A Study on Traffic-demand-aware Collision-free Channel Assignment for Multi-radio Multi-channel Wireless Mesh Networks

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複数無線機を備えたマルチチャンネル無線メッシュ網における通信要求を考慮した衝突のないチャンネル割当手法に関する研究

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Abstract

Multi-radio Multi-channel (MRMC) technology can greatly reduce the collision and enhance network performance in Wireless mesh networks (WMNs). At present, there are tremendous amount of work on channel assignment (CA) in MRMC WMNs, which shows that routing configuration combined with channel assignment reduces collisions. However, in the current state of the art, there is no joint channel assignment and routing scheme that achieves collision-freedom with 3-5 channels considering traffic demand. On the other hand, the potential ability of the combination of CA and routing under partially overlapping channels (POCs) in MRMC WMNs has not been sufficiently explored. In this thesis, I explored the ability of MRMC WMNs and designed new collision-free channel assignment methods as described in the following:

First, I analyzed CSMA-aware static channel assignment (CASCA), and in-depth evaluation and simulation is conducted to confirm the good performance of the base collision-free CA scheme. Second, I proposed traffic-demand-aware collision-free channel assignment (TACCA), which is a new joint CA and routing scheme that achieves collision-freedom with 3-5 orthogonal channels, which also minimizes the network-wide utility under a given traffic demand matrix. Different from CASCA, I formulated the optimization problem as mixed-integer linear programming (MILP) to introduce a traffic engineering function. Third, by exploiting all the channels defined in IEEE 802.11 2.4 GHz band channels, I designed a new joint CA and routing scheme using POC interference models. The proposed scheme called traffic-demand-aware collision-free partially overlapping channel assignment (TAC-POCA) significantly improved the spatial reuse of radios, and achieved collision-freedom in combination with the CSMA-aware interference model and the shared link capacity model extended for POCs.

In summary, I study on jointing channel assignment and routing schemes in IEEE 802.11-based MRMC WMNs, and formulate this joint problem as a MILP. I proposed two traffic-demand-aware collision-free channel assignment schemes (i.e., TACCA and TAC-POCA) for MRMC WMNs. Both schemes achieve collision-freedom under the OCs and POCs, respectively, and I confirmed through traffic simulation that they significantly improve the overall channel reuse and efficiently improve the network capacity.

概要

各ノードが複数無線機を備え，異なるチャンネルを割り当てられる MRMC (Multi-radio Multi-channel) 技術により無線メッシュ網の性能は大きく向上し，フレーム間の衝突も大幅に低減された．現在までに数多くの MRMC 無線メッシュ網を対象としたチャンネル割当法が提案されている．しかし，3〜5 チャンネルでフレームの衝突を避ける手法で，通信要求を考慮して負荷分散をするものは見当たらない．また，部分的に周波数が重複するチャンネル（POC: Partially Overlapping Channels)による空間利用効率の探求も十分に行われているとは言えない．そこで本論文では，MRMC 無線メッシュ網に関する研究を進め，次に示すようにフレーム間衝突を避けるチャンネル割当法を設計・提案する．

まず，現在提案されている中で唯一，フレーム間衝突を避けるチャンネル割当手法である CASCA (CSMA-aware Static Channel Assignment)を対象として，詳細なシミュレーション評価を行い，CASCA がフレーム間衝突を避けることで高い通信性能を持つことを示した．次に，CASCA の CSMA に基づいた干渉モデルを継承した新たな経路制御とチャンネル割当の複合最適化問題を設計した．本手法 TACCA (Traffic-demand-aware Collision-free Channel Assignment) は，CASCA とは異なり，入力として与えられる通信要求に対して負荷分散機能を備えるために混合整数線形計画問題（MILP: Mixed Integer and Linear Problem)として定式化した．さらに，IEEE 802.11 の 2.4GHz 帯チャンネルの性能を引き出すために，新たに部分的に重複するチャンネル POC に基づいた干渉モデルを導入した経路制御とチャンネル割当の複合問題 TAC-POCA (Traffic-demand-aware Collision-free Partially Overlapping Channel Assignment) を設計した．

このように，本論文では，IEEE 802.11 に基づいた MRMC 無線メッシュ網における経路制御とチャンネル割当の複合問題を検討し，混合整数線形計画問題として定式化した．具体的には，直交チャンネルと非直交チャンネルを扱う 2 手法 TACCA と TAC-POCA を提案した．最適化問題を解いた上で，ネットワークシミュレータによる性能評価を行った結果，両者ともに優れた空間利用効率を示し，ネットワークの通信性能を向上し，無線メッシュ網の通信容量を著しく向上できることが示された．

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Chapter 1

Introduction

1.1 MRMC WMNs

Wireless mesh network (WMN) is a multihop wireless network characterized by low deployment cost that consists of mesh routers and Internet gateways [1][2][3][4][5]. It is a special ad hoc network with static topologies where unlike the general ad hoc networks mesh routers have no energy limitations. WMN deployments are found in surveillance, building automation, remote health care delivery, and smart grids [6] [7][8] [9][10]. With the multiple hops and a mesh topology, the WMN architecture generally consists of three levels as described below.

The top level comprises one or several gateways, which connect to both the WMN and the wired Internet and forward traffic between these two types of networks. This level can be absent if no Internet access is required and the WMN is only used for local communication.

The intermediate level comprises numerous mesh routers, which are the vertices in the mesh topology and relay the traffic within the WMN. To enable wide and low-cost deployment, the link and physical layer protocols adopted by mesh routers are international standards such as the IEEE 802.11 [11] protocol or the IEEE 802.16 [12] protocol according to the current practice.

The bottom level comprises many wireless local area networks (WLANs) or mobile phone cells depending on the usage of WMNs. Either a WLAN or a mobile phone cell generally consists of an access point (AP) and a certain number of wireless clients (e.g., laptops or mobile phones) that are the real producers and consumers of the wireless traffic.

Mesh routers are the fundamental part of wireless mesh network, which gives routing support for network traffic of mesh clients. Note that, the gateways and the APs also have the full functionality of the mesh routers besides interfacing with the Internet and the wireless clients respectively, so they both play double roles. And in the study of WMNs, researchers

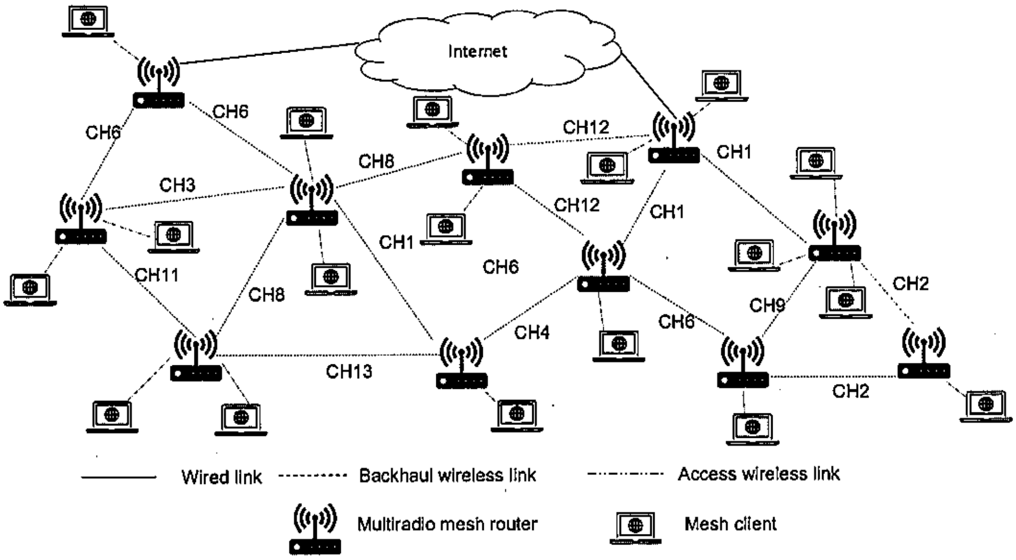


Fig. 1.1 MRMC WMNs Architecture

mainly focus on the issues of mesh routers, leaving the Internet or the WLAN/cell issues to other areas of research. With the development of advanced radio technologies, multiple radio configurations allow the utilization of the available multiple channels, so the links can transmit data simultaneously as long as they work on different channels. Therefore, multi-radio multi-channel (MRMC) technology can greatly increase the network capacity and to reduce the interference level over the network [13] [14] [15] [16][17]. In MRMC WMNs architecture, each router is equipped with multiple radios, and each radio can be operated on one of the several distinct channels. The network architecture of MRMC WMN is illustrated in Fig. 1.1. Multi-radio mesh routers are connected through wireless links over multiple channels. Mesh clients are connected to mesh routers through different set of links referred to as network access links. Mesh clients are user entities with no routing functionality.

Even though MRMC WMN technology bring many benefits to WMNs, it also introduces some operational issues to achieve ubiquitous deployment of WMNs. First, the design complexity is increased in some WMN protocols such as routing and channel assignment (CA) [18]. In single-radio single-channel WMNs, CA is simple and routing does not need to consider the channel state because all nodes use the same channel. However, in MRMC WMNs, the CA algorithm needs to assign different channels to the radios at each node and concurrently must select a channel for each link in the path through the routing process. Therefore, the protocol in MRMC WMNs needs more sophistication to regulate the spatial resources and optimize network performance. Otherwise, WMNs may perform poorly due to inefficient utilization of the multiple available channels and the multiple radios at its disposal [19] [20][21].

Second, the interaction between routing and CA is another critical factor influencing network performance. Some studies tackle routing and CA separately or regard CA as the lower layer protocol of routing [22]. These studies fail to consider the traffic information in the CA stage and thus is not able to reap the benefits of joint optimization between CA and routing. In the same way, routing protocols cannot evaluate link quality and interference effectively and the improvement in network performance is limited [22] [23].

1.2 IEEE 802.11 Standard

The availability and flexibility of IEEE 802.11 components make it a good candidate for wireless mesh deployment [24] [25][26]. IEEE 802.11-based networks provide a cheap and flexible wireless access capability and are easy to deploy in campuses, airports, and hospitals. Links in 802.11-based MRMC WMN can be operated on one of the several channels (i.e., 13 channels for 802.11 2.4 GHz).

Like any 802.x protocol, the 802.11 protocol covers the medium access control (MAC) and physical layers. The standard currently defines a single MAC which interacts with three PHYs as follows: frequency hopping spread spectrum in the 2.4 GHz band, direct sequence spread spectrum in the 2.4 GHz band, and infrared. The MAC layer defines two different access methods, the distributed coordination function (DCF) and point coordination function (PCF). We now describe the DCF in detail (since the PCF cannot be used in ad hoc networks, it is not described here).

The basic access mechanism, the DCF, is basically a carrier sense multiple access with collision avoidance (CSMA/CA) mechanism. CSMA protocols are well known in the industry, the most popular being the Ethernet, which is a CSMA with collision detection (CSMA/CD) protocol. A CSMA protocol works as follows.

