjust the transmission rate [15]. In a Multi-radio scenario, a network node has multiple radios each with its own MAC and physical layers. Communication on these radios is totally independent. Moreover, one radio has multiple channels, although it can only use one channel at any moment. Each

channel may adjust its transmission rate through different modulation schemes. MRMC increases the capacity of the network from different aspects. Multi-radio allows mesh node simultaneous sending and receiving through different radios to its neighbors; multi-channel allows channels to be reused across the network, which expands the available spectrum and reduces the interference; and multi-rate provides various options of transmission coverage and latency.

Several characteristics of broadcast and multicast must be taken into account while designing broadcast and multicast protocols for MRMC WMNs. First, broadcast and multicast are concerned with multi-hop communication. Not only nodes within one hop, but also nodes within two or more hops away, affect data transmission and reception, and channel assignment at a node. Second, broadcast and multicast are accomplished in a distributed way. The distributed protocols are required to achieve scalability for a very large wireless network. Third, broadcast and multicast cooperatively work as multipoint-to-multipoint communication. Any network node with mesh networking capability is able to communicate with all its neighboring mesh nodes. Thus, multipoint-to-multipoint communications can be established among the mesh nodes. Interference may occur due to the simultaneous transmissions of closed nodes. Fourth, mobility has a trivial impact on the performance. Mesh routers in WMNs are assumed to be static or have minimal mobility. Only the mobile mesh clients may result in dynamic topology change. Thus, topology change is less of a concern in WMNs. As a consequence, the main design goal is shifted from maintaining connectivity to finding a high-throughput broadcast tree or multicast paths. Therefore, towards this goal, new channel and link quality metrics have to be considered. Fifth, due to WBA and no acknowledgment in broadcast and multicast messages, the coverage and the forward delivery rate of the link should be considered while designing the channel and link quality metrics, but the reverse delivery rate of the link should not. Therefore, reliable and efficient broadcast and multicast are important fundamental problems in MRMC WMNs.

This dissertation presents a set of broadcast and multicast protocols and mathematical formulations to achieve the design goal in MRMC WMNs. First, the broadcast problem with full consideration of both inter-node and intra-node interference is studied. The interference-aware broadcast protocol simultaneously achieves full reliability, minimum

broadcast or multicast latency, minimum redundant transmissions, and high throughput. Second, the problem of minimum cost broadcast, or minimum number of transmissions, in MRMC WMNs, is investigated. Minimum cost broadcast potentially allows the design of schedule algorithm more effective and efficient. The proposed protocol with static channel assignment reduces the interference to improve the throughput. Finally, the interference optimization multicast problem in WMNs with directional antennas is addressed. Directional transmissions can greatly reduce radio interference and increase spatial reuse. Multicast routing found by the interference-aware algorithm tends to have fewer channel collisions.

I.2 PROBLEM STATEMENT

The main goals of this dissertation are as follows:

1. To define new link-quality-based metrics with full consideration of the interference for broadcast and multicast in MRMC WMNs, and to use the new metrics to design bandwidth efficient broadcast protocols to simultaneously achieve full reliability, minimum latency, and minimum redundant transmissions.
2. To formulate and solve the minimum cost broadcast problem in MRMC WMNs, and to analyze the impact of the number of radios and channels on the broadcast cost.
3. To formulate and solve the interference optimization multicast problem in WMNs with directional antennas.
4. To validate and compare the results of mathematical formulations and algorithms in goals 2 and 3 using extensive computational results.

I.3 DISSERTATION OUTLINE

The remaining part of this dissertation is organized as follows. Chapter II reviews the recent literature on state-of-the-art broadcast and multicast for WMNs, and identifies the open issues in MRMC WMNs. Chapter III introduces the network model and new link and channel quality metrics. A basic broadcast tree protocol is proposed for MRMC WMNs

with single rate, single token, and single source. The theoretical analysis, correctness proof, and extensive simulations are also performed. Chapter IV addresses the minimum cost broadcast problem in MRMC WMNs with predetermined channel assignment and static channel assignment, respectively. Both mathematical formulation and heuristic algorithms, centralized and distributed, are presented. The interference optimization multicast problem in WMNs with directional antennas is presented in Chapter V. Finally, concluding remarks and future research are given in Chapter VI.

CHAPTER II

RELATED WORK

This Chapter reviews the recent literature of state-of-the-art broadcast and multicast for wireless network. The review also presents the techniques related to the work presented in this dissertation, including the channel quality assessment schemes, the routing metrics in wireless networks, channel assignment schemes, and directional antennas.

This Chapter is organized as follows. Section II.1 first examines the routing metrics for unicast, and then explains the reasons to design new channel and link quality metrics based on the characteristics of broadcast and multicast in wireless networks. Section II.2 summarizes relevant work of broadcast and multicast for wireless network with single radio single channel and MRMC scenarios. Section II.3 discusses channel assignment in MRMC wireless networks, for unicast, broadcast, and multicast communications. Section II.4 discusses the relevant work using directional antennas for multicast in wireless networks.

II.1 CHANNEL QUALITY ASSESSMENT

The importance of interference impact on wireless networks has never been underestimated. Recently, significant research efforts have been devoted to exploring how interference changes the principle of networks design [16, 18, 19, 20, 21]. Very often interference-aware routing protocols [15, 22, 23, 24, 25], and interference-aware MAC layer protocols [24, 26, 27] assume that either a *priori* information about the interference is known, or a 0-1 function is applied to the link, i.e., a link either works (1) or does not work (0). The work in [28] defines the measurement of interference, and estimates the link interference in a static single-radio single-channel experimental wireless network. The way that calculates the interference, however, is not practical in real-world mesh networks. Therefore, finding a practical wireless interference-aware metric to improve the system performance is critical.

Routing metrics other than the hop-count metric for unicast have been proposed [8, 12, 13, 14, 15]. The first notable study is presented in [13], in which a metric termed as

Expected Transmission Count (ETX) is defined to find a high-throughput path. The *ETX* of a link is calculated using the forward and reverse delivery rates of the link. The *ETX* of a path is then the sum of the *ETX* for each link in the path. Although *ETX* does very well in homogeneous single-radio environments, it does not perform as well in environments with different data rates or multiple radios as indicated in [15]. A more comprehensive metric is defined to assign weights to individual links based on the *Expected Transmission Time (ETT)* of a packet over the link. The *ETT* is a function of the loss rate and the bandwidth of the link. The individual link weights are combined into a path metric called a *Weighted Cumulative ETT (WCETT)* that explicitly accounts for the interference among links that use the same channel. The *WCETT* metric provides a tradeoff between channel diversity and path length when incorporated into a routing protocol. Unfortunately, the *WCETT* can only be obtained in an experimental network. It is not practical to get the information of the *WCETT* in an operating network.

In wireless networks, data packets are handled differently at the link layer in unicast routing and broadcast/multicast, and the difference has direct implications on the design of high-throughput link-quality metrics. Most broadcast and multicast protocols use link-layer broadcast to leverage WBA. WBA improves the reliability of data transfer and hence increases efficiency. In contrast, data packets in unicast are handled using link-layer unicast. The most commonly used link/MAC layer protocol in wireless ad hoc networks is IEEE 802.11 MAC layer protocol. 802.11 MAC layer unicast involves an RTS/CTS exchange before sending data. RTS/CTS exchange avoids the hidden terminal problem by reserving the channel via a virtual carrier sense mechanism, which reduces the probability of collision during data transfer. Further, the receiver acknowledges data transmission. If an acknowledgment is not received, the MAC layer reattempts the data transmission for a number of times. In contrast, 802.11 MAC layer broadcast and multicast do not involve any RTS/CTS exchange, which increases the probability of collisions. Furthermore, broadcast and multicast do not involve any link layer acknowledgment or data retransmission, which further reduces the reliability of broadcast and multicast transmission. The above mentioned differences in unicast and broadcast/multicast data transmissions have two major implications on the design of link-quality metrics. First, the link quality that matters is

bidirectional in unicast, but unidirectional in broadcast and multicast. In the case of unicast, a successful data transfer consists of a successful transfer of a data packet from a sender to a receiver followed by a successful transfer of an acknowledgment from the receiver to the sender, in addition to an exchange of RTS/CTS between the sender and the receiver. Hence, the overall quality of a link depends on the link characteristics in both forward and reverse directions. In the case of broadcast, there is no acknowledgment and thus a successful data transfer only depends on the link quality in the forward direction. Hence, in broadcast, the link quality of the reverse direction should not be considered in the link-quality metric as it may distort the metric value of a link. Moreover, since in broadcast there is no retransmission, a data packet has only one chance to properly travel from one node to another. This implies that unlike unicast, for loss-rate-based link-quality metrics such as *ETX*, a path metric that is simply calculated by adding the metric values of the individual links along the path does not properly reflect the quality of the entire path. Instead, a product of the metric values of the individual links better reflects the quality of the path. The above differences between unicast and multicast suggest that the link-quality metrics designed for unicast can not be directly used in broadcast and multicast protocols.

Chapter III presents two metrics to assess the link and channel qualities, and a distributed interference-aware broadcasting protocol that uses two metrics to build a high-performance broadcasting tree for MRMC WMNs.

II.2 BROADCAST AND MULTICAST IN WIRELESS NETWORKS

Due to the *Broadcast Storm Problem* [29], pure flooding is never used in practice. Two widely used methods are probabilistic and tree-based approaches. In the probabilistic broadcasting approach (also called gossip-based approach) [30, 31, 25, 32, 33], when a node first receives a broadcasting message, it broadcasts the message to its neighbors with a probability of p and discards the message with a probability of $1 - p$. Factors, including the node degree and network degree, may contribute to the determination of gossiping probability. Effectively, the nodes participating in the broadcasting build a tree. The probabilistic approach demonstrates several desirable features, such as scalability and fault-tolerance.

The challenges for this approach are how to find the appropriate gossiping parameters and how to guarantee 100% reliability. In the tree-based approach [17, 30, 34, 35, 36, 37], a broadcasting tree is constructed first before the broadcasting messages are actually transmitted. By using local topological information or the entire network topological information, a sub-optimal tree can be constructed to reduce redundant transmissions. The tree-based method can achieve a deterministic performance. However, a nontrivial overhead is involved to construct the tree regardless of whether the tree is constructed in a centralized or a distributed way.

Many broadcasting protocols have been developed for wireless ad hoc networks with different focuses: reliability, broadcast latency, or redundant transmissions. In [38, 39, 40, 41, 42], the focus is to ensure 100% reliability, i.e., every node in the network is guaranteed to receive the broadcast message. In [17, 30, 34, 43], the focus is to achieve a minimum broadcast latency, i.e., the time that the last node in the network receives the broadcast message is minimized. In [25, 30, 44, 37, 45], the focus is to alleviate the *Broadcast Storm Problem* by reducing the redundant transmissions. These performance metrics are often contradictory goals. In an effort to minimize latency and the number of retransmissions, a broadcast schedule is developed for collision free broadcasting [30]. While the results are promising, the assumption of a single-radio single-channel and single-rate model limits its usage in MRMC networks. The work in [46] presents a distributed algorithm to minimize transmission. It generates a Connected Dominating Set (CDS) as the virtual backbone of wireless ad hoc networks by first constructing a Maximal Independent Set (MIS), then by connecting the nodes in the MIS. The algorithm has an approximation factor of at most 8. Unfortunately, all of the aforementioned protocols assume a single-radio single-channel model and/or a generalized physical model, which does not take into account the impact of interference.

Special routing mechanisms have been engineered to achieve efficient multicast support in ad hoc networks. Many of them have been defined as an extension of unicast ad hoc routing protocols, but most of them have been specially designed for multicast. In the first group, an extension to the unicast Ad Hoc On-Demand Distance Vector (AODV) proposed under the name of MAODV is proposed in [10]. The implementation of a gateway

between MAODV as the ad hoc routing protocol and MOSPF [47] as the infrastructure routing protocol is described in [48]. The work limits the implementation to these protocols and proposes to design similar solutions for other protocols. In addition, it requires modifications in both MAODV and OSPF implementations running in the gateway. Examples of multicast ad hoc routing protocols in the second group are CAMP [49], ODMRP [50] and ADMR [7]. However, these protocols do not provide any means to interoperate with the protocols used in fixed IP networks, and do not support the attachment of standard IP multicast nodes to the ad hoc network.

Various heuristic algorithms have been proposed for solving minimum power broadcast/multicast problems, so that the total transmission powers used by the source and the nodes involved in forwarding messages are minimized. The broadcast/multicast incremental power (BIP/MIP) algorithm [5] is most known among these heuristic algorithms. In BIP/MIP, new nodes are added to the tree on a minimum incremental cost basis, until all intended destination nodes are included. Some researches [51, 52] solve the broadcast case; others [53, 54] deal with more general case of multicast. However, most researches adopt the assumption that each node in the network is equipped with only one radio.

Integer linear programming (ILP) has been used for multicommodity flow problem, channel assignment problem for unicast communications, and also for minimum power broadcast/multicast problems in wireless ad hoc networks. ILP is very useful for performance evaluation of heuristic algorithms. In [55], the authors propose a flow-based integer programming model for minimum power broadcast/multicast problem in wireless networks. In the flow-based model, flows to various destinations are indexed separately, and connectivity is ensured by network flow equations. The authors in [54] propose an integer programming model and a relaxation scheme, as well as heuristic algorithms. The continuous relaxation of the model leads to a very sharp lower bound of the optimum. The flow-based model has been extended to formulate minimum power multicast problem with directional antennae in [56].

II.3 CHANNEL ASSIGNMENT IN MULTI-CHANNEL WIRELESS NETWORKS

MRMC WMNs requires efficient algorithms for channel assignment in order to minimize interference or efficient routing. Channel assignment determines which channel a radio interface or a link should use for data transmission. The problem of channel assignment in MRMC WMNs has been studied extensively for unicast communications [57, 58, 59]. One of the channel assignment approaches is static channel assignment [57, 58, 60, 61, 62]. It assigns a channel to a radio either permanently, or for a relatively long time compared to the channel switching delay. The work in [57] uses ILP to find the maximum throughput and the corresponding routes of the network. In [58], the authors propose a linear optimization model channel allocation and interface assignment model. The work in [60] proposes a centralized channel assignment algorithm where one radio at each node is tuned to a common channel to preserve the original topology. In [61], the authors propose a distributed channel assignment algorithm for mesh nodes whose connectivity graph is a tree. In [62], the authors propose centralized and distributed algorithms for channel assignment problem, and also a linear program formulation with the objective of minimum interference to quantify the performance bounds. Their algorithms assign channels to links directly instead of radios of the nodes. Another channel assignment approach, dynamic assignment approaches [59, 63], assume the radio is capable of fast switching on per-packet basis. It frequently switches the channel on the radio. In SSCH [59], nodes switch channels synchronously in a pseudo-random sequence such that the neighboring nodes meet periodically at a common channel to communicate. In [63], the authors study how the capacity of multi-channel wireless networks scales with respect to the number of radio interfaces and the number of channels as the number of nodes grows. Both static and dynamic channel assignment are considered in [64, 65]. The work in [64] presents channel assignment and routing algorithms to characterize the capacity regions between a given set of source and destination pairs. In [65], the authors propose both dynamic and static channel assignment and corresponding link scheduling algorithms under certain traffic demands.

Although many research efforts have been done on various aspects of MRMC WMNs,

such as channel assignment, and throughput optimization, few have been done on multicast/broadcast problems. The problem of channel assignment for multicast/broadcast has only been studied recently [66, 67, 68, 69, 70, 71]. The work in [66] proposes two flexible localized channel assignment algorithms based on s-disjunct superimposed codes. These algorithms support the local broadcast and unicast, and achieve interference-free channel assignment under certain conditions. However, they did not consider the problem of minimizing broadcast redundancy in multi-radio WMNs. The authors in [67] propose a channel assignment and heuristic multicast scheme for IEEE802.11-based MRMC mesh networks, which aims to minimize the interference only from one-hop neighbors. For reducing the broadcast redundancy, the authors in [68] present a routing and channel selection algorithm to build a broadcast tree with minimum Relaying Channel Redundancy in multi-radio WMNs. Relaying Channel Redundancy is defined as the sum of the number of different channels selected by each forward node in the broadcast tree. In [69], the authors propose an interference-aware broadcast algorithm in MRMC WMNs, and jointly consider multiple performance metrics. The objective is to achieve 100% reliability, less broadcasting redundancy, low broadcasting latency, and high goodput. The work in [70] proposes a channel assignment to minimize interference using both orthogonal and overlapping channels. The work in [71] proposes a set of algorithms to achieve low broadcasting latency in MRMC and multi-rate mesh networks. The broadcasting tree is constructed using a set of centralized algorithms with a goal of minimizing broadcasting latency. However, the centralized approach results in a nontrivial overhead to construct and maintain the tree. In addition, these algorithms are evaluated in a 10-node mesh network, thus making it less clear about the scalability of the proposed algorithms.

Chapter IV considers the MCBP in MRMC WMNs with predetermined channel assignment and static channel assignment, and presents the corresponding ILP formulation and heuristic algorithms.

II.4 DIRECTIONAL ANTENNAS FOR MULTICAST IN WIRELESS NETWORKS

The capacity of wireless ad hoc networks is constrained by the interference caused by the neighboring nodes. Using directional antennas creates less interference to other nodes that are outside the beam because the beam is generated only toward a certain direction. Thus, more than one pair of nodes located in each other's vicinity may potentially communicate simultaneously, depending on the directions of transmission. Since the capacity of wireless networks is constrained by the interference caused by the neighboring nodes, the use of directional antennas increases spatial reuse of the wireless channel, enables more efficient MAC designs, and enhances the throughput in the networks. The characteristic of directional antennas introduces unique difficulties in algorithm design. Directional beam provides partial broadcast to the nodes within the beam coverage. Unlike the case of omnidirectional antennas, where the algorithm design depends solely on the radius, three parameters - beam radius, beamwidth, and beam orientation - have to be taken into account for directional antennas. Two types of directional antennas, sectorized antennas or array-based smart antennas, are used for algorithm design and theoretical analysis. Sectorized antennas have fixed sector and beamwidth. Smart antennas have varying degrees of the beam orientation and the beamwidth.

The capacity analysis and capacity improvement provided by the use of directional antennas in wireless networks are researched in [72, 73, 74]. By allowing arbitrarily complex signal processing at the transmitters and receivers, the maximum stable throughput that can be achieved is an increase of $\Theta(\log^2(n))$ [72]. The authors in [73] present that mutual interference by simultaneous transmissions poses bounds on the amount of capacity gain achieved by using directional antennas instead of omnidirectional ones. The work in [74] presents the capacity gain of using directional antennas. It calculates interference-based capacity bounds for a generic directional antenna model as well for as a real-world directional antenna model, and analyzes how these bounds are affected by important antenna parameters like gain and beamwidth. In an arbitrary network, with the reduction of the transmission area and the reduced probability of two neighbors pointing to each other, the

capacity of networks using directional antennas will be improved by a factor of $\frac{2\pi}{\sqrt{\alpha\beta}}$. Here α and β are the beamwidth of transmission and receiving directional antennas, respectively. The capacity stays constant if the beamwidth of transmission and receiving antennas decrease asymptotically as far as $\frac{1}{\sqrt{n}}$. In a random network, the capacity with the use of directional antennas can achieve a gain as large as $\frac{4\pi^2}{\alpha\beta}$.

Several approaches that exploit directional antennas have been proposed in the literature to increase the performance of WMNs. Compared with omnidirectional antennas, directional antennas increase spatial reuse of the wireless channel [75]. In [76], the authors evaluate the performance of several contention-based MAC protocols with the use of simple directional antennas in wireless ad hoc networks. A simple directional antenna refers to a directional antenna that has a fixed number of beams and a fixed beamwidth. The results show that directional antennas reduce MAC contention with a slight relaxation in the connectivity and dilation, and improve throughput without an observable impact on end-to-end delay. In [77], the authors consider MAC protocol design in a wireless local area network (WLAN) equipped multiple-beam array-based smart antennas. They evaluate the one-hop performance of CSMA and Slotted Aloha for such a system. The work in [78] proposes a multi-hop MAC protocol that exploits the characteristics of directional antennas. The design uses multi-hop RTSs to establish links between distant nodes, and then exploits the benefit of higher transmission range, transmit CTS, DATA and ACK over a single hop. The work in [79] considers multiple directional antennas. However, it does not exploit frequency separation, and is designed for the situation with only one available channel.

