Joint Routing and Resource Management for Multicasting Multiple Description Encoded Traffic in Wireless Mesh Networks

JOINT ROUTING AND RESOURCE MANAGEMENT FOR MULTICASTING MULTIPLE DESCRIPTION ENCODED TRAFFIC IN WIRELESS MESH NETWORKS

BY

ABDULELAH ALGANAS, M.A.Sc.

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AUTHOR: Abdulelah Alganas
M.A.Sc.

SUPERVISOR: Dr. Dongmei Zhao

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To my beloved grandmother Loloah May Allah bless her soul

Abstract

This thesis studies multicasting high bandwidth media traffic in wireless mesh networks (WMNs). Traditional multicast methods use a single multicast tree to reach all destinations, and adapt the multicast rate to the destination with the worst path quality. This approach does not fully utilize the network resources nor distinguish the quality of service (QoS) requirements of different users. It also penalizes the users having better path quality and requiring higher QoS. In multi-hop transmissions, the end-to-end transmission rate is limited by the link with the worst transmission conditions. This makes it difficult to multicast high-bandwidth media traffic with good quality. Using multiple description coding (MDC), the source traffic can be split into multiple sub-streams, referred to as descriptions, each of which requires a much lower bandwidth and can be transmitted along separate paths. In this thesis, we study routing and QoS provisioning jointly for multicasting multiple description (MD) encoded media traffic in WMNs. Routing for the multiple descriptions is jointly studied, while considering the channel quality of different links in the network and QoS at individual destinations. The work in this thesis is divided into two parts.

The first part (Chapters 3 and 4) considers balanced descriptions, each of which contributes equally to the quality of the recovered media at a destination, and we study the problem of power efficient multicasting for the MD-encoded media traffic

in WMNs. In Chapter 3, single-hop transmissions are considered. That is, the access points (APs) that store the source traffic communicate with the destination nodes directly. We study two problems jointly, description assignments and power allocations. The former is to assign a description for each AP to transmit, and the latter is to allocate the transmission power for the APs. Different power efficiency objectives are considered, subject to satisfying the QoS requirements of the destination nodes. For each objective, an optimization problem is formulated and heuristic solutions are proposed. Chapter 4 extends the work to multi-hop transmissions, where relay stations (RSs) are available to forward the traffic from the APs to the destinations. We consider two different routing structures based on whether an RS is allowed to forward more than one description. The objective is to minimize the total transmission power of the APs and the RSs in the network, subject to the QoS requirements of the destinations. An optimum problem is formulated and then translated to an integer and linear programming problem, and a centralized scheme with much lower complexity is proposed. Following that, a distributed scheme, referred to as minimum weight k-path scheme, is proposed, which builds one multicast tree for each description. By permitting only neighboring nodes to exchange related information, the scheme allows each node to find its best parent node based on the additional transmission power needed to establish the link.

The second part (Chapter 5) of the thesis considers unbalanced descriptions. Routing for the multiple descriptions is jointly considered with application layer performance, so that the maximum distortion of recovered media at the destinations is minimized. An optimization problem is first formulated, and a centralized scheme with lower complexity is proposed. The centralized scheme first finds a set of candidate paths for each destination based on a predefined set of criteria, then it iteratively expands the multicast trees by only merging the paths that minimize the maximum distortion for all destinations. A distributed scheme is also proposed by modifying the minimum weight k-path scheme. In the modified scheme, each RS makes a local decision to join different multicast trees based on the expected distortion among its connected downstream nodes. The proposed multicasting schemes require much lower implementation complexity, compared to the optimum solutions. The centralized scheme is more suitable for small size networks, and achieves close-to-optimum performance for a wide range of parameter settings. The distributed scheme only requires neighboring nodes to exchange information, and can be implemented to networks with a relatively large number of APs, RSs, and destination nodes.

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Abbreviations

AP	Access Point
BS	Base Station
D2D	Device-to-device
IoT	Internet-of-Things
MDC	Multiple Description Coding
MILP	Mixed Integer Linear Program
MS	Mobile Station
NB-IoT	NarrowBand-Internet-of-Things
NDMT	Node-disjoint Multicast Tree
QoS	Quality of Service
RS	Rely Station
SVC	Scalable Video Coding
TDMA	Time Division Multiple Access
WMN	Wireless Mesh Network

Contents

List of Figures

Chapter 1

Introduction

The demand for content-rich media communications (e.g., video) in wireless networks is rapidly increasing because of the growing number of wireless devices along with the raising popularity of media intensive applications [1]. Providing satisfactory end-to-end quality of service (QoS) for media applications while efficiently utilizing the wireless network resources has received considerable attention recently [2]. In this chapter, we discuss issues related to media multicast in wireless networks, explain the motivations, and summarize the main contributions of this thesis.

1.1 Multicast

Multicasting in wireless networks has been gaining increasingly more attention for providing group applications such as distance learning [3], intelligent transportation [4, 5], video streaming [6], etc. Multicasting to a group of users can be achieved by simply unicasting to individual users or reaching the group of users through a multicasting tree. Compared to the unicasting method, using the multicasting tree method may significantly save the amount of radio resources. On the other hand, conventional multicasting schemes that rely on single tree structure may not be sufficient to satisfy the QoS requirements of different users for media applications.

Firstly, media traffic tends to be bandwidth intensive while the single multicast tree structure is likely to be bandwidth constrained. The transmission throughput in a single multicast tree is limited by the path with the lowest end-to-end throughput [7], which is further determined by the bottleneck link along the path. Although techniques at different protocol layers are available for improving the data transmission rates in wireless networks, such as better transceiver designs, shorter transmission ranges, intelligent interference management and routing, etc., low data rates will continue to be common in order to keep low cost and save battery energy in mobile devices, which is especially important in some networks such as Narrow-Band Internet-of-Things (NB-IoT) networks.

Secondly, devices connected to wireless networks become significantly diversified, from low rate and low receiver bandwidth NB-IoT devices to high rate and high receiver bandwidth smart devices. As a result, a single multicast tree cannot easily accommodate different QoS requirements at the destination nodes. Most research works for multicast streaming traffic adapt the transmission rate to the destination having the worst path quality [7, 8]. This is at the expense of penalizing other users having higher path quality and requiring better QoS. Therefore, a multicast structure that can provide differentiated QoS to heterogeneous users is important for future wireless networks.

Thirdly, most existing multicast routing protocols mainly focus on network layer connectivity problems, and do not have explicit consideration for application layer requirements [9]. They focus on optimizing one or more network metrics such as number of hops, transmission power, or bandwidth utilization. However, these conventional routing metrics are application-agnostic and may not satisfy QoS requirements for media applications.

Future wireless mesh networks (WMNs) require a multicast structure that can provide differentiated QoS to heterogeneous users and efficiently utilize the wireless network resources.

1.1.1 Multiple Description Coding

The new trend in WMNs moves to dense deployments [10]. This provides the opportunity for establishing routing structures where each destination can be reached by one or multiple paths [9]. To take advantage of this network topology, the source traffic for most practical media applications can be split into multiple sub-streams, each of which is delivered to the destinations through separate paths. This approach will help in overcoming limited link capacities as each sub-stream has much lower bandwidth requirements compared to the source traffic, and multiple sub-streams can be combined at the destination nodes to yield higher overall throughput. It can be used to enable QoS differentiation among destinations, where each destination only subscribes to a number of sub-streams that fulfill its required QoS. Furthermore, this approach will also accommodate heterogeneous link qualities, as good quality links can be used to forward the sub-streams with relatively higher bandwidth requirements or even multiple sub-streams.

Different coding techniques can be used for splitting the source traffic into sub-streams, such as layered coding and multiple description coding (MDC) [11, 12]. In particular, MDC is a source-channel coding technique that is capable of encoding a media source into multiple independently decodable sub-streams (or descriptions). Each description can reconstruct the source media with a certain fidelity, and the quality of the recovered media depends on which and how many descriptions have been correctly received. This is done with the expectation that the destination will still be able to retrieve the source traffic from any subset of the descriptions, albeit with a penalty in media quality. The benefits and robustness of MDC come at a price of added redundancy among the descriptions. One of the most common applications for MDC is in video multicast, such as video-on-demand, distant learning, and group video conferencing [11, 12]. MDC does not require a base layer to reconstruct the media. This makes MDC different from traditional layered scalable coding, in which the reconstruction of the source media highly depends on receiving the most significant layer (e.g., base layer), and the decoding of the higher enhancement layer relies on correctly decoding all the lower enhancement layers alongside the base layer. Moreover, MDC is different from single stream coding where the overall perceived quality at the destination is highly affected and limited by the dynamics of a single path.

The aforementioned properties make MDC a capable candidate for enhancing media delivery in WMNs. However, how to route the multiple descriptions in order to take advantage of the benefits of MDC and multiple available paths in WMNs, satisfy different QoS requirements of the destinations, and efficiently utilize the wireless network resources can be a very complicated issue. The main reasons are i) although each description has a much lower rate than that of the original source, the aggregate rate of all the descriptions is higher than the original source traffic rate; and ii) the multiple multicast trees may share and compete for network resources, such as relay nodes, and their transmissions jointly affect the received media quality of multiple destinations.

1.2 Multicasting MD-encoded Traffic in WMNs

The multipath diversity in WMNs brings advantages for multicasting MD-encoded traffic. Delivering multiple descriptions along different paths provides robustness to stream failures compared to multicasting the source traffic directly. This is because the probability of multiple descriptions experiencing poor transmission conditions simultaneously is greatly decreased [13, 14, 15]. Moreover, MDC in conjunction with the multiple multicast trees allows the destinations to subscribe to a number of descriptions according to their own requirements and available bandwidth [15, 16]. This addresses the heterogeneity issue among destinations, where nodes requiring different QoS join multiple multicast trees based on their available bandwidth [17]. Furthermore, the achievable rate at the destination can be greatly increased by aggregating the rate of multiple descriptions received over separate paths [18]. It also relieves the source node from clustering the destinations into multiple groups and adapting the multicast transmission rate for individual groups. Instead, destinations can choose to sustain a certain data rate by only subscribing to a subset of the multiple descriptions. Therefore, MDC combined with a multiple-tree structure is a promising technique for media transmissions over WMNs. However, optimizing the construction of multiple multicast trees in terms of routing efficiency, resource allocations, and QoS provisioning is a challenging problem compared to constructing traditional single tree as it involves building multiple multicast trees and coordinating resource allocations among the different sessions.

1.2.1 Power Efficient Multicast Routing

The current works on multicasting MDC traffic in wireless networks mainly focus on building multiple multicast trees without considering transmission power of the nodes, where connectivity between nodes is assumed to be already established and support the descriptions rates [14, 15, 19, 20, 21]. Although these works show the advantage of combining MDC with multipath multicast to provide better error resilience, higher data rate, differentiated QoS, and load balancing in the network, further research is required for better utilizing the radio resources while building the multiple trees and transmitting the descriptions. Recent research efforts on power efficient multicasting in wireless networks are mainly for a single session [22, 23, 24], and the results cannot be applied directly to achieve power efficiency in building multiple multicast trees. This is because the multiple multicast trees can share relay nodes and this makes the power consumption of different multicast trees correlated.

1.2.2 Distortion-Aware Multicast Routing

Transmission errors in wireless channels result in packet losses, which degrade media quality at the destinations. By splitting the source traffic into multiple descriptions and transmitting them along different trees, MDC provides increased fault tolerance that helps mitigate this effect. However, the quality of recovered media at a destination is determined by the successfully received descriptions. Traditional routing methods for multicasting traffic target single sessions only and mainly focus on optimizing network layer metrics, such as throughput [25, 26] and reliability [27]. These approaches are not well suited for multi-session multicast, such as multicasting MD-encoded traffic, since path selections for different sessions have joint effects on the application layer performance.

1.3 Motivation and Contributions of the Thesis

The motivation of this thesis is to jointly study the multi-session routing and application-layer performance problem for multicasting MD-encoded media traffic in WMNs, and the objective is to efficiently utilize the available network resources while satisfying the application layer QoS requirements. Towards this objective, the proposed work is divided into three chapters and the main contributions are summarized as follows.

In Chapter 3, we study multicasting MD-encoded media traffic in WMNs, where the source traffic is available at a number of access points (APs), and each AP can reach the mobile stations (MSs) directly by adjusting the transmission power based on the link conditions. The source traffic is encoded into multiple equally important descriptions, and the QoS requirement at an MS is determined by the number of required descriptions. Each AP transmits one description, and forms a single-hop multicast group to reach a certain number of MSs. Different APs can transmit the same or different descriptions. We study two problems jointly, description assignments and power allocations. The former is to assign a description for each AP to transmit, and the latter is to allocate the transmission power for each AP. Two objectives are considered subject to satisfying the requirements of the MSs, one is to minimize the total transmission power of all the APs, and another is to minimize the maximum transmission power of the APs. An optimization problem for each objective is formulated and solved. For each objective, a centralized scheme and a distributed scheme are proposed, and their performance is compared with the optimum. The proposed heuristic schemes have lower complexity compared to the optimal solutions and achieve good performance.

In Chapter 4, we extend the system by considering that multi-hop transmissions are allowed for the APs to reach the MSs through one or multiple relay stations (RSs). We consider two different routing structures based on whether an RS is allowed to forward more than one description. The objective is to minimize the total transmission power of the APs and the RSs, while satisfying the QoS requirements of the MSs. A mixed integer linear program (MILP) is formulated for the joint routing and power allocation problem in order to build K multicast trees, and a centralized scheme with much lower complexity is proposed. Following that, a fully distributed scheme, referred to as minimum weight k-path scheme, is proposed, which builds one multicast tree for each description by only requiring one-hop neighbors to exchange information. Numerical results show that the proposed schemes achieve good performance compared to the optimum solution, and outperforms a spanning tree based scheme.

In Chapter 5, we study the problem of distortion-aware routing for multicasting MD-encoded media traffic in WMNs. For each link, there is a certain probability that it can correctly transmit a given description or combined multiple descriptions. The goal is to build multiple multicast trees, each of which is rooted from one AP and delivers one description to a group of MSs, so that the maximum distortion of recovered media at the MSs is minimized. An MILP is first formulated for the routing and multicast tree construction problem, and a centralized heuristic scheme with much lower complexity is then proposed. Following that, a distributed heuristic scheme is proposed by modifying the minimum weight k-path scheme that was introduced in Chapter 4. Numerical results demonstrate that the heuristic schemes can achieve good quality compared to the optimum solution, and outperform using a shortest-path based scheme for multicasting the multiple descriptions or multicasting the original source traffic directly.

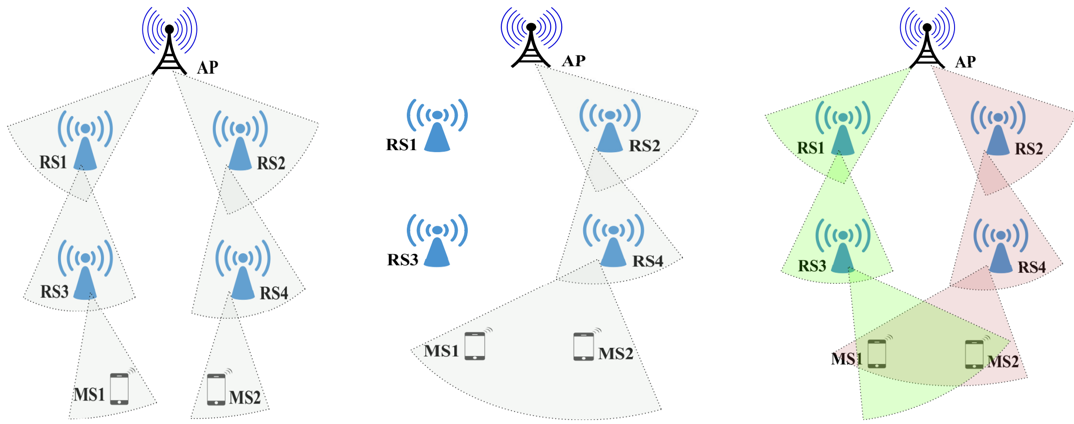
Chapter 2

Background and Related Work

This chapter starts with an overview of the related work on tree-based and mesh-based multicast routing, and summarizes the works on energy-efficient and power-efficient multicast routing. It then switches to provide an overview on works that combine MDC and routing, and finally briefly discusses cross-layer routing.

2.1 Tree-Based Multicast Routing

Multicast is an important transmission mechanism that provides communications to a group of destinations interested in the same content. Multicast can be achieved by simply unicasting to individual users (Fig 2.1a); however, utilizing multicast trees is more desirable since it may significantly save the amount of radio resources. Multicast routing structures can be divided into tree-based and mesh-based [9]. The tree-based multicast routing builds a forwarding tree from a single source node, which is the root of the tree, and terminates branches of the tree at the destination nodes (Fig 2.1b). In this type of approaches, there is only one path between the source node and any



(a) Unicasting to each destination (b) Single tree-based multicast (c) Mesh-based (multitree) multicast

Figure 2.1: Different multicast approaches

destination in the multicast tree. In the mesh-based multicast routing, more than one tree is used where each destination can be reached through multiple paths (Fig 2.1c). Compared with mesh-based routing, tree-based routing is more simple and efficient, and therefore utilized by most multicast methods for route generation [28, 29]. Below we discuss some issues related to the tree-based routing when multicasting media traffic.

2.1.1 Constrained Rate

The data rate in a single tree-based multicast is limited by the worst link in the tree [26], which is called the "crying baby" problem, where destinations with good path qualities may not be able to receive higher rates. Therefore, maximizing multicast throughput has been one of the main objectives in research on tree-based multicast. A higher multicast rate can be achieved through intelligent routing [25, 30] and relay station selection [31]. In [30], maximizing multicast throughput in multi-hop

WMNs is achieved by jointly optimizing routing and power control, where a network coding technique is used for multicast routing and a game theoretic method is used for power allocations. In [31], a maximal ratio combiner is studied to enhance signal-to-noise ratio (SNR) in two-hop cooperative multicast transmissions. Two relay selection schemes are proposed, and it is shown that allocating half of the total transmission power to the AP and the other half among relays minimizes the outage probability and increases QoS for media multicast. Multicast throughput can be improved by intelligently selecting frequency channels and allocating bandwidth resources to different links in multi-hop transmissions. In [32], two heuristic schemes for multicast channel assignment, Level Channel Assignment (LCA) and Multichannel Multicast (MCM), are proposed to improve multicast throughput in WMNs. A multicast tree is first built with a goal of minimizing the number of relay nodes to the destinations, then dedicated channels and partially overlapping channels are assigned to nodes to improve the network capacity. An alternative approach for increasing multicast throughput is through using network coding [33], which, however, may require special network topology (e.g., butterfly structure) and not be implemented in randomly distributed networks.

2.1.2 Limited Support for Heterogeneous QoS

The single tree-based multicast structure cannot easily take into consideration different QoS requirements at the destinations. Most research studies for multicast streaming employ rate adaptation schemes, where they pick the destination with the worst path as the leader of the multicast group and adapt to the rate that can reach this leader [7, 8]. Such rate adaptive schemes guarantee that all the destinations in the multicast group can receive some multicast contents; however, they penalize users with good paths and capable of receiving higher rates and requiring better QoS. Recently, there has been active research to enable QoS differentiated multicast in WMNs. Some studies suggest source (or AP) selection in WMNs to improve throughput and provide multi-rate multicasting [34, 35]. In these works, destination nodes are clustered into groups, correspondent multicast trees are constructed from different sources to associated groups, and then each source adapts the rate based on the destination with the worst path conditions in the group. This approach provides differentiated QoS for different groups, but destinations within a group are still served with the same rate. Moreover, its implementation relies on the existence of multiple source nodes in the network. Scheduling can be used to facilitate video multicasting with heterogeneous QoS over time division multiple access (TDMA)-based WMNs. In [36], a framework is proposed for effective video multicast that uses scalable video coding (SVC) to encode the traffic into a base layer and multiple enhancement layers. In the framework, relay nodes can obtain a minimum length schedule by dropping some layers while satisfying the requirements of the destinations. This approach adapts the transmission rate to individual tree branches instead of having the same transmission rate for all the tree branches; however, all the destinations reached by the same tree branch will be served with the same QoS that is determined by the data rate along the branch.

A wide range of research has been done to study multicasting in multi-channel multi-radio WMNs. How to assign channels to different radios and transmissions is one important problem in these systems. However, channel assignments in most of the works have been studied separately from multicast routing, such as in [32, 37, 38].

In [39], Multi-Gateway Multi-Rate (MGMR) multicast routing is proposed to deal with bandwidth heterogeneity of multicast receivers in WMNs with the goal of maximizing the total achieved data rates while preserving fairness among the receivers. The proposed algorithm first strategically associates each destination with a gateway, then assigns channels based on traffic loads of individual links, and finally allocates different transmission rates to links. The work in [40] proposes a parallel low-rate transmission media multicast scheme, in which every node is equipped with multiple channels and the parallel transmissions at the multiple channels together can deliver a full media flow to the destinations over extended areas with improved QoS. In these works, it is assumed that all nodes in the network are equipped with the same number of radios, and the performance of the system depends on the number of the radios at the transmitting nodes.

2.1.3 Prone to Link/Node Failures

The single tree-based multicast structure is prone to link or node failures, where some destinations may not be able to receive any data in case of a node/link failure. Since there is only one path between the source and a destination in single tree-based structures, if this path is disconnected, then the destination will need to reestablish an end-to-end path to receive any data. Several studies have been conducted to improve the reliability of tree-based multicasting. In [25], a new multicast routing metric, referred to as expected multicast transmission count (EMTX), is proposed, which represents the combined effect of MAC-layer re-transmissions, wireless broadcast advantage, and link quality for each single-hop transmission. A single multicast tree is built with the objective of minimizing the sum of EMTXs over all forwarding nodes in the multicast tree. This approach shows the effectiveness of using EMTX-based approach to reduce the number of hop-by-hop re-transmissions and increase the reliability and successful delivery compared to the shortest path tree (SPT) approaches. The multicast routing protocol proposed in [41] considers the link stability caused by the limited link duration, and constructs the multicast tree as a Steiner tree that maximizes the minimum path duration in the tree. The resulted multicast tree provides higher stability compared to other multicast routing protocols in terms of packet delivery ratio, multicast route lifetime, and control message overhead.

2.2 Mesh-based Multicasting

Multipath routing techniques have been extensively used in unicast scenarios to improve bandwidth utilization [42], increase end-to-end throughput [43], reduce end-to-end delay [44, 45], provide fault-tolerance [46], and balance traffic load among the network nodes [45, 47]. Utilizing multiple paths to reach each destination in multicasting will result in a mesh-based routing structure [9], which can potentially improve the robustness to node or link failures, compared to a single tree-based routing. Moreover, a mesh-based routing structure allows QoS differentiation among the destinations as traffic can be sent over multiple multicast trees, and each destination can choose to join the multicast trees based on its QoS requirements. Routing multicast traffic through multiple multicast trees also makes it possible to serve high-bandwidth traffic by splitting the source traffic into multiple lower-bandwidth sessions, which helps balance the traffic loads among different links and relay nodes in the network. However, mesh-based multicast routing structures are more complicated to build and maintain and require more overhead compared to tree-based multicast routing structures [9, 19]. The multiple multicast trees may share or compete for the relay nodes or transmission links. In node-disjoint multicast, the multicast trees do not share any relay nodes; while in link-disjoint multicast, the multicast trees may share relay nodes but do not share any common transmission links. Node-disjoint multicast trees show higher degree of independence among the multicast trees compared to link-disjoint multicast trees [48].

In recent years, mesh-based multicast routing strategies have emerged to fulfill QoS requirements and overcome network constraints in various wireless networks. In [49], a route discovery scheme is designed to find suitable paths for the multiple multicast trees, then a bandwidth reservation scheme is proposed to allocate time slots for each forwarding node and coordinate transmissions among the multicast trees. Their results show that using multipath multicast trees can meet the bandwidth and QoS requirements of different destinations while reducing network blocking caused by insufficient bandwidth. The work in [50] proposes a multipath multicast reliable neighbor selection (MMRNS) scheme, which selects neighboring nodes that satisfy a certain reliability threshold to establish the multicast trees. The multipath multicast trees are then assigned priority levels to carry various priority data to the destinations. Their results show that utilizing the multiple multicast trees increases the success delivery ratio and reduces data transmission delay. In [51], a distributed multicast tree generation scheme is designed to minimize minimizes the number of hops between source and destinations pairs. For each node in the multicast tree, an alternative path is maintained to provide higher robustness by enabling fast recovery in case of a link failure. In [20], multiple multicast trees are constructed, each of which satisfies a fraction of required bandwidth, and network coding is utilized across the multicast trees in order to reduce the total bandwidth consumption.

Building multiple multicast trees is an effective way to fulfill the high demanding multimedia applications. In [52], a distributed scalable video coding (SVC) multicast algorithm is proposed, which finds multiple backup paths to each destination, and reserves partial bandwidth along each backup path. The resulted multicast topology enhances the robustness of the multicast to link failures in the primary paths. The work in [21] constructs K-maximally node-disjoint multicast trees and employs multiple description coding to provide robustness to video multicast. The scheme shows good protection against link failures and packet losses.

Although results above have shown that utilizing multiple multicast trees can greatly increase the multicast throughput, success delivery ratio, and robustness to link/node failures, most of these works assume that connectivity and links between nodes in the network are already established, and focus on finding multipath multicast trees without considering power efficiency at forwarding nodes or QoS at the application layer.

2.3 Power/Energy Efficient Multicast

With the growing interest in green networking and the use of renewable energy sources, saving transmission power and energy while providing reliable communications has become an important issue in wireless networks. One method toward energy efficient networking is to put network nodes into low-power or sleep mode as much as possible [53, 54]. Energy efficient multicast can also be achieved through intelligently scheduling the transmissions of different nodes [55, 56], for example, by maximizing the number of simultaneously transmitting users or minimizing total time needed to complete all transmissions. Other techniques, such as network coding [57, 58, 59] and cooperative relaying [60, 61], can also be used to improve energy or power efficiency in multicast, where network coding helps reduce the transmission energy by combining multiple data packets into one transmission and reducing the total number of transmissions, and cooperative relaying takes advantage of both the direct and relayed transmissions to achieve the same QoS at the destinations with reduced energy consumption.

Jointly considering multicast routing and transmission power has received a considerable amount of interest in the literature. The work in [62] proposes a scheme that jointly considers power allocations and routing in wireless ad-hoc networks with lossy links, so that reliable unicast and single session tree-based multicast can be achieved with minimum expected total energy consumption. Multicast routing is proposed in [22], where a genetic algorithm is developed to reduce the total energy consumption of the multicast tree subject to the end-to-end delay constraints. A centralized method is proposed in [23] that integrates multicast routing and transmission power control to satisfy the bandwidth demands of the destination nodes. MILP is formulated and then solved using Lagrangian relaxation. The work in [63] proposes a multicast algorithm that maximizes energy efficiency of the network by first utilizing network coding to maximize the throughput and minimize nodes communication times, then using a sleeping scheme to lower the power consumption of individual nodes in the multicast tree.

The aforementioned works all address single tree-based multicast structures, where only one path exists between the source and each destination. Building multiple multicast trees can be much more complicated than building a single multicast tree, since the relay node selection in one multicast tree will affect the choice that other multicast trees can make, all of which together jointly affect the QoS performance at the destinations and the resource utilization efficiency of the entire network. For example, for multicast trees that do not share common relay nodes, inclusion of a relay node in one multicast tree limits the choice of relay nodes of other multicast trees; and for multicast trees that are allowed to share relay nodes, transmission power of the shared relay nodes affects transmission quality of all these multicast trees. In this thesis, we study the problem of building multiple multicast trees jointly with transmission power allocations and application layer performance. This problem is NP-hard since the underlying problem of packing Steiner trees is NP-hard [64].

2.4 Multicasting Multiple Description Traffic

Multiple description coding (MDC) has emerged as an effective error resilience method to improve the quality of media streaming over error-prone networks [11, 12, 65]. MDC is a source-channel coding technique that encodes the source traffic into multiple independently decodable streams (or descriptions), which are then transmitted separately over the network. This is done with the expectation that the source can be approximated from any subset of the descriptions, and the quality improves with the number of correctly received descriptions. The descriptions are correlated with each other so that missing data can be estimated by the available data from the received descriptions. Therefore, unlike other layered coding methods, such as scalable video coding, MDC does not require a base layer to reconstruct the media. Fig. 2.2 demonstrates the basic framework for a multiple description encoder/decoder involving two descriptions. It shows the case where MD coder encodes the original source into two descriptions S1 and S2 with bit rates R1 and R2, respectively [66]. The two descriptions S1 and S2 are sent over different channels or links. At the receiver side, if only description S1 (or S2) is received, then decoder 1 (or decoder 2) is used which results in distortion rate D1 (or D2); however, if both descriptions S1 and S2 are received, then decoder 0 is used which yields higher quality than that of decoder 1 or 2.

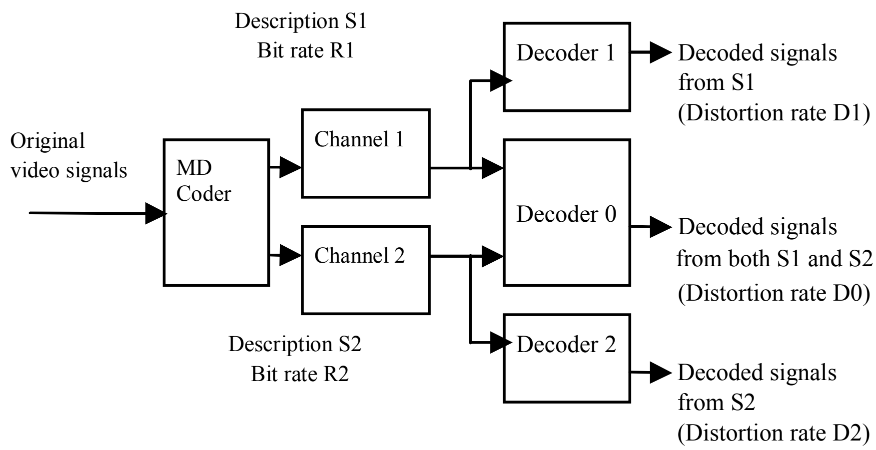


Figure 2.2: MD Coder for two descriptions

Different MDC schemes have been proposed to generate descriptions [11, 12]. In general, these schemes can be divided into four domains: spatial [67], temporal [68], frequency [69], and compressed [70]. The work in [11] provides a good review and comparison for different MDC schemes.