A station desiring to transmit senses the medium. If the medium is busy (i.e., some other station is transmitting), the station defers its transmission to a later time. If the medium is sensed as free, the station is allowed to transmit. These kinds of protocols are very effective when the medium is not heavily loaded, since it allows stations to transmit with minimum delay. But there is always a chance of stations simultaneously sensing the medium as free and transmitting at the same time, causing a collision. These collision situations must be identified so the packets can be re-transmitted by the MAC layer, rather than by the upper layers. The latter case will cause significant delay. In order to overcome the collision problem, the 802.11 uses a CA mechanism coupled with a positive acknowledge scheme, as follows:

(i) A station wanting to transmit senses the medium. If the medium is busy, it defers. If the medium is free for a specified time, called the distributed inter-frame space (DIFS) in the standard, the station is allowed to transmit.

(ii) The receiving station checks the cyclic redundancy check (CRC) of the received packet and sends an acknowledgment (ACK) packet. Receipt of the ACK indicates to the transmitter that no collision occurred. If the sender does not receive the ACK, it re-transmits the frame until it receives an ACK or throws it away after a given number of re-transmissions. According to the standard, a maximum of seven re-transmissions are allowed before the frame is dropped.

In order to reduce the probability of two stations colliding due to not hearing each other, the well-known "hidden terminal problem," the standard defines a virtual CS (carrier sensing) mechanism: a station wanting to transmit a packet first transmits a short control packet called request to send (RTS), which includes the source, destination, and duration of the intended packet and ACK transaction. The destination station responds (if the medium is free) with a response control packet called clear to send (CTS), which includes the same duration information.

All other stations receiving either the RTS and/or the CTS set their virtual CS indicator, called a network allocation vector (NAV), for the given duration and use this information together with the physical CS when sensing the medium. The physical layer carrier sensing function is called clear channel assessment (CCA). The NAV state is combined with CCA to indicate the busy state of the medium. This mechanism reduces the probability of the receiver area collision caused by a station that is "hidden" from the transmitter during RTS transmission, because the station overhears the CTS and "reserves" the medium as busy until the end of the transaction. The duration information on the RTS also protects the transmitter area from collisions during the ACK (from stations that are out of range of the acknowledging station). It should also be noted that, due to the fact that the RTS and CTS are short frames, the mechanism also reduces the overhead of collisions, since these short transmissions allow faster recognition of collisions than would be possible for the transmission of an entire packet.

As we know, besides the hidden node problem, wireless packet networks also face the exposed node problem. A hidden node is one that is within the interfering range of the intended destination but out of the sensing range of the sender. Hidden nodes can cause collisions on data transmission. Exposed nodes are complementary to hidden nodes. An exposed node is one that is within the sensing range of the sender but out of the interfering range of the destination. If exposed nodes are not minimized, the available bandwidth is underutilized. However, in the 802.11 MAC layer protocol, there is almost no scheme to deal with this problem.

1.3 Interference of MRMC WMNs

Interference is the foremost factor that degrades the wireless network performance, so the primary goal of channel assignment is to minimize interference within the MRMC WMNs by utilizing multiple radios and multiple channels.

1.3.1 Interference Model

To address the interference issue, a model describing the interference effect needs to be assumed. Currently, there are generally two models, the *physical model* and the *protocol model*, used to determine whether a wireless transmission is successful [27]. Consider a wireless network with N nodes, denoted by $n_i(1 \leq i \leq N)$.

Protocol model: Assume each node n_i has a transmission range of R and an interference range of R'. The interference range defines the longest distance from which the transmission of one node can affect the simultaneous reception of the other node. The interference range is potentially larger than the transmission range. In the protocol model, if node n_i transmits to node n_j, the transmission is successful if the distance between n_i and n_j is within R and no other nodes within R' of n_j are transmitting at the same time. If n_j needs to send acknowledgement (ACK) packets to n_i for reliable transmission, the protocol model also requires that no other nodes within R' of n_i are transmitting simultaneously. This enables transmissions in both directions to be successful.

Physical model: This model uses the signal-to-noise ratio at the receiving node to determine whether the packets can be received successfully. Suppose node n_i wants to transmit to node n_j. Let SS_{ij} be the signal strength of n_i' s transmission received at n_j, and NS_j be the total noise at n_j, which includes the interference from other ongoing transmissions in the network. Thus, the transmission from n_i to n_j is successful as long as $SS_{ij}/NS_j \geq SNR_{thresh}$, where SNR_{thresh} is the threshold of signal-to-noise ratio.

The physical model is more accurate than the protocol model, because it takes into account the complex attenuation of wireless signal in different environments. However, the protocol model is simpler and easier to derive efficient channel assignment algorithms. Up to now, most studies based their channel assignment algorithms on protocol interference models.

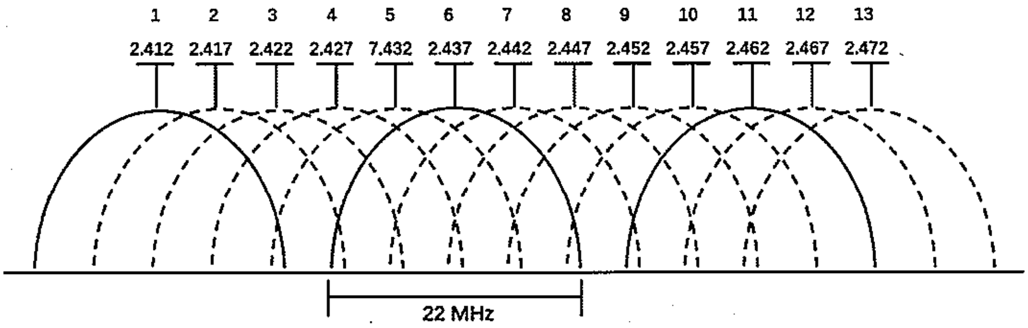


Fig. 1.2 IEEE 802.11 2.4 GHz ISM Band

1.3.2 Interference Type

It is known that, on the IEEE 802.11 2.4 GHz band, there are 13 available channels, each of which has a spread of about 22 MHz and the center frequencies of channels are 5 MHz apart, which is shown as Fig. 1.2. Therefore, any two channels with a separation over 5 (channels) are called orthogonal channels (OCs e.g., channels 1, 6, and 11 are OCs), among which signals do not overlap with one another. Otherwise, they are partially overlapping channels (POCs); Their signals overlap with each other, e.g., channel 1 and 3 are POCs. Hoque et al.[28] classified the interference of IEEE 802.11-based MRMC WMNs into three types:

(1) Co-Channel Interference (CCI)

When two in-range transmitters operate on the same channel, they interfere with each other, and such interference is called as co-channel interference (CCI). CCI is the most common type of interference that exits in almost wireless networks. It refers to the fact that radios belonging to two nodes, operating on the same channel would interference with each other, if they are within the interference range of each other. This effectively means that parallel communications from two separate in-range nodes is not possible.

Most previous studies of channel assignment considered OCs only and based their algorithms on CCI models.

(2) Adjacent Channel Interference (ACI)

When two transmitters operate on relatively close channels that partially overlap, they cause lesser degree of interference, which is referred to as adjacent channel interference (ACI). See Figure 1.2 again, the channel number represents the center frequency on which the radio operates (e.g. 2.412 GHz for channel 1). The center frequencies are separated by 5 MHz, while each channel has a spread of about 22 MHz. As mentioned before, if signals overlap with each other, they are POCs, e.g., channel 1 and 3 are POCs. The authors of [29][30] studied the interference between partially overlapping channels, and found that the interference between two wireless links depends on both their physical distance and channel separation. When the physical distance is fixed, their interference decreases with the increasing channel separation (the difference between the channel numbers that the two links are configured with). When the channel separation is fixed, their interference decreases with the increasing physical distance. Under a fixed channel separation, the interference range can be defined as the minimum distance at which the two links do not interfere with each other.

Three scenarios are discussed in [31] where the use of partial overlap among the channel can be useful in the context of wireless mesh networks:

Multi-channel communication: The first scenario is when a node can communicate with two of its neighboring nodes configured on orthogonal channels (OCs) by operating on a partial overlapping channel. Basically, for a little reduction in throughput, one can use partially overlapping channels and this can give flexibility in topology construction while reducing the extra overhead in channel switching to enable communication.

Throughput improvement: The second scenario is when nodes in a mesh network have only one radio and therefore, they can be configured to only one channel at a time. There is a possibility of network disconnection while assigning different channels to nodes in the network. Channels with partial overlap can be assigned to nodes in such a manner that improves the overall network throughput capacity. In this way, the assignment of partially overlapping channels has to be intelligent enough to utilize the maximum bandwidth available and therefore can result in significant throughput improvements.

Channel re-use: Shorter ranges for frequency reuse can be obtained if two interfering links are assigned partially overlapping channels rather than orthogonal channels. It is possible to significantly improve the overall channel re-use (i.e., by reducing the distance between nodes using POCs) by careful assignment of channels which will result in higher peak throughput.

By considering the partially overlapping channels in addition to OCs, we can fully utilize the channel resource, and therefore further improve the network capacity.

(3) Self-Interference (SI)

Self-interference is defined a transmission from a node interfering with one of its own transmission. This is related to situation when nodes are equipped with multiple radios in a mesh network.

A wireless mesh network utilizing both OCs and POCs may suffer from interference which be characterized as above. Therefore, to achieve collision-free transmission, all of these types of interference have to be considered when designing channel assignment algorithms to exploit the full potential of the available wireless spectrum.

1.4 Key Design Issues of MRMC WMNs

Channel Assignment Schemes. Based on the underling hardware, CA can be implemented in one of three schemes. If the implemented technology does not support any link-level synchronization then only Static CA (SCA) can be implemented and channels are assigned to radio interfaces for a long term. However, if synchronous coordination is supported at link layer then SCA can be implemented with link scheduling (LS) and the wireless link can be active on specific time slots only; it be called SCA-LS. Dynamic CA (DCA) is the general case where radio interfaces are capable of switching their channel in a small time compared with the time slots. Thus, wireless links can operate on different channels at different time slots. For SCA links are allowed to be active on one channel only at all times. In SCA-LS links are allowed to be active on one channel only and on specific time slots. However, if DCA is adopted links can operate on different channels on different time slots.

Traffic and Routing Issues. As in load-aware algorithms, the aggregated traffic loads over mesh routers are required as an input. This traffic information can either be measured/estimated online as in [32][33] or assumed based on a historical profile [34]. WMNs can be used to deliver two types of traffic, the Internet-oriented traffic and point-to-point traffic. Internet-oriented traffic is the traffic received or directed to the Internet [35] [36][37] [38][39]. Either outbound traffic (to the gateway) [35][36] or inbound traffic (from the gateway) [37] can be considered in finding the network configuration. In [32], specific software such as IPFIX system [40] is used at the gateway to collect the traffic information. The upper and lower bound of the traffic demand are assumed to be available for each mesh router [39]. A traffic profiler at each mesh router collects the traffic information and sends it to a centralized entity [41] [33] where point-to-point traffic is assumed. References [42] [43] assume the traffic load is elastic and only information on source-destination communication pairs are considered.