Several heuristic algorithms for energy efficiency or lifetime capacity multicast for energy-constrained wireless networks with directional antennas can be found in [80, 81, 82, 83, 84, 85, 86]. Directional communications can save transmission power by concentrating radio frequency energy toward the intended destination without wasting energy in other directions. The work in [80] for the first time proposes heuristic algorithms for energy savings of the construction of trees for multicast and broadcast in wireless ad hoc networks with directional antennas. The algorithms assume nodes with multiple transceivers and frequencies, and the existence of antennas capable of transmitting at any orientation and with

arbitrary beamwidth above a certain threshold. The authors extend the minimum-energy metric by incorporating residual battery energy based on the observation that long-lived trees should consume less energy and should avoid nodes with small residual energy as well. In [81, 82], the special case of this optimization problem in networks with single beam is extensively studied. An online heuristic algorithm, maximum lifetime routing for multicast with directional antenna, is proposed in [81]. The algorithm starts with a single beam from the source covering all multicast destination nodes, and then iteratively improves the lifetime performance of the current solution by identifying the node with the smallest lifetime and revising routing topology as well as corresponding beamforming behavior. In [83], the authors present a group of distributed multicast algorithms for the network lifetime maximization problem in wireless ad hoc networks with omnidirectional antennas or directional antennas. They prove that the distributed algorithm for a single multicast session using omnidirectional antennas is globally optimal. The algorithms for directional communications improve network lifetime for both single-session and multiple session scenarios. In [84], the authors use the graph theoretic approach, by the first time, to derive the upper bound of the approximation ratio for several centralized and distributed algorithms of maximizing the multicast lifetime for directional communications. It is discovered that these upper bounds are finite numbers. They also present a new distributed constant-factor approximation algorithm in order to achieve a higher performance. In [85], the authors provide a globally optimal solution to multicast lifetime problem of energy-limited wireless ad hoc networks. The lifetime of a multicast session is typically defined as the duration of the network operation time until the battery depletion of the first node in the network, although other definitions, like the time before a percentage of live nodes in the network, are possible. They propose a general Mixed Integer Linear Programming (MILP) formulation that can apply to various configurable antenna models. Each node is equipped with a smart antenna array that can be configured to support multiple beams with adjustable orientation and beamwidth. The experimental results show that using two-beam antennas can exploit most lifetime capacity of the networks for multicast communications. In [87], the authors present the single-session minimum power multicast tree problem in the context of fixed beamwidth directional antennas. They formulate the problem into a

MILP. There is no explicit analytic solution, and the solution is obtained only for small size problems. In [86], the authors investigate the minimum-energy broadcast problem using practical directional antennas. They consider a wide spectrum of directional antenna models, including both sectorized antennas and antenna array-based smart antennas.

Using MRMC actually separates the contending transmissions in the frequency domain. However, with the use of omnidirectional antennas at mesh nodes, a transmission on a given channel requires all other nodes in range to remain silent or use alternative channels. Therefore, although multiple channels can separate the transmissions in the frequency domain, the number of available channels potentially limits the extent of such separation. The performance in wireless networks can be improved while adopting both directional antennas and multiple channels [88, 89]. The authors in [88] analyze the capacity while combining the two technologies of multiple channels and directional antennas. The node in the networks is equipped with multiple interfaces, each interface is associated with one directional antenna, and the directional antenna can operate on different channels. They derive the capacity bounds for arbitrary and random networks. In [89], the authors propose DMesh, a WMN architecture that combines spatial separation from directional antennas with frequency separation from orthogonal channels to improve the throughput of multi-channel WMNs. They also propose a distributed algorithm to perform routing and directional channel assignment in the DMesh architecture.

The works in [90, 91, 92] deal with the routing and scheduling problem in wireless networks with directional antennas. The work in [90] presents an energy-efficient routing and scheduling algorithm that coordinates transmissions in ad hoc networks where each node has a single directional antenna. The algorithm first finds the shortest cost paths to be energy efficient, then achieves that routing based on end-to-end traffic information. Finally, it uses a maximal-weight matching scheme for transmission scheduling to minimize the total communication time. In [91], the authors formulate the maximum flow problem in interference-limited wireless sensor networks with switched beam directional antennas as a mixed integer programming problem. They consider both single-beam antenna and multi-beam antennas scenarios, and present a distributed algorithm to achieve the maximum flow through jointly routing and scheduling. The maximum flow between any given

source destination pair is determined hop by hop and is verified by the proposed feasible condition at downstream nodes. In [92], the authors study the joint routing and scheduling optimization problem based on MILP formulations in WMNs with directional antennas. They assume a spatial reuse Time Division Multiple Access (TDMA) scheme, a dynamic power control that is able to vary the transmission power slot-by-slot, and a rate adaptation mechanism that sets transmission rates according to the Signal-to-Interference-and-Noise ratio. In [93], the authors jointly consider interference and power consumption issues in multihop wireless networks using directional antennas with dynamic traffic. They formulate and optimally solve two power constrained minimum interference single path routing problems.

Interference can make a significant impact on the performance of multi-hop wireless networks. The minimum interference multicast problem in wireless networks with directional antennas has not been investigated much. Chapter V studies this problem, presents Linear Programming (LP) formulation, and proposes a centralized heuristic algorithm to solve the problem.

CHAPTER III

INTERFERENCE-AWARE BROADCAST IN MULTI-RADIO MULTI-CHANNEL WIRELESS MESH NETWORKS

Many broadcasting protocols have been developed for wireless networks. However, most of these protocols assume a single-radio single-channel network model and/or a generalized physical model, which does not take into account the impact of interference. This Chapter presents a Distributed Interference-aware Broadcasting (DIB) protocol for MRMC WMNs. DIB protocol has two phases. In the first phase, each node constructs a local structure by removing bad links and channels. In the second phase, a high-performance broadcasting tree is built by using message passing procedures. The research in this Chapter distinguishes itself in a number of ways. First, an MRMC mesh network model is used. Second, comprehensive link and channel quality metrics are defined to fully take into account interference. Third, four design principles have been identified in the tree building process to combat inter-node and intra-node interference. Finally, a comprehensive performance metric, called power, is defined and which includes reliability, receiving redundancy, latency, and goodput. Analytical and simulation studies verify that DIB protocol is able to achieve 100% reliability, less broadcasting redundancy, low broadcasting latency, and high goodput.

This Chapter is organized as follows. Section III.1 introduces the network model and problem formulation. The new link and channel quality metrics are presented in Section III.2. Section III.3 describes DIB protocol, and analyzes the reliability and message complexity of DIB protocol. Section III.4 provides the simulation results and analysis. Finally, Section III.5 summarizes the content of this Chapter.

III.1 NETWORK MODEL AND PROBLEM STATEMENT

Computer networks are typically modeled by an undirected graph $G = (V, E)$, where V is the set of vertices representing nodes and E is the set of edges representing the communication links. This model, however, may not represent MRMC WMNs in which multiple

links may exist between two nodes and one link may connect to multiple nodes. As a result, the link quality is unidirectional. This Chapter presents a directed graph $\mathbf{G} = (\mathbf{V}, \mathbf{E}_c)$ as the network model for MRMC WMNs. Here \mathbf{E}_c is the set of colored edges representing the directed links. Assume that MRMC WMNs is strongly connected, i.e., \mathbf{E}_c is a strongly connected. A directed link (i, j, c) , which corresponds to the link from node i to node j with channel c , is in set \mathbf{E}_c if and only if the following two conditions hold,

- The Euclidean distance between nodes i and j is no greater than the communication range.
- Node i is tuned to channel c for transmission and node j is tuned to c for receiving.

Two types of interference are considered. They are the inter-node interference, which occurs when adjacent nodes are using the same channel, and the intra-node interference, which happens when multiple channels are used by the same node. In MRMC WMNs, the impact of these types of interference dramatically increases without a proper channel assignment policy.

Given the network model defined above, the problem is to develop a broadcasting protocol to ensure that all nodes in the network quickly receive the broadcasting messages. This problem can be addressed by constructing a broadcasting tree, $\mathbf{T} = (\mathbf{N}^B, \mathbf{E}^B)$, where $\mathbf{N}^B \subset \mathbf{V}$ and $\mathbf{E}^B \subset \mathbf{E}_c$ represent the set of nodes and the set of links that participate in the broadcasting, respectively. Given the fact that the problem of minimum latency broadcasting in wireless networks is NP-hard, the objective is to construct a quasi-optimal tree to achieve 100% reliability, less broadcasting redundancy, low broadcasting latency, and high goodput. Not surprisingly, these performance metrics are often contradictory. Figure 1 shows an 18-node mesh network, in which only the numbered nodes participating in broadcasting (node 1 is the source) and the unfilled nodes receive at least one redundant message. For clarity purposes, each node has only one channel. If the primary goal were efficiency, the broadcasting protocol should result in 4 transmissions and 8 receiving redundancies (Fig. 1a). The price paid, however, is 94% reliability (one node is not covered). If the primary goal were reliability, the broadcasting protocol should result in 5 transmissions and 11 receiving redundancies (Fig. 1b). Certainly, more redundancies bring more

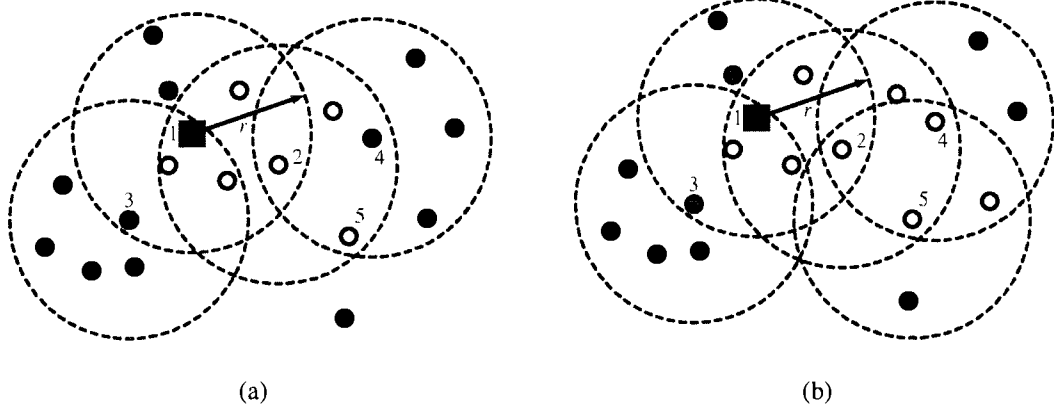


FIG. 1: Illustration of the performance tradeoff of the number of transmissions, receiving redundancy and reliability for broadcast in a wireless mesh network.

interference and thus increase the latency. So, one of the design challenges of broadcasting protocols is to find a solution that has a favorable tradeoff.

III.2 CHANNEL AND LINK METRICS FOR BROADCAST AND MULTICAST

A single comprehensive parameter is defined to quantify the quality of each link and channel, respectively. Table 1 lists the notations used in this Chapter.

For the link from node i to node j with channel c , the link metric is defined as

$$w_{ij,c} = R_c \times DR_{ij,c}, j \in \mathbf{N}_c(i) \quad (1)$$

where R_c is the transmission rate of channel c , and $DR_{ij,c}$ is the packet delivery rate from node i to node j with channel c . The packet delivery rate can be approximated using the techniques described in [15, 13].

To measure the quality of a channel, the qualities of all links that use the channel must be taken into account. Additionally, to increase the channel usage, a channel that has been tuned for receiving by a large number of neighbors should be granted a higher weight. Thus, the channel metric is defined as

TABLE 1: Notations for interference-aware broadcast protocol.

| | |
|--|--|
| $\mathbf{N}(i)$ | Set of nodes within the communication range of node i |
| $\mathbf{N}_c(i)$ | Set of nodes that are tuned to channel c for receiving, $\mathbf{N}_c(i) \subset \mathbf{N}(i)$ |
| $\mathbf{E}(i)$ | Set of links connected to node i |
| $\mathbf{C}(i)$ | Set of channels node i has |
| Children_{i} | Set of nodes that receive the broadcasting messages from node i , initially empty |
| Father_{i} | Node that transmits the broadcasting messages to node i , initially empty |
| $i \xrightarrow{c} j$ | Transmission link from node i to node j with channel c |

$$w_{i,c} = R_c \frac{\sum_{j \in \mathbf{N}_c(i)} DR_{ij,c}}{|\mathbf{N}_c(i)|} \frac{|\mathbf{N}_c(i)|}{|\mathbf{N}(i)|} = R_c \frac{\sum_{j \in \mathbf{N}_c(i)} DR_{ij,c}}{|\mathbf{N}(i)|} \quad (2)$$

Note that only the good links and channels that have a weight greater than or equal to the link threshold, noted as \overline{w}_l , and channel threshold, noted as \overline{w}_c , are eligible to participate in broadcasting.

III.3 DISTRIBUTED INTERFERENCE-AWARE BROADCASTING PROTOCOL

To combat inter-node and intra-node interference, the following principles are used in building the broadcasting tree:

1. A node will not participate in broadcasting if all of its neighbors have already been covered.
2. A node should avoid using the same channel for both transmitting and receiving.
3. When a node chooses a transmission channel, from the node's perspective, a channel with higher weight is preferred, and from the perspective of the node's children, a channel with lower weight is preferred.

4. Adjacent nodes should avoid using the same channel for transmission.

It should be noticed that not all of these principles could be followed in extreme cases. For instance, principles 2 and 4 can not be applied if there are not enough channel resources. For this reason, a MAC-layer scheduler is assumed to avoid channel conflict. For principle 2, if one node has to broadcast and it has only one available transmission channel which is the same as its receiving channel, the receiving and transmission must be scheduled to avoid intra-node interference. For principle 4, if two adjacent broadcasting nodes i and j choose the same transmission channel c the broadcasting of node i and j must be scheduled to avoid inter-node interference. DIB protocol consists of two phases. In the first phase, each node builds a local structure by removing *bad* channels and links. In the second phase, a high-performance broadcasting tree is built by using message passing procedures. Assume all nodes initially share a common channel for exchanging all the control messages.

Phase 1: Construct Local Structures

In phase 1, node i uses its local information $\langle \mathbf{N}(i), \mathbf{E}(i), \mathbf{C}(i) \rangle$ to construct a local structure $\langle \{\mathbf{N}_i^T, \mathbf{N}_i^R\}, \{\mathbf{E}_i^T, \mathbf{E}_i^R\}, \{\mathbf{C}_i^T, \mathbf{C}_i^R\} \rangle$ as follows:

- The good channels for transmission are the subset $\mathbf{C}_i^T = \{c | w_{i,c} \geq \overline{w}_c, c \in \mathbf{C}(i)\}$, and the good channels for receiving are the subset $\mathbf{C}_i^R = \{c | w_{ni,c} \geq \overline{w}_l, n \in \mathbf{N}(i), c \in \mathbf{C}(i)\}$.
- The good links for transmission are the subset $\mathbf{E}_i^T = \{i \xrightarrow{c} j | w_{ij,c} \geq \overline{w}_l, j \in \mathbf{N}(i), c \in \mathbf{C}_i^T\}$, and the good links for receiving are the subset $\mathbf{E}_i^R = \{n \xrightarrow{c} i | w_{ni,c} \geq \overline{w}_l, n \in \mathbf{N}(i), c \in \mathbf{C}_i^R\}$.
- The outgoing neighbors of node i (neighbors that are going to receive the broadcasting messages from node i) are the subset $\mathbf{N}_i^T = \{j | i \xrightarrow{c} j \in \mathbf{E}_i^T, j \in \mathbf{N}(i), c \in \mathbf{C}_i^T\}$, and the incoming neighbors of node i are the subset $\mathbf{N}_i^R = \{n | n \xrightarrow{c} i \in \mathbf{E}_i^R, n \in \mathbf{N}(i), c \in \mathbf{C}_i^R\}$.

In summary, phase 1 removes all bad channels and links whose weights are below the thresholds. Once the local structure is built, node i can easily identify the good transmission

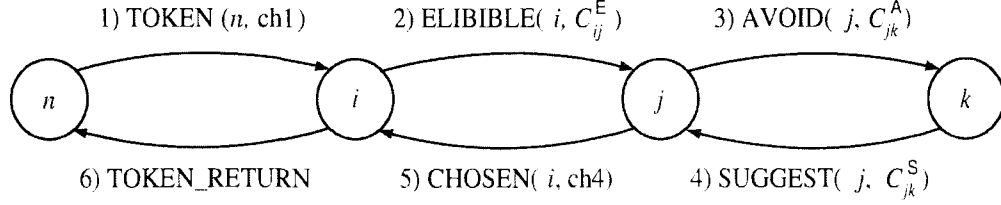


FIG. 2: Illustration of message passing procedures in phase 2 of distributed interference-aware broadcasting protocol.

channels and links from node i to node j , which are $\mathbf{C}_{ij} = \{c | i \xrightarrow{c} j \in \mathbf{E}_i^T, c \in \mathbf{C}_i^T\}$ and $\mathbf{E}_{ij} = \{i \xrightarrow{c} j | c \in \mathbf{C}_{ij}\}$, respectively.

Phase 2: Build the Broadcasting Tree Using Message Passing Procedures

Figure 2 illustrates the main idea of phase 2. Assume node n has already chosen ch1 for broadcasting, $\mathbf{C}_{ij} = \{\text{ch4}, \text{ch3}, \text{ch1}\}$, $\mathbf{C}_{jk} = \{\text{ch3}, \text{ch4}\}$, and $\mathbf{C}_k^T = \{\text{ch1}, \text{ch4}\}$. Notice that the order of channels indicates the quality from high to low. Assuming node i needs to participate in broadcasting, it needs to decide which channel should be used.

Initially, node n generates a **TOKEN** message that contains its ID and broadcasting channel (ch1). Once node i receives the **TOKEN** message, it sends out an **ELIGIBLE** message to node j containing a list of eligible channels that node i may use for broadcasting, $\mathbf{C}_{ij}^E = \mathbf{C}_{ij} - \{\text{ch1}\} = \{\text{ch4}, \text{ch3}\}$. Observing that \mathbf{C}_{jk} and \mathbf{C}_{ij}^E consist of two common channels, node j sends out an **AVOID** message to node k . The **AVOID** message includes a set of channels, $\mathbf{C}_{jk}^A = \mathbf{C}_{ij}^E = \{\text{ch4}, \text{ch3}\}$, that may cause interference should they be chosen by node k as its receiving channels. Notice that \mathbf{C}_{jk}^A can also be interpreted as the potential channels for node i as its transmission channels. Node k responds to node j by generating a **SUGGEST** message including a set of channels \mathbf{C}_{jk}^S that node j should avoid using for transmission and that node i may used for transmission. In this example, \mathbf{C}_k^T has no impact on node i since it has one channel (ch1) which is not included in \mathbf{C}_{jk}^A . Therefore, $\mathbf{C}_{jk}^S = \mathbf{C}_{jk}^A = \{\text{ch4}, \text{ch3}\}$. Node j chooses the best channel (ch4) from \mathbf{C}_{jk}^S that should be used as its receiving channel and then responds to node i with a **CHOSEN** message. The

CHOSEN message includes the particular channel (ch4) that will be used by node i for broadcasting.

After choosing its broadcasting channel, node i generates a TOKEN message to node j , and the above procedures are repeated until node j selects its broadcasting channel. Node j then sends the TOKEN_RETURN message to node i , and node i finally passes the TOKEN_RETURN message to node n . This concludes the entire process.

In this example, node i has to use 2-hop information to decide its broadcasting channel. In other cases, 1-hop information is enough. For example, if $\mathbf{C}_{jk} = \{\text{ch3}, \text{ch2}\}$, node i can immediately identify ch4 as its transmission channel without issuing an ELIGIBLE message. The main procedures in phase 2 are presented as follows.

- TOKEN procedure

When receiving a TOKEN message from node n , node i decides whether or not to participate in broadcasting and chooses its transmission channel if it participates.