MDC provides several advantages for multimedia streaming in wireless networks over other approaches:

- highly satiable for best-effort video streaming where re-transmission is not desirable. For MDC, correctly decoding one of the descriptions is enough to approximate the source with acceptable quality, while the probability of loosing multiple descriptions simultaneously is less likely [13, 71].

- supports heterogeneous receivers requiring different QoS. MDC in conjunction with multiple-tree structure allows the receivers to subscribe to the number of descriptions according to the characteristics of their requirements and available bandwidth [72].

- balances traffic loads among links/nodes in the network by splitting the original source into multiple descriptions with lower bandwidth requirements and sending them over different paths [21].

- suitable for transmitters with limited transmission power because of the lower rates of individual descriptions compared to the original source [73].

- provides robustness to stream failure when transmitting multiple descriptions along different paths since the probability of multiple paths experiencing poor transmission conditions simultaneously is greatly decreased.

- allows wireless networks to transmit high-bandwidth media traffic by aggregating the bandwidth of the multiple paths that transmit different descriptions at the destinations [18].

The works in [13, 18, 74] utilize multipath routing to deliver MD-encoded traffic for unicast. In [13] multipath routing is jointly designed with packet scheduling in order to reduce packet transmission delay and balance network traffic load in WMNs. In [18], information of routing MD-encoded traffic through multiple paths is used to estimate packet loss probabilities and reduce error propagation caused by path loss. Similar objective is achieved in [74], where MD-encoded traffic routed through multiple paths is opportunistically merged at intermediate nodes to combat error propagation and improve image/video quality. The works in [14, 15, 16, 17] study multicast traffic that is encoded using MDC. An OFDMA network is considered in [17], where subcarrier assignments and power allocations are jointly studied to maximize system level energy efficiency. In [14], the results show that utilizing MDC video multicast can effectively deal with frequent link failures and diverse link qualities. The work in [15] is to build multiple multicast trees, disjoint or nearly disjoint, simultaneously to improve video quality. The multiple disjoint multicast trees are built sequentially for video multicast in [16], which shows increased receiving rate at the destinations.

2.5 Cross-layer Video Multicasting

In traditional communication networks, an end-to-end connection is established through the layered protocol stack [75]. This stack imposes strict boundaries between layers by only permitting adjacent layers to exchange information. This abstracts the internal details of each layer in order to simplify usage and deployment [76]; however, it limits the performance of the system since it prevents some necessary information sharing between non-adjacent layers. For example, knowing the current physical channel conditions will help the application layer to adapt the media rate in order to optimize the end-to-end QoS. Cross-layer designs aim to enable information exchanges and interactions between multiple layers [76, 77]. This allows different layers to coordinate with each other and jointly optimize the network performance. In recent years, cross-layer design approaches have been increasingly utilized to satisfy QoS requirements for media multicast applications over wireless networks, such as [78, 79, 80, 81, 82]. Most of the works are concerned with scalable video coding, and may not be applicable to MD-encoded traffic. In this thesis, we will study multicast routing for MD-encoded traffic in WMNs by jointly considering physical link conditions and application layer performance.

Chapter 3

Power Efficient Multicasting for Multiple Description Traffic in Single-Hop WMNs

In this chapter, we study the problem of power efficient multicasting of MD-encoded traffic in single-hop WMNs, where a number of access points (APs) transmit directly to the mobile stations (MSs). Different from existing works on multicasting MDC traffic, we consider that each MS has its own quality requirements, and emphasize on efficient transmission power allocations of the APs in order to satisfy the requirements of the MSs. Each AP can transmit at most one description and form a single-hop multicast group. The number of MSs that an AP can reach depends on its transmission power and the link gains to individual MSs. We study the problem of joint description assignments and power allocations for the APs. Two objectives are considered: 1) minimizing the total transmission power of the APs; and 2) minimizing the maximum transmission power of the APs. For each objective, a centralized and a distributed scheme are proposed, and their performance is compared with the optimum. The goal of minimizing the total transmission power is to efficiently utilize the overall resources in the network, while the goal of minimizing the maximum transmission power of the APs is to balance the transmission power and load among the APs.

The remainder of this chapter is organized as follows. In Section 3.1, the system model is described, followed by an optimization problem that is formulated for the description assignments and power allocations, where the objective can be minimizing the total power in the network or the maximum transmission power of the APs. In Section 3.2 a centralized scheme is proposed for each objective, and in Section 3.3 a distributed scheme is proposed for each objective. Numerical results are shown in Section 3.4 to demonstrate the performance of the proposed schemes. Finally, the main results are summarized and concluding remarks are given in Section 3.5.

3.1 System Description and Problem Formulation

We consider a wireless network that consists of a number of APs and MSs. In a lot of content delivery systems the contents are pre-cached at individual APs [83, 84, 85], and only the last hop should be scheduled whenever requests are received from the MSs, and this is the scenario considered in this chapter. We focus on the downlink transmissions for multicasting traffic from the APs to the MSs. Traffic originates from the APs and is encoded into multiple equally important descriptions. The QoS of the received media at an MS is directly related to only the number of distinctly received descriptions but not which descriptions. MSs requiring better signal quality should receive more descriptions. The exact relationship between the desired QoS (for example, distortion of the reconstructed media) at the destination and the number of required descriptions is dependent on specific implementations of the multiple descriptions coding [11, 86, 87, 88, 89], and is beyond the scope of this thesis. When the multiple descriptions are not equally important (unbalanced descriptions), the QoS requirement (e.g., distortion) of an MS cannot be simply mapped to the number of received descriptions, and most likely, there are specific descriptions that an MS should receive in order to satisfy its QoS requirement. In this case, less freedom is available to deliver the descriptions to the MSs, and the problem is less complicated. In addition, the formulation below is applied to networks that are used to deliver other types of contents, where each description here is replaced with one content type, and each MS may require one or multiple of the contents.

We consider that all the APs have access to all the descriptions, but each can only transmit one description. Extending the work to a more general case that allows each AP to transmit multiple descriptions is straightforward, in which case an AP that is allowed to transmit a descriptions is equivalent to a APs located in the same place and each allowed to transmit one description only. We assume that medium access control is in place and coordinates the transmission time and frequency of the APs, so that transmissions of different APs are orthogonal either in time or frequency without co-channel interference. For example, Time Division Multiple Access (TDMA) like access mechanisms can be employed to schedule APs transmissions, where an MS can only receive from one AP at any given time slot [90]. The transmitted media is not real-time, so that MSs requiring more than one description can buffer the received descriptions and decode the signal after the required number of descriptions have been correctly received. Reference [66] provides different implementations for combining the multiple received descriptions at the receiver.

Table 3.1: Notations used in Section3.1

Symbol	Definition
P_i	Transmission power of AP i
$P_{i,m}$	Minimum required transmission power for AP i to reach MS m
$X_{k,i}$	1 if AP i transmits description k, and 0 otherwise
$Y_{k,i,m}$	1 if MS m can correctly receive description k from AP i, and 0 otherwise
$Z_{k,m}$	1 if MS m can correctly receive at least one copy of description k, and 0 otherwise
k^*_m	Minimum number of descriptions that MS m requires

Table 3.1 lists some of the notations used in this section. We use $i = 1, 2, \ldots, I$ to index the APs, $m = 1, 2, \ldots, M$ to index the MSs, and $k = 1, 2, \ldots, K$ to index the descriptions, where I, M, and K, respectively, are the total number of APs, MSs, and descriptions. We consider single-hop transmissions from the APs to the MSs, and emphasize on the description assignments and transmission power allocations for the APs. Each AP forms a multicast group, and its transmission power determines the receivers in the group. Each MS can be in multiple such multicast groups, depending on the number of descriptions it requires. Furthermore, each description can be assigned to multiple APs, i.e., delivered in multiple multicast groups. Let P_i represent the transmission power of the ith AP. Our objective is to minimize a function of the transmission power of the APs. Below we consider two objective functions, $\min \sum_{i=1}^{I} P_i$ for minimizing total transmission power of all APs, and $\min \max_{i=1}^{I} P_i$ for minimizing the maximum transmission power of the APs. The two objectives are referred to as "min-total" and "min-max", respectively, for a concise presentation in the rest of the chapter.

Define a set of binary variables $X_{k,i}$'s with $X_{k,i} = 1$ if and only if AP i transmits the kth description, and another set of binary variables $Y_{k,i,m}$'s with $Y_{k,i,m} = 1$ if and only if MS m can correctly receive description k from AP i. We then have

$$\sum_{k=1}^{K} X_{k,i} \leq 1, \ \forall \ i = 1 : I \tag{3.1}$$

$$Y_{k,i,m} \leq X_{k,i}, \ \forall i = 1 : I, \ k = 1 : K, \text{ and } m = 1 : M. \tag{3.2}$$

In addition, the transmission power of the AP should be sufficiently high in order to ensure that the transmitted description can reach the MS. That is,

$$\text{if } Y_{k,i,m} = 1, \quad \text{then} \quad P_i \geq P_{i,m} X_{k,i}, \ \forall i = 1 : I, \ k = 1 : K, \text{ and } m = 1 : M \tag{3.3}$$

where $P_{i,m}$ is the minimum required transmission power for AP i to reach MS m, and its value depends on the link gain between AP i and MS m and the specific physical layer implementation such as modulation and channel coding schemes. Throughout this chapter, Shannon's formula is used to find the minimum required transmission power $P_{i,m}$ for AP i to reach MS m. However, the problem formulation and the design of the heuristic schemes are independent from the underlying physical layer implementation as different modulation and channel coding schemes will only affect the absolute value of the minimum required transmission power.

The constraint in (3.3) is not linear, but can be replaced with the following linear constraint

$$P_{i,m} X_{k,i} - C_1 (1 - Y_{k,i,m}) \leq P_i < P_{i,m} X_{k,i} + C_1 Y_{k,i,m}, \ \forall i = 1 : I, \ k = 1 : K, \text{ and } m = 1 : M \tag{3.4}$$

where C_1 can be any number larger than the maximum transmission power of the APs. Note that when $Y_{k,i,m} = 1$, then $X_{k,i} = 1$ because of (3.2).

Define a set of binary variables $Z_{k,m}$'s, so that $Z_{k,m} = 1$ if and only if MS m can correctly receive at least one copy of description k. Based on this definition, we have

$$Z_{k,m} \leq \sum_{i=1}^{I} Y_{k,i,m},\ \forall\ k = 1 : K \text{ and } m = 1 : M. \tag{3.5}$$

In order to have $Z_{k,m} = 1$, MS m should receive description k from at least one AP, the equivalent linear constraints is similar to (3.4). That is,

$$1 - C_2(1 - Z_{k,m}) \leq \sum_{i=1}^{I} Y_{k,i,m} < 1 + C_2 Z_{k,m},\ \forall\ k = 1 : K \text{ and } m = 1 : M, \tag{3.6}$$

where C_2 can be any number larger than 1. The total number of descriptions received at MS m satisfies

$$\sum_{k=1}^{K} Z_{k,m} \geq k_m^*,\ \forall\ m = 1 : M, \tag{3.7}$$

where k_m^* is the minimum number of descriptions that MS m requires. Define $\mathbf{X} = [X_{k,i},\ \forall k, i]$, $\mathbf{Y} = [Y_{k,i,m},\ \forall i, k, m]$, $\mathbf{Z} = [Z_{k,m},\ \forall k, m]$, and $\mathbf{P} = [P_i,\ \forall i]$. Based on the above description, an optimization problem can be formulated as follows

$$\min_{\{\mathbf{X},\mathbf{Y},\mathbf{Z},\mathbf{P}\}} \max_{i=1}^{I} P_i \text{ or } \min \sum_{i=1}^{I} P_i \tag{3.8}$$

$$\text{s.t.} \quad (3.1), (3.2), (3.4), (3.5), (3.6), \text{and } (3.7) \tag{3.9}$$

$$P_i \geq 0,\ X_{k,i}, Y_{k,i,m}, Z_{k,m} \in \{0, 1\},\ \forall i, k, m. \tag{3.10}$$

This is a mixed linear integer optimization problem, which in general is NP-hard problem, and can be solved using commercially available software, such as CPLEX.

For solving this MILP, CPLEX uses branch-and-cut algorithm and simplex method to perform dynamic search over relaxed linear subproblems until the best known solution that satisfies all the integrality requirements is found [91]. Thus, the complexity of the problem grows with the number of variables, where it also has exponential worst case running time. Moreover, it cannot be used in distributed implementation since it requires full knowledge of the network. In the next two sections we propose heuristic methods, which can greatly reduce the complexity of the solutions. In Section 3.2 centralized schemes are proposed, and in Section 3.3 distributed schemes are proposed.

3.2 Centralized Heuristic Schemes

The following notations are used consistently in the proposed schemes in Sections 3.2 and 3.3: $\mathcal{K}_m$ is a set of the descriptions that MS m has received, and initialized to be empty for all m; $z_m = k^*_m - |\mathcal{K}_m|$ is the additional number of descriptions that MS m is expecting to receive; $\mathcal{M}$ is a set of the MSs that have not been fully served (i.e., MSs with $z_m > 0$), and initialized to include all MSs; S_i is the assigned description to AP i, and initialized to zero, which means that no description is assigned to the AP; P_i is the transmission power of AP i, and initialized to zero; and $\mathcal{R}$ is a set of the APs that have not been assigned any descriptions, and initialized to include all the APs. Other notations will be defined when describing individual schemes.

Before describing details of the centralized schemes, we first give some implementation details that are common for both objectives. Each MS measures the link conditions to neighboring APs. This can be done in different ways. For example, the APs can transmit beacon signals at fixed power known to all the MSs. The MSs measure the link conditions based on the received signal strength, and report the link gain information to the APs. When channels are relatively stable, frequently measuring the link gains is not necessary, in which case the overhead for the AP to collect the link gain information is small, and its effect on the data transmissions can be neglected. A centralized scheme is possible if a centralized node is available at the backbone to further collect the link gain information from the APs. In the remaining part of this section, we first present the proposed centralized scheme for the "min-max" objective, and then the centralized scheme for the "min-total" objective.

3.2.1 Minimizing Maximum Transmission Power of APs

In this scheme, we assume that the central node has the information about the network topology. This should be reasonable when the APs and MSs are relatively fixed in their locations. We first represent the network using a graph $G = (V, E)$, where each vertex $v \in V$ is either an MS or an AP, and an edge $(i, m) \in E$ is the link that connects AP i to MS m and has a cost $P_{i,m}$.

When I and M are large, the graph is big and complex to deal with. On the other hand, the number of descriptions required by an MS may be relatively small, which is normally the case since K is usually limited to a small number (MDC with 2 and 3 descriptions is well studied in the literature with practical designs [11]). Therefore, there is no need to always consider the complete graph. When constructing a reduced graph, we first guarantee that each MS is connected to k_m^* APs that have the best link gains to it. That is, there is an edge between MS m and each of the best k_m^* APs. If all these k_m^* APs are assigned to different descriptions and transmit the minimum power to reach MS m, then the QoS requirement of the MS is satisfied, and the max-min objective is achieved for serving this MS. This may not be possible, however, because the APs are shared resources and some may have to serve multiple MSs. Meanwhile, MS m in the reduced graph may be connected to more than k_m^* APs because some APs have to transmit high power in order to reach other MSs even they are not among the k_m^* best APs for MS m.

Algorithm 1 Centralized scheme, minimizing maximum power of APs: part I

Initialize $\mathcal{R} = \{1, 2, \ldots, I\}$, $\mathcal{M} = \{1, 2, \ldots, M\}$, $\mathcal{K}_m = \emptyset$ for all $m = 1, 2, \ldots, M$, and $P_i = 0$ and $S_i = 0$ for all $i = 1, 2, \ldots, I$.
while $\mathcal{R} \neq \emptyset$ and $\mathcal{M} \neq \emptyset$ **do**
  Form sets $\mathcal{M}_d$'s for $d = 1, 2, \ldots, I$ so that $\mathcal{M}_d = \{m : D_m^{\mathrm{MS}} - z_m \triangleq d_m = d\}$.
  $d = 0$ and $E = 0$
  while $d \leq I$ and $E = 0$ **do**
    if $\mathcal{M}_d$ is not empty **then**
      Define $\overline{k}_m = K - |\mathcal{K}_m|$, and find $\overline{k}_{\min} = \min_{m \in \mathcal{M}_d} \overline{k}_m$
      Define $\mathcal{M}_{d,k} = \{m | m \in \mathcal{M}_d \text{ and } \overline{k}_m = \overline{k}_{\min}\}$, and find $(m^*, i^*) = \arg\max_{m \in \mathcal{M}_{d,k}, i \in \mathcal{R}} P_{i,m}$
      Pick up any $k \in [1, K]$ and $k \notin \mathcal{K}_{m^*}$, let $S_{i^*} = k$, $P_{i^*} = P_{i^*,m^*}$, and $\mathcal{R} = \mathcal{R} \setminus \{i^*\}$
      for MS m connected to AP i^* **do**
        if $k \notin \mathcal{K}_m$ and $P_{i^*,m^*} \geq P_{i^*,m}$ **then**
          Update $\mathcal{K}_m = \mathcal{K}_m \cup \{k\}$ and $D_m^{\mathrm{MS}} = D_m^{\mathrm{MS}} - 1$.
          if $\mathcal{K}_m = k_m^*$ **then**
            $\mathcal{M} = \mathcal{M} \setminus \{m\}$
          end if
        end if
      end for
      Update $\mathcal{M}_d$'s based on current z_m and D_m^{MS} for $m \in \mathcal{M}$, and $E = 1$
    else
      $d = d + 1$
    end if
  end while
end while

Given the reduced graph, Algorithm 1 is used to find the assigned descriptions and transmission power for the APs. Two metrics are important for designing this algorithm, z_m and D_m^{MS}. The latter is the total number of APs that are connected to

MS m and have not been assigned a description. Define $D_m^{\text{MS}} - z_m = d_m$, and the value of d_m indicates the flexibility for serving MS m. Smaller d_m means less flexibility. For example, when $d_m = 0$, all the D_m^{MS} APs should transmit different descriptions with sufficient power to reach MS m. For this reason, a set $\mathcal{M}_d$ is formed to include all MSs with $d_m = d$ (Line 3), and MSs in $\mathcal{M}_d$ with $d = 0$ are served first (Line 4). The process switches to larger d if there are no MSs with smaller d (Line 20). Define $\overline{k}_m = K - |\mathcal{K}_m|$ for each MS in $\mathcal{M}_d$, and the MSs with smaller $\overline{k}_m$ have less flexibility regarding which descriptions they expect to receive next. For example, for an MS with $\overline{k}_m = 1$, there is only one specific description that is currently not in $\mathcal{K}_m$ and can satisfy the MS's request. The minimum $\overline{k}_m$ is defined as $\overline{k}_{\min}$ (Line 7). There may be multiple MSs having the same minimum $\overline{k}_m$ in $\mathcal{M}_d$. Among these MSs, we select the MS m^*, which is the MS that requires the highest transmission power from any AP, and the AP that corresponds to this highest power is denoted as i^* (Line 8). After this, one description that has not been received by MS m^* is assigned to AP i^*, the transmission power of the AP is set to reach MS m^*, and then AP i^* is removed from $\mathcal{R}$ (Line 9). With this assignment, other MSs connected to AP i^* may also be served, and their information is updated (Lines 10-17). Any MSs that have received the required number of descriptions are removed from $\mathcal{M}$ (Line 18). The whole process is repeated based on the updated $\mathcal{R}$ and $\mathcal{M}$ until either of the sets is empty. A binary indicator E with initial value 0 is defined (Line 4) and set to 1 after an AP is assigned a description and $\mathcal{M}_d$'s are updated (Line 18), so that the assignment process can restart from $d = 0$ based on the updated $\mathcal{M}_d$'s (Line 2).

In most practical applications, M and I can be much larger than K, and the size of the reduced graph can be much smaller than the original graph. There is

Algorithm 2 Centralized scheme, minimizing maximum power of APs: part II

for $m \in \mathcal{M}$ **do**
  Initialize $k_0 = 1$.
  while $|\mathcal{K}_m| < k_m^*$ **do**
    Select AP i, which is the $(k_m^* + k_0)$th best AP based on link gains to MS m
    if $i \in \mathcal{R}$ **then**
      Pick up any $k \in [1, K]$ and $k \notin \mathcal{K}_m$, let $S_i = k$, and set $P_i = P_{i,m}$; then update $\mathcal{K}_m = \mathcal{K}_m \cup \{k\}$.
      if $\mathcal{K}_m = k_m^*$ **then**
        $\mathcal{M} = \mathcal{M} \setminus \{m\}$
      end if
    else if $S_i \notin \mathcal{K}_m$ **then**
      Set $P_i = P_{i,m}$, and update $\mathcal{K}_m = \mathcal{K}_m \cup \{k\}$.
      if $\mathcal{K}_m = k_m^*$ **then**
        $\mathcal{M} = \mathcal{M} \setminus \{m\}$
      end if
    else if $S_i \in \mathcal{K}_m$ **then**
      Let $k_0 = k_0 + 1$
    end if
  end while
end for

no guarantee that a feasible assignment exists in the reduced graph. If $\mathcal{M} = \emptyset$ after Algorithm 1 is performed, the assignment process is completed. Otherwise, Algorithm 2 is performed by making use of the edges that were dropped earlier when forming the reduced graph. The basic process is that if $|\mathcal{K}_m| < k_m^*$ for any MS m, the $(k_m^* + 1)$th best AP is selected based on link conditions to the MS. If the AP has not been assigned a description, then it is assigned to one description that the MS has not received (Lines 5-6); if the AP has been assigned a description that is not received by the MS, the AP increases its transmission power to reach the MS (Lines 10-11); and if the AP has been assigned a description that is already received by the MS, then no change is done to the AP, and the next best AP for the MS is selected (Lines 15-16). For the first two cases, the MS is removed from $\mathcal{M}$ if the required number of descriptions have been received (Lines 7-9 and 12-14). This process is repeated until $\mathcal{M}$ is empty.

Note that running Algorithm 1 on the reduced graph is based on the assumption that the number of descriptions is relatively small compared to the number of APs and MSs in the complete graph, in which case the reduced graph includes a smaller number of links than the original graph. On the other hand, if the number of APs and MSs is not much greater than the number of descriptions, Algorithm 1 can be run on the original graph directly and there is no need for running Algorithm 2.

Before finishing this subsection, we briefly analyze the computational complexity of the scheme for the worst case. In Algorithm 1, the **while** loop between Lines 2 and 23 should run for at most $\min\{I, M\}$ times, in between the **while** loop between Lines 5 and 22 runs at most I times. Within the **while** loops, the complexity for performing the minimization function in Line 7 is at most $O(M)$, the arg max function in Line 8 is at most $O(IM)$, and the **for** loop between Lines 10 and 17 is at most $O(M)$. Therefore, the overall complexity of Algorithm 1 is at most $\min\{I, M\} \times I \times (O(M) + O(IM) + M) = \min\{O(I^2M^2), O(I^3M)\}$. For Algorithm 2, the **for** loop between Lines 1 and 19 should run for at most M times, and the **while** loop between Lines 3 and 18 should run for at most K times. Therefore, the complexity of Algorithm 2 is at most $O(MK)$.

3.2.2 Minimizing Total Transmission Power of APs

Consider any typical stage in an assignment process, each AP i is assigned a description S_i (including $S_i = 0$) and transmission power P_i ($P_i = 0$ if $S_i = 0$). If MS m has not received its required number of descriptions, then among all the APs with $S_i \notin \mathcal{K}_m$ (as a special case, $S_i = 0 \notin \mathcal{K}_m$ for all m), the one that needs to increase its transmission power by the minimum amount is selected to serve the MS. This strategy is applied when serving each MS, so that the extra power required for serving each additional description to each MS is minimized, then the total transmission power of all the APs is minimized when the process is finished. The scheme is shown in Algorithm 3, where $L_{mi} = \max\{P_{i,m} - P_i, 0\}$ is a label for the edge from AP i to MS m, which is the extra power required for AP i to reach MS m based on its current transmission power. The initial value for L_{mi} is $P_{i,m}$ (Line 1) because $P_i = 0$ for all APs.

The algorithm works in iterations. In each iteration, the first z_m APs that have the smallest labels to MS m are selected from the APs with $S_i \notin \mathcal{K}_m$ (Line 5), and stored in a set $\mathcal{I}_m$ (Line 6). Given m, $L_{m[i_m]}$ is defined as the ith smallest label among the L_{mi}'s for all i's with $S_i \notin \mathcal{K}_m$. Based on this definition, the $[z_m]$th AP has

Algorithm 3 Centralized scheme, minimizing total transmission power of APs

Initialize $P_i = 0$ and $S_i = 0$ for all i, $\mathcal{K}_m = \emptyset$ for all m, $L_{mi} = P_{i,m}$ for all i and m, and $\mathcal{M} = \{1, 2, \ldots, M\}$.
while $\mathcal{M} \neq \emptyset$ **do**
  for $m \in \mathcal{M}$ **do**
    Let $z_m = k_m^* - |\mathcal{K}_m|$,
    Find $L_{m[1_m]}$, $L_{m[2_m]}$, $\ldots$, $L_{m[z_m]}$ for all i with $S_i \notin \mathcal{K}_m$
    Form $\mathcal{I}_m = \{[1_m], [2_m], \ldots, [z_m]\}$
  end for
  Let $m^* = \arg\max_{m \in \mathcal{M}} L_{m,[z_m]}$
  for $i \in \mathcal{I}_m$ **do**
    if $S_i = 0$ **then**
      Pick up any $k \in [1, K]$ and $k \notin \mathcal{K}_{m^*}$, and set $S_i = k$ and $P_i = P_{i,m^*}$
      Update $\mathcal{K}_{m^*} = \mathcal{K}_{m^*} \cup \{k\}$
    else if $S_i \notin \mathcal{K}_{m^*}$ **then**
      Set $P_i = P_i + L_{m^*i}$
      Update $\mathcal{K}_{m^*} = \mathcal{K}_{m^*} \cup \{S_i\}$
    end if
    for $n \in \mathcal{M}$ **do**
      Recalculate $L_{ni} = \max\{L_{ni} - L_{m^*i}, 0\}$
      if $L_{ni} = 0$ and $k \notin \mathcal{K}_n$ **then**
        $\mathcal{K}_n = \mathcal{K}_n \cup \{k\}$
      end if
    end for
    $\mathcal{I}_{m^*} = \mathcal{I}_{m^*} \setminus \{i\}$
  end for
  $\mathcal{M} = \mathcal{M} \setminus \{m^*\}$
end while

the largest label among all APs in $\mathcal{I}_m$, and the label of this AP is used as a power indicator for MS m. Among all the MSs, the one with the largest power indicator is selected to be served next (MS m^* in Line 8). Although the total amount of power for serving any MS m separately cannot be less than $\sum_{i\in\mathcal{I}_m} P_{i,m}$, serving MS m^* first may have an additional benefit. Since MS m^* has the largest power indicator, while AP $i \in \mathcal{I}_{m^*}$ transmits a description at power P_{i,m^*}, it is more likely that the transmission can reach other MSs, e.g., MS n, which has lower power indicator. In this way, the total number of transmitting APs and total transmission power of the APs may be reduced.

Lines 9-24 give the process for serving MS m^*. For each AP $i \in \mathcal{I}_{m^*}$, if it has not been assigned a description (Line 10), it is assigned a description that has not been received by MS m^*, and the transmission power is set to P_{i,m^*} (Line 11); otherwise, the AP should increase its power to reach the MS (Line 14). The set $\mathcal{K}_{m^*}$ is then updated (Lines 12 and 15). Meanwhile, the increased transmission power from AP i changes the label from it to all other MSs, and these labels are updated (Line 18). A zero label to an MS indicates that the AP can reach it, and the set of received descriptions of the MS is updated (Lines 19-21). After this, AP i is removed from $\mathcal{I}_{m^*}$ (Line 23). This serving process for MS m^* is repeated until $\mathcal{I}_{m^*}$ is empty, when MS m^* has received the required number of descriptions and is removed from set $\mathcal{M}$. The next MS is then served until $\mathcal{M}$ becomes empty.

Regarding the computational complexity, the **while** loop between Lines 2 and 26 should run for at most M rounds. The **for** loop between Lines 3 and 7 runs for at most M rounds. In between, the complexity to form $\mathcal{I}_m$ is at most $O(KI)$. This gives the complexity of $O(MKI)$ for the **for** loop. After this, Line 8 requires a complexity of

$O(M)$ at most. Next, the **for** loop between lines 9 and 24 runs for at most I rounds. In between, the **for** loop between Lines 17 and 22 should run at most M times. Therefore, the total complexity for the algorithm is $M \times (O(MKI) + O(M) + IM) = O(M^2KI)$.

3.3 Distributed Heuristic Schemes

In some application scenarios, a central station may not be available at the backbone of the network, or the complexity to collect the global information and run the centralized schemes is too high. In this section we first propose a distributed scheme for the "min-max" objective and then for the "min-total" objective. In these schemes, each MS sends description requests to the APs, and updates its description requests by periodically listening to the description assignment information from the APs. Each AP selects a description and decides its own transmission power upon receiving the description requests. MSs are still required to measure link gains from individual APs and report related information to the APs during description requests, but there is no need for a single node to collect all the link gain information.

3.3.1 Minimizing Maximum Power of APs

The basic operations performed at MS m and AP i are shown in Algorithms 4 and 5, respectively. In Algorithm 4, $\mathcal{R}_m$ is a set of the APs that MS m has not received a description from, and z_m is the additional number of descriptions that MS m still needs to receive. Their initial values are set in Line 1. Before receiving the required number of descriptions, the MS forms a set $\mathcal{I}_m$, which includes the first z_m APs in

Algorithm 4 Distributed scheme for minimizing maximum power: for MS m

1: Initialize $\mathcal{K}_m = \emptyset$, $\mathcal{R}_m = \{1, 2, \ldots, I\}$, and $z_m = k^*$.
2: **while** $|\mathcal{K}_m| < k^*_m$ **do**
3:     Find $P_{[1_m],m}$, $P_{[2_m],m}$, ...,$P_{[z_m],m}$, and $P_{[z+1_m],m}$ for all $P_{i,m}$'s with $i \in \mathcal{R}_m$, find δ_m, and form $\mathcal{I}_m = \{[1_m], [2_m], \ldots, [z_m]\}$.
4:     MS m sends a description request to all APs in $\mathcal{I}_m$.
5:     **if** MS m receives a description k from AP i **then**
6:         **if** $k \notin \mathcal{K}_m$ **then**
7:             $\mathcal{K}_m = \mathcal{K}_m \cup \{k\}$, and send a "description received" message to AP i
8:             **if** $i \in \mathcal{R}_m$ **then**
9:                 Update $\mathcal{R}_m = \mathcal{R}_m \setminus \{i\}$
10:             **end if**
11:         **end if**
12:     **end if**
13:     Update $z_m = k^*_m - |\mathcal{K}_m|$ and δ_m
14: **end while**

$\mathcal{R}_m$ that have the best link gain to it (Line 3), and multicasts a description request to the APs (Line 4).