Routing algorithms in wireless ad hoc networks are categorized as proactive (table-driven), reactive (on-demands), and hybrid algorithms. In proactive algorithms such as [44] [45] [46], routing table is built individually through exchanging routing information with other nodes in the network. In reactive algorithms such as [47] [48] [49], no routing tables are maintained and instead each node triggers the route discovery process whenever it has traffic to deliver to a destination. Hybrid algorithms [50] [51] [52] [53] implement the concepts of proactive and reactive routing protocols. Ad hoc routing protocols are extended to be used in WMNs. The routing decisions in these protocols are decentralized process and each node is responsible to make its routing decision. On the other hand, in centralized routing paradigm routing decision is performed at a centralized entity and nodes build their routing/forwarding table based on the updates received from a centralized entity. In WMNs, if traffic is identified per mesh client then mesh routers must maintain a forwarding entry for each mesh client and layer-2 addresses are used to identify each flow. This is similar to 802.11s standard with hybrid wireless mesh protocol (HWMP) where path selection is based on layer two addressing. However, path selection is usually associated with scalability issues. On the other hand, if the traffic is identified per mesh router and flow is defined as aggregated traffic that originated from one mesh router to another mesh router, then layer-3 routing is used. In most cases, centralized routing approaches follow the latter definition of flow. A TCP-level flow path selection is assumed in [32]. However, this introduces more overheads to the routing layer. Centralized routing proposals built routing tables based on source-destination manner, where both source and destination addresses are required in the routing decision. With centralized routing in MRMC WMN, modification is required on the routing table structure and the address resolution protocol (ARP). However, a complicated routing scheme is required for dynamic CA especially if no static binding is applied between radio interfaces and neighbors. For better exploitation of the topology structure of MRMC WMN, multi-path routing is assumed in most related works to achieve load balancing. However, the out-of-order problem and the configuration complexity are the main drawbacks of multi-path scheme[32].

Topology and Connectivity Issues. Several mechanisms have been used in the literature to control the topology formations in WMNs. This includes power control [54] [55][56], the use of directional antennas [57] [58], and routing [59] [60] [61] [62]. Furthermore, in MRMC architecture CA is another factor that determines the physically connected topology. An overview of the topology control mechanisms and issues in MRMC WMNs is presented in [63]. In centralized algorithms, the full network topology is assumed to be available at the centralized entity. Topology can be obtained using existing routing protocol such as optimized link state routing (OLSR) [32] or the network management protocol as in [38]. In order to define different possible types of topology formation, researchers define logical links as the set of potential links that directly connect mesh routers if proper channels are assigned to their radios, and define the physical links as the actual wireless links with designated channels assigned to them. Since inappropriate mapping can lead to disjoint topology, mapping the logical link onto physical link must be carefully determined. Furthermore, assigning channels to all logical links affects the channel diversity on the network. This is due to node-radio constraint, more specifically with a small number of radio interfaces. On the other hand, physical links need to be mapped onto the active links, where active links are the set of links carrying traffic and are determined by routing algorithm. However, some works allow multiple physical links to exist between adjacent mesh routers which need to be considered in the routing procedure. Meanwhile, connectivity must also be addressed in CA algorithms to prevent isolating parts of mesh routers from receiving the control messages and the configuration updates from the centralized controller.

1.5 Channel Assignment and Routing

In a typical topology, some of the mesh nodes serve as gateways, and the traffic to and from these gateways may be much higher than traffic elsewhere in the network. The traffic loads on each link are affected by the choice of routing protocol and the associated routing metric. Therefore, the optimal choice of CAs for a given set of traffic demands and a given routing protocol may be quite different from that for a different set of demands or a different routing protocol.

Conversely, if we are given a specific CA and asked to choose routes optimally, the choice of routes would depend on the CA. In a WMN, when a flow is routed over a particular link, it not only reduces the available capacity of that link, but also the available capacity on other co-channel links within carrier sense range. This is because all the co-channel links within carrier sense range share the same total bandwidth for their transmissions. This key difference between wired and wireless networks makes it important to consider CA when choosing routes in WMNs.

Fig. 1.3 illustrates the importance of accounting for the CA in route selection. In this scenario there are two available routes between a source S and a destination D. One route is S–A–D, and involves two hops both of which use the same channel *channel*1. The other involves three hops, and uses a different channel on each hop. We consider two traffic scenarios. In the first scenario, suppose all channels are very lightly loaded, and that the traffic between S and D is also small as compared to the link capacities. In that case the end-to-end delay between S and D is dominated by the transmission time for the packet on each hop, which is given by L/B, where L is the length of the packet (including headers) and B is the link data rate. If all links have the same data rate B, then the best route from the viewpoint of minimizing delay is the two hop route S–A–D. The S–A–D route also uses fewer network resources since it utilizes only two links instead of three.

Now consider a different scenario in which we are interested in maximizing the throughput that the flow between S and D can obtain. Such a scenario might arise if the flow is a TCP stream, e.g., a file transfer between S and D. In this case, the end-to-end throughput available between S and D is only B/2 if the traffic is routed over S–A–D since both the S–A and A–D links use the same channel and hence share the same bandwidth. However, if the traffic is routed over S–B–C–D, the available end-to-end throughput is B, since each link can be active simultaneously because all three links use a different channel.

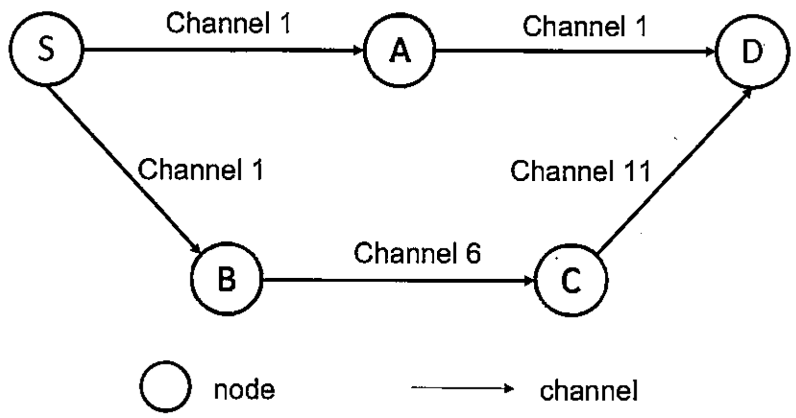


Fig. 1.3 Two Paths between a Source S and a Destination D

The above discussion illustrates that there is a close relationship between CA and routing in mesh networks. Therefore, in order to maximize performance, the two problems should be treated jointly rather than separately. However, in practice the joint problem is generally too hard to solve optimally.

1.6 Main Work

In this study, I focus on combined channel assignment and routing to achieve collision-free transmission in MRMC WMNs. The main work are described as following:

(1) CASCA (CSMA-Aware Static Channel Assignment) which is the first collision-free static channel assignment scheme within 3-5 channels ever appeared in the literature is analyzed in detail, and conducted in-depth evaluation and simulation. Due to the evaluation of CASCA is not enough (only optimization evaluation is done completely) so that whether it has good network performance or not is not clarified sufficiently. Therefore, I first evaluate the performance of CASCA in both grid topology and random topology. Simulation results prove that the channel assignment of CASCA is mostly collision free if wireless interference model is up-to-date. The simulation results also showed that CASCA outperforms the conventional channel assignment method CLICA (Connected Low Interference Channel Assignment), and revealed several specific properties of CASCA.

(2) I introduce a traffic demand matrix into CASCA, and formulate a joint channel assignment and routing problem within MILP framework. Note that the traffic demand matrix is defined statically although the demand dynamically changes with time. In practice, we can assume that the dynamism of the demand is sufficiently small and so we can define

the traffic demand matrix that comprehend the dynamics based on some measurement or estimation of the real traffic.

(3) I newly introduce a CSMA-aware shared link capacity model to leverage the property of CSMA into link capacity computation and traffic engineering. Capacity modeling in relation with channel assignment is essential for routing to optimize the network performance. In the CSMA-aware interference model, links within the carrier-sensing range may be assigned with the same channel. Due to the characteristics of CSMA, all of those links within the carrier sensing range share the link capacity.

(4) With the CSMA-aware interference model and CSMA-aware shared link capacity model introduced, I achieved a traffic-demand aware collision-free channel assignment that optimizes MRMC WMN under given traffic demands. My scheme TACCA (Traffic-demand-Aware Collision-free Channel Assignment) is the first joint channel assignment and routing scheme which achieves collision-free transmission with small number of channels in the literature. Unlike CASCA that does not consider traffic demands, TACCA consistently selects both routing paths that satisfies the link capacity constraint, and channels that consistently avoid collisions.

(5) I newly introduce POCs into TACCA, and design a reasonable channel assignment scheme TAC-POCA (Traffic-Demand-Aware Collision-free Partially Overlapping Channel Assignment) to exploit the effectiveness of POCs.

(6) I jointly solve the channel assignment and routing problems using POCs, and showed that POCs are significantly effective to improve spatial reuse in WMNs. Furthermore, I confirmed that TAC-POCA keeps collision freedom property in network simulation with SINR-based interference model, and the proposed CSMA-aware interference model with POCs actually work in networks.

To avoid ambiguity, let me note that the term "collision freedom" in this thesis is used to represent the zero-collision schedule (i.e., the channel assignment and routing) just under a rational interference model proposed in this thesis. This thesis introduces two interference model based on the behavior of physical radio and CSMA MAC protocol, and obtains zero-collision schedules through my MILP formulations. These schedules are collision free in theory, but may not be exactly collision free in the real environment due to the gap between my model and the reality.

As described above, in this thesis, based on CSMA-aware interference model and CSMA-shared capacity model, I deeply study on jointing channel assignment and routing in IEEE 802.11-based MRMC WMNs, and proposed two traffic-demand-aware collision-free channel assignment schemes for MRMC WMNs. Without modifying IEEE 802.11 protocol, I make all channels employed in MRMC WMNs, and significantly improve the overall channel reuse and efficiently improve the network capacity.

Chapter 2

Overview of Channel Assignment in MRMC WMNs

2.1 Channel Assignment Overview

MRMC WMN has attracted numerous numbers of research efforts to utilize the advantages that this network is offering. Several proposed approaches on channel assignment (CA) algorithms, multichannel MAC protocols, multichannel routing metrics, links scheduling (LS), multichannel multicast protocols, power and topology control, and network planning exist in the literature. However, the designs that are considering combinations of these issues have shown more efficient performance such as joint routing and link scheduling [64], joint CA and power control [65], joint QoS multicast routing and CA [66], joint gateway selection, transmission slot assignment, routing and power control [67], joint CA, power control and routing [68], joint CA, power control and rate assignment [69], joint routing and topology control with directional antennas [58], and partially overlapped CA [70] [71].