On arrival of $\text{TOKEN}(n, \text{ch}_{ni})$ at node i , do the following,

// ch_{ni} is the chosen broadcasting channel from n to i

for all j such that $j \in \mathbf{N}_i^T - \{n\}$ **do**

$\mathbf{C}_{ij}^E = \mathbf{C}_{ij} - \{\text{ch}_{ni}\}$ // \mathbf{C}_{ij}^E is the set of eligible channels that i may use for broadcasting

$\forall c \in \mathbf{C}_{ij}^E$, sort \mathbf{C}_{ij}^E by descent order of $w_{i,c} - w_{j,c}$

Send $\text{ELIGIBLE}(i, \mathbf{C}_{ij}^E)$ to node j

Wait $\text{CHOSEN}(i, \text{ch}_{ij})$ from node j

// ch_{ij} is the chosen transmission channel of i

if $\text{ch}_{ij} \neq \text{NULL}$ **then**

Add j to $\mathbf{Children}_i$ with channel ch_{ij}

end if

Remove links $\{i \xrightarrow{c} j | c \in \mathbf{C}_{ij}, c \neq \text{ch}_{ij}\}$ from \mathbf{E}_i^T and \mathbf{E}_{ij} // Lemma 2 refers to this as RO1

end for

```

for all  $m$  such that  $m \in \mathbf{N}_i^R - \{n\}$  do
    Send NOTIFY( $i, \bigcup_{j \in \mathbf{N}_i^T - \{n\}} \{ch_{ij}\}$ ) to node  $m$ 
end for

for all  $j$  such that  $j \in \mathbf{Children}_i$  do
    Send TOKEN( $i, ch_{ij}$ ) to node  $j$ 
    Wait TOKEN_RETURN from node  $j$ 
end for

Send TOKEN_RETURN to node  $n$ 

End

```

- ELIGIBLE procedure

When receiving an ELIGIBLE message from node i , node j makes a decision to either accept node i as its father (and thus has a broadcast link from node i) or reject nodes i as its father.

On arrival of ELIGIBLE (i, \mathbf{C}_{ij}^E) at node j , do the following,

```

if Father $_j \neq \text{NULL}$  then
     $ch_{ij} = \text{NULL}$     //  $i$  does not need to transmit to  $j$ 
else if  $\mathbf{C}_{ij}^E = \emptyset$  then
    // the only good transmission channel from  $i$  to  $j$  is same as  $i$ 's receiving channel
    if  $|\mathbf{E}_j^R| = 1$  then
         $ch_{ij} = c$ , s.t.  $n \xrightarrow{c} j \in \mathbf{E}_j^R$ 
        //  $j$  chooses  $i$  as its father with channel  $ch_{ij}$ 
    else
         $ch_{ij} = \text{NULL}$     //  $j$  receives from other neighbors
    end if
else
    for all  $k$  such that  $k \in \mathbf{N}_j^T - \{i\}$  do
        if  $|\mathbf{C}_{jk}| = 1$  then

```

```

if  $C_{ij}^E = C_{jk}$  then
     $C_{jk}^S = C_{ij}^E$  //  $C_{jk}^S$  includes the channel that  $j$  will avoid using for trans-
    sion
else
     $C_{jk}^S = C_{ij}^E - C_{jk}$ 
end if
else if  $|C_{jk}| = 2$  then
    if  $C_{ij}^E = C_{jk}$  then
        Send AVOID( $j, C_{ij}^E$ ) to node  $k$ 
        Wait SUGGEST( $j, C_{jk}^S$ ) from node  $k$ 
    else if  $C_{jk} \cap C_{ij}^E \neq \emptyset, C_{jk} \cap C_{ij}^E \neq C_{jk}, C_{jk} \cap C_{ij}^E \neq C_{ij}^E$  then
         $C_{jk}^S = C_{ij}^E - C_{jk}$ 
    else
         $C_{jk}^S = C_{ij}^E$  //  $k$  has no impact on the decision
    end if
else
     $C_{jk}^S = C_{ij}^E$ 
end if
end for
if  $\bigcap_{k \in \mathbf{N}_j^T - \{i\}} C_{jk}^S \neq \emptyset$  then
    Choose  $ch_{ij}$  from  $\bigcap_{k \in \mathbf{N}_j^T - \{i\}} C_{jk}^S$  with highest weight
else
    Choose  $ch_{ij}$  from  $\bigcup_{k \in \mathbf{N}_j^T - \{i\}} C_{jk}^S$  with maximal counts
end if
end if
Remove links  $\{i \xrightarrow{c} j | c \in \mathbf{C}_j^R, c \neq ch_{ij}\}$  from  $\mathbf{E}_i^R$ 
    // Lemma 2 refer to this removing as RO2
for all  $m$  such that  $m \in \mathbf{N}_j^R - \{i\}$  do
    Send NOTIFY( $j, \{ch_{ij}\}$ ) to node  $m$ 

```

```

end for
if  $ch_{ij} \neq \text{NULL}$  then
     $Father_j = i$  //  $j$  chooses  $i$  as its father
end if
Send CHOSEN( $i, ch_{ij}$ ) to node  $i$ 

```

End

- AVOID procedure

When receiving an AVOID message from node j , node k uses its own transmission channel(s) information to help node j choose its receiving channel.

On arrival of AVOID (j, \mathbf{C}_{jk}^A) at node k , do the following,

```

if  $Father_k \neq \text{NULL}$  then
    //  $k$  already has a father. Note that  $j$  can't be  $k$ 's father.
    Remove links  $\{j \xrightarrow{c} k | c \in \mathbf{C}_k^R\}$  from  $\mathbf{E}_k^R$ 
    // Lemma 2 refer to this removing as RO3
    Send SUGGEST( $j, \mathbf{C}_{jk}^A$ ) to node  $j$ 
else if  $|\mathbf{C}_k^T| = 1$ , and  $\mathbf{C}_k^T \subset \mathbf{C}_{jk}^A$  then
    Send SUGGEST( $j, \mathbf{C}_k^T$ ) to node  $j$ 
else
    Send SUGGEST( $j, \mathbf{C}_{jk}^A$ ) to node  $j$ 
end if

```

End

- NOTIFY procedure

Once node i chooses its broadcasting channels, it sends out a NOTIFY message to its neighbors to let them lower the priority of the chosen channels in their transmission

channels sets. The NOTIFY message also effectively lessens the hidden terminal problem and exposed terminal problem.

On arrival of NOTIFY (i, \mathbf{C}_{ij}^N) at node j , do the following,

for all c such that $c \in \mathbf{C}_{ij}^N$ **do**
 Lower the priority of channel c in \mathbf{C}_j^T
end for

End

To summarize phase 2, node i uses its local structure and the ones from its neighbors to build a local broadcasting branch, $\mathbf{B}_i = \{j, i \xrightarrow{\text{ch}_{ij}} j | \text{ch}_{ij} \neq \text{NULL}, j \in \mathbf{N}_i^T, \text{ch}_{ij} \in \mathbf{C}_i^T\}$. Eventually, a broadcasting tree is constructed, $\mathbf{T} = \bigcup_{i \in \mathbf{N}} \mathbf{B}_i$. As can be seen, DIB protocol has good scalability since at maximum 2-hop information is needed.

III.3.1 Interference Analysis of Distributed Interference-Aware Broadcasting Protocol

Figure 3 illustrates the possible interference scenarios of DIB protocol. Assume node 1 broadcasts to nodes 2 and 3 with a channel c_1 , and nodes 2 and 3 are two forward nodes that participate in the broadcast. Actually, there is no parent-child relationship between nodes 2 and 3, and it does not matter that nodes 2 and 3 have a same parent or two different parent nodes.

There are three cases while deciding the broadcast channels of nodes 2 and 3. The first case considers the interference between nodes 2 and 3 if there exist any direct link from node 2 to 3 or from node 3 to 2. The interference exists only if they choose a common transmission channel, which is implicitly solved by DIB protocol. Recall that the local structure is built after removing bad links whose metrics do not satisfied the threshold. If the interference between nodes 2 and 3 in a common channel is large enough, at least one of the channel metrics must be very low. Therefore, the probability of such a choice is negligible, although it is not null since the channel assignment is constrained by the number of available channels and their metrics. In the second case, there does not exist any

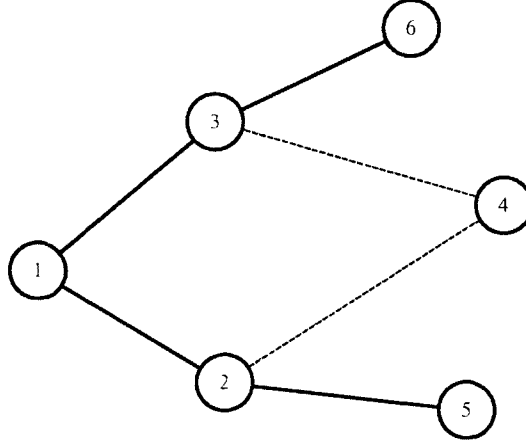


FIG. 3: Interference analysis of distributed interference-aware broadcasting protocol.

direct link between nodes 2 and 3, and they choose a common channel for broadcast. The interference occurs if there are any common outgoing neighbors of nodes 2 and 3, such as node 4. It is similar as hidden terminal problem. In the third case, nodes 2 and 3 have no common outgoing neighbors. They can choose a common channel for broadcast no matter whether there exist direct link(s) between nodes 2 and 3. It is similar to exposed terminal problem. The following two NOTIFY messages are used to solve the interference due to the cases 2 and 3. In DIB protocol, after the transmission link from node i to j with channel k is decided, node i sends NOTIFY messages to its incoming neighbors in N_i^R that includes i 's transmission channel k . In response, any neighbor node l in N_i^R will avoid using k as its transmission channel if there are any common outgoing neighbor nodes between nodes i and l . Moreover, node j sends NOTIFY messages to its incoming neighbors in N_j^R that include j 's receiving channel k . Node l in N_j^R will avoid using k as its transmission channel.

The interference analysis implies that a MAC-layer scheduler may be needed for interference free broadcasting. The scheduling problem for broadcast/multicast is another optimization problem. From the discussion of interference in DIB protocol, the protocol can not guarantee interference free caused by about three cases, mainly due to the limited number of available channels. In the case without enough channel resources, if one node has to forward broadcast messages and it has only one available transmission channel

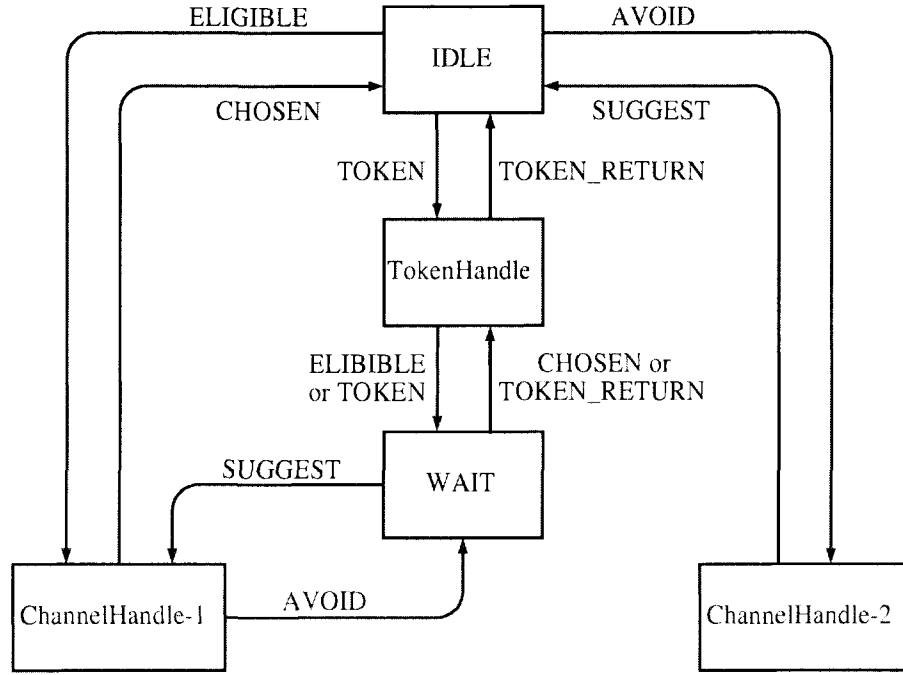


FIG. 4: Finite state machine of the message passing procedures in phase 2 of distributed interference-aware broadcasting protocol.

which is the same as its receiving channel, its receiving and transmission must be scheduled at different time slots to avoid intra-node interference. If two adjacent forward nodes are within the interference range of each other and choose the same transmission channel, their broadcasting must be scheduled to avoid inter-node interference.

III.3.2 Finite State Machine of Phase 2 in Distributed Interference-Aware Broadcasting Protocol

Figure 4 shows the finite state machine for the general case of phase 2. Each node is in one of five states, as follows:

- **IDLE**: Either no message is received or messages have been handled.
- **TokenHandle**: Upon receiving a **TOKEN** message, a node sends an **ELIGIBLE** message to each of its outgoing neighbors telling them the eligible channels and then turns into the **WAIT** state. After receiving all responded **CHOSEN** messages,

the node keeps all the transmission channels and removes the other channels. After that, the node sends a TOKEN message to each of its children and moves into the WAIT state waiting for TOKEN_RETURN. Finally, after receiving all responded TOKEN_RETURN messages from its children, the node sends back a TOKEN_RETURN message to its father and moves back to the IDLE state.

- ChannelHandle-1: Upon receiving an ELIGIBLE message, a node sends out an AVOID message to its outgoing neighbors and then moves into the WAIT state. After receiving all responded SUGGEST messages from these neighbors, the node chooses one channel as its receiving channel and removes other unnecessary links to its neighbors. Finally, the node sends back a CHOSEN message to its father and moves to the IDLE state.
- ChannelHandle-2: Upon receiving an AVOID message, a node computes a set of channels that may not be used as a receiving channel and then sends its upstream node a SUGGEST message including the channel set. Finally, the node goes back to the IDLE state.
- WAIT: In this state, a node waits for the response of an ELIGIBLE or TOKEN message from its neighbors and moves to the TokenHandle state once it receives one of them. The node may also wait for the response of a AVOID message and moves to ChannelHandle-1 state once it receives it.

III.3.3 Reliability Analysis

Recall that the original mesh network is strongly connected. Therefore, the proof of 100% reliability is to prove that the broadcasting tree obtained from DIB protocol is still strongly connected.

Definition 1. *A strongly connected path (SCP) is a directed path in which only good links are included.*

Definition 2. *A directed graph or network is strongly connected if there is at least one SCP between any pair of vertices/nodes.*

Definition 3. *A directed broadcasting tree is strongly connected if there is at least one SCP from the source node to any other node.*

Lemma 1. *After phase 1 is completed, the union of all local structures is still strongly connected.*

Proof. The union of all local structures is the same as the initial strongly connected graph removing the bad links. For the initial graph, the removing of bad links does not cause the connectivity loss of the graph based on Definition 2.

Lemma 2. *All removing operations in phase 2 do not cause the connectivity loss of any node in the graph.*

Proof. Recall that both RO1 and RO2 remove the links between node i and its outgoing neighbor j except the ones with channel ch_{ij} . This removal does not cause the connectivity loss of nodes i and j , because node i already has a father and node j has at least one link to node i with channel ch_{ij} . RO3 removes all the links connected to node k except the one to its father. Node k maintains the connectivity because it gets the connection through its father node.

Lemma 3. *After phase 2 is completed, if there exists an SCP from source node s to an arbitrary node i , there also exists an SCP from s to node j , where $j \in \mathbf{N}_i^T$.*

Proof. After phase 2 is completed, there are two cases for the connection between nodes i and j . First, there exists a direct link between nodes i and j . According to the definition of SCP, an SCP that adds one good link at one end is still an SCP. Let $P(s\aleph ij)$ denote one SCP from s to i , where \aleph represents a list of intermediate nodes along the path. Thus, $P(s\aleph ij)$ is also an SCP. Second, there is no direct link between nodes i and j due to the fact that all direct links between i and j are removed. From Lemma 2, the removing operations in phase 2 do not cause the connectivity loss of any node involved. Node j must have another node instead of i as its father node. The connectivity of node j is maintained through j 's father, and thus there exists an SCP from node s to node j .

Theorem 1. *The broadcasting tree obtained from DIB protocol is strongly connected.*

Proof. After DIB protocol is completed, a node's connections consist of links that participate in broadcasting. The union of every node's connections is the broadcasting tree. From Lemma 3, any node in the broadcasting tree has an SCP from the source node. Thus the broadcasting tree is strongly connected.

Theorem 2. *The depth of the broadcasting tree obtained from DIB protocol is bounded.*

Proof. During the execution of DIB protocol, nodes in the network can be classified into three sets: \mathbf{N}^B , the set containing the nodes that have already been added to the current broadcasting tree, \mathbf{N}^C , the set containing the nodes that have a connection to the current broadcasting tree, and \mathbf{N}^O , the set containing all the other nodes in the network. Let $\overline{\mathbf{N}^O}$ denote the set of the nodes in \mathbf{N}^O that have connections to any node in \mathbf{N}^C . As the process moves on, a node in \mathbf{N}^C will receive a TOKEN message from a node in \mathbf{N}^B and is triggered to start the message passing procedures. Upon receiving the TOKEN_RETURN message, the node either joins \mathbf{N}^B or stays in \mathbf{N}^C . In either case, the protocol ensures that nodes in $\overline{\mathbf{N}^O}$ will join \mathbf{N}^C . Apparently, the size of \mathbf{N}^O keeps decreasing as the TOKEN moves forward. Once \mathbf{N}^O becomes empty, the construction of the broadcast tree is finished. Since the size of \mathbf{N}^O is a bounded number and keeps decreasing until \mathbf{N}^O is empty, the broadcast tree is built in finite steps. Therefore, the broadcasting tree has a bounded depth. In the worst case, the depth of the constructed broadcasting tree is at most N . Thus, the depth of the broadcasting tree obtained from DIB protocol is bounded by $O(N)$.

III.3.4 Control Messages Complexity

Theorem 3. *The number of control messages does not exceed $4|E_{\overline{C}}|$, where $|E_{\overline{C}}|$ is the number of directed links. Notice that multiple directed links between a pair of nodes with different channels are counted once.*

Proof. The number of control messages that node i needs to send can be counted as follows. First, the number of TOKEN and TOKEN_RETURN messages does not exceed the number of its neighbors since node i only needs to send one TOKEN message to each child and one TOKEN_RETURN message to its father. Second, node i sends one ELIGIBLE message to each outgoing neighbor (excluding its father) and one CHOSEN message to each incoming

TABLE 2: Simulation configurations for interference-aware broadcast protocol.

| | |
|------------------------|-------------------|
| Size of the topography | 2500 × 2500 m |
| Communication range | 250 m |
| Propagation model | Two-ray ground |
| MAC protocol | 802.11 CSMA based |
| Bandwidth of links | 1 Mbps |
| Packet length (L) | 250 Bytes |
| Traffic rate (r) | 50 packets/s |
| Total traffic | 1000 packets |

neighbor. Third, node i sends no more than one AVOID message to each outgoing neighbor and no more than one SUGGEST message to each incoming neighbor. Fourth, node i sends no more than one NOTIFY message to each incoming neighbor. Notice that each type of message needs to be transmitted at most once between any pair of nodes since all the channel information is included in the message. In summary, no more than four control messages will traverse each directed link, and the total number of control message is bounded by $4|E_C|$. Equivalently, the message complexity of Phase 2 is $O(N^2)$, where N is the number of nodes in the network.

III.4 SIMULATIONS AND ANALYSIS

Extensive simulations are conducted to evaluate the performance of DIB protocol. The simulations use ns-2, a discrete event network simulator. For comparison purpose the performance of Probabilistic Broadcasting (PB) and Pure Flooding (PF) are also simulated, in which a channel is randomly chosen for broadcasting. For PB protocol, three probabilities (0.5, 0.7, and 0.9) are used to study different scenarios. Table 2 specifies the configurations of simulations. When deploying the network, nodes are randomly placed with a constraint of connectivity. Four performance metrics are measured: reliability, redundancy, latency, and goodput.