The ideal case is that all the APs in $\mathcal{I}_m$ transmit different descriptions to MS m with the lowest power to reach the MS, then the MS's requirement is fully satisfied, and the "min-max" objective is achieved for serving MS m. However, the APs are shared by the MSs, and each may receive requests from multiple MSs. In order to help the APs make better decisions towards minimizing the maximum transmission power, extra information should be included in the description requests. Assume two APs in $\mathcal{I}_m$ transmit the same description but the other $z_m - 2$ APs all transmit different descriptions to MS m, then another AP in $\mathcal{R}_m$ but not in $\mathcal{I}_m$ should serve MS m. Given this situation, the maximum transmission power for serving MS m is minimized if the $(z_m + 1)$th best AP (in terms of link gain to MS m) in $\mathcal{R}_m$ can serve the MS. Compared to the ideal case, the minimum extra transmission power in this case is defined as $\delta_m = P_{[z_m+1],m} - P_{[z_m],m}$. This "extra power" information is included in the description request as it is important to help the APs make decisions about which MSs they each should serve in order to achieve the overall "min-max" power objective as will be seen when describing the operations at the APs. Each MS constantly listens to descriptions from all the APs. Each time the MS receives a new description (which may or may not be transmitted from the APs to which it sent requests to), it updates $\mathcal{K}_m$, $\mathcal{R}_m$, z_m and δ_m (Lines 5-13) , and sends a "description received" message to the AP to cancel a previously sent description request.

Before introducing details of the scheme at the APs, two notations are defined as follows.

- D_i^{AP}: degree of AP i. It is equal to the total number of MSs that are still requesting descriptions from AP i. During the assignment process, as the MSs receive more descriptions, they make requests to fewer APs. When $|\mathcal{K}_m| = k_m^*$ for all m, D_i^{AP} becomes zero for all i.

- $D_{i,j}^{\text{s}}$: degree of AP j sensed by AP i. This information is used to help neighboring APs coordinate with each other. For AP i, while receiving requests from the MSs and recording its own D_i^{AP} value, information included in the requests also helps it partially monitor the description requests to neighboring APs. The value of $D_{i,j}^{\text{s}}$ is the number of requests that are sent to both APs i and j. It is easy to see that $D_{i,j}^{\text{s}} = D_{j,i}^{\text{s}}$, $D_{i.j}^{\text{s}} \leq D_j^{\text{AP}}$, and $D_{i,j}^{\text{s}} \leq D_i^{\text{AP}}$.

Algorithm 5 shows the decision making process at AP i, where $\mathcal{Q}_i$ is a set of the MSs that are requiring descriptions from the AP. Although there is no direct contact between any of the APs, each AP tries to collect some information about its neighboring APs, and uses this information to reduce unnecessary transmissions. While receiving the description requests from the MSs, AP i updates D_i^{AP}, and records

Algorithm 5 Distributed scheme for minimizing maximum power: states for AP i

Initialize $S_i = 0$
while $S_i = 0$ **do**
  Update $\mathcal{Q}_i$, D_i^s and $D_{i,j}^s$'s for all $j \neq i$ based on currently received requests
  $j^* = \arg\max_j D_{i,j}^{\mathrm{s}}$
  if $D_i^{\mathrm{AP}} > D_{i,j^*}^{\mathrm{s}}$ **then**
    Enter active state
  else
    Enter waiting state for a short time τ
    if Description requests updated **then**
      Update $\mathcal{Q}_i$
    end if
    Enter active state
  end if
  if In the active state **then**
    Find $m^* = \arg\max_{m \in \mathcal{Q}_i} \delta_m$
    Pick up $k \in [1, K]$ and $k \notin \mathcal{K}_{m^*}$
    Set $S_i = k$ and $P_i = P_{i,m^*}$
  end if
end while

$D_{i,j}^{s}$ for $j \neq i$. The AP makes a decision to enter either active or waiting states based on the relative values of D_i^{AP} and $D_{i,j}^{\mathrm{s}}$'s. When $D_i^{\mathrm{AP}} > \max_{j \neq i} D_{i,j}^{\mathrm{s}}$, AP i is in the active state; and when $D_i^{\mathrm{AP}} = \max_{j \neq i} D_{i.j}^{\mathrm{s}}$, AP i enters the waiting state for a short time period τ.

At the active state, the AP selects an MS to serve, and based on the information included in the MS's request it selects a description and decides the transmission power to reach the MS (Lines 14-18). If AP i receives requests from multiple MSs, it chooses to transmit to MS m^*, which is the MS with the largest δ_m. The AP randomly picks up one description that is not in $\mathcal{K}_{m^*}$, and sets the transmission power to reach the MS (meanwhile, other MSs that can correctly receive the same description update their information as described in Algorithm 4).

When $D_i^{\mathrm{AP}} = D_{i,j^*}^{\mathrm{s}}$, all the descriptions sent to AP i are also sent to AP j^*, which implies that the two APs are very likely to be close to each other. For this reason, it is likely that a description sent by one AP can also be received by the MSs sending requests to the other AP, and there is no need for the two APs to send the same description. By entering the waiting state, the AP allows its neighboring AP to make a decision first so that it does not send the same description. As MSs receive descriptions from the first AP, they will update their description requests. The decision for entering the waiting or active states is performed locally at individual APs without interactions. Due to the fully distributed implementation, it is possible that both APs i and j^* enter the waiting state or the active state simultaneously. In this case, it is possible that they both decide to transmit the same description to the same sets of the MSs. This is the price paid by adopting the distributed solution. However, when there is at least one MS that sends the request to AP i (or j) and not

AP j (or i), then $D_i^{\mathrm{AP}} > D_{i,j}^{\mathrm{s}}$ ($D_j^{\mathrm{AP}} > D_{j,i}^{\mathrm{s}}$), then simultaneously entering active or wait states will not occur between these two APs.

3.3.2 Minimizing Total Transmission Power of APs

The basic idea of this heuristic scheme is to allocate descriptions to APs in order to serve MSs with the worst channel conditions first. While doing so, some other MSs may be served automatically, and this may save the total transmission power of the APs for serving all the MSs. After all the MSs are served, some MSs may realize that they have received multiple copies of the same description, and inform the APs from which they receive earlier copies to cancel unnecessary transmissions, which further reduces the total transmission power of the APs.

Algorithm 6 Minimizing total transmission power of APs: for MS m

```
Initialize 𝒦_m = ∅, ℛ_m = {1, 2, ..., I}, 𝒟_{m,k} = ∅ and Î_{m,k} = 0 for all k.
while |𝒦_m| < k*_m do
    i* = arg min_{i∈ℛ_m} P_{i,m}
    Send a description request to AP i*
    if Description k is received from AP j then
        if k ∈ 𝒦_m then
            𝒟_{m,k} = 𝒟_{m,k} ∪ {Î_{m,k}}
        else
            𝒦_m = 𝒦_m ∪ {k}
        end if
        Î_{m,k} = j
        ℛ_m = ℛ_m \ {j}
    end if
end while
```

The operations done by MS m are shown in Algorithm 6, where $\hat{I}_{m,k}$ is used to record the AP from which MS m receives the most recent copy of description k, $\mathcal{R}_m$ is a set of APs from which MS m has not received any descriptions from, and $\mathcal{D}_{m,k}$ is a set used to record all other APs from which MS m has received other (duplicate) copies of description k. Initially, $\hat{I}_{m,k} = 0$ and $\mathcal{D}_{m,k} = \emptyset$ for all k, meaning that no copy of the description has been received. Before receiving all the required number of descriptions, MS m makes description requests to the APs. Each request includes the indexes of the descriptions currently in $\mathcal{K}_m$. MS m always sends a description request to the AP that has the best link gain to it in $\mathcal{R}_m$ (Lines 3-4). As the MS also listens for descriptions from different APs, it may receive description k from AP j, which may or may not be the same AP that the MS sent a request to. If the received description is a duplicate copy of description k, it adds the current $\hat{I}_{m,k}$ to $\mathcal{D}_{m,k}$ (Line 7), and updates $\hat{I}_{m,k} = j$ (Line 11); otherwise, it updates $\mathcal{K}_m$ (Line 9), and records $\hat{I}_{m,k} = j$ (Line 11). AP j is then removed from $\mathcal{R}_m$ (Line 12). The process is repeated until the required number of descriptions have been received.

The operations done at AP i after it receives a description request are shown in Algorithm 7, where $\mathcal{M}_i$ is a set of the MSs that the AP serves, which is empty at the beginning. AP i keeps $\mathcal{Q}_i$, which is a set of the MSs from which it receives description requests. Upon receiving description requests from one or multiple MSs, if the AP currently is not assigned a description, it chooses to serve the MS (denoted as m^*) that requires the highest power from it (Line 4), and adds the MS into $\mathcal{M}_i$. The AP then checks $\mathcal{K}_{m^*}$ included in the description request, randomly selects one description not in $\mathcal{K}_{m^*}$ to transmit, and sets its transmission power to reach the MS (Line 5). After it has selected a description, it sets the transmission power to reach all the MSs in $\mathcal{Q}_i$ that have not received the same description, and adds these MSs into $\mathcal{M}_i$ (Lines 9-10). These MSs are then removed from $\mathcal{Q}_i$ (Line 12). After this process, if $\mathcal{Q}_i$ is still not empty, it means that MS $n \in \mathcal{Q}_i$ has received the same description from other APs, and AP i simply removes n from $\mathcal{Q}_i$ (Line 12).

Algorithm 7 Minimizing total transmission power of APs: for AP i

---

1: Initialize $\mathcal{M}_i = \emptyset$, $S_i = 0$ and $P_i = 0$.
2: **while** $\mathcal{Q}_i \neq \emptyset$ **do**
3:   **if** $S_i = 0$ **then**
4:     $m^* = \arg\max_{m \in \mathcal{Q}_i} P_{i,m}$ and $\mathcal{M}_i = \mathcal{M}_i \cup \{m^*\}$
5:     Pick up $k \in [1, K]$ and $k \notin \mathcal{K}_{m^*}$, then set $S_i = k$ and $P_i = P_{i,m^*}$
6:     $\mathcal{Q}_i = \mathcal{Q}_i \setminus \{m^*\}$
7:   **else**
8:     **for** MS $n \in \mathcal{Q}_i$ **do**
9:       **if** $S_i \notin \mathcal{K}_n$ **then**
10:         $P_i = \max\{P_i, P_{i,n}\}$, and $\mathcal{M}_i = \mathcal{M}_i \cup \{n\}$
11:       **end if**
12:       $\mathcal{Q}_i = \mathcal{Q}_i \setminus \{n\}$
13:     **end for**
14:   **end if**
15: **end while**

Because of the fully distributed operations, all MSs make independent description requests, and all APs make their decisions without coordinating with each other, it may happen that some MSs receive multiple copies for the same description. As described earlier, MS m does not have to receive any descriptions from APs in $\mathcal{D}_{m,k}$. Algorithm 8 is performed to reduce the transmission power of these APs, where Lines 2-6 are performed at MS m, and Lines 9-12 are performed at AP i. After MS m has received all the required descriptions, it sends a cancellation message to each AP in the duplicate sets. Upon receiving a cancellation message from MS m, AP i removes the MS from its served set $\mathcal{M}_i$, and adjusts its transmission power to be enough for serving only the remaining MSs in $\mathcal{M}_i$. The transmission power of the AP is reduced if $P_{i,m}$ is larger than the power for the AP to serve the remaining MSs in $\mathcal{M}_i$. The transmission power of AP i is zero if $\mathcal{M}_i$ is empty.

Algorithm 8 Minimizing total transmission power of APs: decreasing transmission power

```
for m = 1 : M do
    for k ∈ K_m do
        if D_{m,k} ≠ ∅ then
            MS m sends a cancellation message to all APs in ∪_k D_{m,k}
        end if
    end for
end for
for i = 1 : I do
    if AP i receives a cancellation request from MS m ∈ M_i then
        M_i = M_i \ {m}
        P_i = max_{m∈M_i} P_{i,m}
    end if
end for
```

3.4 Results

In this section we demonstrate the performance of the proposed description assignment and power allocation schemes, and compare them with the optimum solutions. We simulate a system where the APs and MSs are randomly distributed in a circular system area with radius of 1km, and a minimum distance between any two APs is 30m. The source traffic is encoded into 3 equal weight descriptions. Each MS has an equal probability to require 1 to 3 descriptions. The Shannon's formula is used to find the required transmission power for AP i to reach MS m. That is, $P_{i,m} = \frac{\left(2^{r_b/B_{i,m}}-1\right)P_n}{G_{i,m}}$, where r_b=3 Mbps is the transmission rate of each description, $B_{i,m}$ = 1Mhz is the transmission bandwidth, P_n = -90dBm is the noise power, and $G_{i,m}$ is the link gain between AP i and MS m. We consider both path loss and log-normal fading, and the link gain is given by $G_{i,m} = G(d_0) \times \left(\frac{d_{i,m}}{d_0}\right)^{-\alpha} \times 10^{-\frac{X_{i,m}}{10}}$, where $d_{i,m}$ is the distance between MS m and AP i, d_0 = 100m is the reference distance, α = 2 is the path loss exponent, $X_{i,m}$ is a normally distributed random variable with zero mean and

2dB standard deviation, and $G(d_0) = (4\pi d_0 f/c)^2$ is the path loss at the reference distance with frequency $f = 2.4$ GHz and light speed $c = 3 \times 10^8$ m/s. Note that using different physical layer implementations may affect the transmission power of nodes while the overall qualitative relationship among different solutions will remain consistent.

For min-total solutions, Fig. 3.1 and Fig. 3.2, respectively, show the total AP transmission power as the number of APs and MSs changes. Fig. 3.1 shows that given the number of MSs, the total transmission power of the APs decreases as the network has more APs. This is because each MS will have a higher chance to be served by the APs with good link gains. The figure also shows that the reduction of total AP transmission power becomes less obvious when the number of APs becomes large. This is because almost all the MSs can receive their desired number of descriptions from nearby APs that transmit sufficiently low power, and adding more APs has little effect on the transmission power of the serving APs. This observation is more obvious when $M = 10$ than $M = 60$, because in the former case a smaller number of APs is sufficient to satisfy the requirements of all MSs.

By comparing the optimum, the centralized, and the distributed solutions in Fig. 3.1, we can see that when the number of MSs is relatively small (e.g., $M = 10$), the difference in total AP transmission power between the three solutions is also relatively small; and when the number of MSs increases (e.g., to $M = 60$), the gap between the three solutions increases. Specifically, when the number of MSs is small, a small number of APs are needed in order to serve all the MSs, and therefore, the pressure for optimizing the decisions regarding which APs should serve which MSs is relatively low. In this case, the distributed scheme can have performance similar

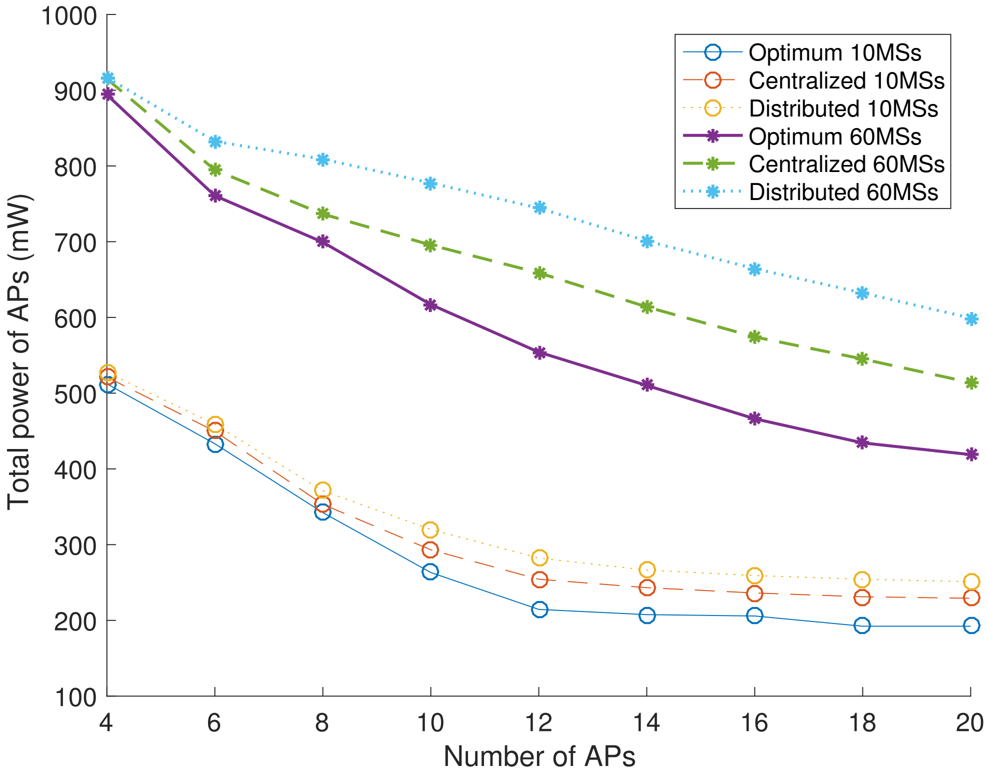


Figure 3.1: Minimizing total transmission power: total power versus number of APs

to the centralized solution, and very close to the optimum one. As there are more MSs, more APs should transmit, in which case, it becomes increasingly important to optimize both the description assignments and power allocations. The distributed schemes do not optimize the decisions globally, and therefore, have to sacrifice some performance by having more APs transmit higher power. The centralized schemes have the global information, which helps coordinate decisions between the APs, and achieves better performance than the distributed schemes.

Fig. 3.2 shows that given the number of APs, the total transmission power increases as there are more MSs, because each AP should serve more MSs and the worst link gain determines the transmission power of the AP. The figure also shows that the total AP transmission does not increase very much as the number of MSs is

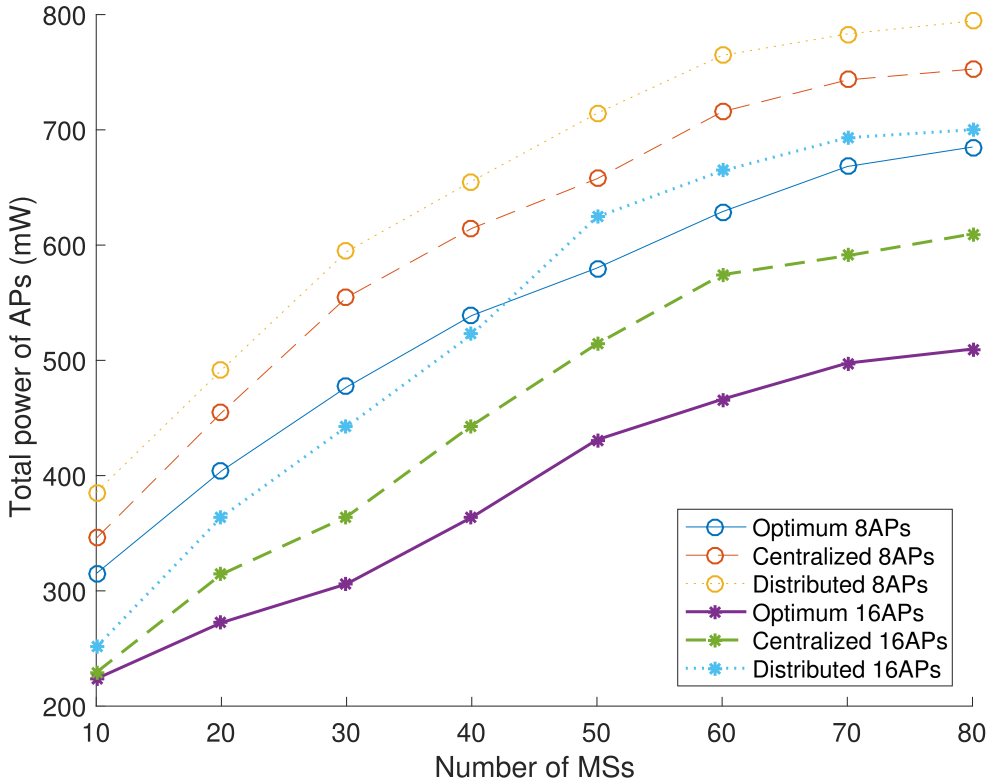


Figure 3.2: Minimizing total transmission power: total power versus number of MSs

above a certain value. At this point, the transmission power of the APs assigned to each description may be sufficient to cover the entire service area, and adding more MSs does not require changes to the description assignment or transmission power of the APs. By comparing the optimum, the centralized, and the distributed solutions in Fig. 3.2, we can see that when the number of APs is relatively small (e.g., $I = 8$), the difference in total AP transmission power between the three solutions is relatively small, compared to the difference when the number of APs is larger (e.g., $I = 16$). When there are more APs, there is more flexibility to choose which APs should serve which MSs. In this case, the centralized scheme can take advantage of the link diversity provided by more APs and save the total transmission power;

while the distributed scheme has little information for coordinating the description assignment among the APs, which results in some MSs being served by APs with poor link gains.

For the min-max solutions, Fig. 3.3 and Fig. 3.4, respectively, show the maximum transmission power of the APs as the number of APs and MSs increases. It is seen from the figures that the maximum transmission power decreases with the number of APs and increases with the number of MSs. Fig. 3.3 shows that when the number of APs is relatively small, increasing the number of APs can greatly decrease the min-max power as the chance for an MS to be served by nearby APs increases. After most of the MSs have been served by APs with sufficiently good link gains, further increasing the number of APs does not affect the min-max power significantly. This can also be seen from the figure as the curves become relatively flat when the number of APs becomes large. Fig. 3.3 also shows that when the number of APs is relatively small, the difference between the three solutions is very small, which indicates that heuristic schemes can achieve close-to-optimum performance.

Both Figs. 3.3 and 3.4 show that when the number of MSs is small, the difference between the three solutions is also very small, because the number of APs is sufficiently large so that all the MSs can be served by the APs that have the best link gains to them, and there is hardly any AP that has to serve distant MSs with poor link gains. For this reason, globally optimizing the description assignment and power allocation does not gain much compared to the heuristic schemes, and a distributed scheme can achieve almost as good of a performance as the centralized scheme, or even the optimum solution. Fig. 3.4 also shows that as the number of MSs increases, the min-max power increases slowly for small I (e.g., $I = 8$) but faster for large I

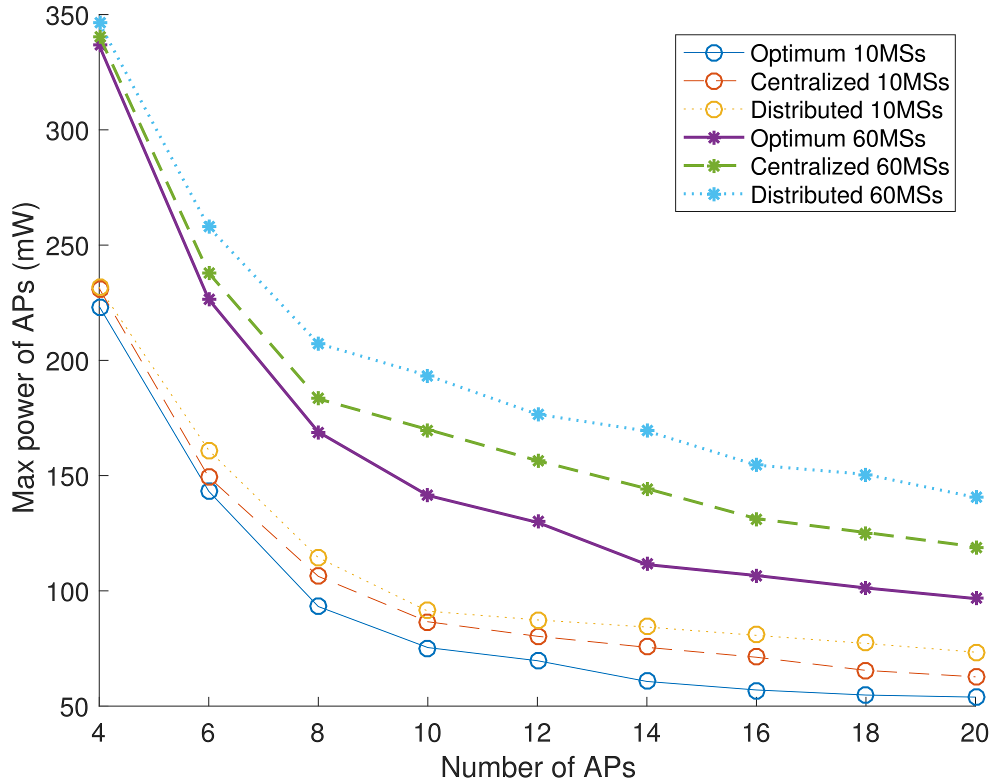


Figure 3.3: Min-Max APs transmission power: max power versus number of APs

(e.g., $I = 16$). This is because when I is small, the average distance between the APs and the MSs is large, and higher min-max power is required even when there is a small number of MSs. Because of this, transmissions of the APs automatically cover a large geographical area. When more MSs are added to the system, less power increase is needed.

Fig. 3.5 and Fig. 3.6, respectively, show the total transmission power of the APs versus number of APs and number of MSs when performing the proposed min-total and min-max schemes. Fig. 3.7 and Fig. 3.8, respectively, show the maximum transmission power of the APs versus number of APs and number of MSs when performing the proposed min-total and min-max schemes. The figures show that all the min-total

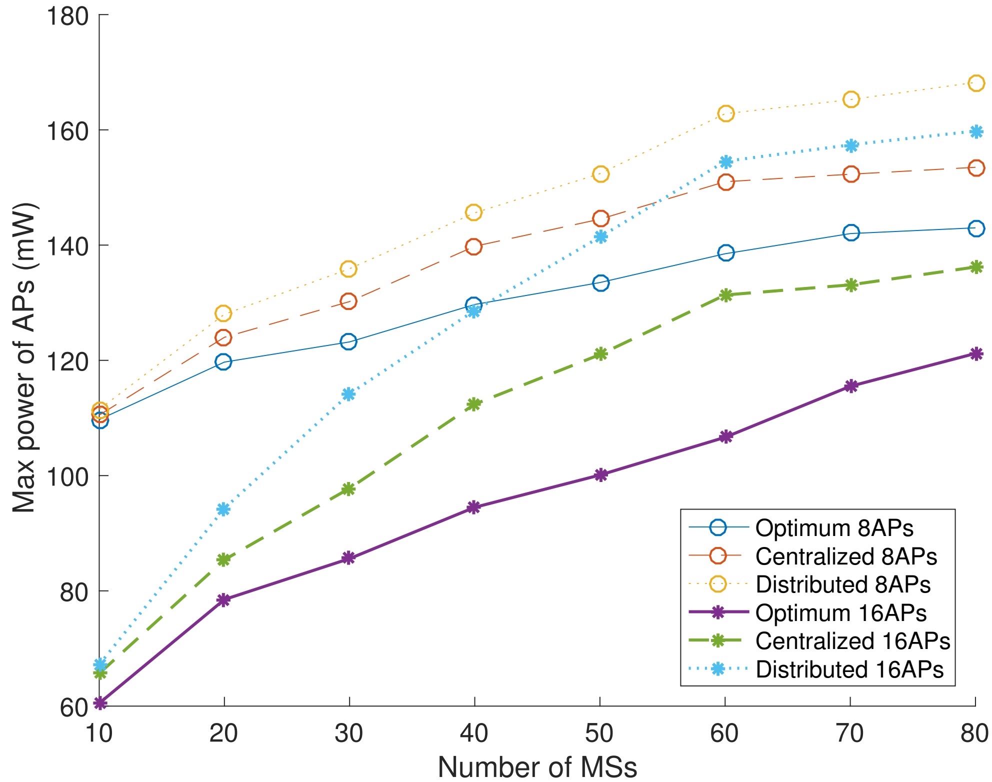


Figure 3.4: Min-Max APs transmission power: max power versus number of MSs

solutions indeed achieve much lower total transmission power than the min-max solutions, and all the min-max solutions achieve much lower maximum transmission power than the min-total solutions. In the min-max solution, APs try to limit their maximum power, which leads to more APs to transmit; while in min-total solution, fewer APs may transmit but some may have to transmit very high power. In the proposed min-max schemes, the basic idea is to minimize the transmission power of individual APs for serving each MS without considering how many APs should transmit; while in the proposed min-total schemes, the maximum transmission power of individual APs is not a concern, and all the steps done in both the centralized and distributed solutions are towards reducing the total transmission power of all APs.