Due to channel assignment algorithms aim to assign channels to the radio interfaces with the objective of minimizing overall interference over wireless links, and maximizing communication performance, CA can either be solved as a separated problem as in [72] [73] or jointly solved with routing as in [34] [35]. Furthermore, it can be developed as centralized solutions [34] [35] and distributed solutions [74] [75]. The availability of the entire network view makes centralized solution more effective than distributed solutions, which only relayed on local information. Typically, CA algorithms must have knowledge on network load in order to assign channels to links. However, some other algorithms do not require any traffic information, as in [59], where the interference is minimized by conserving a k-connected topology. Joint design approaches in WMNs are surveyed in many works in the literature such as [8] [13] [76] [77][78].

As routing is the most effective joint factor to reduce collisions among links and improve performance of networks. In this study I focus on combined channel assignment and routing.

2.2 Problem Formulation and Approaches

The CA algorithms have been designed in the literature for different optimization objectives and metrics.

(1) Optimization Objective Functions

Below is the set of optimization objective functions and metrics:

(i) Maximize aggregated network throughput [33] [37] [39] [42] [79].

(ii) Maximize achievable scaling factor (λ) [35] [36] [37] [80] [81].

(iii) Maximize the aggregated utility of flows [43].

(iv) Minimize the maximum interference on all channels [35] [82].

(v) Maximize the minimum un-utilized capacity on links [83].

(vi) Maximize the cross-section good-put [34].

(vii) Minimize the path length and link contention [38] [84].

(2) Mathematical Formulation Constraints

The general set of constraints to be considered in the mathematical formulation of the CA problem can be divided into five sets as follows.

(i) Flow Routing Conservation Constraints. These constraints ensure that for each traffic flow f from source to destination the net amount of traffic out of each mesh router is equal to the flow rate (f_r) if the mesh router is the source of the traffic and ($-f_r$) if it is the destination and otherwise 0. More constraints can be added to the problem to determine the routing scheme (for multi-path or single-path).

(ii) Radio Constraints. These constraints ensure that the number of channels assigned to each incident link on a mesh router (at any given time slot for dynamic CA) does not exceed the number of radio interfaces at that node. This integer-value constraint can be relaxed to linear constraints to ensure that the total load on the links on each node is not higher than the number of radios on that node multiplied by the channel capacity.

(iii) Interference Constraints (or Capacity Constraints/Schedule Ability Constraints). These constraints ensure that the amount of data flows on interfered links does not exceed a specific value. This is to constraint the maximum contention level over the collision domains if contention-based MAC is considered or to ensure a feasible interference-free link scheduling if contention-free MAC is used.

(iv) Link Capacity Constraints. These constraints ensure that the traffic load on a wireless link is not exceeding the link capacity. This constraint is implicitly considered under the interference constraints if only sufficient condition for schedule-ability is considered.

(v) Fairness Constraints. These constraints ensure fairness in allocating resources to different traffic flow demands.

(3) Approaches

Integer Linear Programming: One approach to obtaining an optimal CA (for a suitable objective function) is to pose the problem as an integer linear program (ILP). However, the CA problem which is part of CA problem is an NP-hard [34], where, with given link loads, finding the CA for a set of radio interfaces such that the link loads are schedulable is NP-hard problem. Moreover, interference-free link scheduling problem for a given link flows is also NP-hard [85]. Therefore, the problem is then transformed into a linear programming problem by relaxing some constraints [35] [37] [42] [79] [80]. The problem can then be considered as multi-channel multi-commodity flow problem with constraints on radios, interference, and link capacities. The optimal solutions are obtained for feasible problems only [39] [83] or with some fairness considerations [35] [80]. Due to the NP-hardness of the problem, standard methods and solvers are not able to solve the problem for real-life network sizes. A set of heuristic algorithms [33] [34] [43] [86] and meta-heuristic algorithms [39][83] are proposed in the literature [35] [36] [37] [80]. Furthermore, approaches can also be classified based on their execution time into online [33] [43] and offline for planning stage [39]. While an ILP-based formulation can yield optimal solutions using standard ILP software, the required run-time to find the optimal solution can be very high for even modest-sized networks. However, by terminating the search after a certain time, or by using non-integer relaxations, useful bounds to the objective function can be computed.

Graph-Theoretic Approaches: The CA problem can be viewed as a coloring problem on the reach-ability graph. Given a finite number of colors (i.e., channels), the goal is to assign the colors to edges while satisfying the constraint that the number of distinct colors assigned to edges incident on a node is not more than the number of radios at that node. Furthermore, we may seek to find a coloring that optimizes some objective function. In general, posing the CA problem as a coloring problem reveals the computational hardness of the problem; several authors have developed formulations which they have shown to be NP-hard [87].

The graph-theoretic approach can be useful for considering questions such as the minimum number of channels required to achieve maximum capacity or the maximum achievable capacity with a given number of channels. The first question is closely related to the "strong edge-coloring" problem [87] [88]. The question of maximum achievable capacity is addressed [89], where the authors derive upper and lower bounds for the capacity.

2.3 Current Status of Orthogonal Channel Assignment

Joint channel assignment and routing schemes have been in progress for decades. Routing configuration is effective to reduce interference among links because it can make a part of links inactive and arrange logically sparse networks. In the formulation of optimization problems, several interference models have been considered such as single/double disk models [27], SINR (Signal to Interference plus Noise Ratio) model [90], and k-hop model [91], etc. Those models basically determine the range of interference, and two links within the range of each other collide if they communicate simultaneously. To avoid collision, those two links must use orthogonal channels. Hence, it is naturally easier to reduce collision in sparser networks. One typical use case of channel assignment is WMNs with commodity 802.11 interfaces, where nodes have multiple NICs to which channels are assigned in coordination with routing configurations. Since the number of available orthogonal channels in 802.11 is small, to eliminate collisions under smaller number of channels is a key challenge. Also, as the joint channel assignment and routing problem has been proved to be NP-hard [92], exploring efficient algorithms to find optimal solutions is another important challenge.

As a study tackling the challenges, Marina et al. [93] formulate a channel assignment problem based on traditional conflict graphs under protocol (i.e., single-disk) interference model, and provided a greedy algorithm. The result shows that heavy collisions remain with as many as 3-5 orthogonal channels. Raniwala et al. [34] proposed a centralized joint channel assignment and routing algorithm under double-disk interference model, and designed a heuristic algorithm to solve it. Although they incorporate joint routing scheme, their method still does not perform with 3-5 orthogonal channels. Lin et al.[39] proposed to apply genetic algorithm for the joint channel assignment and routing problem under protocol interference model. Although their method achieved better optimal than conventional optimization methods, collision freedom is not achieved with 3-5 channels. Avallone et al. [94] formulates a layer-2.5 forwarding scheme considering flow rate. They achieved a collision-free channel assignment under the assumption that links in a collision domain can share capacity within the sum of flow rates. However, to realize this without collision, some time-slot based scheduling under layer-2.5 forwarding is required, and MRMC WMNs with commodity 802.11 NICs (Network Interface Cards) do not support it. As above, collision freedom in MRMC WMNs with small number of channels is still a challenging problem.

Recently, a significant progress is brought in CASCA [95], which introduces a new CSMA-aware interference model. The CSMA-aware model allows two links located within the carrier-sense range to use the same channel, whereas making two links that invoke hidden-terminal problem use different channels. Simultaneously, CASCA allows to use longer paths than the shortest paths by k-hops in order to reduce collisions. This achieved collision-free channel assignment with 3-5 orthogonal channels in both grid and random scenarios. However, since they neither treat traffic demands nor provide full routing function, CASCA lacks flexibility in terms of practical efficacy.

In [83] and its directed-antenna extension [96], authors made a MILP-based formulation of joint channel assignment and routing problems with the constraint of forwarding paths length. The scheme, i.e., TiMesh which proposed in [83] aims at avoiding collisions using RTS/CTS handshakes so that links in a collision domain shares the capacity. However, RTS/CTS not only reduces performance due to the exposed terminal problem [97], but also does not work well in real environment due to interference of RTS/CTS frames. Through the simulation results, in Chapter 4 we will show that the introduced CSMA-aware interference model significantly reduces collisions compared to RTS/CTS schemes.

2.4 Current Status of Partially Overlapping Channel Assignment

For channel assignment, most existing researches confined transmission to OCs, and focused on mitigating co-channel interference by combining other aspects such as routing, QoS and so on [35] [64] [66] [69] [67] [98] [99] [100] [101]. However, since two adjacent orthogonal channels should be separated by a certain bandwidth, orthogonal separation has a waste of spectrum. To enhance the spectral utilization, the concept of POC was introduced. Mishra [29] [30] put forward the pioneering idea of using POC. They showed that POCs utilization can lead to better utilization of the spectrum and throughput improvement by designing a practical interference model among POCs, and by demonstrating to apply it to channel assignment. After that, researchers came to make investigations about it successively. As mentioned early, routing is the most effective factor to reduce collisions among links and improve performance of networks. Under POCs, two ways are proposed in the surveyed channel assignment approaches. In one way, channel assignment is viewed as a lower-layer mechanism and does not consider the traffic load, while routing is viewed as an upper-layer mechanism and is fully responsible for distributing the traffic load, i.e., routing is independent of channel assignment [28] [71] [102] [103] [104] [105] [106]. In the other way, channel assignment and routing are viewed to be mutually dependent, so they are combined in order to obtain optimal network performance.

However, only a few studies on channel assignment using POCs considered the routing factor. Yang et al.[107] designed a POC assignment scheme with effective interference avoidance and load balancing for WMNs, but they assumed routing paths are pre-determined by AODV (Ad hoc on-demand distance vector) routing protocol. Wang et al. [108] explored how to exploit POCs to perform end-to-end channel assignment in order to achieve effective end-to-end flow transmissions, and proposed ELIA-POCA (End-to-end Load-aware partially channels assignment) for MRMC WMNs. They also assumed routing paths are pre-determined by the shortest paths. Liu et al. [109] proposed two load-aware channel assignment schemes, Load-Aware CAFPO and Load-Aware CAEPO-G, to exploit the POCs for wireless mesh networks under the IEEE 802.11 standards. However, they used bandwidth-aware AODV to determine the routing paths, which is based on the shortest paths, and thus the performance on collision avoidance is limited.

Rad et al.[102] proposed a joint channel assignment, interface assignment, and scheduling algorithm for MRMC WMNs when all OCs and POCs are being used. The joint problem is formulated as a linear mixed-integer program with a few integer variables. Their method adopts SINR-based interference model and takes pairwise interference between links into account. Simulation results show that there is a significant performance improvement in terms of achieving high network capacity and a lower bottleneck link utilization when all the POCs within IEEE 802.11 2.4 GHz frequency band are used. However, there are three drawbacks. First, they also assume the routing paths are pre-determined. Second, although they used SINR-based interference model, their model simply considers the pairwise effect between two links and does not consider effects among multiple links, which is a partial consideration of the SINR model. Third, they do not consider the hidden-terminal effects; they assumed that nearby links assigned with the same channel can share their capacity even if they are in hidden-terminal relationship. As above, currently there no scheme that simultaneously optimize channel assignment and routing in the context of POC studies.