The reliability is defined as $Rel = \frac{\sum_{i=1}^N M_i}{NM}$, where M is the number of packets that the source node sends out, and M_i is the number of packets (excluding duplicates) that node



FIG. 5: Packet transmission and reception time in a broadcast session.

i received. The average receiving redundancy is defined as $Red = \frac{\sum_{i=1}^N \sum_{j=1}^M X_{i,j}}{\sum_{i=1}^N M_i} - 1$, where $X_{i,j}$ is the total number of the j th packet (including duplicates) received by node i . The transmission redundancy is indicated by the percentage of the number of nodes participating in the broadcasting. $Red_T = \frac{\sum_{i=1}^N \sum_{j=1}^M B_{i,j}}{NM}$, where $B_{i,j}$ is a 0-1 function that indicates whether node i broadcasts the j th packet (1) or not (0). The average latency is defined as $Lat = \frac{\sum_{i=1}^N \sum_{j=1}^M (t_{i,j} - t_{j,start})}{\sum_{i=1}^N M_i}$, where $t_{i,j}$ is the time node i receives the j th packet, and $t_{j,start}$ is the time the source node sends out the j th packet as depicted in Fig. 5. $\max_{(i,j)}\{t_{i,j}\}$ is the time of the last node receiving the last packet. The goodput of the system is defined as $Gdp = \frac{L}{NM} \sum_{i=1}^N \sum_{j=1}^M \frac{1}{t_{i,j} - t_{j,start}}$, where L is the packet length. To ease the performance comparison, a comprehensive metric called *power* is defined as $P = \frac{Rel \times Gdp}{Lat \times Red}$. The power is defined in this way because a mesh network is expected to provide high reliability and goodput with small latency and redundancy. Notice that the transmission redundancy is an unclear factor of the system performance, and thus it is not used in the definition of power.

The first experiment studies the reliability of the three protocols. As can be seen from Fig. 6, the proposed DIB protocol consistently achieves 100% reliability. PB and PF protocols, however, can not achieve 100% reliability due to serious contentions and interference. To resolve the heavy contention problem, a longer backoff time is needed. Thus, some broadcast messages are dropped. To make the situation worse, the significant interference among adjacent nodes causes continuous collisions. That is why even PF protocol cannot achieve 100% reliability. To further study how the traffic load impacts the reliability, two traffic rates are used in Fig. 6.

When the traffic rate $r = 50$ packets/s, both PB and PF protocols have to handle the new broadcasting messages while the previous messages are still buffered in the transmission queue. Thus, the broadcast messages keep accumulating at each node. The timing of

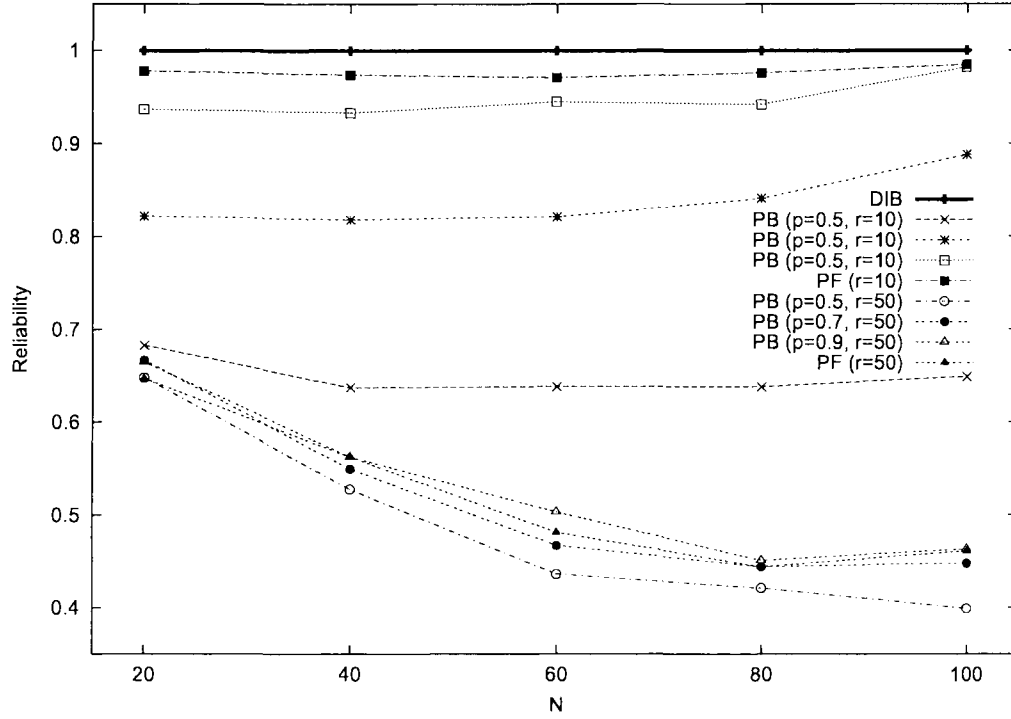


FIG. 6: Reliability for interference-aware broadcast as a function of the number of nodes.

broadcasting for the new messages is highly correlated with that for the accumulated messages. Therefore, collisions occur not only in the same broadcast message, but also among the consecutive messages. That is why the reliability of PB and PF protocols are decreasing while the number of nodes is increasing. When the traffic rate $r = 10$ packets/s, the contention of consecutive messages is much less and is not the dominant factor. Thus, the reliability is much higher and keeps increasing while the number of nodes is increasing. In the rest of the simulations, three protocols are compared under a heavy traffic load ($r = 50$ packets/s).

Figure 7 shows the average number of redundancies each node receives under different network sizes. DIB protocol significantly reduces the receiving redundancy because only the nodes included in the broadcast tree relay the broadcast messages and only the nodes that tune to the same channel as the transmitting nodes receive the broadcast messages. Naturally, PF protocol performs the worst. PB protocol reduces the receiving redundancy a little compared to PF protocol. However, its redundancy increases linearly as the number

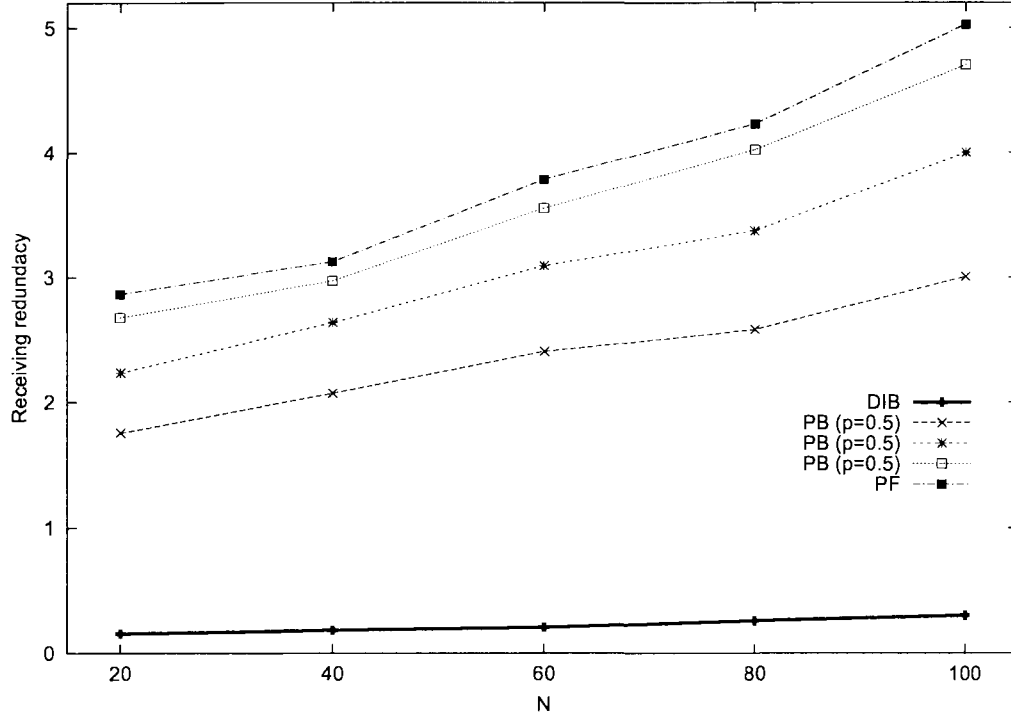


FIG. 7: Receiving redundancy for interference-aware broadcast as a function of the number of nodes.

of nodes increases. This is because the denser the network, the greater the number of neighboring nodes.

Figure 8 shows the average transmission redundancy. Obviously PF protocol has the highest transmission redundancy since every node is participating in broadcasting. The transmission redundancy of PB protocol heavily relies on the chosen probability. The bigger the probability, the higher the redundancy. The transmission redundancy of DIB protocol is only dependent on the broadcasting tree and is not related to the node degree. Thus, there is no notable increment of redundancy while the number of nodes is increased. The redundancy is within the range of 30-40%. It is interesting to notice that the transmission redundancy of PB and PF protocols is decreasing while the number of the nodes is increasing. This is due to the fact that their reliability is decreasing, and thus fewer nodes participate in the broadcasting.

The latency performance is illustrated in Fig. 9. It can be seen that both PB and PF

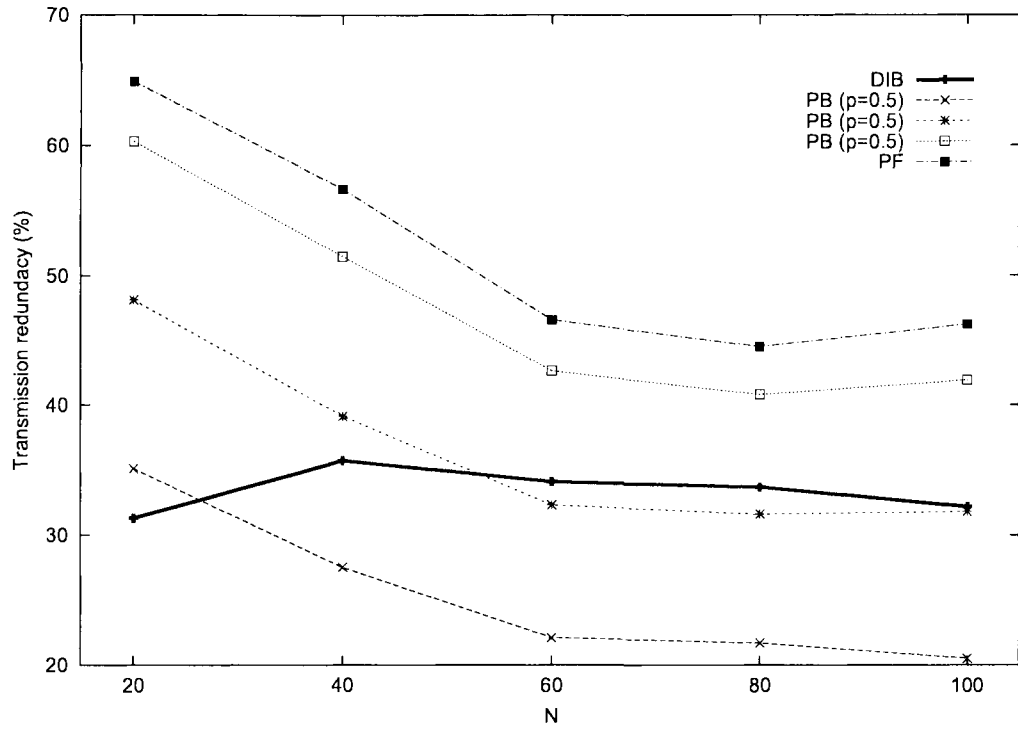


FIG. 8: Transmission redundancy for interference-aware broadcast as a function of the number of nodes.

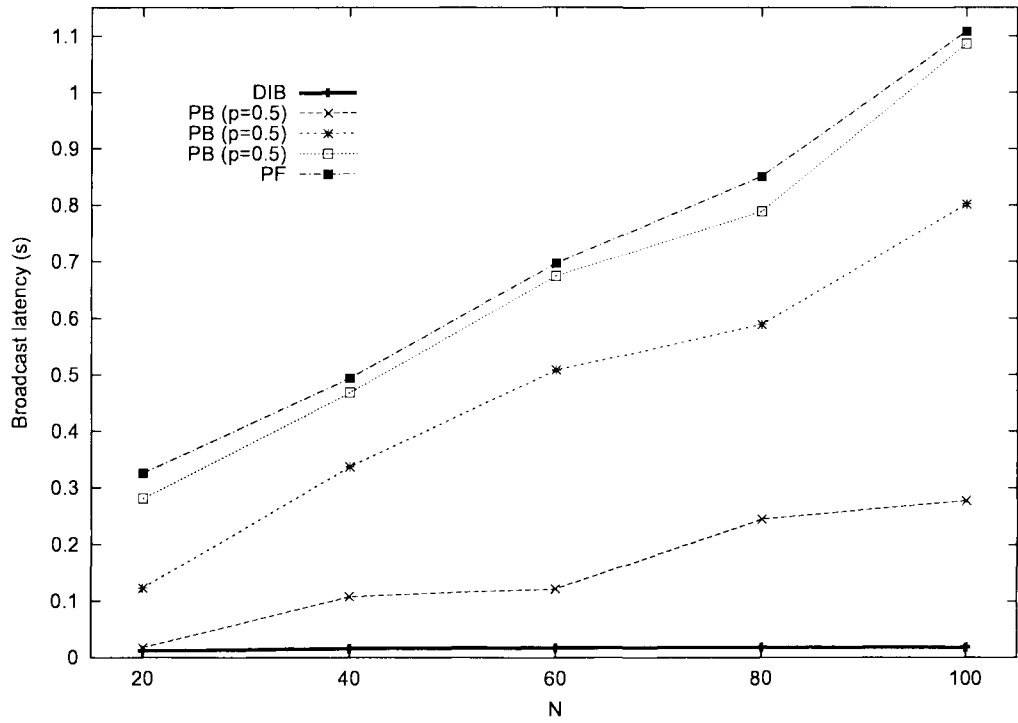


FIG. 9: Broadcast latency for interference-aware broadcast as a function of the number of nodes.

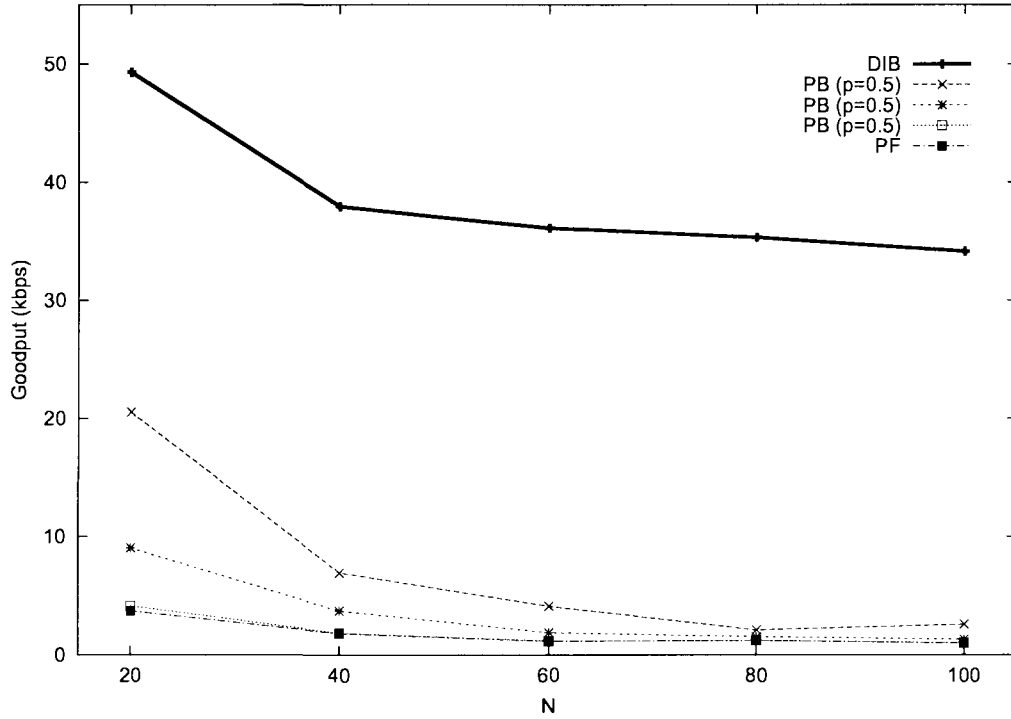


FIG. 10: Goodput for interference-aware broadcast as a function of the number of nodes.

protocols have large latencies that increase with the network size. DIB protocol, however, consistently achieves very small latency, as explained below. In PB and PF protocols, the large numbers of transmission and receiving redundancies results in serious collisions and thus causes longer backoff time. As shown in Fig. 7, the increase in network size further aggravates the situation. In addition, nodes that are farther from the source have larger backoff times. Consequently, it takes a longer time for these nodes to receive the messages. On the other hand, DIB protocol significantly reduces the receiving redundancy. The probability of collision is negligible. Therefore, most of the transmissions are successful at the first attempt. While the number of nodes increases, the broadcasting latency of DIB protocol is only increased slightly since the ratio of the longer path nodes to the shorter path nodes is increased slightly.

Figure 10 clearly demonstrates that the goodput of DIB protocol significantly outperforms PB and PF protocols. One important observation is that the goodput of all three

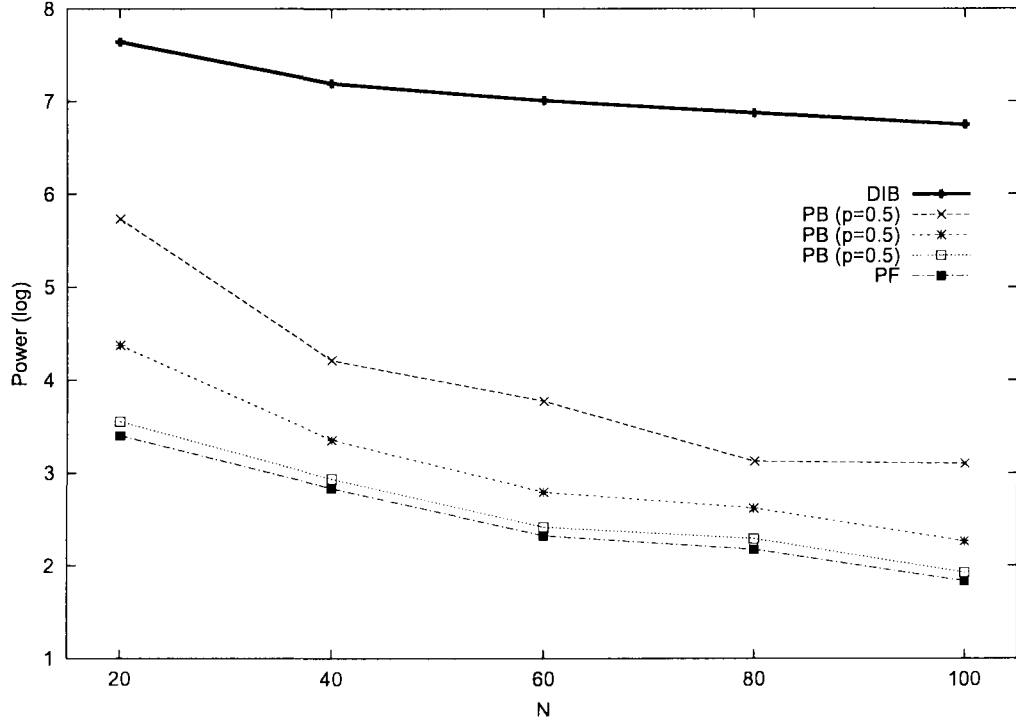


FIG. 11: Power for interference-aware broadcast as a function of the number of nodes.

protocols decreases as the number of nodes increases. According to the definition of goodput, each non-redundant received message contributes to the goodput. Also the goodput varies inversely with the latency. In general, a node far away from the source node has a higher probability of having a long path, and thus a larger latency, than one closer to the source node. Therefore, with the latency being inversely proportional to goodput, a node with a longer path has less goodput than the one with a shorter path. As the total number of nodes is increasing, the proportion of nodes with longer distances increased accordingly. Therefore, the goodput of all three protocols is decreased. It is speculated that the goodput will become saturated at some point as deploying more nodes has little impact on the proportion of path length.

As can be seen in Fig. 11, DIB protocol significantly outperforms the other two protocols in power performance.

III.5 SUMMARY

This Chapter presented two metrics to assess the link and channel qualities and a DIB protocol to build a high-performance broadcasting tree for MRMC WMNs. Both intra-node and inter-node interference were taken into account in the development process. The protocol has demonstrated good scalability since only 2-hop information is needed to build a global quasi-optimal broadcasting tree. A simulator to simulate MRMC WMNs has been developed to evaluate the proposed DIB protocol. Simulation results have suggested that DIB protocol is able to achieve 100% reliability, less broadcasting redundancies, low broadcasting latency, and high goodput. To better justify the performance, a comprehensive network performance metric, called power, has been defined.