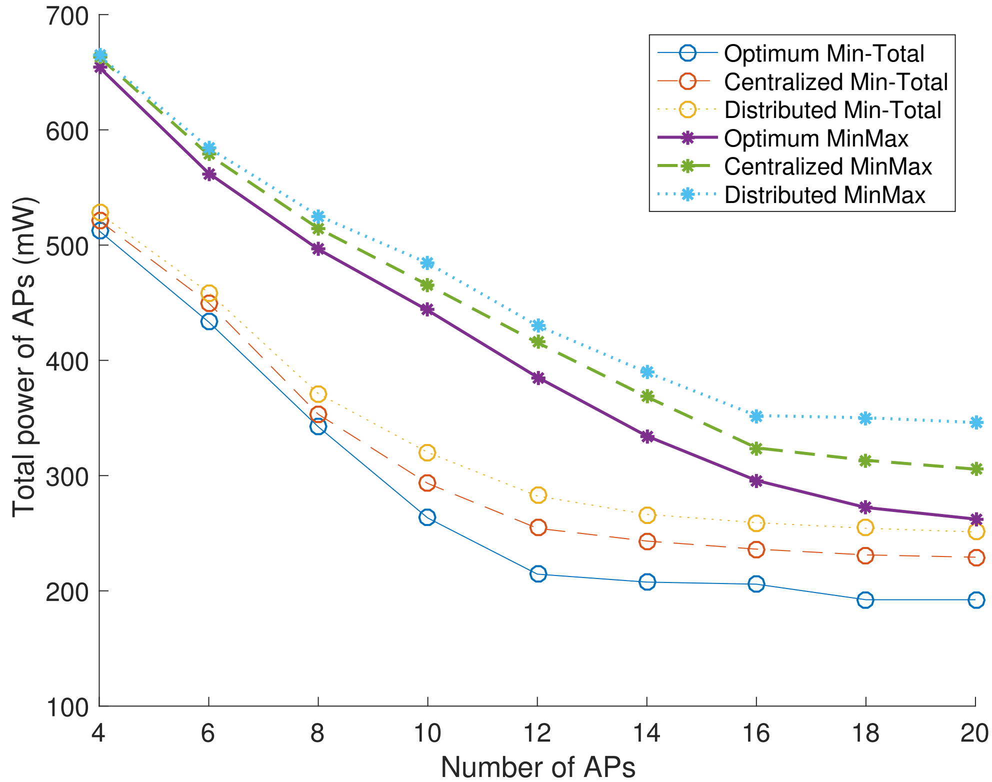


Figure 3.5: Comparison between min-max and min-total power schemes: total power versus number of APs (10 MSs)

3.5 Summary

In this chapter, we have studied the problem of power efficient multicasting for MD-encoded media traffic in single-hop WMNs. Two objectives were considered: 1) minimizing the total transmission power in the network, and 2) minimizing the maximum transmission power of the APs. Optimal problems for power allocations and description assignments have been formulated, and both centralized and distributed heuristic schemes have been proposed for each objective. The results have shown that the proposed heuristic schemes performed well compared to the optimum solution under different network configurations. Minimizing the total transmission power in the

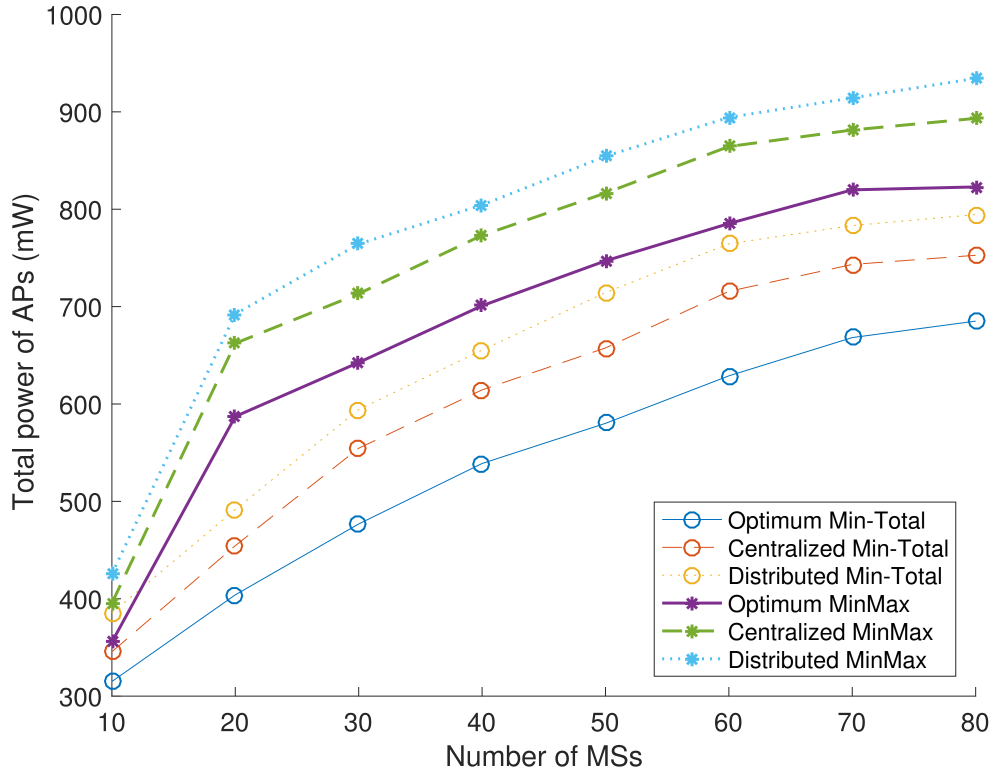


Figure 3.6: Comparison between min-max and min-total power schemes: total power versus number of MSs (8 APs)

network forced multiple APs to transmit at a high transmission power in order to cover larger service area, while at the same time many other APs may not transmit any descriptions. On the other hand, minimizing the maximum transmission power at the APs balanced the transmission power and load among all the APs, but the overall total transmission power in the network is greatly increased.

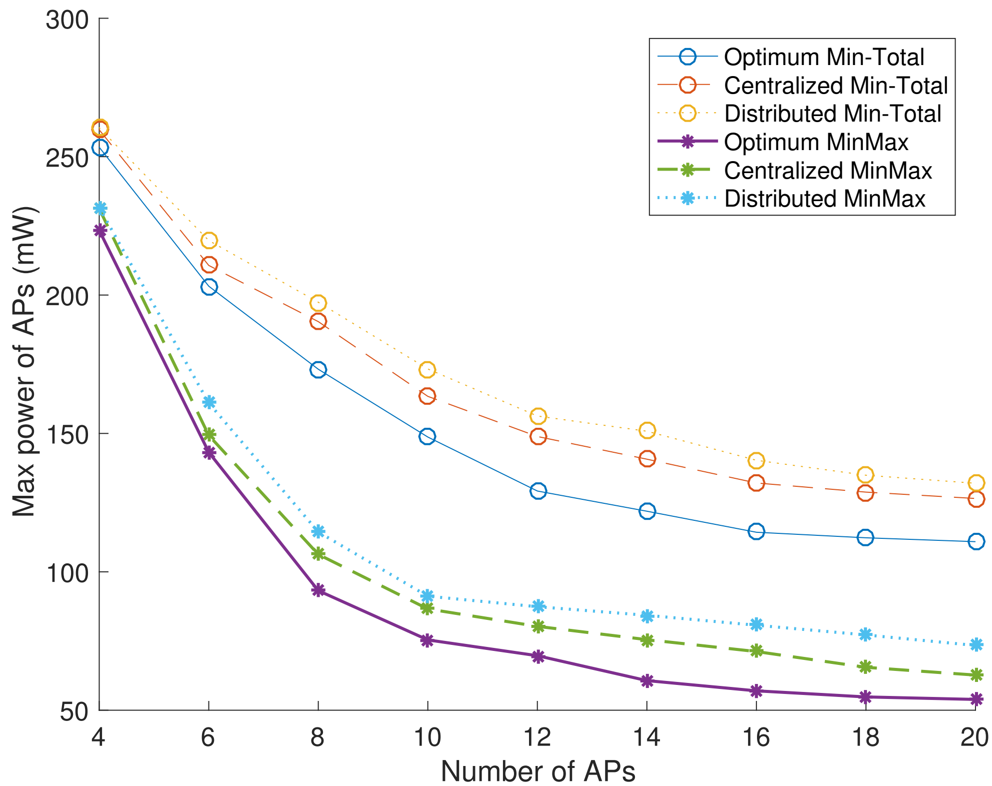


Figure 3.7: Comparison between min-max and min-total power schemes: max power versus number of APs (10 MSs)

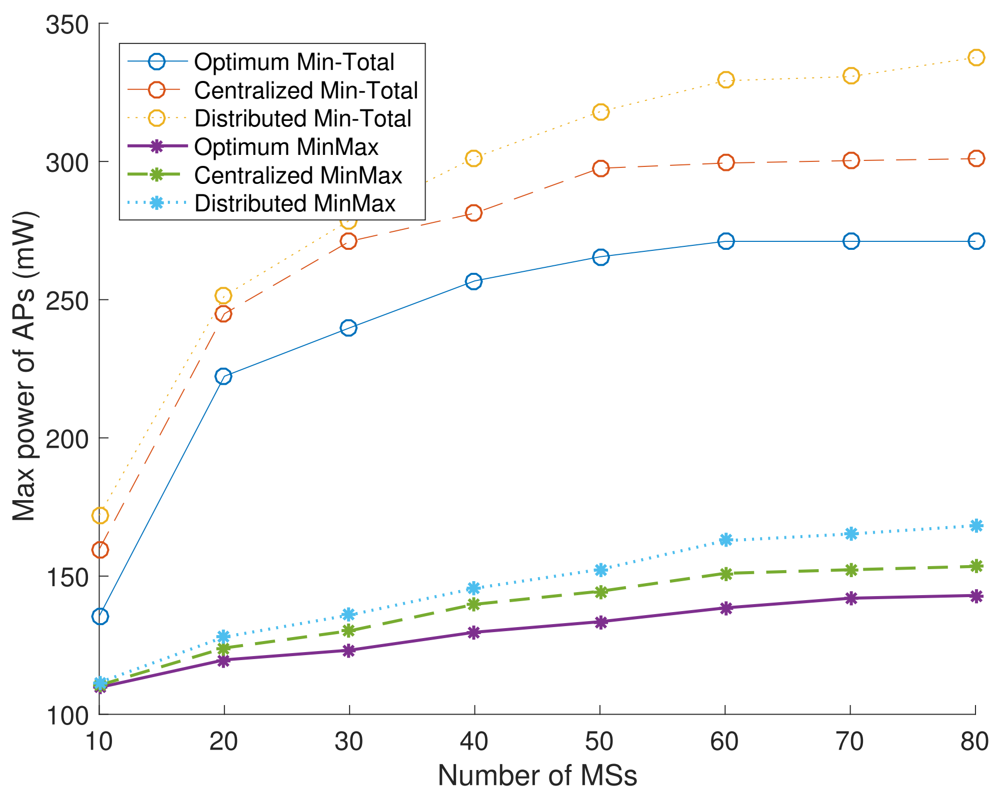


Figure 3.8: Comparison between min-max and min-total power schemes: max power versus number of MSs (8 APs)

Chapter 4

Multicasting Multiple Description Media in Multi-hop WMNs

In this chapter, we continue our study on multicasting MD-encoded media traffic in WMNs. Different from Chapter 3, where the focus was on single-hop transmissions, in this chapter we consider that the APs can transmit multiple descriptions to the MSs via relay stations (RSs) through multi-hop transmissions. Our objective is to minimize the total transmission power in the network, subject to the QoS requirements of the MSs. Multiple multicast trees will be built, each of which is rooted from one AP and delivers one description. Based on the number of descriptions that each RS is allowed to forward, the multiple multicast trees may or may not be allowed to share RSs. An optimization problem is formulated for the general case, and a centralized scheme with lower complexity is proposed for the case where each RS can only be in at most one multicast tree. For systems that do not have a central node, a fully distributed scheme, referred to as minimum weight k-path scheme, is proposed. The scheme requires only neighboring nodes to exchange information to establish the parent-child relationship in order to build the multiple multicast trees, where the multiple multicast trees may or may not be allowed to share RSs.

The remainder of this chapter is organized as follows. In Section 4.1, the system model is described. In Section 4.2 the centralized multicast scheme is proposed for the case where each RS is only allowed to forward one description. The distributed minimum weight k-path scheme for the general case is presented in Section 4.3. Numerical results are shown in Section 4.4 to demonstrate performance of the proposed schemes. Section 4.5 summarizes the chapter.

4.1 System Description and Problem Formulation

We consider a wireless network that consists of an AP, a number of RSs and MSs. The AP is the source of all traffic, which is encoded into K equally important descriptions using MDC. The AP is equipped with K radios, each of which is for transmitting one description. The RSs can be either specially deployed nodes or simply MSs that do not carry their own traffic. Same as in Chapter 3, we assume that all the transmissions are orthogonal.

Table 4.1 lists some of the notations used in this section. We use $i = 1, 2, \ldots, R$ to index the RSs, $m = 1, 2, \ldots, M$ to index the MSs, and $k = 1, 2, \ldots, K$ to index the descriptions, where R and M, respectively, are the total number of RSs and MSs. Let k_m^* be the minimum number of descriptions required by MS m. The objective is to build a multicast tree for each description and allocate transmission power to the AP and the RSs in the multicast trees, so that all the MSs receive their required number of descriptions, and the total transmission power in the network is minimized.

Let $S_{\max}$ and l, respectively, be the maximum and actual number of descriptions

Table 4.1: Notations used in Section4.1

Symbol	Definition
$\mathcal{G}(\mathcal{V},\mathcal{E})$	Graph representation of the network
$\mathcal{V}$	Set of vertices in $\mathcal{G}$
$\mathcal{E}$	Set of edges in $\mathcal{G}$
r_b	Rate of each description
$G_{i,j}$	Channel gain between nodes i and j
$B_{i,j}$	Transmission bandwidth between nodes i and j
$S_{\max}$	Maximum number of descriptions an RS can forward
$P_{l,i,j}$	Minimum required transmission power for node i to send aggregated rate of l descriptions to node j
P_i	Transmission power of node i
k_m^*	Minimum number of descriptions required by MS m
L_k	Number of MSs receiving description k
$X_{k,i,j}$	Number of flows of description k on link (i,j)
$Y_{k,i,j}$	1 if link (i,j) is sending description k, and 0 otherwise
$u_{i,l}$	1 if node i is transmitting l different descriptions, and 0 otherwise

that an RS can forward. When $S_{\max}=1$, each RS is allowed to forward at most one description. That is, each RS can be in at most one multicast tree, and therefore, the K multicast trees do not share any RSs (referred to as node-disjoint multicast trees). When $S_{\max}>1$, an RS may be in l ($l \le S_{\max}$) different multicast trees, each for a different description. When $l>1$, the RS may i) transmit the descriptions one after another, or ii) aggregate all the l descriptions into one transmission. The formulation for case i) is the same as $l=1$ by replacing each RS forwarding l descriptions with l RSs each forwarding one description. For case ii), the aggregate rate of l descriptions is lr_b, where r_b is the data rate of each description. In order for node i, which is forwarding l descriptions, to reach node j (which may be another RS or an MS), the minimum transmission power $P_{l,i,j}$ is given by Shannon's formula as

$$P_{l,i,j} = \frac{2^{\frac{l r_b}{B_{i,j}}} - 1}{G_{i,j}/P_n}, \tag{4.1}$$

where $G_{i,j}$ is the channel gain between nodes i and j, P_n is the background noise power, and $B_{i,j}$ is the transmission bandwidth between the two nodes. In the remaining of this chapter we only consider Case ii). Note that constraint 4.1 can be written using different modulation and channel coding schemes since the problem formulation and the design of the heuristic schemes are independent from the underlying physical layer implementation. Thus, using different modulation and channel coding schemes will only affect the absolute value of the minimum required transmission power.

Define a graph $\mathcal{G} = (\mathcal{N}, \mathcal{E})$ with $\mathcal{N}$ as a set of the vertices and $\mathcal{E}$ as a set of the edges. For the set of vertices, $\mathcal{N} = \mathcal{S} \cup \mathcal{A} \cup \mathcal{R} \cup \mathcal{M} \cup \mathcal{D}$, where $\mathcal{A}$, $\mathcal{R}$, and $\mathcal{M}$, respectively, are a set of the transmitters at the AP, a set of the RSs, and a set of the MSs; the set $\mathcal{S}$ includes only one node s, which is a virtual source of the traffic; and the set $\mathcal{D}$ includes only one node d, which is a virtual sink that accumulates all traffic. The virtual source is only connected to the transmitters at the AP, and the virtual sink is only connected to the MSs. These virtual nodes are created to complete the graph. For the set of edges, $(i, j) \in \mathcal{E}$ if and only if there is a link from node i to node j, where $i, j \in \mathcal{N}$. The formulation below considers the transmission of each description from the virtual source to an MS as one flow. Define $X_{k,i,j}$ so that $X_{k,i,j} = f$ if description k is carried by link (or edge) (i, j) and reaches f MSs (directly or through other RSs), where f is a non-negative integer. We have

$$\sum_{\forall j \text{ with } (i,j)\in\mathcal{E}} X_{k,i,j} - \sum_{\forall j \text{ with } (j,i)\in\mathcal{E}} X_{k,j,i} = \begin{cases} L_k, & i \in \mathcal{S} \\ -L_k, & i \in \mathcal{D} \\ 0, & i \in \mathcal{A}\cup\mathcal{R}\cup\mathcal{M} \end{cases} \tag{4.2}$$

where L_k is the total number of flows for description k, or the total number of MSs that receive description k. It is also the total number of outgoing flows from the virtual source and the total number of incoming flows to the virtual sink for description k. In order to satisfy the number of descriptions required by all MSs, we should have

$$\sum_k L_k \geq \sum_{m\in\mathcal{M}} k_m^*. \tag{4.3}$$

Let $\mathcal{K}$ be a set of all descriptions. For each $k \in \mathcal{K}$, each MS outputs at most one flow to the sink. That is,

$$X_{k,m,j} \leq 1, \qquad k \in \mathcal{K},\ m \in \mathcal{M},\ j \in \mathcal{D}. \tag{4.4}$$

Define a set of binary variables $Y_{k,i,j}$, so that $Y_{k,i,j} = 1$ if the link from node i to node j carries description k, and $Y_{k,i,j} = 0$ otherwise. Then

$$\frac{X_{k,i,j}}{C} \leq Y_{k,i,j} \leq X_{k,i,j}, \qquad k \in \mathcal{K},\ (i,j) \in \mathcal{E}, \tag{4.5}$$

$$\sum_{k\in\mathcal{K}} \sum_{\forall i \text{ with } (i,j)\in\mathcal{E}} Y_{k,i,j} \geq k_j^*, \qquad j \in \mathcal{M}, \tag{4.6}$$

where C is a large number so that $0 \leq \frac{X_{k,i,j}}{C} \leq 1$ for all k in $\mathcal{K}$, i and j with $(i,j) \in \mathcal{E}$. In (4.5), when $X_{k,i,j} \geq 1$, we have $Y_{k,i,j} = 1$; otherwise, $Y_{k,i,j} = 0$; constraint (4.6) specifies the total number of descriptions reaching MS j.

In order to enforce a multicast tree structure for each description without considering the virtual sink, every node except the virtual sink should have at most one active incoming link for each description. That is,

$$\sum_{\forall i \text{ with } (i,j)\in\mathcal{E}} Y_{k,i,j} \leq 1, \qquad j \in \mathcal{A}\cup\mathcal{R}\cup\mathcal{M},\ k\in\mathcal{K}. \tag{4.7}$$

Define a binary variable $u_{i,l}$ with $u_{i,l} = 1$ if node i is transmitting l different descriptions, and $u_{i,l} = 0$ otherwise. Then

$$\sum_{l=1}^{S_{\max}} u_{i,l} \leq 1, \quad i \in \mathcal{A}\cup\mathcal{R}. \tag{4.8}$$

The relationship between $Y_{k,j,i}$ and $u_{i,l}$ is given as

$$\sum_{k\in\mathcal{K}} \sum_{\forall j \text{ with}(j,i)\in\mathcal{E}} Y_{k,j,i} = \sum_{l=1}^{S_{\max}} l \cdot u_{i,l}, \quad i \in \mathcal{A}\cup\mathcal{R}, \tag{4.9}$$

where the left-hand side is the total number of unique descriptions that node i receives, and equal to the total number of descriptions that node i should transmit. This is guaranteed by (4.2) and (4.7), where the former ensures that the number of incoming flows is the same as the number of outgoing flows for $i \in \mathcal{A}\cup\mathcal{R}$, and the latter prohibits a node from receiving duplicate copies of the same description. From above, the transmission power of node i should satisfy the following relationship

$$P_i \geq \left[u_{i,l} - (1 - Y_{k,i,j})\right] P_{l,i,j}, \quad k\in\mathcal{K},\ \forall(i,j)\in\mathcal{E}, \quad l = 1,\ldots,S_{\max} \tag{4.10}$$

In (4.10), when $Y_{k,i,j} = 0$ or $u_{i,l} = 0$, the right-hand side is 0 or negative, the constraint is satisfied as long as P_i is not negative; when $Y_{k,i,j} = 1$ and $u_{i,l} = 1$, $P_i \geq u_{i,l}P_{l,i,j}$.

Define $\mathbf{X} = [X_{k,i,j},\ \forall k \in \mathcal{K},\ (i,j) \in \mathcal{E}]$, $\mathbf{Y} = [Y_{k,i,j},\ \forall k \in \mathcal{K},\ (i,j) \in \mathcal{E}]$, $\mathbf{U} = [u_{i,l},\ \forall i \in \mathcal{A} \cup \mathcal{R},\ l = 1, \cdots, K]$, $\mathbf{P} = [P_i,\ \forall i \in \mathcal{A} \cup \mathcal{R}]$. and $\mathbf{L} = [L_k,\ \forall k \in \mathcal{K}]$. With the above constraints and description, an optimization problem can be formulated as follows:

$$\mathbf{OPT}: \min_{\{\mathbf{X},\mathbf{Y},\mathbf{U},\mathbf{P},\mathbf{L}\}} \sum_{i \in \mathcal{A} \cup \mathcal{R}} P_i \tag{4.11}$$

$$\text{s.t.} \quad (4.2) - (4.10)$$

$$X_{k,i,j} \in \{0, 1, 2, \ldots\},\ k \in \mathcal{K},\ (i,j) \in \mathcal{E} \tag{4.12}$$

$$Y_{k,i,j}, u_{i,l} \in \{0, 1\},\ k \in \mathcal{K},\ (i,j) \in \mathcal{E} \tag{4.13}$$

OPT is a mixed linear integer optimization problem, which in general is NP-hard problem, and can be solved using commercially available software, such as CPLEX. For solving this MILP, CPLEX uses branch-and-cut algorithm and dual simplex method to perform dynamic search over relaxed linear subproblems until the best known solution that satisfies all the integrality requirements is found [91]. Thus, the complexity of the problem grows with the number of variables, where it also has exponential worst case running time. Moreover, it cannot be used in distributed implementation since it requires full knowledge of the network. Next we design heuristic schemes that require much lower implementation complexity.

4.2 Centralized Heuristic: $S_{\max} = 1$ Case

In this section we design a centralized heuristic scheme for the case when every RS is only allowed to transmit a single description (e.g., $S_{\max} = 1$). For the general case of $S_{\max} = K$, multiple multicast trees can be built sequentially one after another until the requirements of all MSs are satisfied. The objective of the proposed scheme is to build K node-disjoint multicast trees (NDMTs) from the original graph $\mathcal{G}$, so that each of the NDMTs is for multicasting one different description, and the number of NDMTs that cover MS m is at least k_m^*. This is a greedy algorithm. The decision-making process is implemented at the AP, which should collect information about link gains between different network nodes, build the full graph $\mathcal{G}$ first, and then search the best paths for building each multicast tree. In this scheme, we assume relatively static channel conditions, so that the graph is not changed for a relatively long time. Assigning descriptions to individual RSs is trivial in this scheme, as the only restrictions are: i) all the RSs in the same NDMT forward the same description, and ii) RSs in different NDMTs forward different descriptions.

The main scheme is shown in Algorithm 1. The K NDMTs are denoted as $\mathcal{G}_k$, where $k = 1, 2, \ldots, K$. We use $\mathcal{G}_0$ to represent the remaining graph after removing all $\mathcal{G}_k$'s ($k \neq 0$) from the original graph, i.e., $\mathcal{G}_0 = \mathcal{G} \setminus \cup_{k=1}^{K} \mathcal{G}_k$. Initially, $\mathcal{G}_k$ is empty for all $k > 0$ and $\mathcal{G}_0 = \mathcal{G}$. The transmission power of the AP and all RSs is zero, i.e., $P_i = 0$ for all $i \in \mathcal{A} \cup \mathcal{R}$. For an edge (i, j), a weight $w(i, j)$ is defined as the additional transmission power needed for node i to reach node j based on the current transmission power of node i, i.e., $w(i, j) = \max\{P_{i,j} - P_i, 0\}$. Initially, $w(i, j) = P_{i,j}$, for all $(i, j) \in \mathcal{E}$. The weight is updated each time P_i is changed.

The scheme includes two main parts, one for building paths in the NDMTs, and

Algorithm 1 Greedy method for generating K NDMTs

Require: $\mathcal{G}$, $k_m^* \ \forall m$
Ensure: $P_i \ \forall m$, $\mathcal{G}_k \ \forall k$
Initialize $\mathcal{G}_0 = \mathcal{G}$, $\mathcal{G}_k = \emptyset \ \forall k$, $\mathcal{M}_r = \mathcal{M}$, and $P_i = 0 \ \forall i \in \mathcal{R} \cup A$.
while $\mathcal{M}_r \neq \emptyset$ **do**
  $k_{\max} = \max_{m \in \mathcal{M}_r} k_m^*$ and $\mathcal{M}^{'} = \{m | m \in \mathcal{M}_r, k_m^* = k_{\max}\}$
  while $\mathcal{M}^{'} \neq \emptyset$ **do**
    Call Algorithm 2 for each $m \in \mathcal{M}^{'}$
    $n = \arg\max_{m \in \mathcal{M}^{'}} W_{\max\min,m}$
    for All **Path** $\in \mathcal{P}_n$ **do**
      for All $(i, j) \in$ **Path do**
        $P_i = \min\{P_i + w(i,j), P_{\max}\}$
        for All $(i, j^{'}) \in \mathcal{G}$ **do**
          $w(i, j^{'}) = \max\{0, w(i, j^{'}) - w(i, j)\}$
        end for
      end for
    end for
    $\mathcal{M}^{'} = \mathcal{M}^{'} \setminus \{n\}$ and $\mathcal{M}_r = \mathcal{M}_r \setminus \{n\}$
  end while
end while

another for assigning transmission power. Given the complexity of the problem, the two parts cannot be completely separated. The scheme is performed iteratively, with each iteration for building paths and assigning transmission power in order to serve one MS. Within the iteration for serving MS m, k_m^* node-disjoint paths are found from the AP to the MS by adding extra branches to the existing NDMTs if necessary.

We now describe details of Algorithm 1. In each iteration, all the MSs that have not been fully satisfied form a set $\mathcal{M}_r$, among which those requiring the largest number of descriptions ($k_{\max}$) form a set $\mathcal{M}^{'}$. The MS that is served next will be selected from $\mathcal{M}^{'}$, mainly because these MSs will determine the maximum number of NDMTs required in the network. When these MSs are served satisfactorily, there is a high possibility that the requirements of other MSs are satisfied too.

Algorithm 2 Finding $k_{\max}$ node-disjoint paths to MS m

Require: $\mathcal{G}_k\ \forall k \in \mathcal{K}$

Ensure: $\mathcal{P}_m$, $\mathcal{G}_k\ \forall k$, and $W_{\max\min,m}$

Initialize $k = 0$, $\mathcal{P}_m = \emptyset$, and $\mathcal{T} = \{1, 2, \ldots, K\}$
while $u < k_{\max}$ **do**
    $W_{\min,m} = \infty$
    for $k \in \mathcal{T}$ **do**
        Find $\mathbf{Path}_k$, the path with minimum weight from AP to MS m in $\mathcal{G}_0 \cup \mathcal{G}_k$
        if $W_k < W_{\min,m}$, where W_k is the weight of path $\mathbf{Path}_k$ **then**
            $W_{\min,m} = W_k$
            $\zeta = k$
        end if
    end for
    $\mathcal{P}_m = \mathcal{P}_m \cup \{\mathbf{Path}_\zeta\}$
    $\mathcal{G}_0 = \mathcal{G}_0 \setminus \{i | i \in \mathcal{R} \cap \mathbf{Path}_\zeta\}$, and $\mathcal{G}_\zeta = \mathcal{G}_\zeta \cup \{i | i \in \mathcal{R} \cap \mathbf{Path}_\zeta\}$
    $\mathcal{T} = \mathcal{T} \setminus \{\zeta\}$
    $u = u + 1$
end while
$W_{\max\min,m} = \max_{\mathbf{Path}_\zeta \in \mathcal{P}_m} \{W_\zeta\}$

Among the MSs in $\mathcal{M}'$, we still need to choose one to serve first. In order to make this decision, for each MS m in $\mathcal{M}'$, we first call Algorithm 2, which returns $\mathcal{P}_m$ and $W_{\max\min,m}$. $\mathcal{P}_m$ is a set of the $k^*_m (= k_{\max})$ node-disjoint paths that have the minimum weights from the AP to MS m. Each of these paths has a weight, which is the total weight of all the edges along the path. $W_{\max\min,m}$ is the maximum of these k^*_m path weights. Among all the MSs in $\mathcal{M}'$, the one with the maximum $W_{\max\min,m}$ is served next, which is denoted as MS n in Algorithm 1. The reason for selecting this MS is that serving this MS first requires the RSs along the paths to transmit at relatively high power which may automatically serve other MSs This helps reduce the total number of transmitting RSs, and therefore reduce the total transmission power.

Before describing how to serve MS n, we first explain Algorithm 2. All the $k_{\max}$ paths that will be added to $\mathcal{P}_m$ should be from different NDMTs. We define $\mathcal{T}$ as a set of indexes of the candidate NDMTs from which the next minimum weight paths will be created for MS m. At the beginning, $\mathcal{T}$ includes all numbers from 1 to K and $\mathcal{P}_m$ is empty. Given the current $\mathcal{P}_m$ and $\mathcal{T}$, in order to find the next path to be added to $\mathcal{P}_m$, we first find the path with the minimum weight from the AP to MS m based on graph $\mathcal{G}_0 \cup \mathcal{G}_k$, and W_k records the path weight. This is done for all $k \in \mathcal{T}$, and the path with the minimum weight is added to $\mathcal{P}_m$. That is, the newly added path is located in $\mathcal{G}_0 \cup \mathcal{G}_\zeta$, where $\zeta = \arg\min_{k \in \mathcal{T}} W_k$. Meanwhile, we update $\mathcal{T}$ by removing ζ from it, and update $\mathcal{G}_0$ and $\mathcal{G}_\zeta$ by moving all RSs along the newly found path from $\mathcal{G}_0$ to $\mathcal{G}_\zeta$. This process is repeated until $k_{\max}$ paths are included in $\mathcal{P}_m$, and the maximum weight of all the paths in $\mathcal{P}_m$ is recorded as $W_{\max\min,m}$. This completes the process for creating $k_{\max}$ node-disjoint paths for MS m. Based on the updated $\mathcal{G}_k$'s, Algorithm 2 is run for another MS in $\mathcal{M}'$, and the whole process for constructing the NDMTs is completed after the algorithm is run for all the MSs in $\mathcal{M}'$. Two points should be emphasized here. First, this process is completely based on weights, and does not assign transmission power to any nodes. This means that at this point, all the nodes still have zero transmission power. Second, the order of selecting MSs from $\mathcal{M}'$ to run Algorithm 2 does not affect the final results, because this does not affect weights of the links, which are what the algorithm is based on when finding node-disjoint paths.