On the other hand, in the content of OCs, several advanced joint channel assignment and routing schemes has been proposed. Especially, in [110], by incorporating the CSMA-aware interference model, we proposed a joint channel assignment and routing scheme called TACCA, which achieves collision-freedom with 3-5 OCs in IEEE 802.11 2.4 GHz based MRMC WMNs. In addition, to provide good load-balancing performance, TACCA minimizes the network-wide utility under a given traffic demand matrix. However, TACCA deals with channel assignment under OCs, resulting in a low spatial utilization. Due to the difference of interference estimation in OCs and POCs, POCs are not directly applicable to TACCA in WMNs. Therefore, in Chapter 5, I propose a new scheme TAC-POCA (Traffic-Demand-Aware Collision-free Partially Overlapping Channel Assignment) that newly introduce POCs into the CSMA-aware interference model and the CSMA-aware shared capacity model to achieve collision-free transmission while considering traffic engineering.

2.5 The First Collision-freedom CA Scheme

2.5.1 Background

It is known that the hidden terminal problem is significantly harmful in communication performance in WMNs [111], and many studies have been made to mitigate the harmful effect of HTs. RTS/CTS included in IEEE 802.11 standard would be the best-known countermeasure for HT problem. However, as reported in several studies [97] [112] [113] [114], RTS/CTS cannot actually be an effective solution in practice due to the rough interference model assumed in it. To effectively leverage MRMC radio resources and to improve performance of WMNs, collision-free CA techniques are required.

Yoshihiro, et al. [95] proposed a static channel assignment scheme CASCA (CSMA-Aware Static Channel Assignment) that achieves collision-free communications in MRMC WMNs within 3-4 orthogonal channels while maintaining network connectivity. Because the channel assignment problem is NP-Hard [92], they formulated it as a PMAX-SAT (Partial MAXimum SATisfiability) problem. To eliminate collisions among communication frames, they introduce a CSMA-aware interference model, and allow two links located within the carrier-sense range to share the same channel resource, whereas making two links located in hidden-terminal positions use different channels. Additionally, they further reduced collisions by excluding a part of links from a set of links that forward packets while simultaneously guaranteeing feasible paths for any pair of source-destination nodes. CASCA is the first collision-free static channel assignment scheme within 3-4 channels ever appeared in the literature. The main contributions of CASCA are shown in the following.

(1) Based on the newly introduced CSMA-aware interference model, they achieved collision-free transmission using limited orthogonal channels without requiring MAC modifications or tight synchronization.

(2) They included constraints on the number of NICs, the number of channels, and the partial routing functionality in the channel assignment problem to achieve more flexible routing, and formulated the problem within the framework of PMAX-SAT, and this work is the first PMAX-SAT based formulation of a channel assignment problem.

Due to this study bases on this CSMA-aware interference model, next the system model, problem formulation and solving of CASCA will be described in following.

2.5.2 System Model

(1) Network Model and Assumption

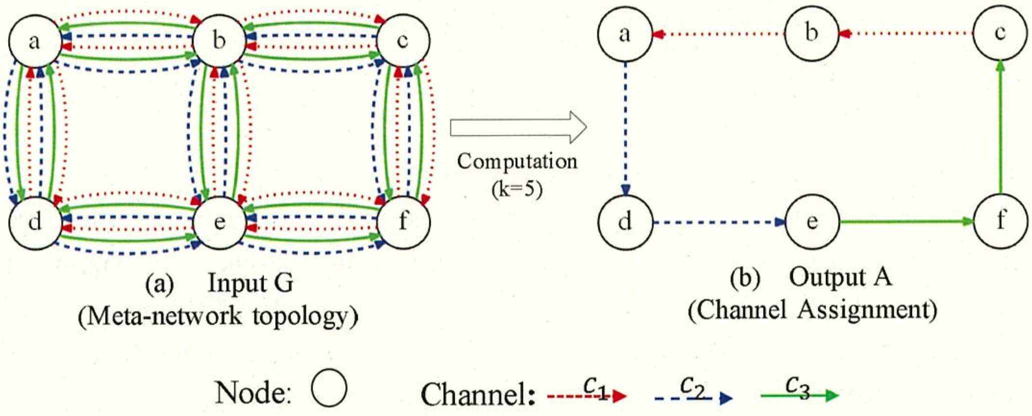


Fig. 2.1 Formulation of the Channel Assignment Problem

In [95], the MRMC WMN is considered as a *meta-network topology* $G = (V, E)$, where V indicates a set of nodes equipped with λ_v NICs built on IEEE 802.11 standard, and E represents a set of direct links. They let R be the communication range and C be a set of available orthogonal channels, where $|C|$ represents the number of the channels. A link is denoted by $e = (u, v, c) \in E$, where $u \in V$ and $v \in V$ are neighbor nodes located within the communication range R, and have the common channel $c \in C$. Since the definition of links includes a channel, links used for communication is determined according to the applied channel assignment. To catch up with this setting, they defined multiple links between every neighbor node pairs corresponding to each available channel in C in their network model. Fig. 2.1(a) illustrates their network model in case of $|C| = 3$, in which $2|C|$ links are defined between every neighboring node pairs.

They define the *channel assignment* $\mathscr{A} = (V, F)$ on G, where $F \subseteq E$. In their channel assignment, each NIC must operate on one distinct channel. Therefore, the total number of channels used on all in-coming and out-going links at node $v \in V$ must be less than or equal to λ_v. Fig. 2.1(b) illustrates a schedule of channel assignment where $\lambda_v = 2$. They also assumed that link (u, v, c) may not exist in F even if u and v such that $(u, v) \in E$ have the common channel assigned to them.

This definition enables them to introduce partially a routing functionality into the channel assignment algorithm, in which they can restrict links used in packet forwarding to reduce interference as long as $\mathscr{A}$ is connected, i.e., the connectivity of the network is guaranteed.

(2) CSMA-aware Interference Model

In CASCA, authors introduced a CSMA-aware interference model, which is built on the single disk model where the communication range and interference range are the same, and is defined as R. In CSMA-aware interference model, a group of nodes within the carrier-sensing range can share a single channel, among which IEEE 802.11 DCF avoids collision of frames. By making use of IEEE 802.11 DCF, they could reduce the number of channels especially in case of high-density networks. Therefore, in this study, they regarded that two directed links interfere with each other only if they are located in the hidden-terminal position. They defined that link $e_2 = (u_2, v_2, c_2)$ is interfered by link $e_1 = (u_1, v_1, c_1)$ iff (if and only if) either of the following conditions are met:

Condition 1: Collision between two Data frames

(1) $c_1 = c_2$,

(2) $(u_1, u_2, c_1) \notin E$,

(3) $(u_1, v_2, c_1) \in E$.

Condition 2: Collision between Data and Ack frames

(1) $c_1 = c_2$,

(2) $(u_1, u_2, c_1) \notin E$,

(3) $(v_1, v_2, c_1) \in E$.

See Fig. 2.2 for example. Fig. 2.2(a) shows the case of *Condition 1*, where the Data frames on e_1 interferes the Data frames on e_2. In Fig. 2.2(a), node v_2 is within the carrier-sensing range R of node u_2, nodes v_1 and v_2 (they may be the same node) are both within the carrier-sensing range of node u_1, but u_1 is outside of the carrier-sensing range of node u_2. Collision occurs at node v_2 when both nodes u_2 and u_1 simultaneously transmit data frames to node v_2 and v_1, respectively. On the other side, Fig. 2.2(b) shows the case of *Condition 2* where the Ack frames on e_1 interferes the Data frames on e_2. In Fig. 2.2(b), node v_2 is within the carrier-sensing range of u_2, both nodes u_1 and v_2 (they must be different nodes) are within the carrier-sensing range of v_1, but node u_1 is outside the carrier-sensing range of u_2. Then, the Ack frame from v_1 and the data frame from u_2 may collide at v_2 if they are transmitted simultaneously. Note that interference between two Ack frames are ignored since the probability is low because the size of Ack frames is small enough.

They defined $I_G = \{(e_1, e_2) | e_1 \text{ interferes } e_2\}$ as the set of interfering link pairs in G that satisfy either of *conditions 1* or 2. In CASCA, authors formulated the optimization problem to minimize $|I_{\mathscr{A}}|$, which is the number of interfering link pairs in $\mathscr{A}$.

(3) Partially Routing Functional Model

Routing and channel assignment can be effective in improving overall network performance with reduced interference. Usually, some routing protocols such as OLSR work

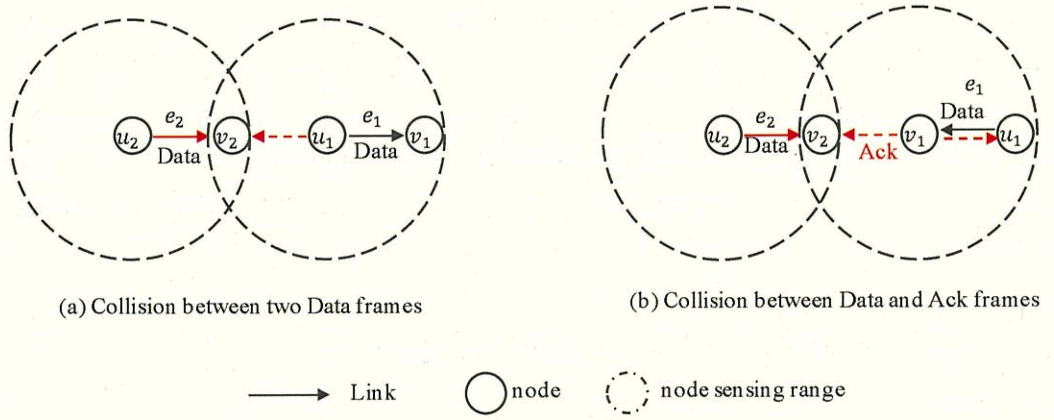


Fig. 2.2 Two Patterns of Interference

over the topology to determine the next-hop nodes. To maintain network connectivity and further reduce the number of required channels in CASCA, they introduced partially routing functionality to the channel assignment problem.

Recall that the *channel assignment* $\mathscr{A}$ consists of a set of links $F \subseteq E$, which affords restriction on routing decision by removing links from E (i.e., only the links in F are available in forwarding packets). Therefore, in their problem formulation, they introduced a pre-configured value k as the level of restriction on path length. They let $\delta^{G}_{u\to v}$ be the distance from u to v on G, and F is constrained by $\delta^{\mathscr{A}}_{u\to v} \leq \delta^{G}_{u\to v} + k$. Because $\delta^{G}_{u\to v}$ is constant, if k increases, the communication path goes longer, while the interference level goes lower. This enables them to adjust path-lengths in order to surely obtain collision-free *channel assignment*. Note that larger number of k leads to smaller number of links in $\mathscr{A}$. Decreasing links in E naturally leads to lower interference level, whereas increasing k simultaneously leads to sub-optimal communication paths that prolong the path length. Consequently, there is the trade-off between path optimality and interference level.