CHAPTER IV

MINIMUM COST BROADCAST IN MULTI-RADIO MULTI-CHANNEL WIRELESS MESH NETWORKS

The tree-based broadcast approach performs broadcasting through a virtual backbone or a broadcasting tree. This Chapter addresses the minimum cost broadcast problem in MRMC WMNs. In the network model, every node broadcasts at a fixed transmission range, hence all transmission costs are identical. With this assumption, the problem of minimum cost broadcast in a wireless network is equivalent to the problem of minimum number of transmissions. The problem is then formulated as an ILP model that considers the cases without channel assignment and with static channel assignment, respectively. In the case without channel assignment, there exists a channel assignment in the network, and the problem is to minimize the broadcast cost and reduce the interference amongst the adjacent neighbors. In the second case, each node has a set of available channels to be selected, and the minimum cost problem and the static channel assignment are jointly considered. The static channel assignment can fully exploit the channel diversity, and also further reduce the interference in the network. Corresponding centralized and distributed heuristic algorithms are proposed to minimize the number of broadcast transmissions with full reliability. In the heuristic algorithms, each node participates in broadcasting if chosen to maintain the network connectivity or to achieve maximum coverage. Extensive numerical results are presented to demonstrate the performance.

This Chapter is organized as follows. The network model and problem formulation is described in Section IV.1. Section IV.2 presents a set of heuristic algorithms for tree construction, and analyzes the time and message complexity of the algorithms. Section IV.3 provides the computational experiments. The Chapter is summarized in Section IV.4.

IV.1 SYSTEM MODEL AND PROBLEM FORMULATION

The MCBP has been studied for single radio single channel scenario. However, it has not been investigated much in MRMC WMNs. Such a problem is very different from

that in the single radio single channel scenario. In MRMC WMNs, the presence of multi-radio allows a node to send and receive at the same time; the availability of multi-channel allows channels to be reused across the network, which expands the available spectrum and reduces interference. The channel assignment in MRMC WMNs is used to assign multiple radios of every node to different channels. It determines the actual network connectivity since adjacent nodes have to be assigned to a common channel. Transmission on different channels makes different groups of neighboring nodes, and leads to different interference. Moreover, the selection of channels by the forward nodes impacts on the number of radios needed for broadcasting.

IV.1.1 System Model

In an MRMC WMN, each node has one or multiple radios, and each radio is tuned to one of the available non-overlapping channels in the system. Assume that all radios have a common transmission range, r . There is a specified source node that has to broadcast a message to all other nodes in the network. Any node can be used as a forward node to reach neighbor nodes in the network. Nodes that transmit, including the source node, are called forward nodes. Nodes that receive a transmission but do not retransmit it are classified as leaf nodes. The node that has not received the transmission is uncovered.

The network is represented by an undirected graph $\mathbf{G} = (\mathbf{V}, \mathbf{E}_c)$, where \mathbf{V} is the set of vertices and \mathbf{E}_c is the set of colored edges. WMNs are generally relatively dense, and the initially connected nodes are studied. Therefore, the assumption is that the MRMC mesh network is connected. \mathbf{G} is referred to the connectivity graph of the network. Let $|\mathbf{V}|$ and $|\mathbf{E}_c|$ denote the numbers of vertices and edges in \mathbf{G} , respectively. Let N denote the total number of vertices in \mathbf{V} . The set of available non-overlapping orthogonal frequency channels in the system is denoted by \mathbf{C} . Each vertex in \mathbf{V} represents a node in the network. An undirected edge (ij, k) , which corresponds to the link between node i and node j on channel k , is in \mathbf{E}_c if and only if the following two conditions hold,

- The Euclidean distance between nodes i and j is no greater than the communication range.

- One radio of node i is tuned to channel k for transmission and one radio of node j is tuned to k for receiving.

In the static channel assignment, to assign a channel to a link between a pair of nodes actually assigns a common channel to a specific radio of each node. The link between a pair of nodes is represented as two directed edges (ij, lk) and (ji, mk) . (ij, lk) corresponds to the edge from the l th radio of node i to node j on channel k , and (ji, mk) corresponds to the edge from the m th radio of node j to node i on channel k . Therefore, the undirected link (ij, k) is equivalent to two directed edges, (ij, lk) and (ji, mk) .

Given the network model defined above, the MCBP is to construct a broadcast tree, $\mathbf{T} = (\mathbf{V}(\mathbf{T}), \mathbf{E}(\mathbf{T}))$, to ensure that all nodes in the network receive the broadcast messages with minimum number of transmissions. $\mathbf{N}(\mathbf{T}) \subset \mathbf{V}$ and $\mathbf{E}(\mathbf{T}) \subset \mathbf{E}_c$ represent the set of nodes and the set of links that participate in the broadcasting, respectively. Denote $\mathbf{V}(\mathbf{T}, k)$ as the set of nodes in $\mathbf{V}(\mathbf{T})$ broadcasting on channel k .

Definition 4. *The cost on channel k in the broadcast tree \mathbf{T} equals $|\mathbf{V}(\mathbf{T}, k)|$. The tree cost is defined as the sum of the number of transmissions on each channel in \mathbf{T} , i.e., $\text{cost}(\mathbf{T}) = \sum_{k \in \mathbf{C}} |\mathbf{V}(\mathbf{T}, k)|$.*

Definition 5. *Minimum Cost Broadcast Problem: The MCBP is to find a broadcast tree \mathbf{T} in \mathbf{G} and spans all nodes in \mathbf{G} with the least tree cost.*

IV.1.2 Integer Linear Programming Formulation without Consideration of Channel Assignment

An ILP formulation is presented to solve the MCBP without consideration of channel assignment optimally. The channel assignment is given independently from the broadcasting because the channel assignment strategy is influenced by many factors, such as unicast traffic. Assume the existing channel assignment is static during the process of broadcasting and keeps the networks connected. The ILP formulation without consideration of channel assignment is summarized in Fig. 12.

The network topology and existing static channel assignment are described by a set of binary variables $E_{ij,k}$. $E_{ij,k}$ equals 1 if there is an undirected edge (ij, k) exists in \mathbf{E}_c , and

$$\text{minimize } \sum_{k \in C} \sum_{i \in V} Y_{i,k}$$

$$s.t. \quad X_{ij,k} - E_{ij,k} \leq 0; \quad \forall i, j \in V, i \neq j, \forall k \in C \quad (3)$$

$$\sum_{j \in \{V \setminus i\}} F_{ij} = D; \quad i = \text{source} \quad (4)$$

$$\sum_{j \in \{V \setminus i\}} F_{ji} = 0; \quad i = \text{source} \quad (5)$$

$$\sum_{j \in \{V \setminus i\}} (F_{ji} - F_{ij}) = 1; \quad i \in \{V \setminus \text{source}\} \quad (6)$$

$$F_{ij} - D \sum_{k \in C} X_{ij,k} \leq 0; \quad \forall i, j \in V, i \neq j \quad (7)$$

$$Y_{i,k} - X_{ij,k} \geq 0; \quad \forall i, j \in V, i \neq j, \forall k \in C \quad (8)$$

$$E_{ij,k} \in \{0, 1\}; \quad \forall i, j \in V, \forall k \in C \quad (9)$$

$$X_{ij,k} \in \{0, 1\}; \quad \forall i, j \in V, \forall k \in C \quad (10)$$

$$F_{ij} \geq 0; \quad \forall i, j \in V \quad (11)$$

$$Y_{i,k} \in \{0, 1\}; \quad \forall i \in V, \forall k \in C \quad (12)$$

FIG. 12: The integer linear programming formulation for the minimum cost broadcast Problem without consideration of channel assignment.

0 otherwise as constraint (9). A resulting broadcast tree is represented by a set of binary variable $X_{ij,k}$. $X_{ij,k}$ equals 1 if the broadcast tree includes an edge (ij, k) , and 0 otherwise as constraint (10). Clearly, constraint (3) indicates that if an undirected edge (ij, k) is included in the tree, it must exist in \mathbf{G} .

Based on the network flow model [55], the ILP formulation ensures that the resulting broadcast tree reaches all nodes in \mathbf{V} . Flow conservation constraints (4)-(7) keeping all nodes connected and ensures that there are no loops in the broadcast. Constraint (4) represents that the source node injects $D = N - 1$ units of supply into the network. The number of units equals the total number of destinations in the network. Each destination node consumes one unit of supply when the flow goes through it. Constraint (5) indicates

that there is no input flow to the source node. Constraint (6) indicates that each non-source node consumes 1 unit of supply. At each forward node, this flow is split into sub-flows, and the supply is split based on the number of nodes in the sub-tree of the forward node. The amount of supply of each sub-flow equals the number of the nodes in the sub-tree. Therefore, each forward node receives an amount of supply that equals the number of nodes through the paths in the sub-tree, and each leaf node receives and consumes exactly one unit of supply. Denote the aggregate amount of supply going from vertex i to vertex j on any channel as a continuous flow variable, F_{ij} . Thus, if i is a forward node and there exist an edge from i to j in the tree, F_{ij} is positive, and 0 otherwise as constraint (11). Constraint (7) define the relationship between two sets of variables, F_{ij} and $X_{ij,k}$. It represents that only when an edge from vertices i to j on any channel is included in the broadcast tree is it possible that $F_{ij} > 0$.

To obtain the objective function which minimizes the tree cost, a set of binary auxiliary variables, $Y_{i,k}$, is introduced in the formulation. $Y_{i,k}$ equals 1 if node i is a forward node on channel k in the broadcast tree, and 0 otherwise as constraint (12). If an edge is in the tree, is incident from vertex i , and operates on channel k , then $Y_{i,k} = 1$. Constraint (8) relates the $Y_{i,k}$ variables to the $X_{ij,k}$ variables.

The cost on channel k in the broadcast tree is the sum of $Y_{i,k}$ over all nodes i in \mathbf{V} , $|\mathbf{V}(\mathbf{T}, k)| = \sum_{i \in \mathbf{V}} Y_{i,k}$. According to Definition 4, the objective function is:

$$\text{minimize } \sum_{k \in \mathbf{C}} \sum_{i \in \mathbf{V}} Y_{i,k}.$$

IV.1.3 Integer Linear Programming Formulation with Static Channel Assignment

For ILP formulation with static channel assignment, several radio constraints have to be added into the formulation in Fig. 12. The additional constraints for ILP formulation with static channel assignment is summarized in Fig. 13. Denote I_i as the number of radios of node $i \in \mathbf{V}$. A static channel assignment scheme A assigns node v I_i different channels. The channel assignment (i, lk) represents the channel k is assigned to l th radio interface of node i .

If an undirected edge (ij, k) exists in \mathbf{E}_c after the channel scheme A , two directed edges

$$E_{ij,k} - \sum_{l \in I_i} E_{ij,lk} = 0; \forall i, j \in V, i \neq j, \forall k \in C \quad (13)$$

$$X_{ij,k} - \sum_{l \in I_i} X_{ij,lk} = 0; \forall i, j \in V, i \neq j, \forall k \in C \quad (14)$$

$$\sum_{l \in I_i} X_{i,lk} \leq 1; \forall i \in V, \forall k \in C \quad (15)$$

$$\sum_{k \in C} X_{i,lk} \leq 1; \forall i \in V, \forall l \in I_i \quad (16)$$

$$X_{i,lk} - \max_{j \neq i} X_{ij,lk} = 0; \forall i \in V, \forall k \in C, \forall l \in I_i \quad (17)$$

$$E_{ij,lk} \in \{0, 1\}; \forall i, j \in V, \forall k \in C, \forall l \in I_i \quad (18)$$

$$X_{ij,lk} \in \{0, 1\}; \forall i, j \in V, \forall k \in C, \forall l \in I_i \quad (19)$$

$$X_{i,lk} \in \{0, 1\}; \forall i \in V, \forall k \in C, \forall l \in I_i \quad (20)$$

FIG. 13: The additional constraints of integer linear programming formulation for the minimum cost broadcast problem with static channel assignment.

(ij, lk) and (ji, mk) also exist in \mathbf{E}_c . A set of binary variables $E_{ij,lk}$ for static channel assignment is defined to represent the directed edges between a pair of nodes. $E_{ij,lk}$ equals 1 if there is a directed edge (ij, lk) which exists in \mathbf{E}_c , and 0 otherwise as constraint (18). A resulting broadcast tree is represented by a set of binary variables $X_{ij,lk}$. $X_{ij,lk}$ equals 1 if the broadcast tree includes an edge (ij, lk) , and 0 otherwise as constraint (19). Therefore, constraints (13) and (14) relate between variables $E_{ij,k}$ and $E_{ij,lk}$, $X_{ij,k}$ and $X_{ij,lk}$, respectively.

A set of binary variables $X_{i,lk}$ is defined to represent the channel assignment. $X_{i,lk}$ equals 1 if the channel k is assigned to l th radio interface of node i in the broadcast tree, and 0 otherwise as constraint (20). For a dedicated channel k , since at most one radio will be assigned to k among all radios of node i , $\sum_{l \in I_i} X_{i,lk} \leq 1$ is true for any $k \in C$. Also for a dedicated radio l of node i , static channel assignment will only assign possibly one channel to radio l , thus $\sum_{k \in C} X_{i,lk} \leq 1$ is true for any $l \in I_i$. These two constraints are represented as (15) and (16), respectively. In the resulting broadcast tree, if node i forwards broadcast messages to any node j on channel k at its l th radio, $X_{ij,lk}$ equals to 1. Node i must be a

forwarding node on channel k at the l th radio, thus $X_{i,lk}$ equals to 1 as well. Constraint (17) relates the $X_{i,lk}$ variables to the $X_{ij,lk}$ variables.

IV.2 HEURISTIC ALGORITHMS FOR THE MINIMUM COST BROADCAST PROBLEM

The MCBP is NP-hard, which means in the worst case, it may examine all possible combinations within the search space to find the optimal solution. For large-scale networks, it will be not trivial to find the optimal solutions using the ILP formulations. This Section presents centralized and distributed heuristic algorithms to solve the MCBP. The main idea is to construct a broadcast tree by choosing a forwarding node iteratively. A node participates in broadcasting if is chosen to maintain the network connectivity or to achieve maximum new coverage. The following principles are considered:

1. A node does not participate in broadcast if all its neighbors have already been covered.
2. A node only has one receiving channel.
3. A node with only one available incoming link must be covered by that link.
4. A node may broadcast more than once using different channel on different radio.

IV.2.1 Centralized Algorithms for the Minimum Cost Broadcast Problem

First, a Centralized algorithm for the MCBP Without Channel Assignment (CWCA) is presented. Let **u_set** and **f_set** denote the set of uncovered nodes and the set of forward nodes in \mathbf{V} , respectively. Initially, **f_set** includes the source node, and **u_set** includes all non-source nodes. CWCA iteratively selects forwarding nodes and channels, and updates **f_set** and **u_set** until all nodes are covered. The algorithm first checks the one-hop neighbor nodes of **f_set** in **u_set**. If there exists any node without any incoming links from other nodes in **u_set** and with only one incoming link from any node in **f_set**, this node must be covered to maintains the network connectivity. Thus a node with such a link and maximum new coverage will be selected as a forwarding node. For all other one-hop neighbor nodes

of **f_set** in **u_set**, the algorithm select a forwarding node which covers the maximum number of to-be-covered nodes.

Input: graph $G(\mathbf{V}, \mathbf{E}_c)$, source node s

Output: Forwarding and receiving channel \bar{f}_i and \bar{r}_i for $\forall i \in \mathbf{V}$

$\bar{f}_i = \bar{r}_i = 0$

u_set = $\mathbf{V} - \{s\}$;uncovered set

f_set = $\{s\}$;forward set

while **u_set** $\neq \emptyset$ **do**

while $\exists j \in \mathbf{u_set}$ such that $\sum_{k \in C_i} \sum_{l \in \mathbf{u_set}} E_{ij,k} = 0$ **do**

for all $\sum_{k \in C_l} \sum_{j \in \mathbf{f_set}} E_{ij,k} = 1$ **do**

 select l with $\bar{f}_l = k$ to cover j

 update **f_set** and **u_set**

end for

end while

 select $i \in \mathbf{f_set}$ with \bar{f}_i to maximize coverage

 update **f_set** and **u_set**

end while

In the algorithm CWCA, the channel selection is based on the existing channel assignment. The Centralized algorithm for the MCBP with Static Channel Assignment (CSCA) can further reduce the interference in the resulting broadcast tree. CSCA follows the same procedure as CWCA. The main difference is that the forward node has a set of available channels and the channel selection is constrained by the number of radios in CSCA.

IV.2.2 Distributed Algorithms for the Minimum Cost Broadcast Problem

Without loss of generality, assume that the radios are assigned from the first to the last, and the first radio of every non-source node is the receiving channel. Each non-source node has exactly one receiving radio. A Distributed algorithm for the MCBP with Static Channel

Assignment (DSCA) is proposed as follows.

Input: graph $G(\mathbf{V}, \mathbf{E}_c)$, source node s ,

Output: Forwarding channel set $\bar{\mathbf{f}}_i$ and receiving channel $\bar{\mathbf{r}}_i$ for $\forall i \in \mathbf{V}$

$\mathbf{u_set} = \mathbf{V} - \{s\}$;uncovered set

$\mathbf{f_set} = \{s\}$;forward set

Phase 1: initialize the local branch of node i

reset $\bar{\mathbf{f}}_i$ and $\bar{\mathbf{r}}_i$

$id = 1$; ID of the next available radio

$\mathbf{u_set}_i = \mathbf{V}(i) - \{s\}$

$\mathbf{f_set}_i = \emptyset$

if $i = s$ **then**

Set s as active

$\mathbf{f_set}_s = s$

assign maximum coverage channel k to $\bar{\mathbf{f}}_{s,id}$, $\forall k \in C_s$

sends an ACTIVE message to each j on k if $E_{sj,k} = 1$

update $\mathbf{u_set}_s$

end if

Phase 2: handle ACTIVE message

if $i \neq s \wedge i$ is not active **then**

set $\bar{\mathbf{r}}_i$ and set i as active

end if

$id = id + 1$

if $id \leq I_i$ **then**

calculate maximum coverage channel k , $\forall k \in C_i$

sends a TEST message to each j on k if $E_{ij,k} = 1$

sends a COVERED message to each m , $\forall m \in \mathbf{u_set}_i$

end if

Phase 3: handle TEST message

if only receive TEST message from v , $\forall v \in V$ **then**

 respond an ACK message to v

else

 select a node v with maximum coverage

 respond an ACK message to v

 respond a REJECT message to others

end if

Phase 4: handle ACK message

if $\forall E_{ij,k} = 1$, receiving ACK from j on k **then**

$\mathbf{f_set}_i = i$

 update $\mathbf{u_set}_i$

 assign channel k to $\bar{f}_{i,id}$

 sent an ACTIVE message to each j on k if $E_{ij,k} = 1$

end if

Phase 5: handle COVERED message

update $\mathbf{u_set}_i$

The basic idea of the DSCA algorithm is as follows. Initially, all nodes are idle, and then source node s is activated. The active source node will be assigned a forwarding channel, \bar{f}_s , based on the maximum coverage amongst all available channels. Every reachable neighbor nodes of s with channel \bar{f}_s will be the child of s on \bar{f}_s . Then an ACTIVE message with the forward set information is sent to every child on channel \bar{f}_s . The ACTIVE message is used to cover and activate a new node. Every child node becomes active upon receiving the ACTIVE message, and tunes its receiving channel to \bar{f}_s . For any active node, including the source node, if it has available radios and channels, it chooses a maximum coverage channel and sends a TEST message to each neighbor on that channel. The TEST message includes the coverage information. The receiving node uses it to compare the coverage from multiple possible transmitters. If in a given period, a node receives more than one TEST message, it compares the coverage of all TEST messages. It then responds an ACK message to the one with maximum coverage, and responds a REJECT message to

others. The REJECT message includes the coverage and channel information of the winner. In the case that a node receives multiple TEST messages with same maximum new coverage from different senders, a winner can be chosen either randomly or by considering the interference factor. If the neighbor receives only one TEST message, it sends back an ACK message. While a node receives an ACK message, it will be assigned the forwarding channel, and send an ACTIVE message to every child on the channel. After any channel assignment is determined, the forward set and uncovered set will be updated. The child node will be assigned the receiving channel as well. While a node receives a REJECT message, it notices that the neighbor node has been covered by another node. Thus it updates its uncovered set. To reduce the potential interference, it also decrease the priority of the channel piggyback from the REJECT message. This process is executed iteratively until all nodes in the network are covered.

The proof of the correctness of DSCA algorithm and the analysis of the time and message complexity are given as follows.