We now switch back to Algorithm 1 and describe the power allocation process for serving MS n. With the overall objective of minimizing total transmission power of AP and RSs, the objective for serving MS n is to minimize the total increase in transmission power from all the RSs. Recall that for each link/edge (i, j), $w(i, j)$ is the additional power required for node i to reach node j based on the current transmission power of node i. For each link (i, j) along a path in $\mathcal{P}_n$, the minimum transmission power of node (AP or RS) i to reach node j is the current P_i plus $w(i, j)$, or P_i is updated as $P_i + w(i, j)$. After this, the weights of all outgoing links from node i are reduced by $w(i, j)$ or to zero, whichever is larger. After this, MS n's requirements are fully satisfied and it is removed from both $\mathcal{M}'$ and $\mathcal{M}_r$. Based on the updated $\mathcal{M}'$, node-disjoint paths are found again for all the MSs in the set by calling Algorithm 2, and the new MS n is then selected. The transmission power of the RSs along the node-disjoint paths for this MS is updated. The process is repeated until $\mathcal{M}'$ is empty. After this, a new $\mathcal{M}'$ is formed based on the current $\mathcal{M}_r$, and the process is repeated until $\mathcal{M}_r$ is empty.

Before finishing this subsection, we briefly analyze the computational complexity of the scheme for the worst case. The complexity of this algorithm is highly influenced by the number of MSs, as we recalculate node-disjoint paths for all MSs in $\mathcal{M}'$ by repeatedly calling Algorithm 2 each time an MS is fully served. Using the Dijkstra shortest path algorithm with Fibonacci heap implementation, the computational complexity of Algorithm 2 is $C_2 = O(K^2(E + (M + R)\log(M + R)))$, where E is the total number of links, which depends on M, R, and maximum transmission power of the AP and RSs as it determines how many other nodes a given node can reach. With this, the overall computational complexity of Algorithm 1 is approximately $C_1 = M(O(M)+MC_2+O(M)+KR(M+R))$, where the first M on the right-hand side of the expression is for the **while** loop in Line 2, the first $O(M)$ is for the maximization function in Line 3, MC_2 is for the **while** loop in Line 4, and the next $O(M)$ is for the **argmax** function in Line 6, and the last term is for the power allocation process. We can further simplify C_1 as $C_1 = O(EM^2K^2 + M^2K^2(M + R)\log(M + R) + MKR^2)$.

4.3 Minimum Weight k-path Distributed Scheme

The complexity of the greedy scheme can still be high when the number of RSs and MSs is large in the network, where collecting all required information needed to run the scheme may require a considerable amount of signaling overhead. In this section, we propose a minimum weight k-path scheme for building the multicast trees. This is a fully distributed scheme that requires information exchanges between the one-hop neighboring nodes. For each description k, a multicast tree rooted at the kth radio of the AP is constructed to reach some or all the MSs. The scheme is designed for any $S_{\max}$ between 1 and K.

4.3.1 Notations and Information Updates

Before describing the details of the proposed scheme, we first introduce some information and notation related to building the multicast trees.

$\mathcal{K}_i$: a set of descriptions that node i has received. Initially, $\mathcal{K}_i = \mathcal{K}$ for $i \in \mathcal{A}$, and $\mathcal{K}_i = \emptyset$ for all $i \in \mathcal{R} \cup \mathcal{M}$.

$\mathcal{S}_i$: a set of the descriptions assigned for node i to transmit. Initially, $\mathcal{S}_i = \{k\}$ for the kth transmitter in $\mathcal{A}$ and $\mathcal{S}_i = \emptyset$ for all $i \in \mathcal{R}$.

$\mathcal{C}_{i,k}$: a set of the nodes that directly receive description k from node i. Initially, $\mathcal{C}_{i,k} = \emptyset$ for all $k \in \mathcal{K}$ and $i \in \mathcal{A} \cup \mathcal{R}$.

P_i: current transmission power of node i. Initially, $P_i = 0$ for all $i \in \mathcal{A} \cup \mathcal{R}$. Let $l = |\mathcal{S}_i|$, i.e., l is the total number of descriptions that node i is assigned to transmit. In order for node i's transmission to reach node j, we should have $P_i \geq P_{l,i,j}$. If node i can reach node j, node j can correctly receive all l descriptions transmitted by node

i. Thus, P_i is set as follows:

$$P_i = \max_{n \in \cup_{k \in \mathcal{K}} \mathcal{C}_{i,k}} P_{l,i,n}. \tag{4.14}$$

$W_{i,k}$: minimum path weight for delivering description k to node i based on current transmission power and description assignments of the nodes.

$$W_{i,k} = \min_{\forall \mathcal{P}_{i,k}} \sum_{(u,v) \in \mathcal{P}_{i,k}} \max\{P_{|\mathcal{S}_u|,u,v} - P_u, 0\}, \tag{4.15}$$

where $\mathcal{P}_{i,k}$ is a path that can deliver description k from the AP to node i, and (u, v) is a link along the path. Initially, $\mathrm{W}_{i,k} = \infty$ for all $i \in \mathcal{A} \cup \mathcal{M} \cup \mathcal{R}$ and $k \in \mathcal{K}$, and $\mathrm{W}_{i,k} = 0$ for all $i \in \mathcal{A}$ and $k \in \mathcal{S}_i$.

$\mathrm{Parent}_{i,k}$: parent node for node i to receive description k. This is the one-hop neighbor node from which node i can receive description k with the minimum path weight. Initially, $\mathrm{Parent}_{i,k} = 0$ for all $i \in \mathcal{M} \cup \mathcal{R}$ and $k \in \mathcal{K}$.

I_i: additional transmission power that node i needs if it should transmit one more description and stay connected with all its current child nodes. Specifically, if node i is sending l descriptions, or $l = |\mathcal{S}_i|$, then in order to transmit $l + 1$ descriptions to all its current child nodes, the additional power needed is

$$\mathrm{I}_i = \max_{j \in \cup_{k \in \mathcal{K}} C_{i,k}} \max(P_{l+1,i,j} - P_i, 0). \tag{4.16}$$

Initially $\mathrm{I}_i = 0$ for all $i \in \mathcal{A} \cup \mathcal{R}$.

$\mathcal{R}_{i,k}$: a set of nodes that node i has received $\mathrm{DescReq}_{i,k}$ messages (will be introduced later on) from, when node i is not ready to send description k.

- Initially $\mathcal{R}_{i,k} = \emptyset$ for all $k \in \mathcal{K}$ and $i \in \mathcal{A} \cup \mathcal{R}$.
- $\mathcal{R}_{i,k} = \emptyset$ for all $k \in \mathcal{S}_i$.

$\mathcal{T}_i$: a set of pending description requests that node i has sent

- For $i \in \mathcal{M}$, $|\mathcal{T}_i| \leq 1$. That is, each MS keeps at most one pending description request at a time.
- For $i \in \mathcal{R}$, $|\mathcal{T}_i| \leq S_{\max} - |\mathcal{K}_i|$. An RS may have up to $S_{\max} - |\mathcal{K}_i|$ pending description requests.
- For $i \in \mathcal{R} \cup \mathcal{M}$, when node i sends a request for description k, then $\mathcal{T}_i = \mathcal{T}_i \cup \{k\}$.
- For $i \in \mathcal{R} \cup \mathcal{M}$, when node i receives the requested description k, then $\mathcal{T}_i = \mathcal{T}_i \cup \{k\}$.

4.3.2 Messages Exchanged Between Neighboring Nodes

The following are messages that are exchanged between one-hop neighbors:

Announcement$_i$: a message that node i broadcasts to its one-hop neighbors. The message includes $(P_i, \mathcal{S}_i, \mathrm{I}_i, W_{i,k}\ \forall k \in \mathcal{K})$. Initially, the scheme depends on the AP to send the Announcement$_i$ message and propagate the description and path weight information to the nodes one-hop away from it. These nodes, upon receiving the messages from the AP, update their information, and broadcast their Announcement$_i$ messages further, until the information is propagated to MSs. The information included in these Announcement$_i$ messages allows all the nodes to build up their parent nodes and path weights for each description.

- *For the sender node i*: the message is sent each time P_i, $\mathcal{S}_i$, I_i, or $W_{i,k}$ for any $k \in \mathcal{K}$ is changed.
- *For receiver node j*: Algorithm 3 is used to update the parent and path weight information when a node receives an Announcement_i message.

Algorithm 3 Parent node and path weight updates

1: $\tilde{W}_k = \infty \ \forall k \in \mathcal{K}$
2: **for all** $k \in \mathcal{K}$ **do**
3:    **if** $k \in \mathcal{S}_i$ **then**
4:       $\tilde{W}_k = \max\{P_{|\mathcal{S}_i|,i,j} - P_j, 0\}$
5:    **else if** $|\mathcal{S}_i| < S_{\max}$ **then**
6:       $\tilde{W}_k = W_{i,k} + \max\{P_{|\mathcal{S}_i|,i,j} - P_j, \mathrm{I}_i\}$
7:    **end if**
8: **end for**
9: **for all** $k \in \mathcal{K}$ **do**
10:    **if** $\text{Parent}_{j,k} = i$ **then**
11:       $W_{j,k} = \tilde{W}_k$
12:    **else if** $\tilde{W}_k < W_{j,k}$ **then**
13:       $W_{j,k} = \tilde{W}_k$
14:       $\text{Parent}_{j,k} = i$
15:    **end if**
16: **end for**

In Algorithm 3, the first part (Lines 2-8) is to calculate the path weights $\tilde{W}_k$ by assuming that node i is node j's parent node for description k; and the second part (Lines 9-16) is to update the parent and path weight information based on the results in the first part. At the end, the neighboring node through which node j can receive description k with the minimum path weight becomes the parent node of node j for description k.

In the first part, for each description k, $\tilde{W}_k$ is calculated based on different cases:

- If node i is already assigned to transmit description k (lines 3-4), then the path weight for node j to receive description k from node i is the additional power needed for node i to reach node j, where $|\mathcal{S}_i|$ is the current number of descriptions that node i has been assigned to transmit. Note that, $k \in \mathcal{S}_i$ implies that $k \in \mathcal{K}_i$, and therefore, $W_{i,k} = 0$.

- If node i is not assigned to transmit description k and $|\mathcal{S}_i| < S_{\max}$ (lines 5-7), then it is possible to add description k to $\mathcal{S}_i$. In order to transmit description k to node j, node i should transmit $|\mathcal{S}_i| + 1$ descriptions. In line 6, the max function is the additional transmission power needed for node i to reach node j and all node i's existing child nodes.

- When node i is not assigned to transmit description k and $|\mathcal{S}_i| = S_{\max}$, node i is not allowed to transmit description k. Therefore, $\tilde{W}_k = \infty$.

In the second part,

- If $\text{Parent}_{j,k} = i$ (Lines 10-11), then node j updates the path weight for description k;

- otherwise, if $\tilde{W}_k < W_{j,k}$ (Lines 12-15), then node i replaces the current $\text{Parent}_{j,k}$ and becomes the new parent of node j for description k.

DescReq$_{i,k}$: a message sent from node i to its parent node $\text{Parent}_{i,k}$ in order to request the parent node to send description k to it. Description requests are initiated by the MSs. The description requests are propagated through the RSs. When the requests reach the AP or an RS that is already assigned to transmit the description, the AP or RS increases its transmission power to reach the requesting node.

- *For the sender*:

  - For node $i \in \mathcal{M}$, if $|\mathcal{K}_i| < k_i^*$ and $\mathcal{T}_i = \emptyset$, it sends a $\text{DescReq}_{i,k}$ message, where $k = \arg\min_{k \in \mathcal{K} \setminus \mathcal{K}_i} W_{i,k}$.
  - For node $i \in \mathcal{R}$, it sends a $\text{DescReq}_{i,k}$ message if $\mathcal{R}_{i,k}$ changes from empty to nonempty and $|\mathcal{S}_i| < S_{\max}$.
  - After sending the message, node i updates $\mathcal{T}_i = \mathcal{T}_i \cup \{k\}$.

- *For the receiver node* $j = \text{Parent}_{i,k}$,
  - If $k \in \mathcal{S}_j$, node j is ready to serve node i. Node j updates $\mathcal{C}_{j,k} = \mathcal{C}_{j,k} \cup \{i\}$ and adjusts P_j accordingly to reach node i.
  - If $k \notin \mathcal{S}_j$ and $|\mathcal{S}_j| < S_{\max}$, but $k \in \mathcal{K}_j$, node j is ready to serve node i. Node j updates $\mathcal{S}_j = \mathcal{S}_j \cup \{k\}$ and $\mathcal{C}_{j,k} = \mathcal{C}_{j,k} \cup \{i\}$, adjusts P_j accordingly, and sends a $\text{JoinReq}_{j,k}$ message.
  - If $|\mathcal{S}_j| < S_{\max}$ and $k \notin \mathcal{K}_j$, node j updates $\mathcal{R}_{j,k} = \mathcal{R}_{j,k} \cup \{i\}$ and sends a $\text{DescReq}_{j,k}$ message.

Comments:

- Each MS always requests the description with the minimum path weight in order to minimize the total transmission power.

- Each MS keeps at most one pending description request at a time. This prevents flooding parent nodes with requests, especially at the initial run where the path weights for different descriptions are most likely to be equal. It also allows an MS to take advantage of paths being established by neighboring MSs.

JoinReq$_{i,j,k}$: a message that node i sends to node j and requests to join the child set of node j for description k.

- *For the sender*:
  - Node i sends the message if it can receive description k from node j and wants to use node j as its parent node for description k.
  - Node i updates $\text{Parent}_{i,k} = j$ after sending the message.
- *For the receiver*:
  - Node j updates $\mathcal{C}_{j,k} = \mathcal{C}_{j,k} \cup \{i\}$.
  - Node j updates $\mathcal{R}_{j,k} = \mathcal{R}_{j,k} \setminus \{i\}$ if $i \in \mathcal{R}_{j,k}$. This is to cancel the pending description request previously received, if there is one.

DescRemove$_{i,k}$: node i sends the message to $\text{Parent}_{i,k}$

- *For the sender*: node i sends the message if
  - $k \in \mathcal{K}_i$ and it receives description k from node $l \neq \text{Parent}_{i,k}$ (i.e., receives a second copy of description k from node l), or
  - $\mathcal{R}_{i,k} = \emptyset$ and $\mathcal{C}_{i,k} = \emptyset$. That is, node i no longer needs to transmit description k, and therefore, notifies its parent that it does not need to receive the description.
- *For the receiver*: upon receiving the message, node j
  - updates $\mathcal{C}_{j,k} = \mathcal{C}_{j,k} \setminus \{i\}$, and adjusts P_j accordingly; and
  - if $\mathcal{C}_{j,k} = \emptyset$ and $\text{R}_{i,k} = \emptyset$, node j updates $\mathcal{S}_i = \mathcal{S}_i \setminus \{k\}$

CancelReq$_{i,k}$: a message that node i sends to node $\text{Parent}_{i,k}$ to cancel a previously sent $\text{DescReq}_{i,k}$ message.

- *For the sender*:
  - Node i with $k \in \mathcal{T}_i$ sends the message if $k \in \mathcal{K}_i$ or $\mathcal{R}_{i,k} = \emptyset$, and
  - after sending the message, node i updates $\mathcal{T}_i = \mathcal{T}_i \setminus \{k\}$.
- *For the receiver*: upon receiving the message, node j (= $\text{Parent}_{i,k}$)
  - updates $\mathcal{R}_{j,k} = \mathcal{R}_{j,k} \setminus \{i\}$.

4.3.3 Receiving Descriptions

If node i can successfully decode the transmissions from node v, it receives all the descriptions sent from node v. Algorithm 4 gives the updates done at RS i after it receives descriptions from node v, where lines 1-14 are the updates related to $\mathcal{K}_i$, and lines 15-31 are the updates related to $\mathcal{S}_i$.

For RS i that receives description k from node v,

- if $k \notin \mathcal{K}_i$, the set $\mathcal{K}_i$ is updated by adding description k, and the previously sent description request message is canceled.
- if the description is already in $\mathcal{K}_i$, RS i sends $\text{DescRemove}_{i,k}$ message to the current parent.
- In all cases, RS i uses node v to replace its current parent node, and sends $\text{JointReq}_{i,v,k}$ message to node v if RS i requires description k.

After $\mathcal{K}_i$ is updated, RS i also checks if the current $\mathcal{K}_i$ allows it to satisfy any pending requests in the $\mathcal{R}_{i,k}$ sets for each description k.

- If the answer is yes for any k, the nodes in $\mathcal{R}_{i,k}$ will be moved to $\mathcal{C}_{i,k}$, and the transmission power of node i is adjusted accordingly.

- Otherwise, RS i will drop all pending requests and send $\text{DescRemove}_{i,k}$ to its current parent.

When an MS receives descriptions from node v, it runs Algorithm 5. When a new description is received, it is added to $\mathcal{K}_i$, the previously sent description request is canceled, and a $\text{JoinReq}_{i,v,k}$ message is sent. If the same description has been received already from another node, the MS switches to use node v as its new parent node for description k. In addition, when the required number of descriptions have been received, all pending description requests are canceled.

4.4 Results

In this section we demonstrate the performance of the proposed schemes. The system covers a square area of 1km×1km, where the AP is located at the center. The source traffic is encoded into three equally important descriptions, i.e., $K = 3$. We consider both distance-based path loss and log-normal shadowing. The link gain between nodes i and j is $G_{i,j} = G(d_0) \times \left(\frac{d_{i,j}}{d_0}\right)^{-\alpha} \times 10^{-\frac{X_{i,j}}{10}}$, where $d_{i,j}$ is the distance between the two nodes, $d_0 = 100$m is the reference distance, $\alpha = 2$ is the path loss exponent, $X_{i,j}$ is a normally distributed random variable with zero mean and 2 dB standard deviation. The Shannon's formula is used to find the required transmission power from node i to node j. That is, $P_{l,i,j} = \frac{2^{lr_b/B_{i,j}}-1}{G_{i,j}/P_n}$, where $r_b = 3$ Mbps is the transmission rate of each description, l is the total number of descriptions that node i transmits, $B_{i,j} = 1$ MHz is the available bandwidth, and $P_n = -90$ dBm is the background noise power. The RSs and MSs are both uniformly distributed in the system service area with a minimum distance of 30 m between any two RSs. Note that using different physical

Algorithm 4 RS i receives descriptions from node v

for all $k \in \mathcal{S}_v$ **do**
  if $k \notin \mathcal{K}_i$ **then**
    $\mathcal{K}_i = \mathcal{K}_i \cup \{k\}$
    if $k \in \mathcal{T}_i$ **then**
      Send $\text{CancelReq}_{i,k}$ message
    end if
  else
    Send $\text{DescRemove}_{i,k}$ message
  end if
  $\text{Parent}_{i,k} = v$
  if $\mathcal{C}_{i,k} \cup \mathcal{R}_{i,k} \neq \emptyset$ **then**
    Send $\text{JointReq}_{i,v,k}$ message
  end if
end for
for all $k \in \mathcal{K}_i$ **do**
  if $\mathcal{R}_{i,k} \neq \emptyset$ **then**
    if $k \notin \mathcal{S}_i$ **then**
      if $|\mathcal{S}_i| < S_{\max}$ **then**
        $\mathcal{S}_i = \mathcal{S}_i \cup \{k\}$
      else
        $\mathcal{R}_{i,k} = \emptyset$
        Send $\text{DescRemove}_{i,k}$ to $\text{Parent}_{i,k}$
      end if
    end if
    if $k \in \mathcal{S}_i$ **then**
      $\mathcal{C}_{i,k} = \mathcal{C}_{i,k} \cup \mathcal{R}_{i,k}$
      $\mathcal{R}_{i,k} = \emptyset$
      Update P_i and I_i
    end if
  end if
end for

Algorithm 5 MS i receives descriptions from node v

for all $k \in \mathcal{S}_v$ **do**
  if $k \notin \mathcal{K}_i$ **then**
    if $|\mathcal{K}_i| < k_i^*$ **then**
      $\mathcal{K}_i = \mathcal{K}_i \cup \{k\}$
      Send $\text{CancelReq}_{i,k}$
      Send $\text{JoinReq}_{i,v,k}$
    end if
  else
    Send $\text{CancelReq}_{i,k}$
    Send $\text{JoinReq}_{i,v,k}$
  end if
end for
if $|\mathcal{K}_i| = k_i^*$ **then**
  Send $\text{CancelReq}_{i,k}$ $\forall k \in \mathcal{T}_i$
  $\mathcal{T}_i = \emptyset$
end if

layer implementations may affect the transmission power of nodes while the overall qualitative relationship among different solutions will remain consistent.

For comparison, we also simulate a spanning tree (ST) based scheme. In the ST scheme, description assignments and power allocations are performed first by following the proposed centralized scheme in Chapter 3, which assigns descriptions to the RSs and allocates RS transmission power so that at least k_m^* RSs that are assigned to different descriptions can reach MS m in one-hop transmission for all $m \in \mathcal{M}$. Next, all the RSs that have been assigned to description k are grouped into a subgraph $\mathcal{G}_k$, where $k = 1, 2, \ldots, K$. Define $\mathcal{G}_0 = \mathcal{G} \setminus \cup_{k=1}^{K} \mathcal{G}_k$. The approach in [92] is then used to build directed spanning trees to connect each group of the RSs to the AP either directly or through RSs in $\mathcal{G}_0$, whichever minimizes the total transmission power of the AP and the RSs. After we connect the RSs in $\mathcal{G}_1$ to the AP, all intermediate RSs are moved from $\mathcal{G}_0$ to $\mathcal{G}_1$. After this, the RSs in $\mathcal{G}_2$ are connected to the AP via the

RSs in the updated $\mathcal{G}_0$ with the objective of minimizing the total transmission power of the AP and the RSs. This process is repeated until the RSs in $\mathcal{G}_K$ are connected to the AP.

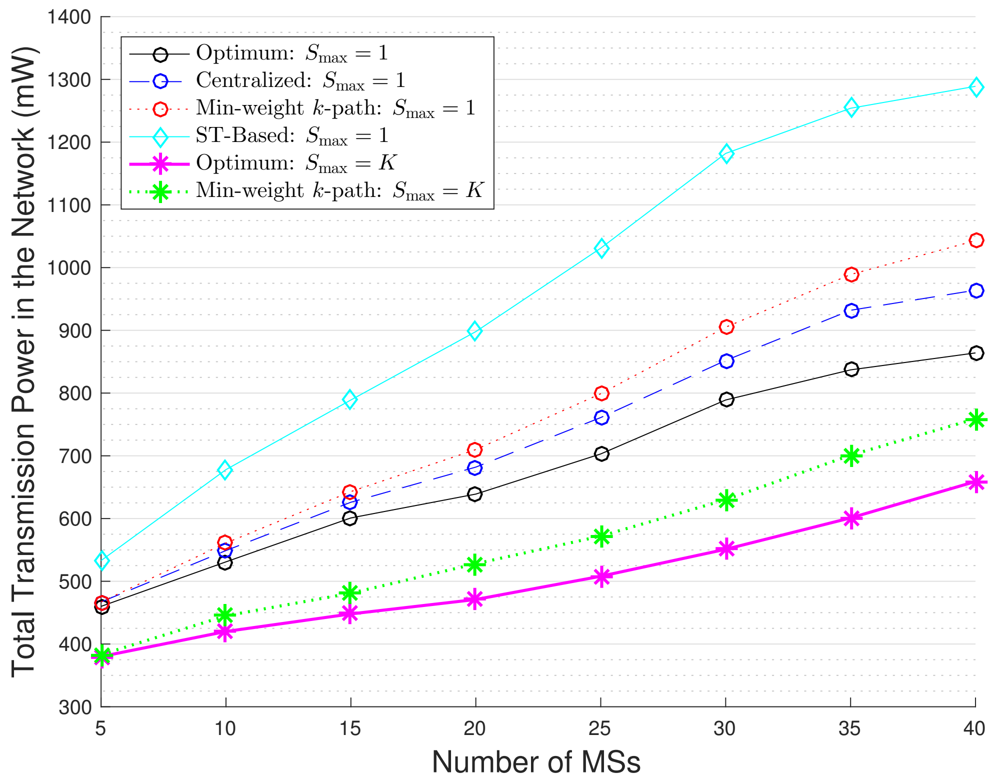


Figure 4.1: Total transmission power versus number of MSs (30 RSs uniformly distributed, $k_m^* = 1, 2,$ or 3 with equal probability for all $m \in \mathcal{M}$)

In Fig. 4.1, 30 RSs are distributed in the system service area, and the number of MSs is changed. Each MS requires 1, 2, or 3 descriptions with equal probability. The figure shows that the total transmission power increases with the number of MSs, and the slope is larger when the number of MSs is relatively smaller, since adding more MSs will most likely require more RSs to transmit or currently transmitting RSs to increase their transmission power. The total transmission power in the network increases faster in case of $S_{\max} = 1$ compared to the case of $S_{\max} = K$, since the latter allows more flexibility in selecting the RSs and allocating transmission power. As the number of MSs becomes larger, the curves gradually become saturated, because the transmissions of the RSs for each description gradually cover most of the system service area, and adding new MSs does not necessarily require the RSs to increase their transmission power or more RSs to transmit. The case of $S_{\max} = 1$ (node-disjoint multicast trees) results in higher total transmission power compared to $S_{\max} = K$, especially when the number of MSs is large. Compared to the case of $S_{\max} = K$, multicast trees in case of $S_{\max} = 1$ may be forced to use RSs with poorer link gains in order to establish disjoint paths. While in the case of $S_{\max} = K$, RSs with good link conditions can be utilized to aggregate descriptions from upstream nodes and forward them to downstream nodes. When $S_{\max} = 1$, both the proposed min-weight k-path scheme and the centralized scheme are very much close to the optimum in terms of total transmission power. This is because most MSs can receive descriptions from their nearest RSs and most transmitting RSs only need to serve one MS, and the pressure for coordinating description assignments and optimizing the total transmission power is not very high. As the number of MSs increases, the available information at individual nodes in the proposed distributed scheme limits its ability to find a better solution, which results in a larger gap between it and the optimum solution. On the other hand, the performance gap between the proposed min-weight k-path scheme and the centralized greedy scheme is very small, even when the number of MSs is large. Among all the solutions, the ST-based scheme results in the highest total transmission power, which is much larger than the total transmission power using the proposed distributed scheme. Finally, in case of $S_{\max} = K$, the proposed min-weight k-path scheme is very close to the optimum especially when the number of MSs is small. The increasing gap in the result when the number of MSs is large is due to lack of global information in the distributed scheme, which may result in that some RSs close to each other send the same descriptions unnecessarily. Similar observations can be obtained from Fig. 4.2, where we have similar setup as

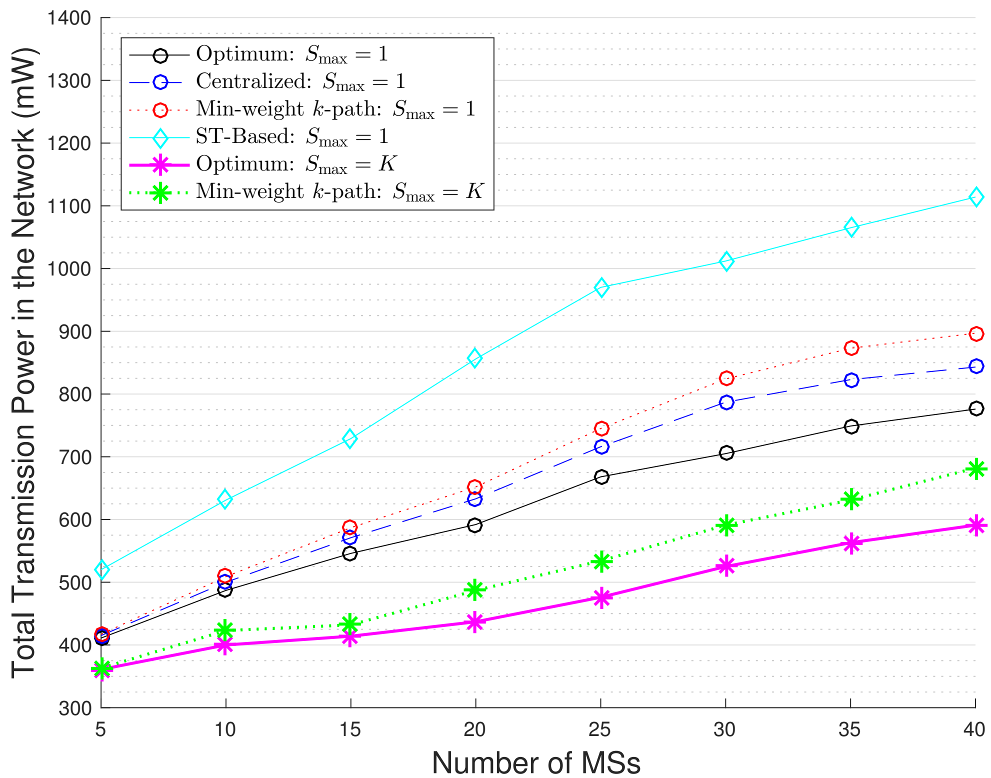


Figure 4.2: Total transmission power versus number of MSs (30 RSs randomly distributed, $k_m^* = 2$ for all $m \in \mathcal{M}$)

in Fig. 4.1 except that all MSs require two descriptions. In Fig. 4.3, we have similar setup as in Fig. 4.1 except that the RSs are distributed evenly in the system area by following the method in [93]. Similar observations as before can be obtained, except that the total transmission power in the network is much lower.