Table 2.1 gives the notations to summarize the definition of system model above all.

2.5.3 Problem Formulation and Solving

(1) Problem Formulation

As mentioned before, $|I_{\mathscr{A}}|$ is the number of interfering link pairs in $\mathscr{A}$. Therefore, the CA problem be formulated as an optimization problem that minimize $|I_{\mathscr{A}}|$ in $\mathscr{A}$. Then, given a meta-topology $G = (V, E)$, they selected a set of links $F \subseteq E$ to form a *channel assignment* $\mathscr{A}$, in which the objective is to minimize the interference level $|I_{\mathscr{A}}|$ as long as the shortest path for every pair of nodes is not prolonged by more than k-hops and the total number of channels used by all in-coming and out-going links of every node $v \in V$ must be less than or

Table 2.1 Notations for System Model

Symbol	**Description**
G	a meta-network
V	a set of nodes
E	a set of direct links
C	a set of available channels
$\|C\|$	number of channels
v or u	a node
c	a channel
λ_v	number of NICs on node v
e or (u,v,c)	a link
$\mathscr{A}$	a channel assignment
F	a set of links in $\mathscr{A}$
$\delta^{G}_{u\to v}$	distance from node u to v in G
$\delta^{\mathscr{A}}_{u\to v}$	distance from node u to v in $\mathscr{A}$
k	a control factor (an integer)
I_G	a set of interfering link pairs in G
$I_{\mathscr{A}}$	number of interfering link pairs in $\mathscr{A}$

equal to λ_v. Formally, the optimization problem is written as follows.

Problem 1:
Input:

- A meta-topology $G = (V,E)$,
- A set of channels C,
- The number of interfaces λ_v for $v \in V$,
- Pairs of interfering links I_G,
- An integer k.

Output:

- Channel assignment $\mathscr{A} = (V,F)$.

Objective Function:

- Minimize the interference level $|I_{\mathscr{A}}|$.

Subject to:

(a) $\delta^{\mathscr{A}}_{u\to v} \leq \delta^{G}_{u\to v} + k$, for all $u, v \in V$.

(b) $|\{c | c \in C, (u,v,c) \in F \text{ or } (v,u,c) \in F, u \in V\}| \leq \lambda_v$, for all $v \in V$.

The input of their problem includes the *meta-topology* $G = (V, E)$ that includes bi-directional links with all neighbors for every channel $c \in C$. The constraint (a) gives a restriction on the paths length with k, and (b) limits the number of channels used on each node. See Fig. 2.1 again. In this example, they set $\lambda_v = 2$, $|C| = 3$, and $k = 5$. I_G is obtained from the model-based interference calculation that is done as a preprocess of the problem generation. The output is the *channel assignment* $\mathscr{A}$. Seen that $\mathscr{A}$ includes far less links than G so that for several pairs of source and destination nodes the length of the shortest path in $\mathscr{A}$ is larger than that in G. To prevent large increase of the path length, they limited the increase with factor k, i.e., for every pair of nodes distance in hop count in $\mathscr{A}$ is less than that in G plus 5, e.g., the distance from node b to c is one hop length in G, whereas in $\mathscr{A}$ the length is $6 \leq 1+5$. In the example of Fig. 2.1, the interference level of $\mathscr{A}$ is zero, i.e., $|I_{\mathscr{A}}| = 0$. By using the factor k, they can reduce the interference level of $\mathscr{A}$, or reduce the number of channels required to achieve zero interference.

(2) Solving the Problem

They follow the same strategy as [92] to solve this optimization problem, i.e., they reduced the problem into the well-known NP-Hard problem called Partial MAX-SAT (PMAX-SAT). Here they concisely introduce PMAX-SAT to which they reduced the channel assignment problem. Let $x_1, x_2, \ldots, x_m$ be logical variables to which values true (1) or false (0) are assigned. As the input of the problem, they have a conjunctive normal form (CNF) formula $\phi = X_1 X_2 \ldots X_n Y_1 Y_2 \ldots Y_m$ where $X_i (1 \leq i \leq n)$ be *hard clauses* and $Y_j (1 \leq j \leq m)$ be *soft clauses*. Given a set of soft and hard clauses as input, PMAX-SAT is a problem of finding an assignment of values that maximize the number of satisfied soft clauses while all the hard clauses are satisfied. For example, if the input $\phi = X \wedge Y$ is given with hard clauses $X = (x_1 \vee)(x_2 \vee \overline{x_3})(x_3 \vee \overline{x_1})$ and soft clauses $Y = (x_1)(\overline{x_2})(\overline{x_3})$, the solution $(x_1, x_2, x_3) = (false, false, false)$ is the optimal solution that satisfy all clauses in X while maximizing the satisfied clauses in Y.

(i) Defining Logical Variables

They translated the input of the scheduling problem into that of PMAX-SAT while the output of PMAX-SAT directly represents the schedule.

They let $l_{(u,v,c)}$ be a logical variable defined for every link $(u, v, c) \in E$, which takes true iff (if and only if) $\mathscr{A}$ includes the link (u, v, c). Note that $L = \{l_{(u,v,c)} | (u, v, c) \in E\}$ represents the schedule. They defined another variable $m^h_{(u,v)}$ for every pair of nodes $u, v \in V$ that takes true iff v is reachable from u in $\mathscr{A}$ within h hops.

(ii) Clause Structure

They generated hard and soft clauses of PMAX-SAT from the input of *Problem 1*. Hard clauses include a basic constraint X_{M^h}; because the value of $m^h_{(u,v)}$ is determined by L, the constraint to keep the proper relationship between $m^h_{(u,v)}$ and L is required. Hard clauses also include two specific constraints X_{dist} and X_{IF}, which corresponds to the constraints (a) and (b) in *Problem 1*. Soft clauses Y represent the interference level to be minimized. As a result, the PMAX-SAT instance reduced from *Problem 1* is represented as $\phi = X \wedge Y$ where $X = \bigwedge_{1 \le h \le d} X^h_M \wedge X_{\text{dist}} \wedge X_{\text{IF}}$. The solution of PMAX-SAT includes a set of values on L, which is the solution, i.e., the channel assignment, for the scheduling problem.

(iii) Generating Hard Clauses

1) Constraint on 1-hop reachability (X_{M^1}): They defined a set of hard clauses X_{M^1} that determines values of $M^1 = \{m^1_{(u,v)} | u, v \in V\}$ according to the values in L. Note that $m^1_{(u,v)}$ is true iff $\mathscr{A}$ includes at least one link from u to v. Namely, $m^1_{(u,v)} = \bigvee_{l_{(u,v,c)} \in F, c \in C} l_{(u,v,c)}$ holds. They define the hard clauses $X_L = \bigwedge_{u,v \in V} (m^1_{(u,v)} \vee \overline{P_{uv}})\ (\overline{m^1_{(u,v)}} \vee P_{uv})$ where $P_{uv} = \bigvee_{l_{(u,v,c)} \in F, c \in C} l_{(u,v,c)}$. Then, if X_{M^1} is satisfied, the values of M^1 are correct.

2) Constraint on h-hop reachability (X_{M^h}): They similarly defined $M^h = \{m^h_{(u,v)} | u, v \in V\}$. The values of M^h are determined according to M^{h-1} and M^1. Specifically, v is reachable from u in h hops, i.e., $M^h_{(u,v)} =$ true, if (i) v is also reachable from u in $h-1$ hops, or if (ii) w is reachable from u in $h-1$ hops and v is reachable from w with 1 hop. The relation among $m^h_{(u,v)}$, $m^{h-1}_{(u,v)}$, and $m^1_{(u,v)}$ is represented as $m^h_{(u,v)} = Q^h_{uv}$ where $Q^h_{uv} = m^{h-1}_{(u,v)} \vee (\bigvee_{\{w | (w,v,c) \in F, c \in S\}} (m^{h-1}_{(u,w)} \wedge m^1_{(w,v)}))$. Thus, they defined a set of hard clauses $X_{M^h} = \bigwedge_{u,v \in V} (m^h_{(u,v)} \vee \overline{Q^h_{uv}})(\overline{m^h_{(u,v)}} \vee Q^h_{uv})$. Then, the values of M^h for any h is correct iff $\bigwedge_{1 \le h \le d} X_{M^h}$ is satisfied where d is the diameter of G.

3) Constraint (a) on the distance restriction (X_{dist}): Constraint (a) $\delta^{\mathscr{A}}_{u \to v} \le \delta^G_{u \to v} + k$ limits the increase of the shortest-path length in the schedule $\mathscr{A}$ by k. Variable $m^{(\delta^G_{(u,v)}+k)}_{(u,v)}$ takes true iff constraint (a) meets. Thus, they define hard clauses $X_{\text{dist}} = \bigwedge_{u,v \in V} m^{(\delta^G_{(u,v)}+k)}_{(u,v)}$. If X_{dist} is true, constraint (a) suffices.

4) Constraint (b) on the number of interfaces (X_{IF}): With Constraint (b), the number of channels used at each node is limited by the number of interfaces on it. First, they defined a variable $s_{u,c}$ that takes *true* iff node $u \in V$ has an interface that use channel $c \in C$. If they defined holds. Furthermore, they let $\mathscr{C}_x = \{C_1, C_2, \dots C_n\}$ be the family of all subsets of C that include exactly x channels, i.e., they enumerate all subsets $C_i \subseteq C$ such that $|C_i| = x$. Then, iff $\wedge_{C_i \in \mathscr{C}_x} (\overline{s_{u,c_1}} \vee \overline{s_{u,c_2}} \vee \cdots \vee \overline{s_{u,c_x}})$ where $(c_1, c_2, \dots, c_x) \in C_i$ holds, then node u does

Table 2.2 Notations for Problem Formulation and Solving

Symbol	Description
$X_i (1 \leq i \leq n)$	a set of hard clauses
$Y_j (1 \leq j \leq m)$	a set of soft clauses
ϕ	a conjunctive normal form (CNF) formula $\phi = X_i Y_j$
$l_{(u,v,c)}$	a logical variable defined for every link $(u,v,c) \in E$
L	the schedule ($L = \{l_{(u,v,c)} \mid (u,v,c) \in E\}$)
$m^h_{(u,v)}$	a variable for every pair of nodes $u,v \in V$ that takes true iff v is reachable from u in $\mathscr{A}$ within h hops.
M^h	a set of $m^h_{(u,v)}$ for a given h
X_{M^h}	constraint on h-hop reachability
d	the diameter of G
X_{dist}	constraint on paths length with k
X_{IF}	constraint on the number of channels used on each node
$s_{u,c}$	a variable that takes true iff node u has an interface that use channel c
$\mathscr{C}_x$	the family of all subsets of C that include exactly x channels
(l_1, l_2)	a link pair in I_G

not use more than x channels. Since the number of channels must be bounded by the number of interfaces λ_u on u, the constraint (b) is satisfied iff the following formula holds: $X_{\text{IF}} = \bigwedge_{u \in V} (\bigwedge_{C_i \in \mathscr{C}_{\lambda_u}} (\overline{s_{u,c_1}} \vee \overline{s_{u,c_2}} \vee \cdots \vee \overline{s_{u,c_{\lambda_u}}})) \wedge (\bigwedge_{\{u \in V, c \in C\}} (s_{u,c} \vee \overline{s_{u,c}})(\overline{s_{u,c}} \vee s_{u,c}))$.