Lemma 4. *In each iteration, there is at least one node chosen as forward node.*

Proof. Donate $\mathbf{G}_c(k)$ as the graph consisting of all covered nodes and corresponding links after the k th iteration to run the message passing protocol in DSCA. Thus $\mathbf{G}_c(k) \subset \mathbf{G}$. Initially, $\mathbf{G}_c(0)$ only contains the source node s . $\mathbf{G}_c(k)$ is partitioned as follows, $\mathbf{G}_c(k) = \bigcup \mathbf{P}_i(k)$, where $\mathbf{P}_0(k)$ is the set of nodes that all of their neighbor nodes are covered nodes, and for any $i > 0$, $\mathbf{P}_i(k)$ is the set of competition nodes. None of nodes from different competition set will compete each other.

Figure 14 demonstrates the node competition under three basis cases. In DSCA, an active node sends out a TEST message with its maximum new coverage to its neighbors, and wins the competition if it receives all ACK messages from the neighbors. If a node receives multiple TEST messages, it responds one ACK to the sender with maximum new coverage, and responds REJECT to others. Nodes compete for TEST message explicitly or implicitly. Two nodes are considered as explicit competition nodes if they have any common node in the TEST messages. Explicit competition nodes are probably not adjacent

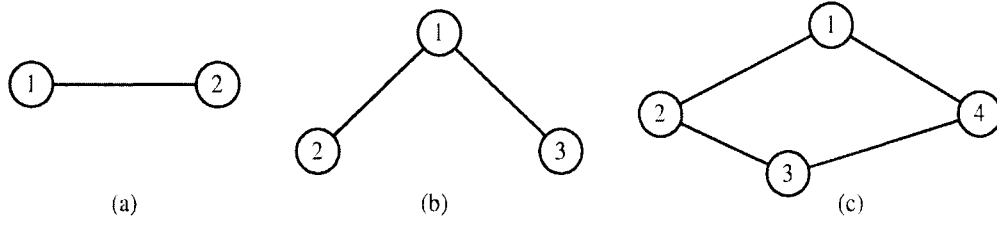


FIG. 14: Example of node competition for the minimum cost broadcast problem with static channel assignment.

nodes. Two nodes are considered as implicit competition nodes if they have any common explicit competition node, or iteratively, at least one pair of their explicit competition nodes has any common node or any common implicit competition node. The link between any pair of nodes represents the explicit competition relationship, instead of the wireless communication.

In a pair of explicit competition nodes, the node with maximum new coverage wins the competition. As depicted in Fig. 14(a), node 1 and 2 are a pair of explicit competition nodes, and the one with maximum new coverage will be potentially chosen as forward nodes. In Fig. 14(b), node 1 and 2, node 1 and 3 are two pairs of explicit competition nodes. Node 1 and 3 are a pair of implicit competition nodes as node 2 is their common explicit competition node. Node 1 will be potentially chosen as forward nodes if it has the maximum new coverage. If node 1 has the minimum new coverage, both nodes 2 and 3 will be potentially chosen as forward nodes depending on the competition with their other explicit competition nodes, respectively. Otherwise, based on the transitivity of inequality, either node 2 or 3, whichever has the maximum new coverage, will be potentially chosen as forward nodes. In Fig. 14(c), there are two pairs of implicit competition nodes, node 1 and 3, node 2 and 4. All other pairs are explicit competition nodes. Only if a node has the maximum new coverage and its implicit competition node has the second maximum new coverage, are the two nodes chosen as forward nodes. For all other cases, there is only one node chosen as a forward node. Therefore, there is one winner between a pair of explicit competition nodes, and at least one winner between two implicit competition nodes. There

is at least one partition $\mathbf{P}_i(k)$ such that $i > 0$ while $\mathbf{G}_c(k) \neq \mathbf{G}$. Thus, in each partition $\mathbf{P}_i(k)$ for $i > 0$, there is at least one node chosen as forward node. Overall, there is at least one node chosen as a forward node in each iteration.

Theorem 4. *DSCA algorithm is solvable.*

Proof. It is sufficient to prove that the message passing protocol in DSCA algorithm is run iteratively until all nodes in the networks are covered. From Lemma 4, there is at least one winner in each $\mathbf{P}_i(k)$ for $i > 0$ in the $k + 1$ iteration. Therefore, after the $k + 1$ iteration, $\mathbf{G}_c(k + 1)$ consists of $\mathbf{G}_c(k)$ and the new covered nodes. As long as $\mathbf{G}_c(k) \neq \mathbf{G}$, $\mathbf{P}_0(k) \neq \mathbf{G}$ since there exists some node with uncovered neighbor nodes. In each partition, excluding $\mathbf{P}_0(k)$, at least one node will be chosen as forward nodes. Thus, the total number of chosen forward nodes in the k iteration at least equals the number of the partitions $\mathbf{P}_i(k)$ for all $i \geq 0$. Once $\mathbf{G} - \mathbf{G}_c(k)$ becomes empty, the construction of the broadcast tree is finished. Since the size of $\mathbf{G} - \mathbf{G}_c(k)$ is a bounded number and keeps decreasing until it is empty, the algorithm solves the problem in finite steps.

Theorem 5. *DSCA algorithm runs in $O(N^2)$.*

Proof. The heuristic involves solving a sequence of the maximum selection problem. The maximum selection is to find the node with maximum new coverage, which runs in linear time. In each partition, the selection problem can be solved independently and simultaneously. Therefore, in any iteration, the selection problem is bound by $O(N)$. Since there are at most N iterations, algorithm DSCA runs in $O(N^2)$.

Theorem 6. *DSCA algorithm has $O(N^2)$ message complexity in overall.*

Proof. Donate the maximum number of radios amongst all nodes in the network as $I = \max_{i \in \mathbf{V}} I_i$. Donate $E_{\bar{C}}$ as the number of links without consideration of channels, i.e., the multiple links between a pair of node with different channels are only counted once. The number of control messages that node i needs to send can be counted. First, the number of ACTIVE does not exceed the number of its neighbors times the number of radios, I_i , since node i only needs to send one ACTIVE message to each child for each radio. Second, node i sends at most I_i TEST message to each neighbor. Third, for each radio, node i sends no

more than either one ACK message or one REJECT message to each neighbor. Fourth, for all I_i radios, node i sends no more than one COVERED message to each neighbor since it is assigned only one receiving channel. Notice that the first three types of messages need to be transmitted no more than the number of radios between any pair of nodes since the channel assignment is static, and the information about a special channel is included in the message. In summary, no more than 3 control messages will traverse any pair of nodes for each radio, and at most 1 COVERED message will traverse any pair of nodes. Since I is the maximum available number of radios, the total number of messages is bounded by $(3I + 1)|E_C|$. Equivalently, the message complexity of DSCA is $O(N^2)$, where N is the total number of nodes in the network.

The Distributed algorithm for the MCBP Without Channel Assignment (DWCA) works similarly to DSCA. The main difference is the group of neighbor nodes on a specific channel is fixed in DWCA because the channel assignment is predetermined. The calculation and comparison of coverage become simpler. The time and message complexity of DWCA are also $O(N^2)$.

IV.3 COMPUTATIONAL EXPERIMENTS

This Section evaluates the performance of the ILP formulations and the heuristic algorithms. The experiments conduct a study of several parameters, i.e., number of nodes in the networks N , number of available channels C , and number of radios per node I . The first two experiments consider the minimum cost broadcast without consideration of channel assignment, and compare the performance of ILP, CWCA and DWCA. Figure 15 shows the average cost while $I = 3$, N varies from 10 to 50, and C varies from 1 to 3. Nodes are randomly deployed within a $1000 \times 1000m$ square area, and the transmission range is set to $250m$ for every node. One node is randomly selected as the source node. In the case without consideration of channel assignment, I_i radios at node i are randomly tuned to selected distinct channels. The connectivity of the network is checked up, and the channel selection is adjusted to maintain the network connectivity. For each configuration, the experiments run 20 randomly generated instances, and the average broadcast costs are compared.

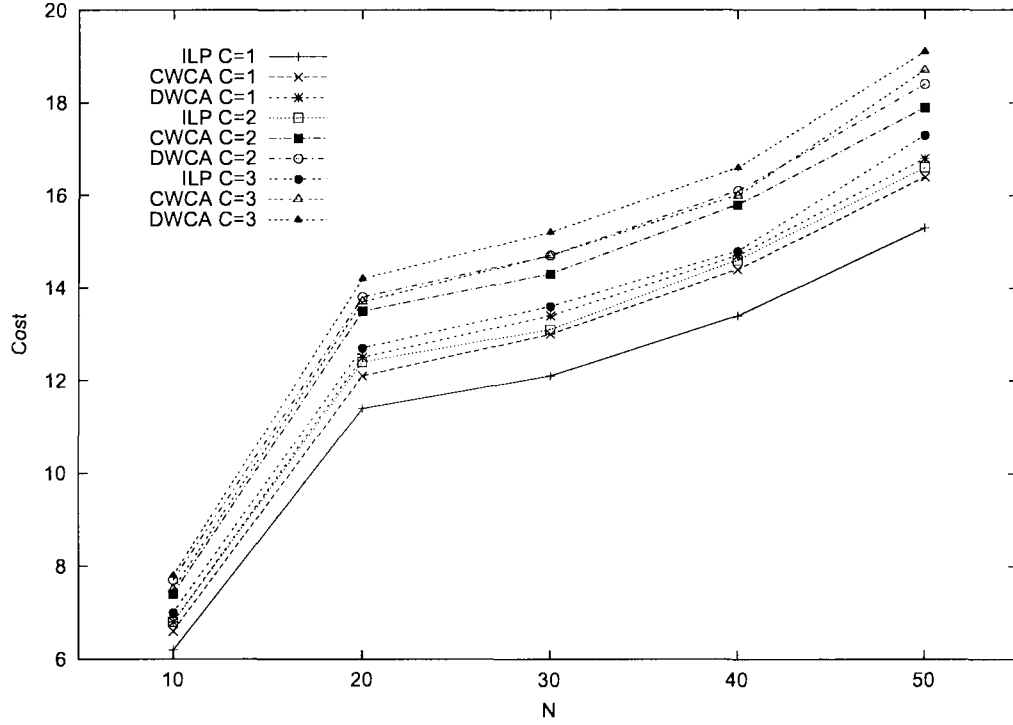


FIG. 15: Broadcast cost for minimum cost broadcast without channel assignment while $I=3$.

Figure 16 shows the average cost while $C = 3$, N varies from 10 to 50, and I varies from 2 to 4. As can be seen from Figs. 15 and 16, ILP provides the optimal, and the two heuristic algorithms perform quite reasonably on average. In all cases, CWCA is less than 10% away from the optimal, and DWCA is less than 12% away from the optimal. Figure 15 demonstrates that, for the same approach, the cost increases while the number of channels increases from 1 to 3. Considering $C = 1$ as the single channel scenario, the cost of ILP increases about 9% for $C = 2$, and less than 13% for $C = 3$, respectively. Since MRMC probably reduces the number of adjacent neighbors on a specified channel, the number of broadcast transmissions will be increased due to the assigned multiple channels at the forward node. In Fig. 16, for the same approach, the cost slightly increases while the number of radios increases from 2 to 4. Compared with $I = 2$, the cost of ILP increases in the range from 2% to 5%. The number of radios has less impact on the cost than does the number of channels.

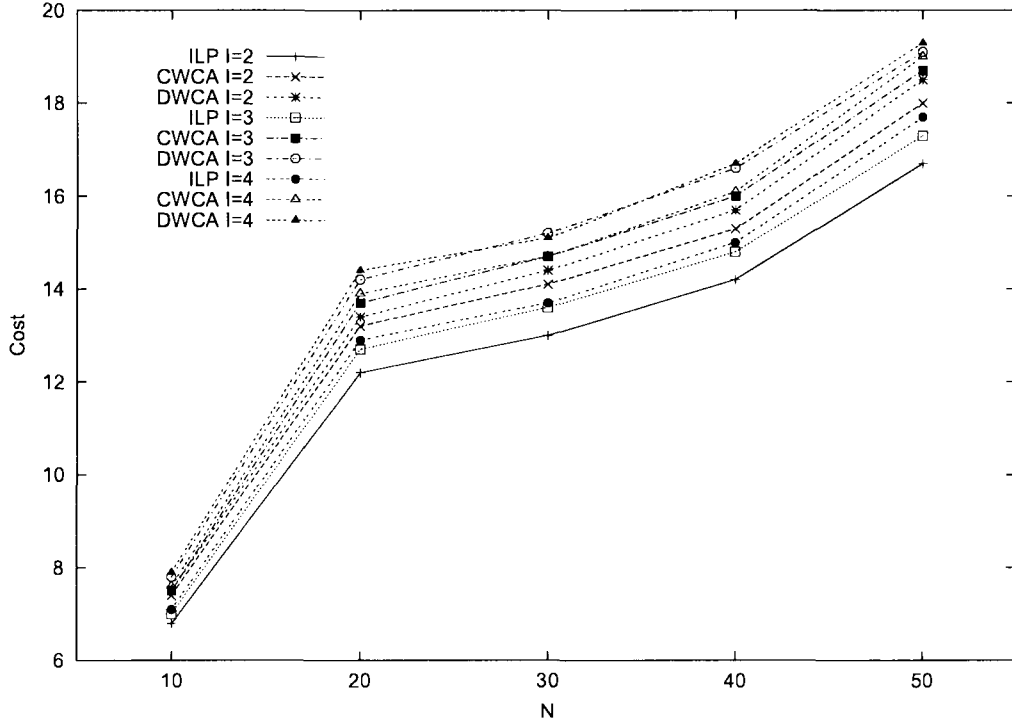


FIG. 16: Broadcast cost for minimum cost broadcast without channel assignment while $C=3$.

In the case with static channel assignment, each node can be tuned to a set of randomly selected distinct channels, and the number of actual tuned channels is constrained by the number of radios. ILP, CSCA and DSCA are compared in the third and fourth experiments. The same parameters are used as in the first and second experiment, respectively. A similar conclusion can be made from Figs. 17 and 18 as from Figs. 15 and 16. In all cases, CSCA is less than 9% away from the optimal, and DSCA is less than 12% away from the optimal. Compared with $C = 1$, the cost of ILP increases at most 13% for $C = 2$, and less than 16% for $C = 3$, respectively. Compared with $I = 2$, the cost of ILP increases in the range from 4% to 8%. Comparing the results in Figs. 15 - 18, the results of MCB with static channel assignment is better than the result of MCB without channel assignment in all configurations. The predetermined channel assignment in MCB without channel assignment can be considered as a special case of channel assignment in MCB with static channel assignment, which may not be the best channel assignment.

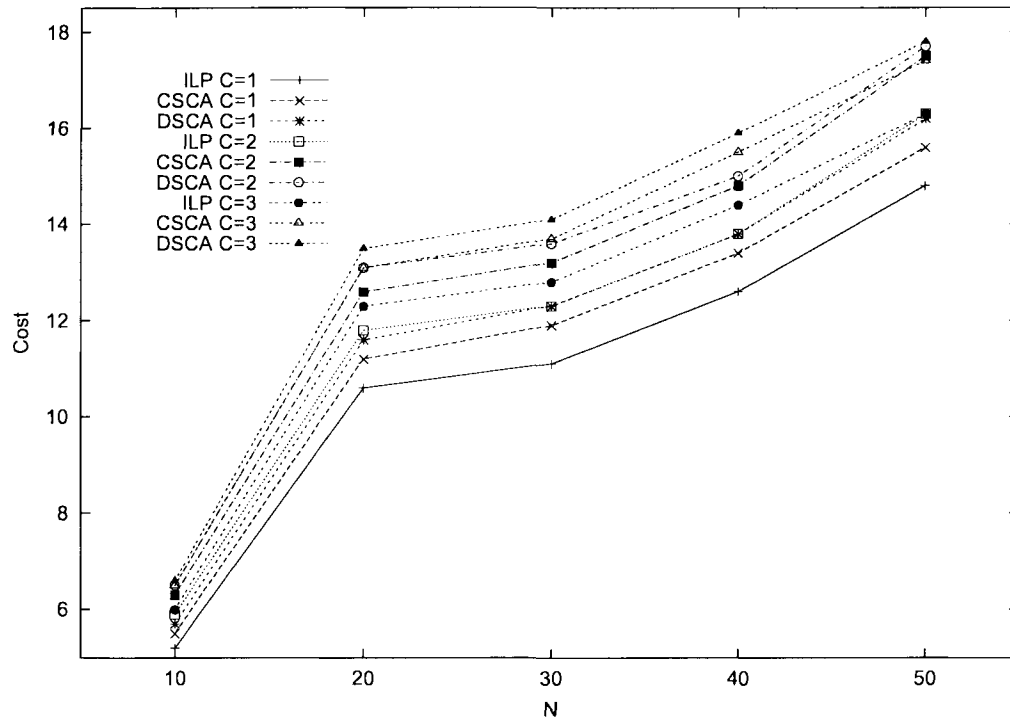


FIG. 17: Broadcast cost for minimum cost broadcast with static channel assignment while $I=3$.

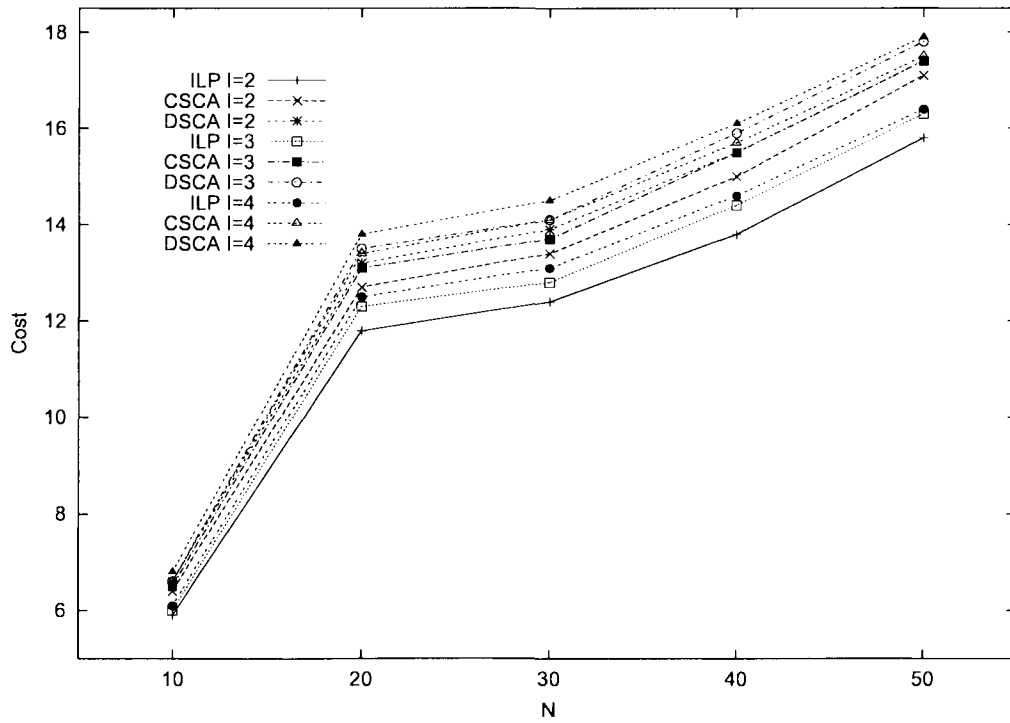


FIG. 18: Broadcast cost for minimum cost broadcast with static channel assignment while $C=3$.