Next, 50 MSs are uniformly distributed in the system service area and the number of RSs is changed. The results are shown in Fig. 4.4. The total transmission power

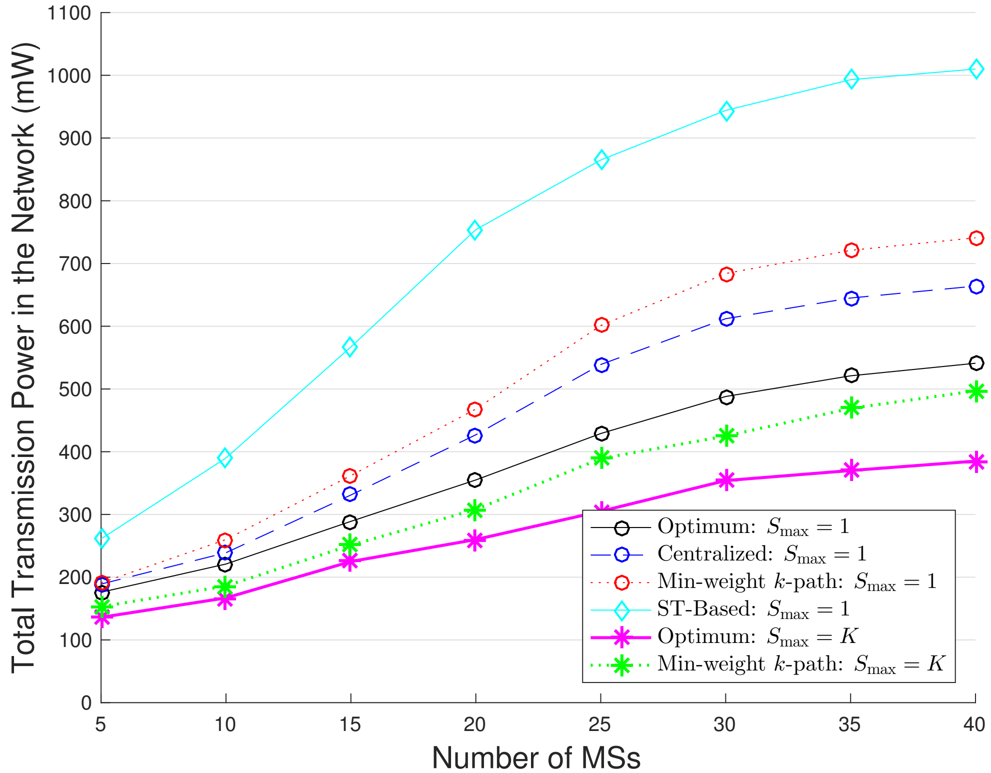


Figure 4.3: Total transmission power versus number of MSs (30 RSs evenly distributed, $k^*_m = 1, 2,$ or 3 with equal probability for all $m \in \mathcal{M}$)

decreases with the number of RSs. This is because having more RSs increases the possibility of using links with better channel conditions. Meanwhile, when the number of RSs is large enough, adding more RSs does not help reduce the total transmission power very much, simply because the channel conditions of most links are sufficiently good and there is little chance that new links created by adding more RSs may have better channel conditions. The total transmission power in the case of $S_{\max} = 1$ is much higher, compared to $S_{\max} = K$, especially when the number of RSs is small due to the strong restriction in selecting RSs to build the paths in different multicast trees in the former case. However, when the number of RSs is large, the gap between the total transmission power between these two cases becomes smaller, since the chance is

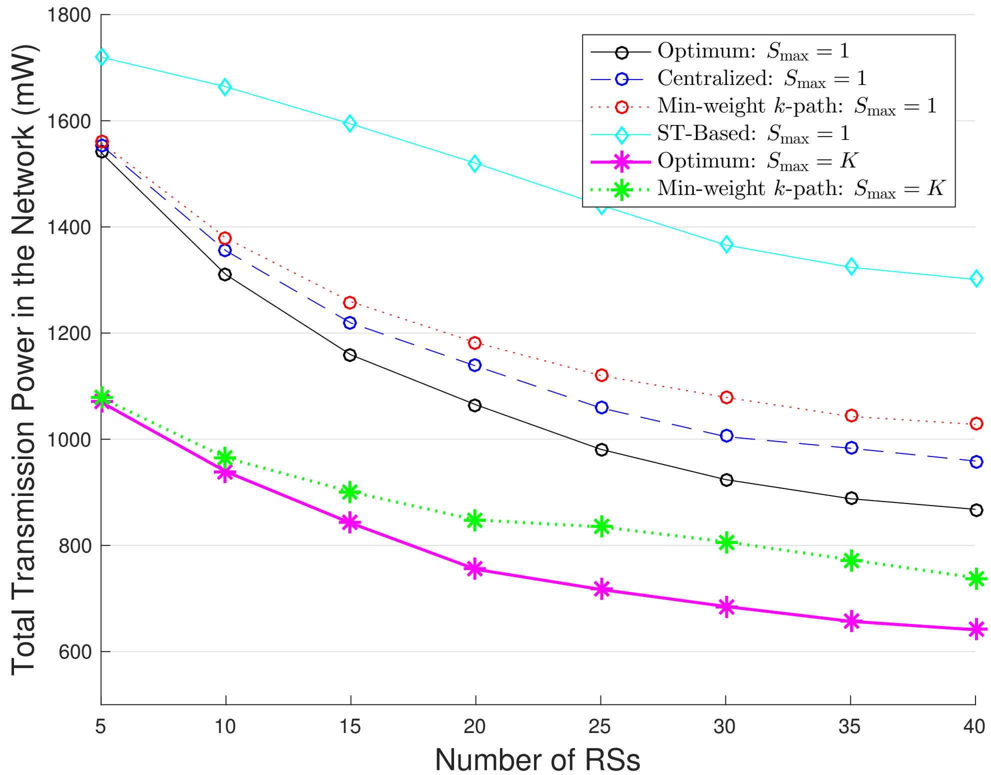


Figure 4.4: Total transmission power versus number of RSs (50 MSs)

higher to find enough links with sufficient good link quality to build the node-disjoint trees.

In Fig. 4.5, we simulate a system with a larger number of MSs and RSs, where we also increase the system service area to 2km×2km. The total transmission power increases with the number of MSs; however, it increases slowly since there is a large number of RSs that can most likely build K multicast trees with sufficiently good channel conditions and each covering the entire system service area.

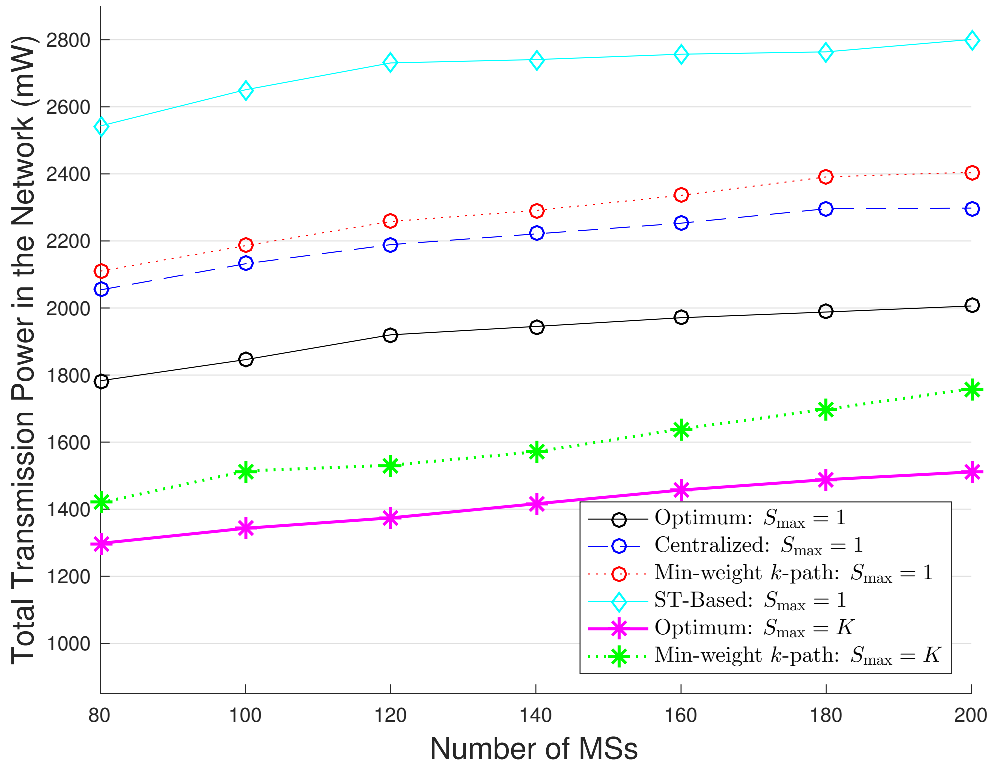


Figure 4.5: Total transmission power versus number of MSs (140 RSs)

4.5 Summary

We have studied the problem of building multiple multicast trees for delivering MD-encoded media traffic in multi-hop WMNs. Two cases have been considered, one does not allow different multicast trees to share RSs, and the other case allows each RS to forward multiple descriptions. A centralized scheme and a distributed scheme have been proposed with an objective to minimize the total transmission power of the AP and the RSs. The centralized scheme is more suitable for small-size networks; and compared to the distributed scheme, the total transmission power achieved by this scheme is closer to the optimum. The proposed minimum weight k-path scheme requires only neighboring nodes to exchange information, and is more suitable for larger size networks.

Chapter 5

Distortion-Aware Multicasting of Multiple Description Media in WMNs

In the previous two chapters, we have studied multicasting media traffic that is encoded into descriptions of equal importance, in which case the QoS at a destination is completely determined by the number of correctly received descriptions. In this chapter, we consider that the media traffic is encoded into unbalanced descriptions and study the problem of distortion-aware routing for multicasting media traffic in WMNs. Multiple multicast trees are built, each of which is rooted from one AP and delivers one description to a group of MSs with the assistance of the RSs. For each link, there is a certain probability that it can correctly transmit a given description depending on the transmission power, rate of the description, and link gain. The distortion of recovered media at an MS is determined by which description or descriptions have been correctly received. The objective is to minimize the maximum distortion of recovered media at the MSs.

The remainder of this chapter is organized as follows. In Section 5.1, the system model is described and the optimum routing problem is formulated. A centralized scheme is proposed in Section 5.2, and a distributed scheme is proposed in Section 5.3. Numerical results are shown in Section 5.4 to demonstrate performance of the proposed schemes. Section 5.5 summarizes the chapter.

5.1 System Description and Problem Formulation

Table 5.1 lists the notations used in this section. Consider media traffic that is encoded using MDC into two descriptions, which is the most widely used scenario in practice [66]. Using more than two descriptions will greatly increase the encoding and decoding complexity and aggregate data rate for similar quality [12]. Also, the rate-distortion behavior of two descriptions is well studied in the literature compared to k descriptions case where $k \geq 3$ [12, 11]. Moreover, using more than two descriptions will increase the routing complexity and messaging overhead as nodes need to constantly update their description assignments based on links conditions and distortion at destinations. Let $\{1, 2\}$ be a set of the descriptions with $k = 1$ for description one and $k = 2$ for description two. Let R_k, $k = 1, 2$, be the rate of description k. Let d_k be the achieved distortion when only description k is received, where $k = 1, 2$. As a special case, let d_0 represent the distortion when both descriptions are received. We have [94]:

$$\begin{cases} d_0 = \frac{2^{-2(R_1+R_2)}}{2^{-2R_1}+2^{-2R_2}-2^{-2(R_1+R_2)}} \cdot \sigma^2, \\ d_1 = 2^{-2R_1} \cdot \sigma^2, \\ d_2 = 2^{-2R_2} \cdot \sigma^2, \end{cases} \tag{5.1}$$

where σ^2 is the source variance, which can for simplicity be set to 1, as it only affects the absolute value of the distortion but not optimum routing selection.

From the end-to-end perspective, let $\pi_{m,k}$ donate the success probability for node m to receive description k, where $k = 1, 2$. Then, the expected distortion at the receiving node m can be written as:

$$\begin{aligned} D_m =& d_0 \cdot \pi_{m,1} \cdot \pi_{m,2} + d_1 \cdot (1 - \pi_{m,2}) \cdot \pi_{,1m} \\ &+ d_2 \cdot (1 - \pi_{m,1}) \cdot \pi_{m,2} + (1 - \pi_{m,1}) \cdot (1 - \pi_{m,2}). \end{aligned} \tag{5.2}$$

Note that the distortion is 1 when both descriptions are lost.

We consider a WMN as shown in Fig. 5.1, which consists of APs, RSs, and MSs, and define $\mathcal{A}$ as a set of the APs, $\mathcal{R}$ as a set of the RSs, and $\mathcal{M}$ as a set of the MSs. For each link (i, j) in the network, the success probability for transmitting description k is denoted as $p_{k,i,j}$, which depends on rate R_k, transmission power, and the link gain as well as the physical layer implementation such as modulation and channel coding schemes. As a special notation, $p_{0,i,j}$ represents the success probability when link (i, j) aggregates both descriptions and transmits at rate $R_1 + R_2$.

We model the network as a directed graph $\mathcal{G}(\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ a set of vertices and $\mathcal{E}$ is a set of edges. To make the flow graph complete, a set $\mathcal{S}$ which contains a single

Table 5.1: Notations used in Section5.1l

Symbol	Definition
$\mathcal{G}(\mathcal{V}, \mathcal{E})$	Graph representation of the network
$\mathcal{V}$	Set of vertices in $\mathcal{G}$
$\mathcal{E}$	Set of edges in $\mathcal{G}$
R_k	Rate of description k
f_k	Number of MSs receiving description k
d_0	Distortion when both descriptions are received
d_k	Distortion when only description k is received, $k = 1, 2$
D_m	Average distortion at MS m
$p_{k,i,j}$	Success probability for link (i, j) to transmit description k, $k = 1, 2$
$p_{0,i,j}$	Success probability for link (i, j) to transmit both descriptions at the same time
$\pi_{i,k}$	Success probability for node i to receive description k, $k = 1, 2$
Λ_m	Success probability for MS m to receive both descriptions
$X_{k,i,j}$	Number of MSs reached by description k carried through link (i, j)
$Y_{k,i,j}$	1 if link (i, j) transmits description k, and 0 otherwise
$Q_{i,k}$	1 if node i transmits description k, and 0 otherwise
$Z_{k,i,j}$	$= Y_{k,i,j} \cdot \pi_{i,k}$
$W_{k,i,j}$	$= Y_{k,i,j} \cdot Q_{i,k'} \cdot \pi_{i,k}$, $k' \neq k$
$\beta_{i,m}$	$= u_{i,m} \cdot \pi_{m,2}$

super source s and a set $\mathcal{T}$ which contains a single virtual sink t are added into the graph $\mathcal{G}$. That is, $\mathcal{V} = \mathcal{S} \cup \mathcal{A} \cup \mathcal{R} \cup \mathcal{M} \cup \mathcal{T}$. The super source s is to represent the origin of the media traffic in the backbone network. We assume that reliable links are available between the super source and the APs, i.e., $p_{k,i,j} = 1$ for $i = s$, $j \in \mathcal{A}$, and $k = 0$, 1, and 2. The virtual sink t is to collect all the flows delivered to the MSs, so that for each flow received by an MS m, there is one outgoing flow from MS m to the virtual sink t.

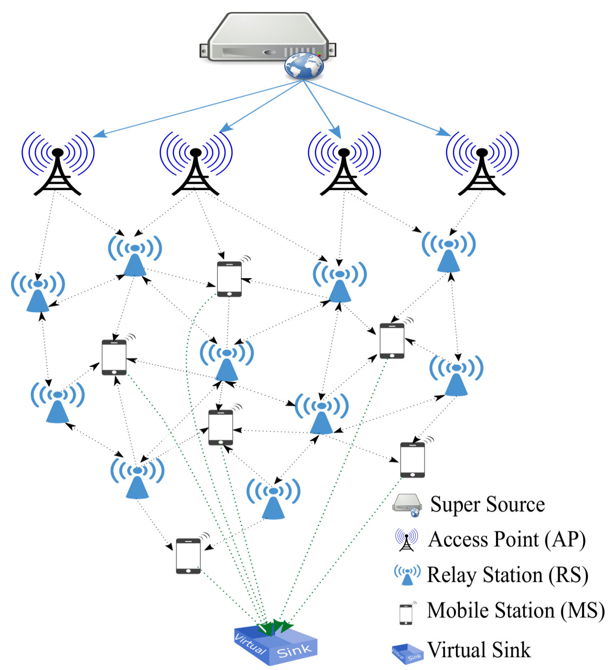


Figure 5.1: Overview of the system model

With the above preliminaries, we now set out to formulate the multi-source routing problem. We define a set of flow variables $X_{k,i,j}$ for $k = 1, 2$ and $(i, j) \in \mathcal{E}$, where $X_{k,i,j} = f$ if description k carried by link (i, j) reaches f MSs (through one or multiple hops), then

$$\sum_{\forall j \text{ with } (i,j)\in\mathcal{E}} X_{k,i,j} - \sum_{\forall j \text{ with } (j,i)\in\mathcal{E}} X_{k,j,i} = \begin{cases} f_k, & i \in \mathcal{S} \\ -f_k, & i \in \mathcal{T} \\ 0, & i \in \mathcal{A} \cup \mathcal{R} \cup \mathcal{M} \end{cases} \tag{5.3}$$

for $k = 1, 2$, where

$$0 \leq f_k \leq |\mathcal{M}| \tag{5.4}$$

and $|\mathcal{M}|$ is the total number of MSs. Constraint (5.3) is a flow balance constraint to guarantee that multicast trees originate at the super source node s and terminate at the virtual sink node t. Constraint (5.4) ensures that the number of copies for each description does not exceed the number of MSs in the network.

We introduce a set of binary variables $Y_{k,i,j}$ for $k = 1, 2$ and $(i, j) \in \mathcal{E}$ as:

$$Y_{k,i,j} = \begin{cases} 1, & \text{if link } (i,j) \text{ transmits description } k, \\ 0, & \text{otherwise.} \end{cases} \tag{5.5}$$

The relationship between $Y_{k,i,j}$ and $X_{k,i,j}$ is given by

$$\frac{X_{k,i,j}}{C} \leq Y_{k,i,j} \leq X_{k,i,j}, \quad k = 1, 2, \ (i, j) \in \mathcal{E} \tag{5.6}$$

where C is a large number so that $0 \leq \frac{X_{k,i,j}}{C} \ll 1$. This constraint forces $Y_{k,i,j}$ to be 1 if $X_{k,i,j} > 0$. For each description, all the paths originated from a given AP form a multicast tree (without considering the virtual nodes). In order to enforce a tree-like structure, we restrict every node except the virtual sink t to have at most one parent node for each description. That is,

$$\sum_{\forall i \text{ with } (i,j)\in\mathcal{E}} Y_{k,i,j} \leq 1, \quad j \in \mathcal{R} \cup \mathcal{M},\ k = 1, 2. \tag{5.7}$$

We then introduce another binary variable defined for each node as follows:

$$Q_{i,k} = \begin{cases} 1, & \text{if node } i \text{ transmits description } k, \\ 0, & \text{otherwise.} \end{cases} \tag{5.8}$$

The value of $Q_{i,k}$ is determined by $Y_{k,i,j}$'s for all j with $(i,j) \in \mathcal{E}$, and given by

$$\frac{\sum_{\forall j \text{ with } (i,j)\in\mathcal{E}} Y_{k,i,j}}{C} \leq Q_{i,k} \leq \sum_{\forall j \text{ with } (i,j)\in\mathcal{E}} Y_{k,i,j} \tag{5.9}$$

for $k = 1, 2$ and $i \in \mathcal{S} \cup \mathcal{A} \cup \mathcal{R}$, where C is a large number so that $0 \leq \frac{\sum_{\forall j \text{ with } (i,j)\in\mathcal{E}} Y_{k,i,j}}{C} \ll 1$. This constraint forces $Q_{i,k}$ to be 1 if node i is sending description k to any node in the network.

Let $\pi_{j,k}$ be the probability for node j to successfully receive description k. As a special case, for the super source, we have $\pi_{s,k} = 1$ for all $k = 1, 2$. If node i is the parent node of node j for description k, then the relationship between $\pi_{j,k}$ and $\pi_{i,k}$ is given as

$$\pi_{j,k} = \begin{cases} \pi_{i,k} \cdot p_{k,i,j}, & \text{if } Q_{i,k'} = 0 \\ \pi_{i,k} \cdot p_{0,i,j}, & \text{if } Q_{i,k'} = 1 \end{cases} \tag{5.10}$$

where $k, k' \in \{1, 2\}$, and $k \neq k'$. In (5.10), the top case represents that node i transmits description k only, and the bottom case represents that node i transmits both descriptions.

In general, we can write $\pi_{j,k}$ in terms of $\pi_{i,k}$'s for all $(i, j) \in \mathcal{E}$ as follows:

$$\pi_{j,k} = \sum_{\forall i \text{ with } (i,j)\in\mathcal{E}} \pi_{i,k} Y_{k,i,j} \left[p_{k,i,j}(1 - Q_{i,k'}) + p_{0,i,j} Q_{i,k'} \right] \tag{5.11}$$

for all $j \in \mathcal{A} \cup \mathcal{R} \cup \mathcal{M}$, $k, k^{'} \in \{1, 2\}$ and $k' \neq k$. In the right-hand side of (5.11), each term in the summation is non-zero only if $Y_{k,i,j} = 1$, in which case, node i is the parent of node j for description k.

Define $\mathbf{X} = [X_{k,i,j},\ \forall k \in \mathcal{K},\ (i, j) \in \mathcal{E}]$, $\mathbf{Y} = [Y_{k,i,j},\ \forall k \in \mathcal{K},\ (i, j) \in \mathcal{E}]$, $\mathbf{F} = [f_k,\ \forall k \in \mathcal{K}]$, and $\mathbf{Q} = [Q_{i,k},\ \forall i \in \mathcal{A} \cup \mathcal{R}, k \in \mathcal{K}]$. The multicast routing problem is then formulated as follows:

$$\text{P1.} \quad \min_{\{\mathbf{X},\mathbf{Y},\mathbf{F},\mathbf{Q}\}} \max_{m\in\mathcal{M}} D_m \tag{5.12}$$

$$(5.2) - (5.4), (5.6), (5.7), (5.9), (5.11)$$

$$Y_{k,i,j}, Q_{i,k} \in \{0, 1\},\ k = 1, 2\ ,\quad i \in \mathcal{V}, (i, j) \in \mathcal{E}$$

$$f_k, X_{k,i,j} \in \{0, 1, \cdots, |\mathcal{M}|\},\ k = 1, 2$$

where the objective is to minimize the maximum distortion for all the MSs.

P1 is not linear because of the objective function and constraint (5.11). We use a similar approach to McCormick's underestimators [95] to replace the bilinear terms. Defines $Z_{k,i,j} = \pi_{i,k} \cdot Y_{k,i,j}$ for $k = 1, 2$ and $(i, j) \in \mathcal{E}$. The value of $Z_{k,i,j}$ is determined using the following constraints:

$$0 \leq Z_{k,i,j} \leq Y_{k,i,j}, \tag{5.13}$$

$$\pi_{i,k} - (1 - Y_{k,i,j}) \leq Z_{k,i,j} \leq \pi_{i,k}, \tag{5.14}$$

for all $i \in \mathcal{A} \cup \mathcal{R} \cup \mathcal{M}$ with $(i,j) \in \mathcal{E},\ k,k^{'} \in \{1,2\}$ and $k' \neq k$. If $Y_{k,i,j} = 0$, constraint (5.13) ensures that $Z_{k,i,j} = 0$, but if $Y_{k,i,j} = 1$, constraint (5.14) ensures that $Z_{k,i,j} = \pi_{i,k}$. Therefore, (5.13) and (5.14) allow us to replace $\pi_{i,k}Y_{k,i,j}$ with $Z_{k,i,j}$ so that (5.11) becomes:

$$\pi_{j,k} = \sum_{\forall i \text{ with } (i,j) \in \mathcal{E}} Z_{k,i,j} \left[p_{k,i,j}(1 - Q_{i,k'}) + p_{0,i,j}Q_{i,k'}\right]. \tag{5.15}$$

for all $j \in \mathcal{A} \cup \mathcal{R} \cup \mathcal{M}$, $k,k^{'} \in \{1,2\}$ and $k' \neq k$.

Next, we proceed to replace the bilinear term $Z_{k,i,j} \cdot Q_{i,k'}$ in (5.15). For this, we define a binary variable $W_{k,i,j}$ to represent the bilinear term $W_{k,i,j} = Z_{k,i,j} \cdot Q_{i,k'}$. The value of $W_{k,i,j}$ is determined using the following constraints similar to (5.13)-(5.14):

$$0 \leq W_{k,i,j} \leq Q_{i,k'}, \tag{5.16}$$

$$Z_{k,i,j} - (1 - Q_{i,k'}) \leq W_{k,i,j} \leq Z_{k,i,j}, \tag{5.17}$$

for all $i \in \mathcal{A} \cup \mathcal{R} \cup \mathcal{M}$ with $(i,j) \in \mathcal{E},\ k,k^{'} \in \{1,2\}$ and $k' \neq k$. Now we can rewrite (5.15) in a linear form as follows:

$$\pi_{j,k} = \sum_{\forall i \text{ with } (i,j) \in \mathcal{E}} p_{k,i,j}(Z_{k,i,j} - W_{k,i,j}) + p_{0,i,j}W_{k,i,j} \tag{5.18}$$

for all $j \in \mathcal{A} \cup \mathcal{R} \cup \mathcal{M}$ and $k = 1, 2$. This is the linearized format of (5.11).

To linearize the objective function, we first define Λ_m as the success probability for MS m to receive both descriptions at the same time. That is

$$\Lambda_m = \pi_{m,1} \cdot \pi_{m,2}. \tag{5.19}$$

Using Λ_m we can write (5.2) in a linear form as follows:

$$D_m = d_0 \cdot \Lambda_m + d_1(\pi_{m,1} - \Lambda_m) + d_2(\pi_{m,2} - \Lambda_m) + 1 + \Lambda_m - \pi_{m,1} - \pi_{m,2}. \tag{5.20}$$

Now we proceed to linearize (5.19). First of all, we can write $\pi_{m,1}$ in a binary format with $u_{l,m} \in \{0, 1\}$ having the magnitude of 2^{-l}. For a given small positive number ϵ, we can have

$$\pi_{m,1} - \sum_{l=1}^{L} 2^{-l} \cdot u_{l,m} \leq \epsilon. \tag{5.21}$$

When L is sufficiently large, we can find $u_{l,m}$'s so that (5.21) holds for any given ϵ. For example, $L = 7$ and $\epsilon = 0.0079$ can guarantee that $\pi_{m,1}$ is accurate up to two decimal places. Now we can write (5.19) as follows,

$$\Lambda_m = \sum_{l=1}^{L} 2^{-l} \cdot u_{l,m} \cdot \pi_{m,2}, \tag{5.22}$$

which is still not linear because of the term $u_{l,m} \cdot \pi_{m,2}$. Further introducing a variable $\beta_{l,m} = u_{l,m} \cdot \pi_{m,2}$, we can define it similar to (5.13) and (5.14) as follows:

$$0 \leq \beta_{l,m} \leq u_{l,m}, \tag{5.23}$$

$$\pi_{m,2} - 1 + u_{l,m} \leq \beta_{l,m} \leq \pi_{m,2}. \tag{5.24}$$

Now constraint (5.22) can be rewritten as follows,

$$\Lambda_m = \sum_{l=1}^{L=7} 2^{-l} \cdot \beta_{l,m}. \tag{5.25}$$

Define $\mathbf{Z} = [Z_{k,i,j},\ \forall k \in \mathcal{K},\ (i,j) \in \mathcal{E}]$, and $\mathbf{W} = [W_{k,i,j},\ \forall k \in \mathcal{K},\ (i,j) \in \mathcal{E}]$, and $\mathbf{U} = [u_{l,m},\ \forall l = 1, \cdots, 7, m \in \mathcal{M}]$, and $\beta = [\beta_{k,i,j},\ \forall k \in \mathcal{K},\ (i,j) \in \mathcal{E}]$. By incorporating all the above, problem P1 can be transformed into the following linear problem:

$$\text{P2.} \quad \min_{\{\mathbf{X},\mathbf{Y},\mathbf{F},\mathbf{Q},\mathbf{Z},\mathbf{W},\mathbf{U},\beta\}} \max_{m \in \mathcal{M}} D_m \tag{5.26}$$

$$(5.3), (5.4), (5.6), (5.7), (5.9), (5.13), (5.14),$$

$$(5.16) - (5.18), (5.20), (5.21), (5.23) - (5.25)$$

$$\pi_{i,k} = 1, \qquad i = S,\ k = 1, 2 \tag{5.27}$$

$$f_k, X_{k,i,j} \in \{0, 1, \cdots, |\mathcal{M}|\},\ k = 1, 2$$

$$Y_{k,i,j}, Q_{i,k}, u_{l,m} \in \{0, 1\},\ k = 1, 2$$

$$Z_{k,i,j}, W_{k,i,j} \in [0, 1],\ k = 1, 2.$$

This is a mixed linear integer optimization problem, which in general is NP-hard problem, and can be solved using commercially available software, such as CPLEX. For solving this MILP, CPLEX uses branch-and-cut algorithm and simplex method to perform dynamic search over relaxed linear subproblems until the best known solution that satisfies all the integrality requirements is found [91]. Thus, the complexity of the problem grows with the number of variables, where it also has exponential worst case running time. Moreover, it cannot be used in distributed implementation since it requires full knowledge of the network. Next we design heuristic schemes with lower complexity.

5.2 Centralized Heuristic Scheme

The scheme proposed in this section requires some overhead for collecting the channel condition information at a central node, which can be located at the backbone network. We consider a relative static WMN, where the nodes, including the APs, RSs, and MSs, have little mobility, so that changes to the link conditions can be neglected for a relatively long time period.

Before discussing the proposed scheme, we clarify the following notations:

- $P_{m,k}$ is a path that delivers description k from the super source to node m
- $\mathcal{G} = \mathcal{G}(\mathcal{V}, \mathcal{E})$ is a graph defined by both the node set $\mathcal{V}$ the edge set $\mathcal{E}$
- For a graph $\mathcal{G}(\mathcal{V}, \mathcal{E})$,
  - "$i \in \mathcal{G}$" is equivalent to "$i \in \mathcal{V}$";
  - "$(i, j) \in \mathcal{G}$" is equivalent to "$(i, j) \in \mathcal{E}$";
  - "$\mathcal{G} \cup \{(i, j)\}$" is equivalent to "$\mathcal{V} \cup \{i, j\}$, and $\mathcal{E} \cup \{(i, j)\}$".
- For a path P
  - "$(i, j) \in P$" returns link (i, j) along P;
  - "$i \in P$" if there exists (i, j) so that $(i, j) \in P$;

– "$\forall (i,j) \in P$" returns an ordered list of the links along P from the upstream to the downstream;

– "$i \in P_1 \cap P_2$" if and only if "$i \in P_1$ and $i \in P_2$";

– "$P \in \mathcal{G}$" returns a path P, along which all nodes and links are in graph $\mathcal{G}$;

– "$\mathcal{G} \setminus P$" returns a graph that is obtained after removing all nodes and links along path P from graph $\mathcal{G}$.