(iv) Generating Soft Clauses

They designed soft clauses as follows: For every link pairs (l_1, l_2) in I_G, they defined a soft clause $(\overline{l_1} \vee \overline{l_2})$, in which if either l_1 or l_2 is false, collision between l_1 and l_2 does not occur, and this clause is satisfied. Consequently, they defined a set of soft clauses $Y = \bigwedge_{(l_1, l_2) \in I_G} (\overline{l_1} \vee \overline{l_2})$. As a result, the number of unsatisfied clauses in Y corresponds to the interference level $|I_{\mathscr{A}}|$.

Table 2.2 gives the notations to summarize the definition above all.

2.6 Chapter Summary

This chapter analyzes the current research status of MRMC WMNs routing and channel assignment in detail, and focuses on the collision-free channel allocation scheme CASCA, which lays the foundation for the design of routing and channel assignment schemes in subsequent chapters.

Chapter 3

Extensive Evaluation and Simulation of CASCA

3.1 Introduction

Typically, WMNs are considered as a wireless network infrastructure to provide a certain area coverage in the rural area, or in case of disasters where cellular phones or Wi-Fi are not available. Collision due to radio interference is a main cause of performance degradation in WMNs, and it should be avoided in practical use of this kind of infrastructure networks. It is known that the hidden terminal problem is significantly harmful in communication performance in WMNs [111], and many studies have been made to mitigate the harmful effect of hidden terminals. RTS/CTS included in IEEE 802.11 standard would be the best-known countermeasure for hidden terminal problem. However, as reported in several studies [97], RTS/CTS cannot actually be an effective solution in practice due to the rough interference model assumed in it. Even in recent years, essential solution for the hidden terminal problem has not been proposed so far. To effectively leverage MRMC radio resources and to improve performance of WMNs, collision-free channel assignment techniques are required.

Marina, et al. [93] proposed a static channel assignment algorithm called Connected Low Interference Channel Assignment (CLICA), which is based on a greedy strategy that minimizes interference under the constraint that the network is connected. Tang, et al. [59] proposed INterference Survivable Topology Control (INSTC) that formulates the similar channel assignment problem as an optimization problem based on linear programming (LP). Ramachandran et al.[72] proposed Breadth First Search Channel Assignment (BFS-CA) that introduces an interference model called multi-radio conflict graph that models the interference in multi-radio environment. Although these schemes [93][59][72] effectively reduce the

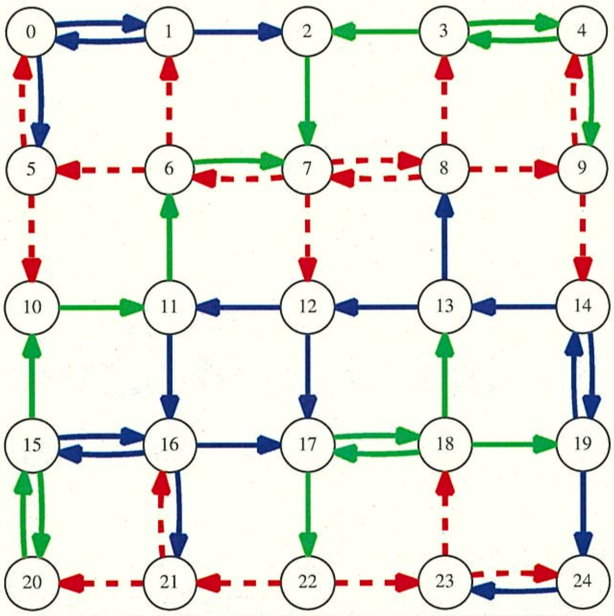


Fig. 3.1 CASCA (grid $k = 2$).

interference effects over the network, they cannot achieve collision-free transmission, and still suffer from considerable interference effects within 3-4 available channels. Yoshihiro, et al. [95] proposed a static channel assignment scheme CASCA (CSMA-Aware Static Channel Assignment) that achieves collision-free communications in MRMC WMNs within 3-4 orthogonal channels while maintaining network connectivity. However, the evaluation of CASCA is not enough (only optimization evaluation is done completely), whether it has good network performance or not is not clarified sufficiently.

To further evaluate CASCA. In this chapter, I evaluate the performance of CASCA in both grid topology and random topology. First, I apply QMAX-SAT solver to solve the problems for each topology, and evaluate the optimization performance of CASCA. Second, I evaluate its communication performance on a network simulator with two different traffic patterns, i.e., point-to-point traffic and Internet-oriented traffic.

3.2 Optimization Performance

The goal of CASCA is to achieve collision-free channel assignment (i.e., $|I_{\mathscr{A}}| = 0$) with the small number of available channels while keeping the network always connected. I would particularly expect at most 4 channels (in many cases, 3 channels) when I suppose IEEE 802.11 standards on 2.4 GHz band. Since $I_{\mathscr{A}}$ is computed for each parameter values such

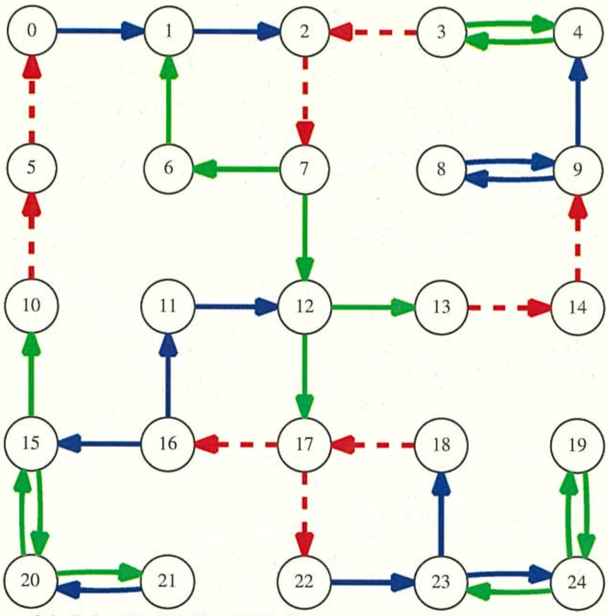


Fig. 3.2 CASCA (grid $k = 10$)

as k and the number of available channels $|C|$, the viewpoint of this evaluation is whether $|I_{\mathscr{A}}| = 0$ is possible or not by adjusting the value of k and $|C|$. Therefore, when the value of $|C|$ is set, I try computing channel assignment starting from small value of k and increasing it gradually to find out collision-free channel assignment.

(1) Method

In the grid topology, I placed 25 nodes in the 5×5 grid shape in which the distance between every neighbor is 400 m both in horizontal and vertical. In the random topology, I placed 30 nodes in the 1500×1500 m square field at random coordination. I generate 10 random topologies to take the average in computing the performance measures in the evaluation. I suppose that the communication range is 530 m (corresponding to 20 dB transmission power), and every node has exactly 2 NICs on it. Recall that, CSMA-aware interference model is built on the single disk model where the communication range and interference range are the same, i.e., R (=530 m). Therefore, a group of nodes within R can share a single channel, and pairs of two directed links which located at the hidden-terminal position, i.e., the pairs that satisfy either of Chapter 2 (*Condition 1* or *2*), are included in I_G. To run CASCA on the two topologies, I obtain the corresponding PMAX-SAT instances, and solve them using the solver called QMAX-SAT developed by Koshimura ([115]), which is an excellent PMAX-SAT solver that won the SAT contest in 2014. As the computational time is relatively small in many cases, CASCA usually runs within 1 Sec in the case that

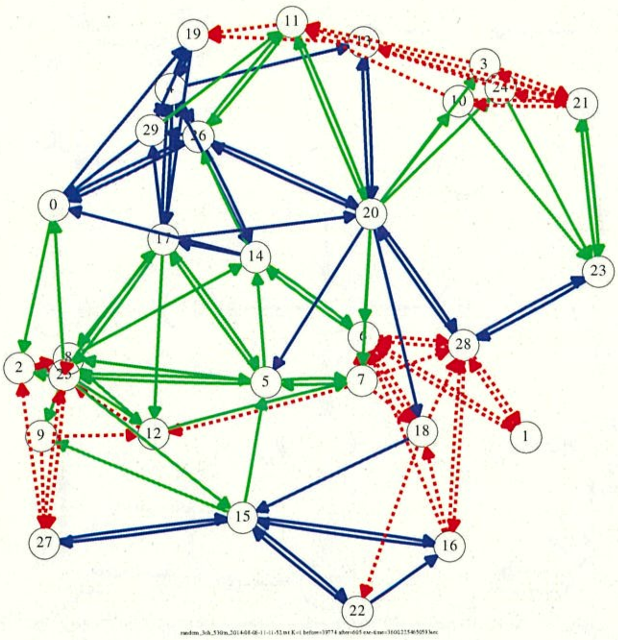


Fig. 3.3 CASCA (random $k = 1$)

the collision-free channel assignments are computed. Otherwise, however, it takes far larger time so I stop running at 3600 sec.

(2) Results

Results are shown in Tables 3.1 and 3.2. Table 3.1 shows the interference level $|I_{\mathscr{A}}|$ for each values of k and the number of available channels $|C|$ in grid topology. I see that $|I_{\mathscr{A}}|$ decreases as k increases, and it achieves $|I_{\mathscr{A}}| = 0$ with $k = 10$ in the 3-channel case and $k = 4$ in the 4-channel case. Since the path lengths can be increased only by even integers, I omitted the odd numbers of k in grid topology. Table 3.2 shows the case of random topology in which I achieve $|I_{\mathscr{A}}| = 0$ with $k = 7$ in the 3-channel case and with $k = 4$ in the 4-channel case. As above, collision-free channel assignment is possible by CASCA with 2 interfaces at every node and 3-4 available channels.

Fig. 3.1, 3.2 , 3.3, and 3.4 illustrates example channel assignments for grid and random topology obtained in my evaluation. Fig. 3.1 and 3.3 are the channel assignments for grid and random topologies when $k = 2$ and $k = 1$, respectively. Fig. 3.2 and 3.4 are the collision-freedom channel assignments when $k = 10$ and $k = 7$ for grid and random topologies, respectively. I see that, as k increases, the available links in the networks decreases. On the other hand, for any value of k, at least one path is kept available for every node pair, i.e., the networks are always kept connected.