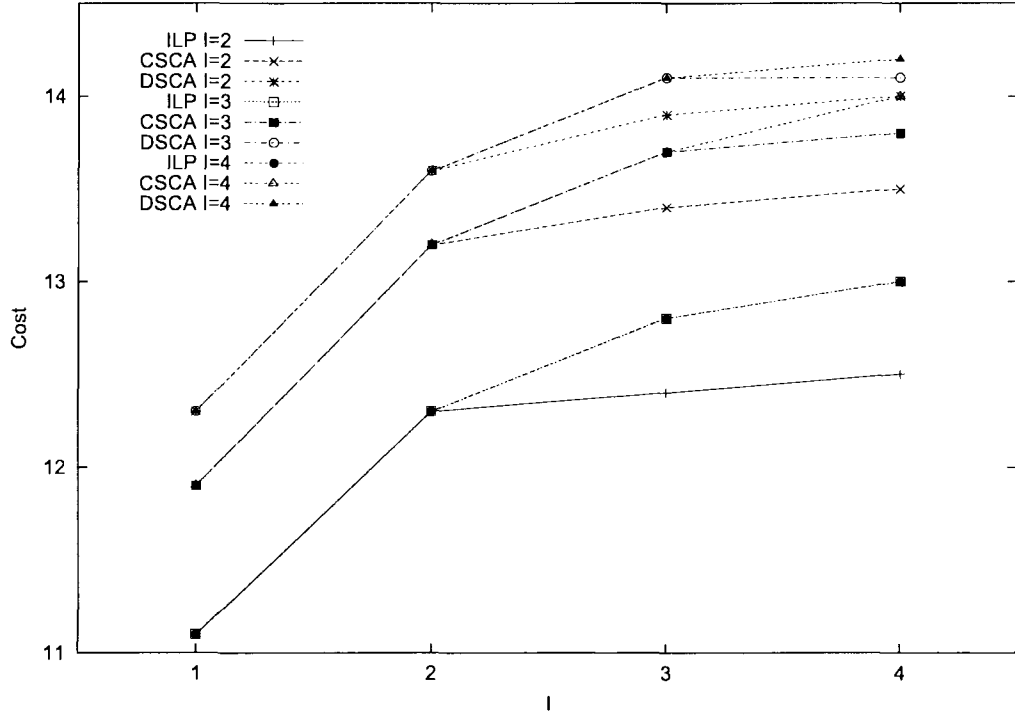


FIG. 19: Broadcast cost for minimum cost broadcast with static channel assignment while $N=30$.

Figure 19 shows the average cost for static channel assignment while $N = 30$, I varies from 2 to 4, and C varies from 1 to 3. It demonstrates that the heuristic algorithms minimize the number of broadcast transmissions. CSCA and DSCA perform quite reasonably on average compared with ILP.

IV.4 SUMMARY

This Chapter presented the MCBP in MRMC WMNs. The problem with preexisting channel assignment and the problem with static channel assignment were considered, respectively. Correspondingly, two ILP formulations have been presented for these two cases. In the case without channel assignment, there exists a channel assignment in the network. The formulation minimizes the broadcast cost and reduce the interference amongst the adjacent neighbors. In the second case, the MCBP and the static channel assignment are jointly considered. The static channel assignment can further reduce interference in the network.

Several corresponding heuristic algorithms, centralized and distributed, to construct the broadcast tree rooted at the source node have been proposed. In the heuristic algorithms, a node is chosen to participate in broadcasting to maintain the network connectivity or to achieve maximum coverage. The distributed algorithms have $O(N^2)$ time complexity and message complexity. Extensive numerical results demonstrate that the heuristic algorithms minimize the number of broadcast transmissions with full reliability and fully exploit the channel diversity.

CHAPTER V

INTERFERENCE-AWARE MULTICAST IN WIRELESS MESH NETWORKS WITH DIRECTIONAL ANTENNAS

This Chapter addresses the problem of multicast routing with the objective of minimizing the interference for WMNs employing directional antennas. It first presents the definition of interference with directional transmissions that are suitable for designing multicast algorithms, and then formulates the minimum interference multicast problem using a linear programming model. Finally, a heuristic algorithm is proposed to solve the problem. Multicast routing found by the interference-aware algorithm tends to have fewer channel collisions and higher network throughput.

This Chapter is organized as follows. The network model and problem formulation is described in Section V.1. Section V.2 presents a heuristic algorithm, and analyzes the time and message complexity of the algorithms. Computational experiments are provided in Section V.3. Section V.4 summarizes this Chapter.

V.1 ANTENNA MODEL AND PROBLEM FORMULATION

V.1.1 Antenna Model

Assume multi-beam sectorized directional antennas as the antenna model. A beam can only be either transmitting or receiving at any instant. The transmission is directional with discrete directions, fixed beam radius, and fixed beamwidth. The reception can be either omnidirectional or directional. Based on the beam pattern of reception, there are directional transmission with omnidirectional reception and directional transmission with directional reception. For directional transmission, beam radius is the same as that of omnidirectional antennas, and beamwidth is determined by the angle of a sector. Every transmitter has K directional antenna elements, each of which spans an angle of α , where $\alpha \leq 2\pi/K$. Let To_i denote the transmission orientation. If $\alpha = 2\pi/K$ and all directional beams are active, the directional antennas function the same as an omnidirectional antenna. For directional

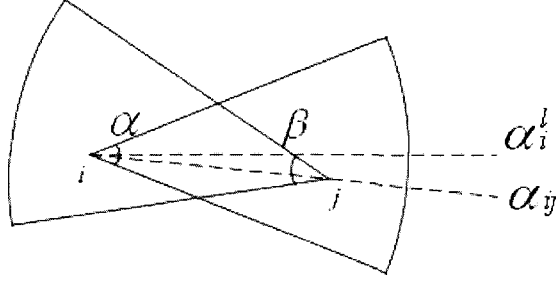


FIG. 20: Beam orientation and angle from sender to receiver for directional transmission and reception.

reception, let β and Ro_i denote the reception beamwidth and orientation, respectively. Assume the side lobes of the antennas are negligible.

Based on the transmission orientation, there are two types of directional antennas, fixed orientation and fixed beamwidth (FOFB) and adjustable orientation and fixed beamwidth (AOFB). FOFB is the simplest antenna model in which an antenna can transmit at a given beamwidth and at a fixed orientation. In FOFB, the orientation of l th beam of node i , α_i^l , remains fixed once it is installed. For AOFB, the beam orientation can be adjusted to different directions to reduce the interference. Each antenna has an adjustable orientation $\alpha_i^l \in [\alpha_{min}, \alpha_{max}]$, but the beamwidth is fixed. Assume the beamwidth is fixed, and the beams of two directional antennas may have overlapping transmission zones for AOFB.

Denote the beam orientation of l th beam of node i as α_i^l , where $l = 1, \dots, K$. Assume the node has the knowledge of its geographical position. Therefore, the angle from sender i to receiver j can be calculated. Denote the angle as α_{ij} as depicted in Fig. 20. Obviously, the angle from node j to node i , α_{ji} , is

$$\alpha_{ji} = \begin{cases} \alpha_{ij} + \pi & \text{for } 0 \leq \alpha_{ij} < \pi \\ \alpha_{ij} - \pi & \text{for } \pi \leq \alpha_{ij} < 2\pi \end{cases}.$$

A set of binary variables b_{ij}^l is defined to represent the possible link from i to j by using the l th beam of node i . A set of binary variables b_{ij}^{lk} is defined to represent the possible link from i to j by using the associated l th and k th beam. With the knowledge of α_{ij} , b_{ij}^l equals 1 if $\alpha_{ij} - \alpha_i^l \in (-\alpha/2, \alpha/2)$, and b_{ij}^{lk} equals 1 if (i, j) can be located in the l th beam of node

i and k th beam of node j such that $\alpha_{ij} - \alpha_i^l \in (-\alpha/2, \alpha/2)$ and $\alpha_{ij} - \alpha_j^k \in (-\beta/2, \beta/2)$. For FOFB, the link (i, j) can be located in the beam

$$l = \lceil K\alpha_{ij}/2\pi \rceil. \quad (21)$$

Denote $l = b_{ij}$ as the transmission beam for link (i, j) , and $k = b_{ji}$ as the reception beam of node j for directional reception. b_{ij} ranges from 1 to K if there exists a beam for link (i, j) . A set of binary variables b_{ij}^l is defined to represent where j is in the l th beam of node i . b_{ij}^l equals 1 if j is in the l th beam of node i , and 0 otherwise.

V.1.2 Interference Model

With directional antennas, two links interfere with each other if a receiver is in the transmitting beams of both transmitters. The interference region is specified not only by the beam radius, but also by the beam orientation and beamwidth. Based on the protocol model in [16], a sender-based interference model with extensions of directional antennas is presented. The model considers directional transmission with omnidirectional reception and directional reception, respectively. The interference region is defined as the area that a transmission of a directional antenna can cover. The transmission will interfere with all the nodes except the intended receiver.

In the protocol model of directional antenna, instead of the circular interference area in omnidirectional antenna, the interference region of directional antenna is a beam. The transmission from node i to node j is successful if j is in the transmission range of i , $d_{ij} \leq r$, where r is the transmission range, and also any node u that in the receiving beam of j from i is not transmitting in the beam covering j . That means that j is outside of the transmission beam of u . Figure 21 shows that the interference model considers directional transmission with omnidirectional reception. The outer dotted circle is the interference range of omnidirectional transmission and reception, and the inner solid line region is the possible interference range of directional transmission with omnidirectional reception in the worst case. Thus, directional transmission with omnidirectional reception actually does not reduce the interference too much.

Joint consideration of directional transmission and directional reception can maximize

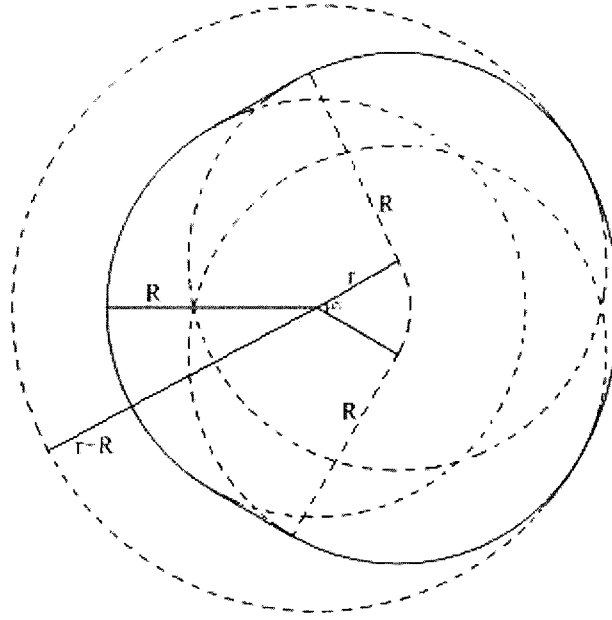


FIG. 21: Interference region of directional transmission and omnidirectional reception.

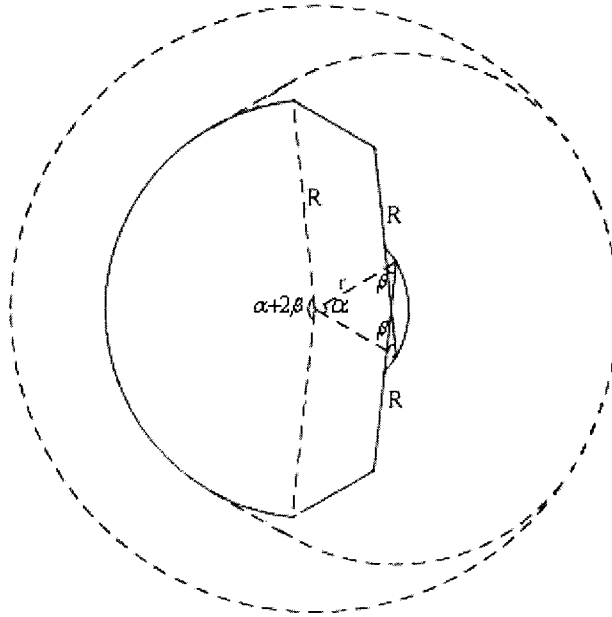


FIG. 22: Interference region of directional transmission and directional reception.

the benefits of directional antennas. Figure 22 shows that the interference model considers directional transmission and directional reception. The inner solid line region is the possible interference range of directional transmission and reception in the worst case, which is less than half of the interference range of directional transmission with omnidirectional reception.

If node X_i transmits to node X_j over a channel, the transmission is successfully completed by node X_j if no nodes within the region covered by X_j 's antenna beam will interfere with X_j 's reception. Denote $j \in \mathbf{N}(i)$ if $|X_i - X_j| \leq r$ and $b_{ij}^{lk} = 1$. Here $|X_i - X_j|$ is the distance between X_i and X_j . $b_{ij}^{lk} = 1$ for l and k indicates that node i is within the region of j 's k th beam and j is within the region of i 's l th beam. For every other node X_k simultaneously transmitting over the same channel, and the guard zone $\Delta > 0$, X_k 's beam does not cover node X_j or the following condition holds,

$$|X_k - X_j| \geq (\Delta + 1)|X_i - X_j|.$$

where X_i also denotes the location of a node. Figure 23 shows interference and two approaches to remove the interference. Figure 23a shows that a transmission from node k will cause interference to i 's transmission to j since the antenna beam of k covers receiver j and the reception beam of j covers both i and k . Figure 23b shows, by adjusting beam orientation of the interference sender, that the interference is removed as the antenna beam of k does not cover receiver j . Figure 23c shows, by adjusting the beam orientation of the receiver, that the interference is removed as the reception beam of j does not cover receiver k anymore.

V.1.3 Problem Formulation

The network is represented by a directed graph $\mathbf{G}(\mathbf{V}, \mathbf{E})$ with a finite node set \mathbf{V} and an edge set \mathbf{E} corresponding to the unidirectional wireless communication links. A multicast request m_s consists of a source node $s \in \mathbf{V}$ and M destination nodes. The set of destination nodes is denoted as $\mathbf{D} = \{d_1, d_2, \dots, d_M\}$, and $\mathbf{D} \subseteq \mathbf{V}$.

Definition 6. A multicast tree for m_s is a directed tree \mathbf{T} in \mathbf{G} such that there is a directed path p_i in \mathbf{T} from s to d_i for $i = 1, 2, \dots, M$.

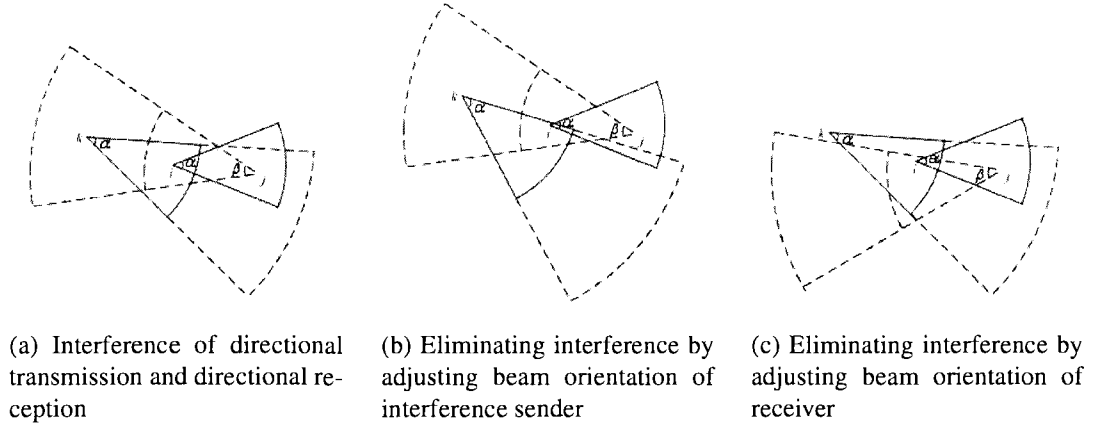


FIG. 23: Interference and interference reduction approaches for directional transmission and directional reception.

Denote $IR(j)$ as the set of nodes that are within node j 's interference range, and R as the interference range. Here $R \geq r$. Thus, for any node k , $k \in IR(j)$ if $|X_k - X_j| \leq R$ and $\exists b(k, l)$ such that $b_{kj}^l = 1$.

Definition 7. For any two forward nodes i and k in multicast tree \mathbf{T} , the interference caused by k to i , denoted by $I(i, k)$, equals 1 if k interferes with any receiver j of node i , and 0 otherwise.

$$I(i, k) = \max_{j \in \mathbf{N}(i), k \in IR(j), m \in [1, K]} b_{ji}^m b_{jk}^m.$$

Definition 8. The interference of a node i in multicast tree \mathbf{T} , denoted by $I(i)$, is the sum of the interference with all nodes and links of \mathbf{T} :

$$I(i) = \sum_{k \in \mathbf{T}} I(i, k).$$

Denote X_{ij} as a set of binary variables that represent the edges of a resulting multicast tree \mathbf{T} , and Y_i^l as a set of binary variables that represent the l th beam of node i participating multicast or not.

Definition 9. The interference of a multicast tree \mathbf{T} , denoted by $I(\mathbf{T})$, is the sum of the

interference amongst all nodes and links of the multicast tree:

$$\begin{aligned} I(\mathbf{T}) &= \sum_{i \in \mathbf{T}} I(i) = \sum_{i \in \mathbf{T}} \sum_{k \in \mathbf{T}} \max_{j \in \mathbf{N}(i), k \in IR(j), m \in [1, K]} b_{ji}^m b_{jk}^m \\ &= \sum_{i \in \mathbf{T}} \sum_{k \in \mathbf{T}} \max_{l, m \in [1, K]} X_{ij} b_{ji}^m Y_k^l b_{kj}^l b_{jk}^m. \end{aligned}$$

Definition 10. A multicast tree \mathbf{T} is said to be a minimum interference multicast tree if $I(\mathbf{T})$ is minimum among all multicast trees for m_s . The Minimum interference Multicast using Directional Antennas (MIMDA) problem seeks a minimum interference multicast tree for m_s .

The minimum interference multicast problem can be formulated as the optimization problem in Fig. 24.

The network topology is described by a set of binary variables E_{ij} . E_{ij} equals 1 if there is an undirected edge (ij) that exists in \mathbf{E} , and 0 otherwise as constraint (30). A resulting multicast tree is represented by a set of binary variable X_{ij}^{lm} . X_{ij}^{lm} equals 1 if the broadcast tree includes an edge (ij) , and 0 otherwise as constraint (31). Clearly, constraint (22) indicates that if an undirected edge (ij) is included in the tree, it must exist in \mathbf{G} .

The network flow model ensures that resulting multicast tree reaches all destination nodes in \mathbf{V} . Flow conservation constraints (23)-(26) keep all nodes connected and ensure that there are no loops in the broadcast. Constraint (23) represents that the source node injects M units of supply into the network. The number of units equals the total number of destinations in the network. Each destination node consumes one unit of supply when the flow go through it. Constraint (24) indicates that there is no input flow to the source node. Constraint (25) indicates that each destination node consumes one unit of supply. At each forward node, this flow is split into sub-flows, and the supply is split based on the number of destination nodes in the sub-tree of the forward node. The supply of each sub-flow equals the number of the destination nodes in the sub-tree. Therefore, each forward node receives a supply that equals the number of destination nodes through the paths in the sub-tree, and each destination node receives and consumes exactly one unit of supply. A continuous flow variable F_{ij} is defined to denote the aggregate amount of supply going from vertex i to vertex j . Thus, if i is a forward node and there exists an edge from i to

$$\text{minimize } \sum_{i \in \mathbf{V}} I(i)$$

$$s.t. \quad X_{ij} - E_{ij} \leq 0; \quad \forall i, j \in \mathbf{V}, i \neq j \quad (22)$$

$$\sum_{j \in \{V \setminus i\}} F_{ij} = M; \quad i = s \quad (23)$$

$$\sum_{j \in \{V \setminus i\}} F_{ji} = 0; \quad i = s \quad (24)$$

$$\sum_{j \in \{V \setminus i\}} (F_{ji} - F_{ij}) = 1; \quad i \in \mathbf{D} \quad (25)$$

$$F_{ij} - MX_{ij} \leq 0; \quad \forall i, j \in \mathbf{V}, i \neq j \quad (26)$$

$$Y_i^l - X_{ij} b_{ij}^l \geq 0; \quad \forall i, j \in \mathbf{V}, i \neq j, \forall l \in [1, K] \quad (27)$$

$$\sum_{j \in \mathbf{V}} X_{ij} b_{ij}^l + \sum_{k \in \mathbf{V}} X_{ki} b_{ik}^l \leq 1; \quad (28)$$

$$I(i) - \sum_{k \in \mathbf{V}} \max_{l, m \in [1, K]} X_{ij} b_{ji}^m Y_k^l b_{kj}^l b_{jk}^m = 0; \quad \forall i, j \in \mathbf{V} \quad (29)$$

$$E_{ij} \in \{0, 1\}; \quad \forall i, j \in \mathbf{V} \quad (30)$$

$$X_{ij} \in \{0, 1\}; \quad \forall i, j \in \mathbf{V} \quad (31)$$

$$F_{ij} \geq 0; \quad \forall i, j \in \mathbf{V} \quad (32)$$

$$b_{ij}^l \in \{0, 1\}; \quad \forall i, j \in \mathbf{V}, \forall l \in [1, K] \quad (33)$$

FIG. 24: The linear programming formulation for the minimum interference multicast problem.

j in the tree, F_{ij} is positive, and 0 otherwise as constraint (30). Constraint (26) defines the relationship between two set of variables, F_{ij} and X_{ij} . It represents that only when an edge from vertices i to j on any channel is included in the broadcast tree is it possible that $F_{ij} > 0$.