The proposed heuristic scheme is given in Algorithms 1-5. Algorithm 1 outlines the process for finding six potential paths that can be used to reach MS m. These paths belong to three versions:

- two a-version paths $P^a_{m,1}$ and $P^a_{m,2}$ (line 1). $P^a_{m,k}$ ($k = 1,2$) is a path built in the original graph $\mathcal{G}$ for delivering description k to MS m with the highest end-to-end success probability by assuming that all links deliver description k only (i.e., no links deliver description $k' \neq k$);

- two b-version paths $P^b_{1,m}$ and $P^b_{m,2}$ (line 4). $P^b_{m,k}$ is a path built in the graph $\mathcal{G} \setminus P^a_{k',m}$ ($k' = 1,2$ and $k' \neq k$) and delivers description k to MS m with the highest success probability by assuming that all links in $\mathcal{G} \setminus P^a_{m,k'}$ deliver description k only;

- two c-version paths $P^c_{m,1}$ and $P^c_{m,2}$ (line 6). $P^c_{m,k}$ is a path built in the original graph $\mathcal{G}$ and delivers description k to MS m with the highest success probability by assuming that all links in $\mathcal{G} \setminus P^a_{m,k'}$ deliver description k only and all links shared with $P^a_{m,k'}$ deliver both descriptions k and k'. Therefore, in line 6, $\tilde{p}_{k,i,j} = p_{k,i,j}$ if $(i,j) \notin P^a_{m,k'}$, and $\tilde{p}_{k,i,j} = p_{0,i,j}$ if $(i,j) \in P^a_{m,k'}$ for $k, k' = 1,2$ and $k' \neq k$.

In Algorithm 1, $S^v_{k,m,i} = k$ in lines 2, 5, and 7 is the temporary description assignment for node i when it is used in the v-version path for MS m, where $v \in \{a, b, c\}$. It is initially set to 0 for all $v \in \{a, b, c\}$, $m \in \mathcal{M}$, $i \in \mathcal{V}$, and $k \in \{1, 2\}$.

Let p_1 and p_2 be the paths for delivering descriptions 1 and 2, respectively. The six paths found above provide four different combinations to serve both descriptions to MS m. That is, $(p_1, p_2) \in \mathcal{P}_m = \{(P^a_{m,1},\ P^b_{m,2}),\ (P^a_{m,1},\ P^c_{m,2}),\ (P^b_{1,m},\ P^a_{m,2}),\ (P^c_{m,1},\ P^a_{m,2})\}$. For the path combination (p_1, p_2), the resulted distortion at MS m is denoted as $D_m(p_1, p_2)$. Algorithm 2 is used to find $D_m(p_1, p_2)$. When a c-version path is used, the two paths may share links, and the success delivery probability of a shared link (i, j) is $p_{0,i,j}$ for each description. The success delivery probability for each path is calculated in lines 1 and 2 in Algorithm 2, based on which (5.2) is used to find the distortion for this path combination.

After all $D_m(p_1, p_2)$'s have been found for MS m, $D^{'}_m$ is the lowest distortion that can be achieved with all the four path combinations. This is in line 9 of Algorithm 1.

Algorithm 3 describes the basic process for building the multicast graph $\mathcal{G}_c$, which is initialized to be empty. Each round within the while-loop is to select the best (p_1, p_2) combination for one MS and add the paths to $\mathcal{G}_c$. In the algorithm, D^*_m is the best distortion that can be achieved based on the current description assignment information. It is initialized to $D^{'}_m$ and updated each time the description assignment is changed. The process starts from the MS m with the highest D^*_m (line 3). For each of the four path combinations $(p_1(q), p_2(q)$ for $q = 1 \cdots 4)$, assuming $p_1(q)$ and $p_2(q)$ are used to provide descriptions 1 and 2, respectively, to MS m, the description assignments for all nodes along these two paths are updated using Algorithm 4, and

Algorithm 1 Finding possible paths for each MS

Require: $\mathcal{G}, \mathcal{M}$
Ensure: Multicast Subgraph $\mathcal{G}_c$

```
Find $P^a_{m,k} = \arg\max_{\forall P_{m,k} \in \mathcal{G}} \prod_{\forall (i,j) \in P_{m,k}} p_{k,i,j}$, $\forall m \in \mathcal{M}$, and $k = 1, 2$
$S^a_{k,m,i} = k, \ \forall i \in P^a_{m,k}, \ m \in \mathcal{M}$, and $k = 1, 2$
for all $m \in \mathcal{M}$ do
    Find $P^b_{m,k} = \arg\max_{\forall P_{m,k} \in \mathcal{G} \setminus P^a_{m,k'}} \prod_{\forall (i,j) \in P_{m,k}} p_{k,i,j}$, $\forall m \in \mathcal{M}, \ k, k' = 1, 2$, and $k \neq k'$ ,
    $S^b_{k,m,i} = k, \forall \ i \in P^b_{m,k}$ and $k = 1, 2$
    Find $P^c_{m,k} = \arg\max_{\forall P_{m,k} \in \mathcal{G}} \prod_{\forall (i,j) \in P_m} \tilde{p}_{k,i,j}$ $\forall m \in \mathcal{M}, \ k, k' = 1, 2$, and $k \neq k'$ ,
    $S^c_{k,m,i} = k, \forall \ i \in P^c_{m,k}$
    $\mathcal{P}_m = \{(P^a_{m,1}, P^b_{m,2}), (P^a_{m,1}, P^c_{m,2}), (P^b_{1,m}, P^a_{m,2}), (P^c_{m,1}, P^a_{m,2})\}$
    Find $D^{'}_m = \min_{(p_1,p_2) \in \mathcal{P}_m} D_m(p_1, p_2)$, where $D_m(p_1, p_2)$ is calculated using Algorithm 2
end for
```

Algorithm 2 Finding initial distortion

```
$\pi_{m,1} = \prod_{(i,j) \in p_1 \setminus p_2} p_{1,i,j} \prod_{(i,j) \in p_1 \cap p_2} p_{0,i,j}$
$\pi_{m,2} = \prod_{(i,j) \in p_2 \setminus p_1} p_{1,i,j} \prod_{(i,j) \in p_2 \cap p_1} p_{0,i,j}$
Find $D_m(\pi_{m,1}, \pi_{m,2})$ using (5.2)
```

$D_{\min,q}$ is the resulted worst case distortion found in Algorithm 5. Algorithms 4 and 5 will be described later on. When the for-loop between lines 5 and 11 in Algorithm 3 is done, q^* is the value of q that results in the lowest $D_{\min,q}$ for all $q = 1 \cdots 4$. At this point, $p_1(q^*)$ and $p_2(q^*)$ are the finalized paths to reach MS m (line 12). The multicast graph $\mathcal{G}_c$ and the final description assignments are updated accordingly in line 13.

Algorithm 3 Build Multicast Subgraph

1: $\mathcal{G}_c = \emptyset$, $\mathcal{M}_c = \mathcal{M}$, and $D^*_m = D^{'}_m \forall m \in \mathcal{M}_c$
2: **while** $\mathcal{M}_c \neq \emptyset$ **do**
3: $\quad m = \arg\max_{n \in \mathcal{M}_c} D^*_n,\ \mathcal{M}_c = \mathcal{M}_c \setminus \{m\}$
4: $\quad q = 1,$
5: $\quad$ **for** $(p_1(q), p_2(q)) \in \{(P^a_{m,1}, P^b_{m,2}),\ (P^a_{m,1}, P^c_{m,2}),\ (P^b_{m,1}, P^a_{m,2}),\ (P^c_{m,1}, P^a_{m,2})\}$ **do**
6: $\quad\quad S^{'}_i(q) = S_i\ \forall\ i \in \mathcal{G}_c$ and $S^{'}_i(q) = 0\ \forall\ i \notin \mathcal{G}_c$
7: $\quad\quad$ Updating description information using Algorithm 4
8: $\quad\quad$ Find $D^*_{q,n}\ \forall n \in \mathcal{M}$ using Algorithm 5
9: $\quad\quad D_{\min,q} = \max_{n \in \mathcal{M}} D^*_{q,n}$
10: $\quad\quad q = q + 1$
11: $\quad$ **end for**
12: $\quad q^* = \arg\min_q D_{\min,q}$
13: $\quad \mathcal{G}_c = \mathcal{G}_c \cup p_1(q^*) \cup p_2(q^*),\ S_i = S^{'}_i(q^*)\ \forall\ i \in \mathcal{G}_c$
14: $\quad D^*_n = D^*_{q^*,n},\ \forall n\ \in \mathcal{M}$
15: **end while**

What makes the process of selecting the (p_1, p_2) combination complicated is that different paths to serve the same or different MSs may share links or nodes. When a node is along two paths that deliver different descriptions, the description assigned to it should be "3" (i.e., assigned to combine and send both descriptions). In Algorithm 4, each round in the outer for-loop is to update the description information of the nodes along one of the two paths. For a link (i, j) along path p_k, the temporary description assigned to node i is k if the node currently has not been assigned a description or has been assigned to description k; otherwise, its temporary description assignment is 3 (lines 4-8). Note that the temporary description assignments $S'_i(q)$ are only for nodes i along paths $p_1(q)$ and $p_2(q)$. Once q^* is found in line 12 of Algorithm 3, the $S'_i(q^*)$'s of the nodes along $p_1(q^*)$ and $p_2(q^*)$ will become the final description assignments of these nodes as in line 13 of Algorithm 3. Meanwhile, this description assignments may affect the temporary description assignments if the nodes are also along the potential paths to any MSs in $\mathcal{M}_c$. The updates of these temporary description assignments are given in lines 9-15 of Algorithm 4.

Algorithm 4 Updating description information

1: $p_1 = p_1(q)$ and $p_2 = p_2(q)$
2: **for** $k = 1:2$ **do**
3:   **for all** $(i,j) \in p_k$ **do**
4:     **if** $S_i^{'}(q) = 0$ **then**
5:       $S_i^{'}(q) = k$
6:     **else if** $S_i^{'}(q) \neq k$ **then**
7:       $S_i^{'}(q) = 3$
8:     **end if**
9:     **for all** $\forall v \in \{a,b,c\}$ and $n \in \mathcal{M}_c$ **do**
10:       **if** $i \in P_{n,k'}^v$ and $k' \neq k$ **then**
11:         $S_{k',n,i,}^v = 3$
12:       **end if**
13:       **if** $i \in P_{n,k}^v$ and $S_i^{'} = 3$ **then**
14:         $S_{k,n,i}^v = 3$
15:       **end if**
16:     **end for**
17:   **end for**
18: **end for**

As soon as the description assignment information is updated, the resulted distortion should be recalculated. This is done in Algorithm 5, which includes three parts. The first part (lines 1-13) is for the nodes in the current multicast graph. The paths for these nodes have already been finalized, but the description assignments of the nodes along these paths may be affected by Algorithm 4 where the nodes distortions need to be recalculated. The second part (lines 14-24) is for node m, which is the node whose path combination $p_1(q)$ and $p_2(q)$ is being examined in Algorithm 3. The resulted distortion is calculated based on this pair of paths. The third part (lines 25-40) is for the remaining nodes that are not yet included in the multicast trees. The temporary description assignments of the nodes along the paths to these nodes may also be changed after running Algorithm 4. Since each of them still has six potential paths as found in Algorithm 1, we need to consider all four different path combinations for each of them, find the distortion based on each combination, and then find the best distortion from the four as $D^*_{q,n}$.

Before finishing this section, we briefly analyze the computational complexity of the scheme for the worst case scenario. For Algorithm 1, if the Dijkstra's shortest path algorithm with Fibonacci heap implementation is used to build different paths (By defining the cost of each link (i, j) as $-\log(p_{k,i,j})$, finding a path with maximum success delivery probability is equivalent to finding a path with the minimum cost, which is a sum of the costs of individual links along the path). The computational complexity to find the paths in lines 1, 4, and 6 is $O(|\mathcal{E}| + |\mathcal{V}| \log |\mathcal{V}|)$, where $|\mathcal{E}|$ is the total number of links and $|\mathcal{V}|$ is the total number of nodes in the network. In addition, the complexity in line 9 is dominated by running Algorithm 2, because the minimization compares only 4 distortions each for one (p_1, p_2) combination. For Algorithm 2, the complexity of finding the distortion for each (p_1, p_2) combination increases linearly with the number of links along the paths and is at most $O(|\mathcal{E}|)$. Therefore, the computational complexity of Algorithm 1 is at most $C_1 = |\mathcal{M}|O(|\mathcal{E}| + |\mathcal{V}| \log |\mathcal{V}| + O(|\mathcal{E}|)) = O(|\mathcal{M}|(|\mathcal{E}| + |\mathcal{V}| \log |\mathcal{V}|))$.

For analyzing the computational complexity of Algorithm 3, we need to find the complexities of Algorithms 4 and 5. For Algorithm 4, the **for** loop between lines 2 and 18 runs for two rounds, the **for** loop between lines 3 and 17 runs for at most $|\mathcal{E}|$ times, and the **for** loop between lines 9 and 16 runs for at most $3|\mathcal{M}|$ rounds (3 possible values for v and at most $|\mathcal{M}|$ possible values for n). Therefore, the overall complexity of Algorithm 4 is at most $C_4 = O(|\mathcal{E}||\mathcal{M}|)$. For Algorithm 5, the complexity for the first part (lines 1-13) and the third part (lines 25-40) each is at most $O(|\mathcal{M}||\mathcal{E}|)$, and the complexity for the second part (lines 14-24) is at most $(2|\mathcal{E}|)$. The overall complexity of Algorithm 5 is $C_5 = O(|\mathcal{M}||\mathcal{E}|))$. Back to Algorithm 3, the **while** loop between lines 2 and 15 should run for at most $|\mathcal{M}|$ rounds. Complexity for finding maximum distortion in line 3 is $O(|\mathcal{M}|)$ (similar for line 9). The **for** loop between lines 5 and 11 runs for 4 rounds each for one path combination. Therefore, the overall complexity of Algorithm 3 is at most $C_3 = O(|\mathcal{M}|(|\mathcal{M}|+4(C_4+C_5+|\mathcal{M}|))) = O(|\mathcal{M}|^2|\mathcal{E}|)$.Thus, the computational complexity for running the proposed scheme is at most $C_1 + C_3 = O(|\mathcal{M}|(|\mathcal{E}| + |\mathcal{V}| \log |\mathcal{V}|)) + O(|\mathcal{M}|^2|\mathcal{E}|)$.

5.3 Distributed Heuristic Scheme

For the distributed heuristic scheme, we modify the minimum weight k-path scheme proposed in Chapter 4. The scheme was originally designed to minimize the total transmission power in the network. We adapt the scheme for minimizing the maximum distortion in this chapter. Before presenting the details, we first define (or redefine) some notations.

Algorithm 5 Recalculating distortion

for $n \in \mathcal{G}_c \cap \mathcal{M}$ **do**
  $\pi_{n,1} = 1,\ \pi_{n,2} = 1$
  for $k = 1 : 2$ **do**
    for all $(i, j) \in P_{n,k}$ **do**
      if $S'_i(q) = k$ **then**
        $\pi_{n,k} = \pi_{n,k} \cdot p_{k,i,j}$
      else
        $\pi_{n,k} = \pi_{n,k} \cdot p_{0,i,j}$
      end if
    end for
  end for
  Find $D^*_{q,n}$ using (5.2)
end for
$\pi_{m,1} = 1,\ \pi_{m,2} = 1$
for $k = 1 : 2$ **do**
  for all $(i, j) \in p_k(q)$ **do**
    if $S'_i(q) = k$ **then**
      $\pi_{m,k} = \pi_{m,k} \cdot p_{k,i,j}$
    else
      $\pi_{m,k} = \pi_{m,k} \cdot p_{0,i,j}$
    end if
  end for
end for
Find $D^*_{q,m}$ using (5.2)
for $n \in \mathcal{M}_c$ **do**
  for $(p_1, p_2) = \{(P^a_{n,1}, P^b_{n,2}),\ (P^a_{n,1}, P^c_{n,2}),\ (P^b_{n,1}, P^a_{n,2}),\ (P^c_{n,1}, P^a_{n,2})\}$ **do**
    $\pi_{n,1} = 1,\ \pi_{n,2} = 1$
    for $k = 1 : 2$ **do**
      for all $(i, j) \in p_k$ **do**
        if $S^v_{k,n,i} = k$ ($v = a$ if $p_k = P^a_{n,k}$; $v = b$ if $p_k = P^b_{n,k}$; $v = c$ if $p_k = P^c_{n,k}$) **then**
          $\pi_{n,k} = \pi_{n,k} \cdot p_{k,i,j}$
        else
          $\pi_{n,k} = \pi_{n,k} \cdot p_{0,i,j}$
        end if
      end for
    end for
    Find $D_n(p_1, p_2)$ using (5.2)
  end for
  $D^*_{q,n} = \min_{(p_1,p_2)} D_n(p_1, p_2)$
end for

5.3.1 Notations

From the minimum weight k-path scheme, the following sets $\mathcal{K}_i$, $\mathcal{C}_{i,k}$, $\mathcal{R}_{i,k}$, and $\mathcal{T}_i$ are used as defined in Chapter 4 without any changes. However, in order to adapt the scheme for min-max distortion based multicast, we redefine $\mathcal{S}_i$, $\text{Parent}_{i,k}$, and $W_{i,k}$, and we also introduce $\tilde{W}_{i,k}$, $\text{BetterParent}_{i,k}$, $\text{PossPar}_{i,k}$, and $\pi_{i,k}(j,s)$ as follows:

$\mathcal{S}_i$: a set of the descriptions assigned for node i to transmit. This is defined similarly to the original scheme, except that it is initialized to $\mathcal{S}_i = \{\}$ for all $i \in \mathcal{A} \cup \mathcal{R}$.

$\pi_{i,k}$: the success delivery probability for node i to receive description k from its parent node $\text{Parent}_{i,k}$. Initially, $\pi_{i,k} = 0$ for all $i \in \mathcal{R} \cup \mathcal{M}$.

$\text{BetterParent}_{i,k}$: a potential parent node that transmits description k and results in better distortion at node i.

$\tilde{\pi}_{i,k}$: the success delivery probability if node i receives description k from $\text{BetterParent}_{i,k}$.

$\text{PossPar}_{i,k}$, $k = 1, 2$: a set of nodes to which node i can send DescReq_k message.

$\text{PossPar}_{i,0}$, a set of nodes to which node i can send both DescReq_1 and DescReq_2 messages.

5.3.2 Finding Possible Distortions

For node i, given $\text{PossPar}_{i,1}$, $\text{PossPar}_{i,2}$, and $\text{PossPar}_{i,0}$, the following five different methods $l = 1 : 5$ are available to select possible parent nodes and corresponding distortion. For the lth method, $p_k(l)$ is the selected parent node for description k.

1. $l = 1$: $p_1(l)$ is selected first from $\text{PossPar}_{i,1}$, and then $p_2(l)$ is selected from $\text{PossPar}_{i,2}$ with $p_2(l) \neq p_1(l)$. That is,

   - $p_1(1) = \arg\max_{j \in \text{PossPar}_{i,1}} \pi_{j,1} \cdot p_{1,j,i}$, and

- $p_2(1) = \arg\max_{j \in \text{PossPar}_{i,2} \setminus p_1(1)} \pi_{j,2} \cdot p_{2,j,i}$.

With this, we have $\pi'_{i,1}(1) = \pi_{j,1} \cdot p_{1,j,i}|_{j=p_1(1)}$, and $\pi'_{i,2}(1) = \pi_{j,2} \cdot p_{2,j,i}|_{j=p_2(1)}$.

2. $l = 2$, $p_1(l)$ is selected first from $\text{PossPar}_{i,1}$, and then $p_2(l)$ is selected from $\text{PossPar}_{i,0}$ with $p_2(l) \neq p_1(l)$. That is,

   - $p_1(2) = \arg\max_{j \in \text{PossPar}_{i,1}} \pi_{j,1} \cdot p_{1,j,i}$, and
   - $p_2(2) = \arg\max_{j \in \text{PossPar}_{i,0} \setminus p_1(2)} \pi_{j,2} \cdot p_{0,j,i}$.

   With this, we have $\pi'_{i,1}(2) = \pi_{j,1} \cdot p_{1,j,i}|_{j=p_1(2)}$, and $\pi'_{i,2}(2) = \pi_{j,2} \cdot p_{0,j,i}|_{j=p_2(2)}$.

3. $l = 3$, $p_2(l)$ is selected first from $\text{PossPar}_{i,2}$, and then $p_1(l)$ is selected from $\text{PossPar}_{i,1}$ with $p_1(l) \neq p_2(l)$. That is,

   - $p_2(3) = \arg\max_{j \in \text{PossPar}_{i,2}} \pi_{j,1} \cdot p_{1,j,i}$, and
   - $p_1(3) = \arg\max_{j \in \text{PossPar}_{i,1} \setminus p_2(3)} \pi_{j,2} \cdot p_{2,j,i}$.

   With this, we have $\pi'_{i,1}(3) = \pi_{j,1} \cdot p_{1,j,i}|_{j=p_1(3)}$, and $\pi'_{i,2}(3) = \pi_{j,2} \cdot p_{2,j,i}|_{j=p_2(3)}$.

4. $l = 4$, $p_2(l)$ is selected first from $\text{PossPar}_{i,2}$, and then $p_1(l)$ is selected from $\text{PossPar}_{i,0}$ with $p_2(l) \neq p_1(l)$. That is,

   - $p_2(4) = \arg\max_{j \in \text{PossPar}_{i,2}} \pi_{j,1} \cdot p_{0,j,i}$, and
   - $p_1(4) = \arg\max_{j \in \text{PossPar}_{i,0} \setminus p_2(4)} \pi_{j,2} \cdot p_{2,j,i}$.

   With this, we have $\pi'_{i,1}(4) = \pi_{j,1} \cdot p_{0,j,i}|_{j=p_1(4)}$, and $\pi'_{i,2}(4) = \pi_{j,2} \cdot p_{2,j,i}|_{j=p_2(4)}$.

5. $l = 5$, both $p_1(l)$ and $p_2(l)$ are selected from $\text{PossPar}_{i,0}$. That is,

   - $p_1(5) = \arg\max_{j \in \text{PossPar}_{i,0}} \pi_{j,1} \cdot p_{0,j,i}$, and

- $p_2(5) = \arg\max_{j \in \text{PossPar}_{i,0}} \pi_{j,2} \cdot p_{0,j,i}$.

With this, we have $\pi'_{i,1}(5) = \pi_{j,1} \cdot p_{0,j,i}|_{j=p_1(5)}$, and $\pi'_{i,2}(5) = \pi_{j,2} \cdot p_{0,j,i}|_{j=p_2(5)}$.

The possible distortion is calculated using (5.2) based on each of the above five combinations as

$$\tilde{D}_i(l) = D_i|_{\pi_{i,1}=\pi'_{i,1}(l), \pi_{i,2}=\pi'_{i,2}(l)}, \qquad l = 1, 2, \ldots, 5 \tag{5.28}$$

5.3.3 Predicting Possible Distortion

When node j is currently transmitting description 1 or 2 but not both, i.e., $\mathcal{S}_j = \{k\}$, for $k = 1, 2$, we want to find out, if it switches to transmit both descriptions, i.e., $\mathcal{S}_j = \{1, 2\}$, how this affects the distortion of its existing child nodes. Since the objective is to minimize the worst system-level distortion, transmitting both descriptions can be done if it helps reduce the system-level distortion. For this reason, node j should first know the worst distortion of its own child node, if it switches to send both descriptions.

When $\mathcal{S}_j = \{k\}$, each of its child nodes v does the following:

- assumes $\mathcal{S}_j = \{1, 2\}$ and updates $\text{PossPar}_{v,1} \backslash \{j\}$, $\text{PossPar}_{v,2} \backslash \{j\}$, and $\text{PossPar}_{v,0} \cup \{j\}$,
- finds $\pi'_{v,k}(l)$ for $l = 1 : 5$ and $k = 1, 2$ using the procedure in Section 5.3.2,
- finds $\tilde{D}_v(l) = D_v|_{\pi_{v,1}=\pi'_{v,1}(l), \pi_{v,2}=\pi'_{v,2}(l)}$ for $l = 1 : 5$,
- finds $\tilde{D}_{\min,v} = \min_{l=1:5} \tilde{D}_v(l)$, and
- sends $\tilde{D}_{\min,v}$ to node j through $\text{JoinReq}_{v,j,k}$ message.

That is, $\tilde{D}_{\min,v}$ is the best possible distortion that can be achieved at node v if node j switches from sending description k only to sending both descriptions.

All the child nodes of node j send their $\tilde{D}_{\min,v}$ values to node j, which finds

$$\mathrm{MaxD}_j = \max_{v \in \mathcal{C}_{j,k}} \tilde{D}_{\min,v}. \tag{5.29}$$

That is, MaxD_j is the worst possible distortion of the existing child nodes if node j switches from sending description k only to sending both descriptions. This value is included in $\mathrm{Announcement}_j$ messages.

5.3.4 Receiving $\mathrm{Announcement}_j$ Message

Upon receiving $\mathrm{Announcement}_j$ message from node j, node i first runs Algorithm 6 to find whether node j can be added to $\mathrm{PossPar}_{i,k}$ for $k = 0, 1, 2$.

- If node j is currently not transmitting any descriptions, then it is added to $\mathrm{PossPar}_{i,k}$ for $k = 0, 1, 2$ (Lines 2-3) since it is available to send any descriptions to node i without affecting the distortion of other nodes;

- If node j is currently transmitting all descriptions, then it can only be added to $\mathrm{PossPar}_{i,0}$ (Lines 4-5);

- if node j is transmitting description k only, then it is added to $\mathrm{PossPar}_{i,k}$ (Line 7). In addition, it may be added to $\mathrm{PossPar}_{i,0}$ if having node j transmits both descriptions can improve the system-level min-max distortion (Lines 9-11). W_0 in Line 8 is the distortion at node i if node j switches to transmit both descriptions. In Line 9, there are two conditions that needs to be satisfied before node j can be added to $\mathrm{PossPar}_{i,0}$, which are : 1) $\mathrm{MaxD}_j \leq D_i$ is true, switching node j from sending only one description to sending both descriptions does not increase the system level worst distortion., and 2) $W_0 < D_i$ is true, having node j transmit an additional description can improve the distortion at node i.

Algorithm 6 Update $\text{PossPar}_{i,k}$ for $k = 0, 1, 2$

1: $\text{PossPar}_{i,k} = \text{PossPar}_{i,k} \setminus \{j\}, \ \forall k = 0, 1, 2$
2: **if** $\mathcal{S}_j = \{\}$ **then**
3: $\quad \text{PossPar}_{i,k} = \text{PossPar}_{i,k} \cup \{j\}, \ \forall k = 0, 1, 2$
4: **else if** $\mathcal{S}_j = \{1, 2\}$ **then**
5: $\quad \text{PossPar}_{i,0} = \text{PossPar}_{i,0} \cup \{j\}$
6: **else**
7: $\quad \text{PossPar}_{i,k} = \text{PossPar}_{i,k} \cup \{j\}$, for $k \in \mathcal{S}_j$
8: $\quad \text{W}_0 = D([\pi_{j,1} \cdot p_{0,j,i}] \ , \ [\pi_{j,2} \cdot p_{0,j,i}])$ using (5.2)
9: $\quad$ **if** $\text{MaxD}_j \leq D_i$ and $\text{W}_0 < D_i$ **then**
10: $\quad\quad \text{PossPar}_{i,0} = \text{PossPar}_{i,0} \cup \{j\}$
11: $\quad$ **end if**
12: **end if**
13: **if** $j \in \cup_{k \in \{0,1,2\}} \text{PossPar}_{i,k}$ **then**
14: $\quad$ Find $p_k(l)$ and $\pi^{'}_{i,k}(l)$ for $l = 1 : 5$ and $k \in \{1, 2\}$
15: $\quad$ Find $\tilde{D}_i(l) = D_i|_{\pi_{i,1}=\pi^{'}_{i,1}(l), \pi_{i,2}=\pi^{'}_{i,2}(l)}$ for $l = 1 : 5$
16: $\quad l^* = \arg\min_{l=1:5} \tilde{D}_i(l)$
17: $\quad$ **if** $\tilde{D}_i(l^*) < D_i$ **then**
18: $\quad\quad \text{BetterParent}_{i,k} = p_k(l^*)$ for $k = 1, 2$
19: $\quad\quad$ Send DescReq_k message to node $\text{BetterParent}_{i,k}$
20: $\quad$ **end if**
21: **end if**

In case that node j is added to any $\text{PossPar}_{i,k}$ for $k = 0, 1, 2$, then Lines 14-20 are used to find whether better parents exist to achieve lower distortion than the current distortion D_i. A $\text{DescReq}_{i,k}$ message is sent to the node if the answer is yes.

5.3.5 Receiving Descriptions

Algorithm 7 is performed by node i, where ρ is the success probability for node i to receive description k from node v. First, if a higher success probability can be achieved for receiving description k, node v will replace the current parent $\text{Parent}_{i,k}$. If node i is an RS and needs to serve description k, then it updates description assignment to include description k. However, if higher success probability cannot be achieved for receiving description k, node i sends $\text{RemoveReq}_{i,k}$ to node v in case node i has requested description k from node v before. Finally, node i cancels pending request in case that node v is $\text{BetterParent}_{i,k}$.

Algorithm 7 receives description k from node v

if $k \notin \mathcal{K}_i$ **then**
    $\mathcal{K}_i = \mathcal{K}_i \cup \{k\}$
end if
$\rho = \pi_{k,v} \cdot p_{k,v,i}$ if $\mathcal{S}_v = \{k\}$ or $\rho = \pi_{k,v} \cdot p_{0,v,i}$ if $\mathcal{S}_v = \{1, 2\}$
if $\rho > \pi_{i,k}$ **then**
    if $i \in \mathcal{M}$ **or** $k \in \mathcal{S}_i$ **then**
        Send $\textbf{RemoveReq}_{i,k}$ to $\text{Parent}_{i,k}$
        Send $\textbf{joinReq}_{i,v,k}$ to node v
    end if
    $\text{Parent}_{i,k} = v$ and $\pi_{i,k} = \rho$
    if $k \in \mathcal{R}_{i,k}$ **then**
        $\mathcal{S}_i = \mathcal{S}_i \cup \{k\}$
    end if
else
    Send $\textbf{RemoveReq}_{i,k}$ to node v
end if
if $v = \text{BetterParent}_{i,k}$ **then**
    Send $\textbf{CancelReq}_{i,k}$ to $\text{BetterParent}_{i,k}$
end if

5.4 Results

We simulate a WMN, where 2 APs, a number of RSs and MSs are uniformly distributed in a circular system service area with radius of 1km. The data rate of the original media is $R = 1.8$ Mbps, and the rates for the two descriptions after MDC are $R_1 = 1.4$ Mbps and $R_2 = 620$ kbps. Here we assume the fixed redundancy between descriptions to be 20% [96]. We consider both path loss and log-normal shadowing. The link gain between nodes i and j is $G_{i,j} = G(d_0) \times (d_{i,j}/d_0)^{-\alpha} \times 10^{-\frac{X_{i,j}}{10}}$, where $d_{i,j}$ is the distance between the two nodes, $d_0 = 100$m is the reference distance, $\alpha = 2$ is the path loss exponent, and $X_{i,j}$ is a normally distributed random variable with zero mean and 2 dB standard deviation. The capacity for link (i, j) is $C_{i,j} = W_{i,j} \log(1 + P_{\max} G_{i,j}/P_n)$, where $P_{\max} = 23$ dBm is the maximum transmission power of each node, $W_{i,j} = 1$ MHz is the available bandwidth, and $P_n = -90$ dBm is the background noise power. The success delivery probability for link (i, j) to deliver description k is $p_{k,i,j} = 1 - \Pr.(R_k \leq C_{i,j})$ [97].