Two sets of binary variables, b_{ij}^l and Y_i^l , are defined in Section V.1. b_{ij}^l equals 1 if j is in the l th beam of node i , and 0 otherwise as constraint (33). Constraint (27) relates Y_i^l variables to X_{ij} and b_{ij}^l variables. Constraint (28) represents that any beam of a forward node in the multicast tree is used for either transmission or reception. To obtain the objective

function which minimizes interference, a set of binary auxiliary variables $I(i)$ is introduced to the formulation. Constraint (29) relates the interference metric $I(i)$ to other variables.

V.2 HEURISTIC ALGORITHM FOR MINIMUM INTERFERENCE MULTICAST USING DIRECTIONAL ANTENNAS

The establishment of a multicast tree for WMNs using directional antennas requires the specification of the transmission beams and reception beams, and the commitment of the needed transceiver resources throughout the duration of the multicast session. This Section presents a Centralized Minimum Interference Multicast (CMIM) algorithm using directional antennas.

CMIM consists of three phases. In the first phase, a minimum cost multicast tree is constructed assuming the use of an omnidirectional antenna. Multicast routing mechanism should be efficient, scalable, robust and with low signaling overhead. Since there may exist non-group mesh nodes that participate in multicast, the design of a multicast tree needs to take reducing data overhead of non-group nodes into account. A cost-efficient multicast tree can reduce data overhead. New branches/paths that reach a new terminal are added to the current multicast tree one by one. This terminal is closest to the source node. The cost of each link in \mathbf{E} is initialized to 1. The cost from the source s to terminal i , $cost(s, i)$, is the minimal cost of all possible paths from s to i . The path cost is defined as the sum of the costs of its constituent links. When a new branch is added into the multicast tree, the costs of links may become 0 due to WBA. Normally, adding a new link (i, j) into multicast tree increments the tree cost by 1. However, if node i is already a forward node before link (i, j) is added, there is no increase on tree cost due to this link. This is because the new link does not increase the number of transmissions or transmitting nodes in T . Therefore, if the new path contains link (i, j) , every link (i, k) , $\forall k \in \mathbf{V}$, in the network becomes zero cost.

In the second phase, each internal node sets the beam orientation of its directional antennas assuming fixed orientation and fixed beamwidth. For every forward node or terminal i , To_i and Ro_i can be calculated according Eq. 21. The l th beam of node i maintains its actual beam coverage, $[b_{i,min}^l, b_{i,max}^l]$, for all receiving nodes in its sector. $b_{i,min}^l$ and $b_{i,max}^l$

Algorithm 1 CMIM

Input: A network graph $G(\mathbf{V}, \mathbf{E})$, source node s , a set of terminals $\mathbf{D} \subset \mathbf{V}$ transmission beamwidth α , reception beamwidth β

Output: A multicast tree \mathbf{T} with forwarding and receiving antenna orientations To_i and Ro_i for $\forall i \in \mathbf{V}$

initialize To_i and Ro_i for all $i \in \mathbf{V}$

$T = \emptyset$

for all $e \in \mathbf{E}$ **do**

$cost(e) = 1$

end for

Phase 1: constructed multicast tree with omnidirectional antenna

while $D \neq \emptyset$ **do**

run Dijkstra's algorithm to compute $cost(s, d)$, the minimum cost from s to each terminal $d \in \mathbf{D}$

$d \leftarrow \underset{i \in \mathbf{D}}{\operatorname{argmin}} cost(s, d)$

add the minimum cost path $P(s, d)$ into \mathbf{T}

for all $(i, j) \in P(s, d)$ **do**

for all $(i, k) \in \mathbf{E}$ **do**

$cost(i, k) = 0$

end for

end for

$D = D - \{d\}$

end while

Phase 2: calculate To_i and Ro_i with fixed orientation and fixed beamwidth

for all $i \in \mathbf{T}$ **do**

set To_i and Ro_i according Eq. 21

end for

Phase 2: update To_i and Ro_i with adjustable orientation and fixed beamwidth

for all $i \in \mathbf{T}$ is a forward node with To_i **do**

if at least two continuous beams in To_i **then**

combine beams based on actual beam coverage

end if

end for

for all $i, j \in \mathbf{T}$ **do**

if i is a receiving node with Ro_i **then**

adjust the orientation of reception antenna Ro_i according Eq. 35

adjust the orientation of transmission antenna To_j according Eq. 34

else

adjust the orientation of transmission antenna To_i or To_j according Eq. 34

end if

end for

are the minimum and maximum value of α_{ij} for all $j \in \mathbf{V}(i)$ and $b_{ij}^l = 1$, respectively, i.e.,

$$b_{i,min}^l = \min_{j \in \mathbf{N}(i) \cup b_{ij}^l=1} \alpha_i^l,$$

and

$$b_{i,max}^l = \max_{j \in \mathbf{N}(i) \cup b_{ij}^l=1} \alpha_i^l.$$

Obviously, $b_{i,max}^l - b_{i,min}^l \leq \alpha$. α_i^l can be adjusted in the range

$$[\alpha_{i,min}^l, \alpha_{i,max}^l] = [b_{i,max}^l - \alpha/2, b_{i,min}^l + \alpha/2]. \quad (34)$$

Similarly, the orientation of reception antenna, α_j^k , can be adjusted in the range

$$[\beta_{j,min}^k, \beta_{j,max}^k] = [\alpha_{ji} - \beta/2, \alpha_{ji} + \beta/2]. \quad (35)$$

In the third phase, the beam orientation of transmission and reception are adjusted to reduce interference. After the second phase, a forward node may use multiple directional antennas to forward the multicast messages. The algorithm first checks whether such beams can be combined into a single or a smaller number of beams. It firsts calculates the actual beam coverage based on the receivers falling into each beam. If the combinational coverage from any two beams is no more than the beamwidth α , these two beams can be combined and the beam orientation is adjusted accordingly. After the combination, the algorithm updates the interference amongst all nodes in the multicast tree, including the forward nodes and leaf nodes or terminals. Note that a terminal may also act as a forward node. If there exists interference between a forward node and a leaf node, the orientation of the reception antenna will be first adjusted to direct far away from the orientation of the transmission antenna without interfering with other forward nodes. The orientation of the transmission antenna will be adjusted if the first attempt does not achieve the objective. If there exists interference between two forward nodes, the interference only occurs from one to another rather than from each other.

Theorem 7. *CMIM algorithm runs in $O(ND|E|)$.*

Proof. The complexity of CMIM is dominated by the *while* loop in the first phase. At each iteration, Dijkstra's algorithm takes $O(N \log N + |E|)$ time. Searching the minimum cost

terminal takes at most $O(D)$ times. Finding the shortest path can be done in $O(N)$ time based on the result of Dijkstra's algorithm. The inner *for* loop takes at most $O(N|E|)$ times. Thus the complexity of each iteration is dominated by the inner *for* loop. Since the *while* loop repeats at most D times, the entire algorithm runs in $O(ND|E|)$ time.

V.3 COMPUTATIONAL EXPERIMENTS

This Section evaluates the performance of the LP formulations and the heuristic algorithms. For comparison purposes, this Section also evaluates the performance of FOFB directional antennas, i.e., CMIM with executing to phase 2 (CMIM-P2), and of omnidirectional antenna (CMIM-O), i.e., CMIM with executing of phase 1. The experiments conduct a study of several parameters, i.e., the number of nodes in the network N , the number of destination nodes D , and the number of directional antennas per node K . In particular, the number of directional antennas determines the beamwidth based on the directional antennas model. Nodes are randomly deployed within a $1000 \times 1000m$ square area, and the transmission range is set to $200m$ for every node. One node is randomly selected as the source node, and a set of nodes is randomly selected as the destination nodes. The number of destination nodes, D , varies from 6 to 12 for different experiments. The number of nodes in the network, N , varies from 10 to 50.

The normalized interference metric, $I(\mathbf{T})/N$, is used to compare the performance. $I(\mathbf{T})/N$ is the ratio of the interference in multicast tree \mathbf{T} , $I(\mathbf{T})$, to the number of nodes in the network, N . The first experiment sets $K=12$, and compares the performance of LP and CMIM. Figure 25 shows the normalized interference while N varies from 10 to 50, and D varies from 5 to 25. Figure 26 shows the normalized interference while $K = 8$, N varies from 10 to 50, and I varies from 5 to 25. Figure 27 shows the normalized interference while $K = 6$, N varies from 10 to 50, and I varies from 5 to 25. As can be seen from Figs. 25, 26, and 27, LP provides the optimal, and the CMIM algorithm performs quite reasonably on average. Using directional antennas has great effect on reducing interference. Even fixed beamwidth directional antennas reduce interference significantly. Phase

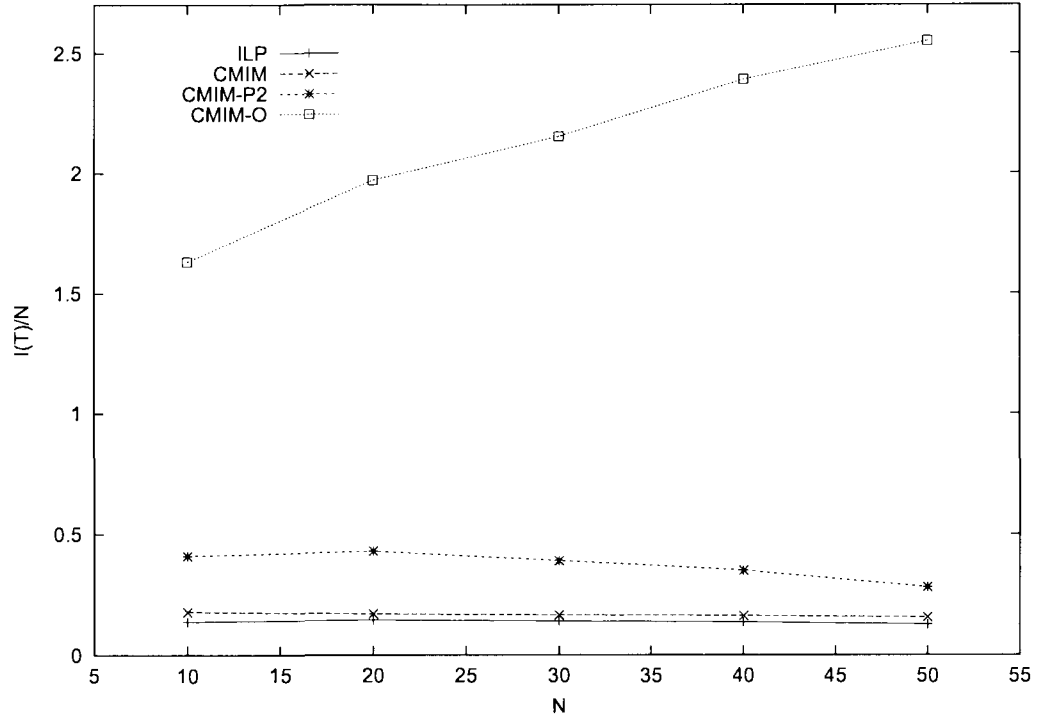


FIG. 25: Interference for multicast as a function of the number of nodes while $K=12$.

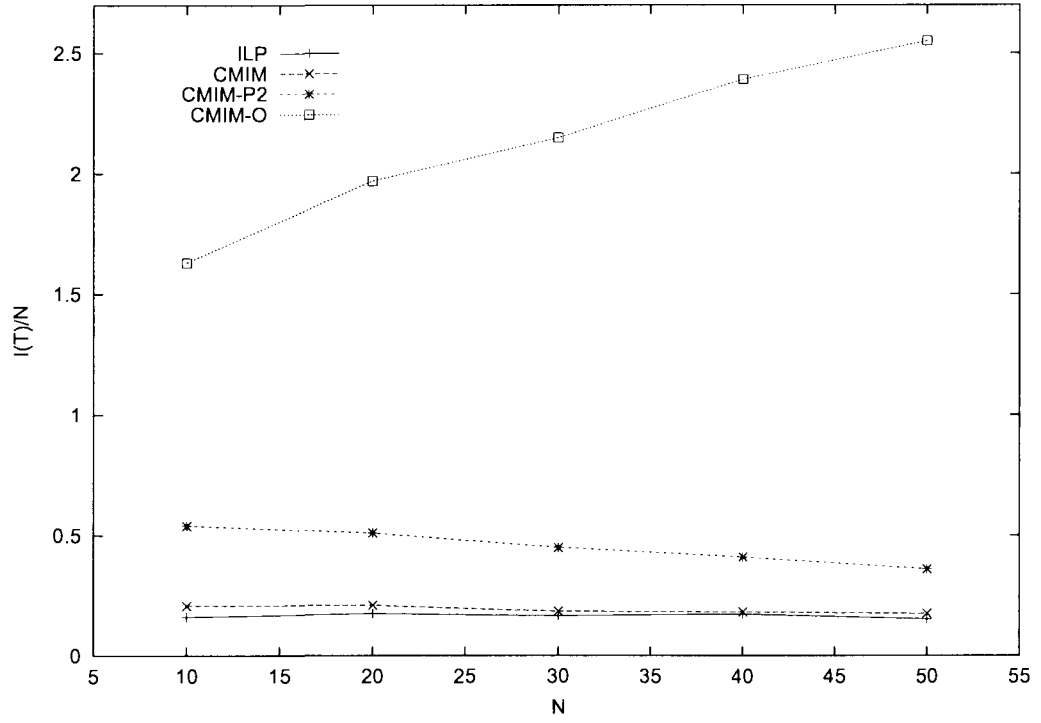


FIG. 26: Interference for multicast as a function of the number of nodes while $K=8$.

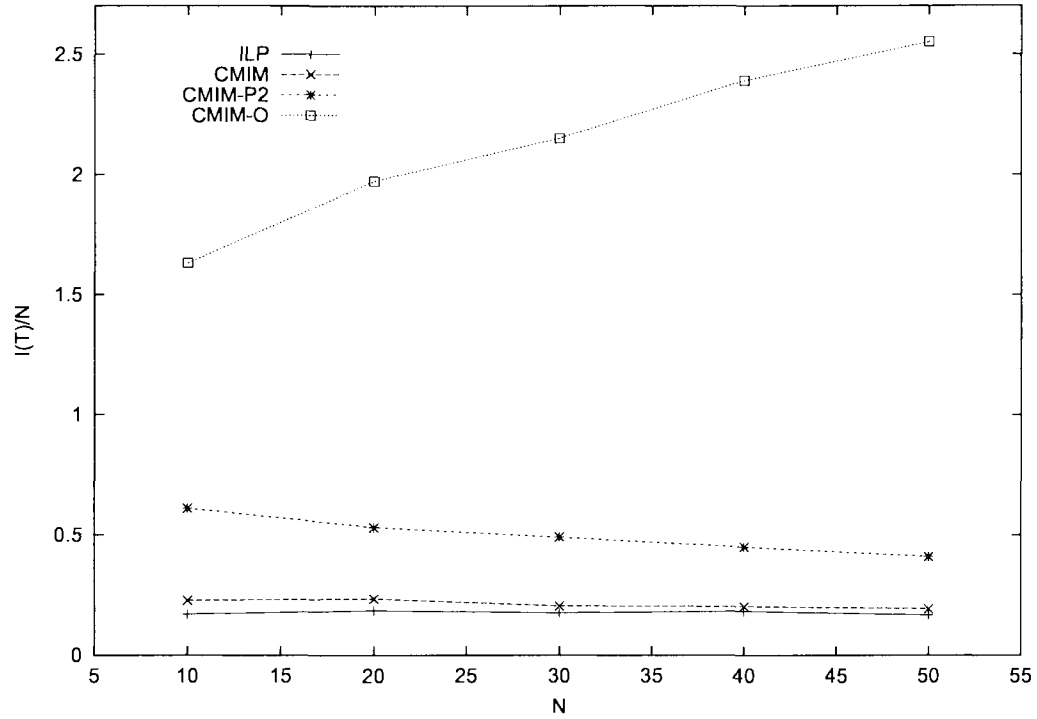


FIG. 27: Interference for multicast as a function of the number of nodes while $K=6$.

3 of CMIM further reduces the interference, and results in near-optimal performance. Directional antennas with adjustable orientation can significantly reduce the interference of multicast compared with fixed orientation and fixed beamwidth ones. Moreover, the more the number of directional antennas, the smaller the beamwidth, and the less the interference.

V.4 SUMMARY

This Chapter presented the interference optimization multicast problem in WMNs equipping with directional antennas. This Chapter defined the interference with directional transmissions that are suitable for designing multicast algorithms, and formulated the minimum interference multicast problem using a linear programming model. A heuristic algorithm has been proposed to solve the problem. The algorithm has $O(ND|E|)$ time complexity and message complexity. Multicast routing found by the interference-aware algorithm tends to have fewer channel collisions and higher network throughput.

CHAPTER VI

CONCLUDING REMARKS AND FUTURE RESEARCH

This Chapter summarizes main contributions and conclusions in Section VI.1 and presents possible future research directions in Section VI.2.

VI.1 CONCLUDING REMARKS

The contributions of this dissertation are listed below.

1. Constructed either the broadcast tree in broadcast protocols or the multicast routing in multicast protocols with only local metric information without the global network topological information to increase the scalability.
2. Developed a Distributed Interference-aware Broadcasting protocol to build a high-performance broadcasting tree while three performance metrics that include reliability, latency, and redundancy were concurrently considered, and four design principles were identified in guiding tree construction to combat inter-node and intra-node interference.
3. Defined link and channel quality metrics for broadcast and multicast to fully take into account interference.
4. Defined a comprehensive performance metric, called power, to quantify the performance of broadcast and multicast protocols. In addition to reliability, latency, and redundancy, achieved network throughput is also considered in power.
5. Proposed both linear programming formulation and algorithm design for the minimum cost broadcast problem in MRMC WMNs.
6. Proposed both linear programming formulation and algorithm design for the interference optimization multicast problem in WMNs using directional antennas.

The following conclusions are obtained through the research work presented in this dissertation.

1. New and practical link and channel metrics for broadcast and multicast are required for designing broadcast and multicast in MRMC WMNs.
2. Distributed Interference-aware Broadcasting protocol achieves 100% reliability, low broadcasting latency, less broadcasting redundancy, and high goodput.
3. The time and message complexity of the proposed distributed heuristic algorithms for the minimum cost broadcast problem are both $O(N^2)$.
4. From the computational experiments for the minimum cost broadcast problem, the number of radios has less impact on the cost than does the number of channels. All heuristic algorithms perform quite reasonably on average, and have a range from 9% to 13% away from the optimal provided by linear programming formulation. The distributed algorithms are comparable to the corresponding centralized algorithms.
5. A small number of radios is sufficient to significantly improve throughput of broadcast and multicast in WMNs.
6. The number of channels has more impact on almost all performance metrics, such as the throughput, the number of transmission, and interference, in WMNs.

VI.2 FUTURE RESEARCH DIRECTIONS

There are several ways to extend this research, which are briefly discussed below.

VI.2.1 Scheduling Scheme for Broadcast/Multicast

The scheduling problem for broadcast/multicast is another optimization problem. From the discussion of interference in DIB, it is noticed that a MAC-layer scheduler may be needed for collision free broadcasting. In the case without enough channel resources, if one node has to forward broadcast messages and it has only one available transmission channel which is the same as its receiving channel, its receiving and transmission must be scheduled at different time slots to avoid intra-node interference. If two adjacent forward

nodes are within the interference range of each other and choose the same transmission channel, their broadcasting must be scheduled to avoid inter-node interference.

VI.2.2 Other Techniques for Broadcast/Multicast Throughput Improvement

Many works have been done towards improving the network capacity of wireless networks under different modalities of communication and/or assumptions, such as with mobility [94, 95], using infinite wireless bandwidth [96, 97], using directional antennas [73, 86, 74], using network coding [98, 99, 100], etc. Much has been done for unicast communication among randomly selected node pairs. There is little effort in understanding how fast common information can be disseminated throughout the network via multihop relays.

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Journal Publications

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