For comparison, we simulate two other centralized routing schemes. The first one is a two-step method given in Algorithm 8, where $\mathcal{P}_m$ is a path from an AP to MS m. First, the success delivery probability for each link (i, j) in the network graph $\mathcal{G}$ is set to be $p_{1,i,j}$, then for each MS m a path $\mathcal{P}^*_{m,1}$ that can deliver description 1 with the highest success delivery probability is added to the multicast graph $\mathcal{G}_c$. After that, each MS m finds a path $\mathcal{P}^*_{m,2}$ in $\mathcal{G}$ that can deliver description 2 with the highest success delivery probability, where the success delivery probability for link (i, j) that is already included in $\mathcal{G}_c$ is $p_{0,i,j}$ and for link (i, j) that is not in $\mathcal{G}_c$ is $p_{2,i,j}$. The second scheme is to multicast the source traffic directly, which is the same as the first two lines in the two-step method, except that the success probability for each link (i, j)

is calculated using the source traffic rate.

Algorithm 8 Two-step scheme

Find $\mathcal{P}^*_{m,1} = \arg\max_{\forall \mathcal{P}_m \in \mathcal{G}} \prod_{\forall (i,j) \in \mathcal{P}_m} p_{1,i,j}$, $\forall m \in \mathcal{M}$
$\mathcal{G}_c = \cup_{\forall m \in \mathcal{M}} \mathcal{P}^*_{m,1}$
for all $(i,j) \in \mathcal{G}_c$ **do**
    $p'_{2,i,j} = p_{0,i,j}$
end for
Find $\mathcal{P}^*_{m,2} = \arg\max_{\forall \mathcal{P}_m \in \mathcal{G}} \prod_{\forall (i,j) \in \mathcal{P}_m} p'_{2,i,j}$, $\forall m \in \mathcal{M}$
$\mathcal{G}_c = \mathcal{G}_c \cup_{\forall m \in \mathcal{M}} \mathcal{P}^*_{m,2}$

Figs. 5.2 (for 10 MSs) and 5.3 (for 30 MSs) show the maximum distortion as the number of RSs changes. The figures show that the maximum distortion decreases with the number of RSs in general, since having more RSs increases the number of links with good channel conditions. Meanwhile, the maximum distortion for the optimum and proposed schemes tend to flatten when the number of RSs is relatively large, since there is a sufficient number of links with good channel conditions. When the number of RSs is small, the different solutions do not have significant difference in terms of the maximum distortion that is achieved. This is because the number of available links is very limited, and there are not many choices for choosing the RSs when building different paths. As the number of RSs increases, the difference between the solutions becomes more obvious. The optimum solution always achieves the lowest maximum distortion, while the centralized scheme achieves close-to-optimum maximum distortion, especially when number of RSs is small. Compared to the optimum and centralized solutions, the distributed scheme only allows nodes to have partial information learned from the nearby neighbors to build their paths, and therefore, results in higher distortion than the optimum solution and the centralized scheme; on the other hand, the proposed distributed scheme achieves much better distortion compared to the two-step method and multicasting the source traffic directly, since the proposed scheme allows neighboring nodes to coordinate with each other in the decision-making process.

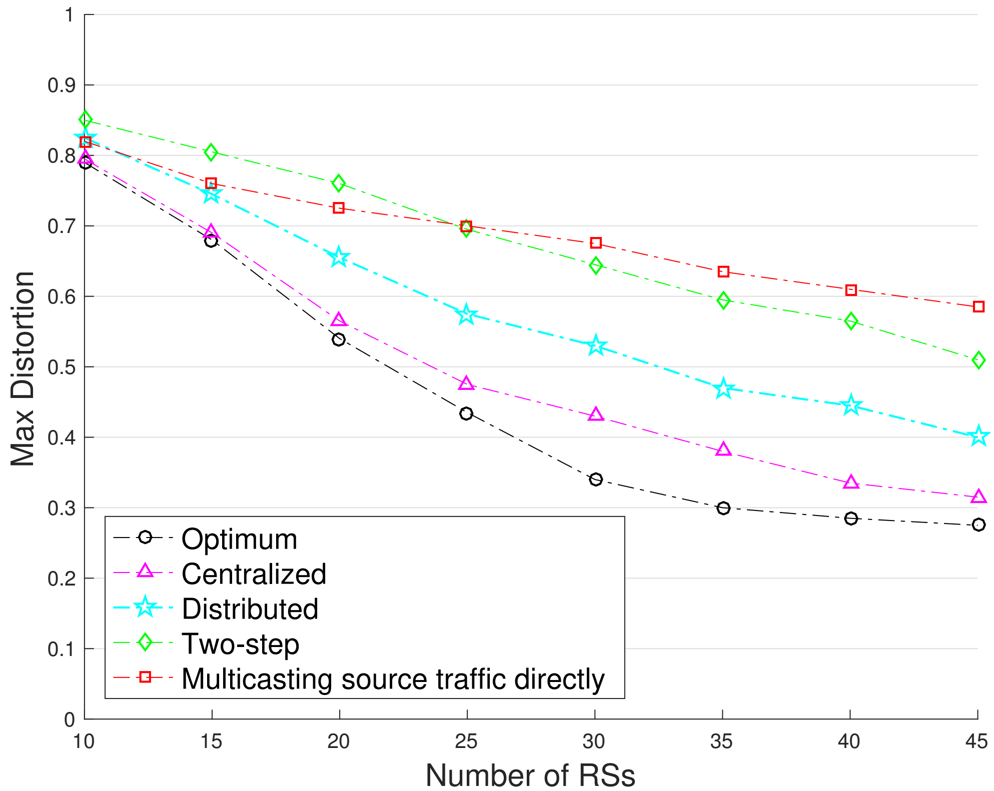


Figure 5.2: Maximum distortion versus number of RSs (10MSs)

Figs. 5.4 and 5.5 show the maximum distortion as the number of MSs changes. It can be seen that the worst distortion increases with the number of MSs in general. This is because having more MSs increases the number of links needed for building the multicast trees, which may require either to have more RSs send both descriptions or to include more links with poor qualities in the multicast trees. The slope of the curves in Fig. 5.4 (for 25 RSs) in general is higher than in Fig. 5.5 (for 45 RSs), since the latter system provides more links with better channel conditions. Comparing

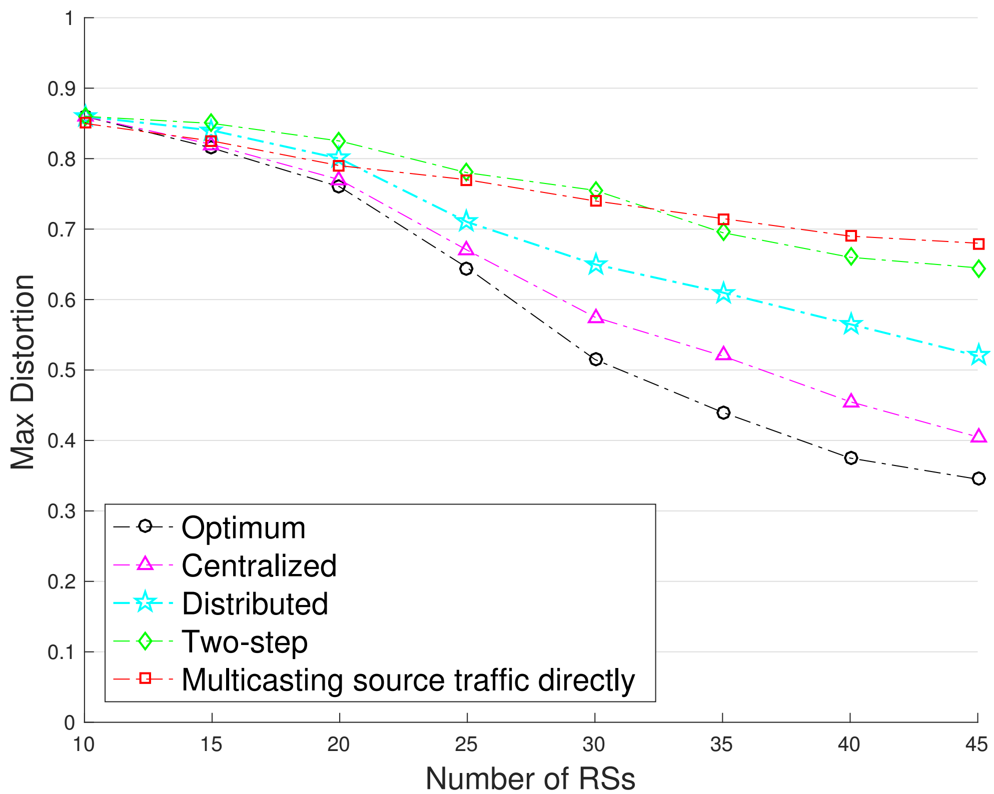


Figure 5.3: Maximum distortion versus number of RSs (30MSs)

the different solutions, the proposed centralized scheme is the one closest to the optimum, especially when the number of RSs or MSs is small. This is because the number of available or required paths is small, and it is more likely for the centralized scheme to find the best or close-to-best paths. It is also seen that in most cases, the proposed distributed scheme achieves much better distortion compared to the two-step method and multicasting the source traffic directly. However, when the number of MSs is large, many neighboring MSs will be competing to influence the local description assignment decisions of the same RSs. Thus, the pressure for coordinating the description assignment among RSs will increase, which in return may result in higher distortion for the MSs.

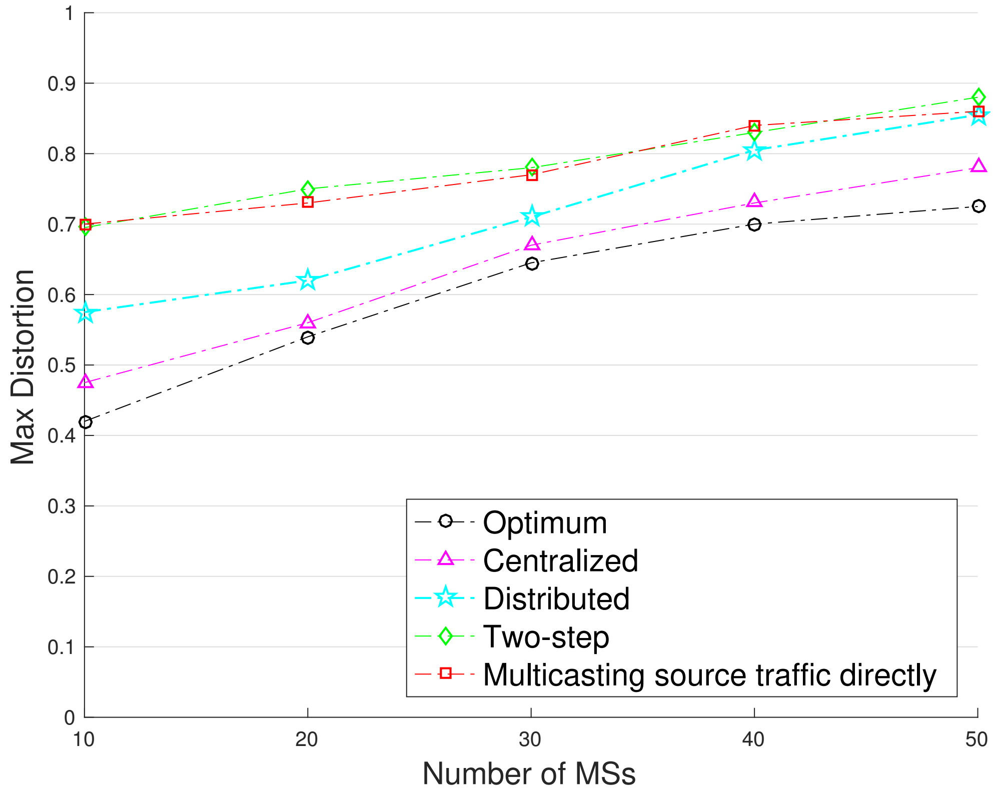


Figure 5.4: Maximum distortion versus number of MSs (25RSs)

Fig. 5.6 and Fig. 5.7 show the maximum distortion under different fading conditions as the number of RSs changes. We set the path loss exponent to be $\alpha = 1.6$ for Fig. 5.6 and $\alpha = 3$ for Fig. 5.7. Moreover, the shadowing effect is removed from the channel fading model for Fig. 5.6, while the shadow standard deviation is set to be 6 dB for Fig. 5.7. In Fig. 5.6, the performance gap between different solutions is relatively small. Since the channel conditions are good in general, i.e., small path loss exponent and no fading, less intelligence is needed to build paths that can deliver both descriptions with sufficiently high success delivery probability. This, however, is less possible when the path loss exponent is high and fading is severe, such as the

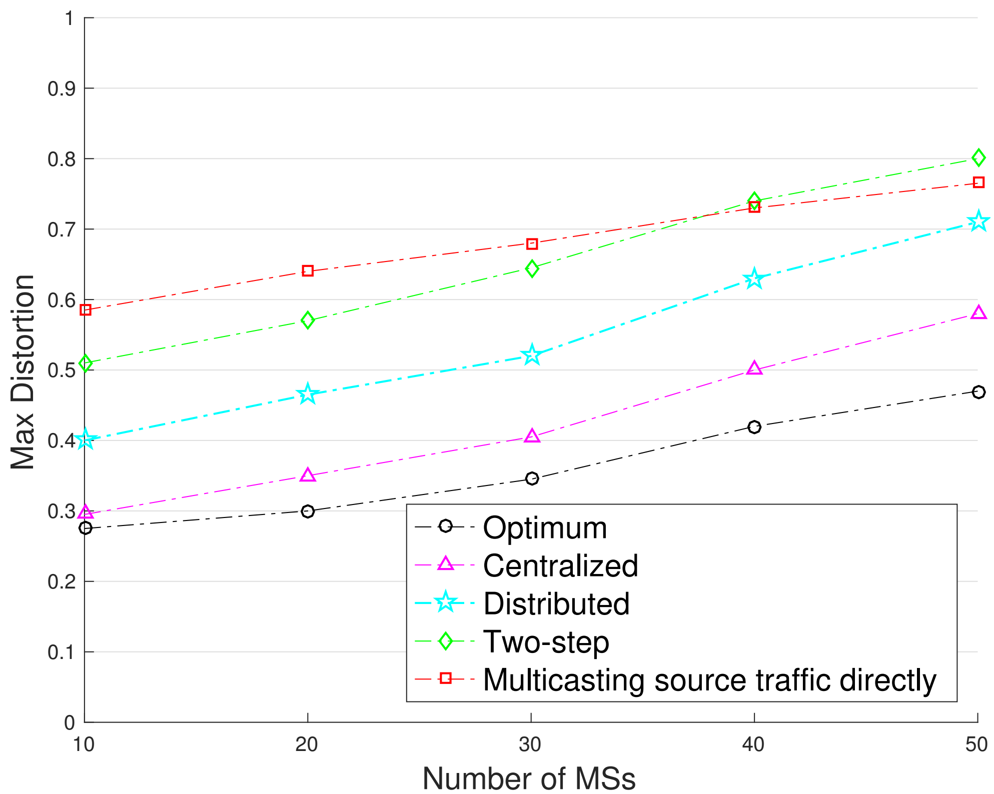


Figure 5.5: Maximum distortion versus number of MSs - (45RSs)

system that Fig. 5.7 is based on. When most of the links are in deep fading, sending the high-rate description does not bring much benefit due to the low probability for successful transmissions. When the number of RSs is small, the optimum and proposed schemes all tend to build one tree to deliver only the low-rate description due to the limited choices of links, and the performance of the three solutions is very much close to each other. As the number of RSs increases, more links with good channel conditions become available. Having global information and searching through all available links become important in order to build paths with sufficiently high success transmission probability. In this case, the gap between the optimum, the proposed central scheme, and the proposed distributed scheme increases. Global information and intelligent searching allow to build trees to transmit both descriptions with reasonably high success delivery probability and reduce the distortion at the destination MSs.

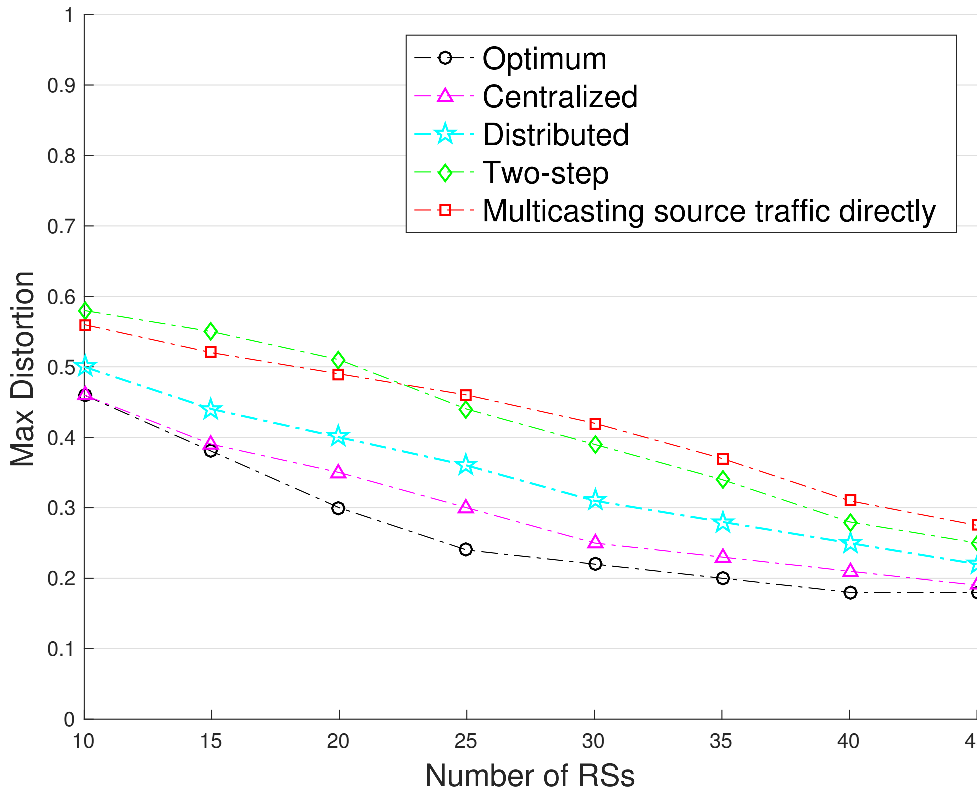


Figure 5.6: Maximum distortion versus number of RSs in good link qualities

In the system that Fig. 5.8 is based on, data rate of the original media is $R = 1.9$ Mbps, and the rates for the two descriptions after MDC are $R_1 = 1.3$ Mbps and $R_2 = 960$ kbps. Comparing to the previous rates, this set of rates means more redundancy between the two descriptions, and receiving only the description of rate R_2 in this setting results in better distortion compared to that in the previous rate setting. Comparing to Fig. 5.2, we see that the gap between the proposed schemes and the other two schemes is much higher in Fig. 5.8, especially when only a small number

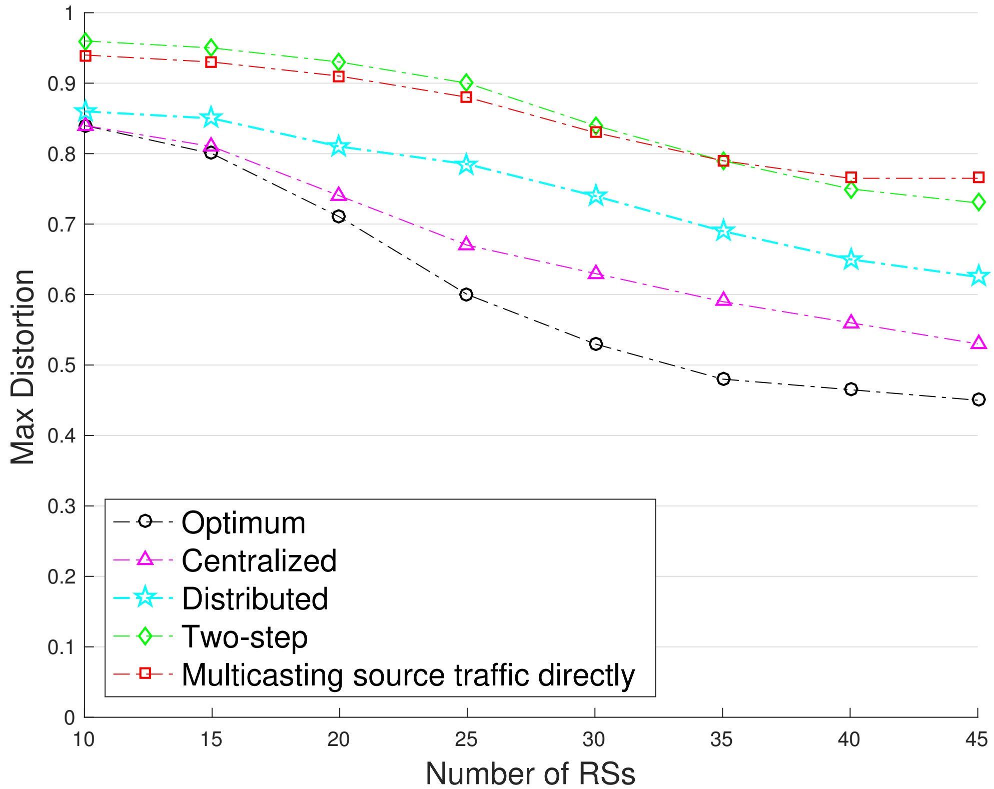


Figure 5.7: Maximum distortion versus number of MSs in bad link qualities

of RSs are available. This is because the schemes can take advantage of the high redundancy between the descriptions to send a single description only when the limited availability of the multipath burden sending both descriptions with high success delivery probability. When the number of RSs increases and most MSs are able to receive both descriptions, then the higher redundancy between the descriptions does not bring obvious advantage since the chance of correctly receiving both descriptions is high.

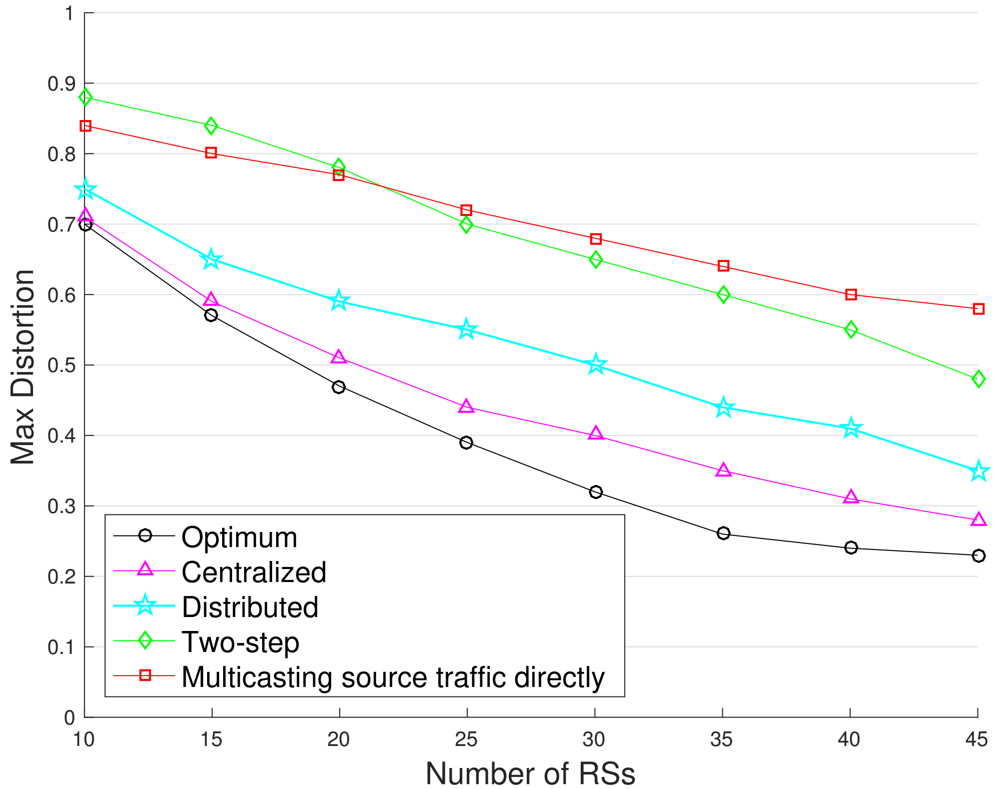


Figure 5.8: Maximum distortion versus number of RSs - different description rates

5.5 Summary

In this chapter, we have studied the problem of distortion-aware routing for multicasting MD-encoded media traffic in WMNs with multiple sources. The distortion of the recovered media at the destinations is minimized by taking advantage of the reduced bandwidth requirement of each description and the diversity gained from delivering multiple descriptions through different paths. We have formulated the optimization problem and proposed a centralized heuristic scheme. Following that, the minimum weight k-paths scheme that proposed in Chapter 4 has been modified to the distortion based objective, while keeping the fully distributed format in implementation. Numerical results have demonstrated that the proposed centralized scheme achieves close-to-optimum distortion over a wide range of parameter settings, and the distributed scheme achieves much better distortion compared to a two-step scheme that relies on building shortest-path trees sequentially. Moreover, the proposed schemes outperform multicasting the source traffic directly.

Chapter 6

Conclusions and Future Work

In this thesis, we have studied the problem of multicasting bandwidth-demanding media traffic in WMNs. MDC was utilized to split the source media traffic into multiple sub-streams, referred to as descriptions, and a multicast tree is established to deliver each of the descriptions. By taking advantage of the lower bandwidth requirements of the individual descriptions and the multiple available paths in the mesh topology, the proposed multicast routing schemes can deliver high-bandwidth traffic while providing differentiated QoS at the destinations.

In the first part (Chapters 3 and 4), we considered balanced descriptions case where destinations have different quality requirements in terms of the number of uniquely received descriptions, and we studied the problem of power efficient multicasting for the MD-encoded media traffic in WMNs. Chapter 3 focused on single-hop transmissions, where a destination requiring multiple descriptions should be covered by at least the same number of APs. Two objectives were considered subject to satisfying the requirements of the MSs, one is to minimize the total transmission power in the network, and another is to minimize the maximum transmission power of the

APs. Optimal problems for power allocations and description assignments have been formulated, and both centralized and distributed heuristic schemes have been proposed for each objective. The results have shown that the proposed heuristic schemes performed well compared to the optimum solution under different network configurations. Minimizing the maximum transmission power balanced the load among all the APs, but the overall total transmission power in the network greatly increases. On the other hand, minimizing total transmission power forces multiple sources to transmit at a high power in order to serve larger area while multiple other sources may not transmit any descriptions.

In Chapter 4, we extended the system studied in Chapter 3 for multi-hop WMNs, where RSs are available to assist in delivering the multiple descriptions traffic to the destinations. Two cases were considered, one does not allow different multicast trees to share RSs, and the other case allows each RS to forward multiple descriptions. For the objective of minimizing the total transmission power in the network, an optimization problem was formulated, and centralized and distributed heuristic schemes were proposed. The results have shown that the proposed solutions achieve good performance compared to the optimum and outperform a spanning-tree based scheme. Moreover, When each RS is only allowed to be in a single multicast tree, the total transmission power in the network is much higher compared to the case where RSs can be in multiple multicast trees. However, limiting each RS to be in only one multicast tree results in a node-disjoint multicast tree structure, which provides better robustness to transmission failures, since the correlation between the multicast trees is reduced and a failure in one multicast tree does not affect the others.

In Chapter 5, we considered unbalanced descriptions case and studied the problem of distortion-aware multicast routing of MDC encoded media traffic in WMNs. An optimization problem was formulated, then a centralized scheme and a fully distributed heuristic scheme were proposed. Numerical results have shown that the proposed schemes achieved close-to-optimum distortion over a wide range of parameter settings. Moreover, the proposed schemes outperform multicasting the source traffic directly when multiple path choices are available in the network or when link qualities are poor.

The research conducted in this thesis can be extended in a number of directions:

- For the problem of power efficient multicasting of MD-encoded media traffic, we assumed that the medium access control is in place and coordinates the transmission time and frequency of different nodes so that the transmissions of different nodes are orthogonal. Further extending the work can be done by jointly considering power allocations, description assignments, and channel or time slot assignments.

- In Chapters 3 and 4, we considered descriptions of equal importance, where the QoS of the received media at a destination is directly related to only the number of distinctly received descriptions but not which descriptions. When descriptions are unbalanced, the QoS requirement (e.g., distortion) of a destination cannot be simply mapped to the number of received descriptions, and extending the proposed minimum weight k-path scheme to this scenario should be further studied.

- Throughout the thesis, the rates of descriptions are assumed to be fixed. Given the transmission power of the nodes, finding the rates of the descriptions that maximize the throughput of the multicast trees can be an interesting problem [98]. Intuitively, having descriptions with higher rates limits the number of links that can be used to build the multicast trees; while having descriptions with lower rates reduces the redundancy between descriptions [99].

- In Chapter 5, the distortion at the destinations can be further improved by allowing APs to adapt description rates based on link qualities and destination QoS requirements [99, 100]. However, this will require network nodes to constantly report link conditions back to the APs, which will highly increase the overhead in the network as well as the routing and resource allocation complexity. Therefore, the feasibility of utilizing such an approach in multi-hop WMNs, where link conditions are continually changing, should be further studied.

- Traffic was assumed to be non-real time, where destinations requiring more than one description can buffer early received descriptions and decode the signal after the required number of descriptions have been received. Future work can be done to consider real-time traffic, where delay constraints are imposed.

- Network coding can be considered while building the multiple multicast trees. Utilizing network coding can potentially reduce transmission power, improve data transmission throughput, etc. However, applying network coding in a mesh topology is a complex problem in which not only routing and resource allocations need to be considered, but also specific coding strategies.

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