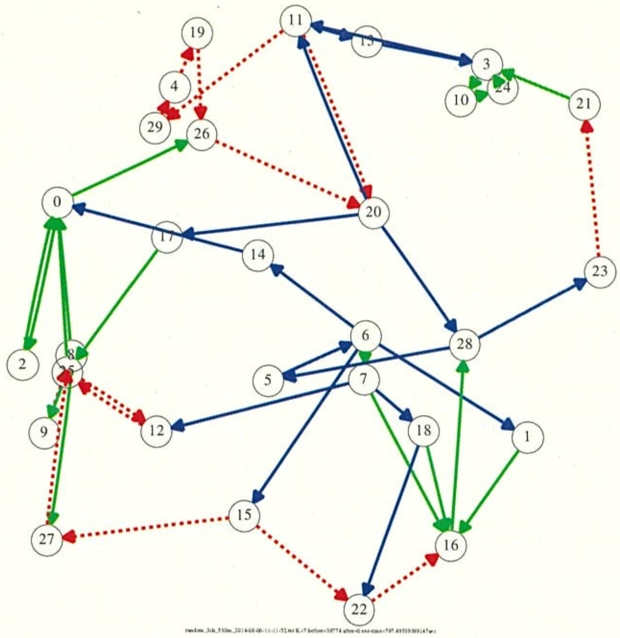


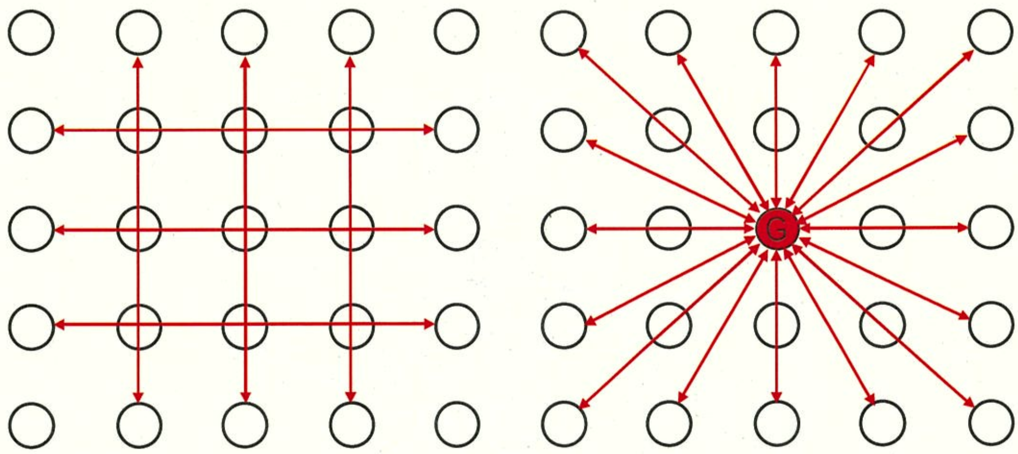
Fig. 3.4 CASCA (random $k = 7$)

Table 3.1 Interference Level $|I_{\mathscr{A}}|$ with 5 × 5 Grid network

CH	k=0	k=2	k=4	k=6	k=8	k=10
2ch	377	121	64	31	26	20
3ch	218	38	11	4	2	0
4ch	158	14	0	0	0	0

Table 3.2 Interference Level $|I_{\mathscr{A}}|$ with Random Network (Avg.)

CH	k=0	k=1	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
2ch	4945.3	843.5	361.2	201.7	141.3	108.3	86.9	69.9	60.7	50.1
3ch	3099.8	431.3	154.2	70.2	36.7	9.4	1.3	0.0	0.0	0.0
4ch	2827.5	306.7	78.0	6.5	0.0	0.0	0.0	0.0	0.0	0.0



(a) Point-to-point Traffic (b) Internet-oriented Traffic

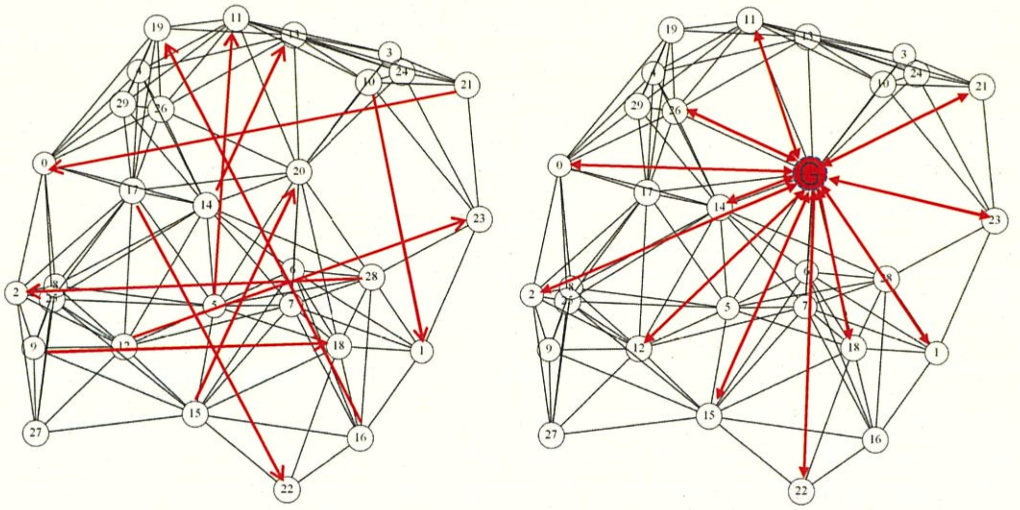
Fig. 3.5 Simulation Scenario for Grid Topology

3.3 Communication Performance

In Sec. 3.2, I showed that CASCA achieves collision-free channel assignment by introducing link limitation in forwarding paths. However, link limitation could degrade the network performance since packets are forwarded along sub-optimal paths. To show the efficacy of CASCA in communication performance against the conventional channel assignment that makes optimal paths available, I conducted traffic simulation and compared the communication performance of CASCA with a conventional channel assignment method CLICA which does not include link limitation. I select CLICA as it is the representative static channel assignment method with topology control that keeps network connectivity. Note that topology control is the key component to reduce conflicts in channel assignment. CLICA is the representative channel assignment method with topology control technique, and from our perspective, there is no other method suitable to compare with the proposed method CASCA. For the comparison, I use network simulator Scenargie [116], which implements up-to-date PHY and MAC models precisely.

(1) Method

To verify the response of CASCA to different traffic patterns, I set scenarios based on point-to-point traffic and Internet-oriented traffic, respectively. Fig. 3.5 (a) shows the scenario of point-to-point traffic pattern in grid network, which I generate 12 bi-directional CBR (Constant Bit Rate) flows. Fig. 3.5 (b) shows the scenario of Internet-oriented traffic in grid network, the center node is set as a gateway node, and all the edge nodes have bi-directional flows with it (i.e., we have 32 CBR flows). Fig. 3.6 (a) shows the scenario of point-to-point



(a) Point-to-point Traffic (b) Internet-oriented Traffic

Fig. 3.6 Simulation Scenario for Random Topology

traffic in random topology, in which I generate 10 random CBR flows in the network. Fig. 3.6 (b) shows the scenario of Internet-oriented traffic in random topology, in which I randomly choose one node as the gateway node, and 12 nodes are randomly chosen that send data frames to the gateway node and receive from the gateway node (i.e., we have 24 CBR flows). To make CASCA working in practice over well-populated IEEE 802.11 devices, I adopt the two-ray ground model as the radio propagation model, and the simulator Scenargie works with SINR interference model. I assume that some routing protocols such as OLSR work over the topology to determine the next-hop nodes, i.e., it chooses the best paths as the routing paths. In this simulation, I manually computed one of the shortest paths for each source-destination pair as the routing path in $\mathscr{A}$. The number of available channels is set to 3. Note that 3 is the number of available orthogonal channels in 2.4 GHz band of IEEE 802.11. I set different value of k for testing, and simulated the networks for 5000 sec. I measured the performance from the end of the 60-sec start up period of the simulation till the time 60-sec before the end. I simulate the scenario with various transmission rates of flows, and measured the throughput, delivery delay, and the number of frame drop as the average of 5 executions. Table 3.3 shows my simulation configurations.

(2) Results

The simulation results are shown in Figs. 3.7 - 3.18. I compared CLICA with CASCA under parameters $k = 4, 6, 8, 10$ and $k = 1, 3, 5, 7$ for grid and random topologies, respectively.

Grid topology: Fig. 3.7 plots the aggregated throughput versus the offered traffic volume for point-to-point traffic pattern. I see that CASCA has better performance than CLICA,

Table 3.3 Simulation Configuration

Items	Values
Simulator	Scenargie Ver.2.1-r20721
# of Channels	3 (channnel 1, 6, 11)
# of Interfaces	2 for each node
MAC and PHY protocols	IEEE 802.11g
Link Speed	6 Mbps
Network Topology	Grid and Random
Traffic Flow	Point-to-point and Internet-oriented
Packet Size	1500 Bytes
Tx Power	20 dbm
Communication Range	530 m
Simulation Time	5000 s

which indicates the excellent performance of CASCA. Note that, in CASCA, the performance with $k = 4$ is the best, which outperform the case $k = 10$, which achieved the collision-free channel assignment in optimization phase. This is because the cases with large k consumes link capacity due to their long forwarding paths, which affects the performance in throughput.

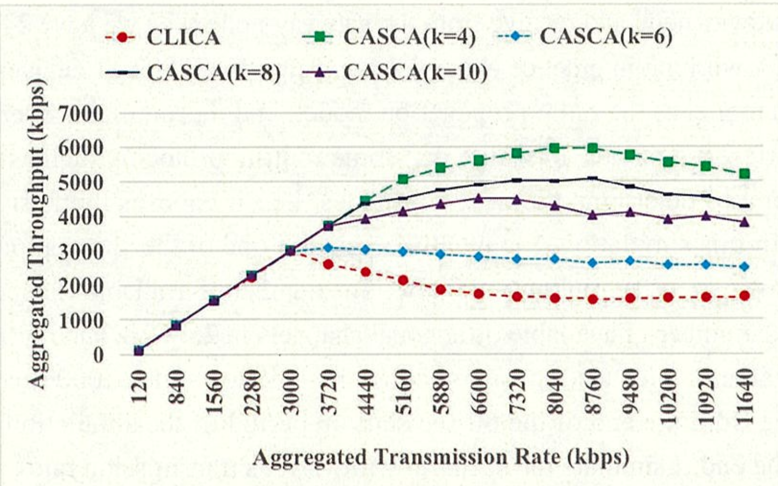


Fig. 3.7 Grid Topology Communication Performance Evaluation Throughput (Point-to-point Traffic)

Fig. 3.8 shows the delivery delay for point-to-point traffic pattern. I see that all cases have points where the delay rapidly increases, where the traffic load of some links exceeds their capacity, resulting in large queuing delay. However, I see the delivery delay of CLICA is the worst on this capacity problem, and CASCA outperforms it.

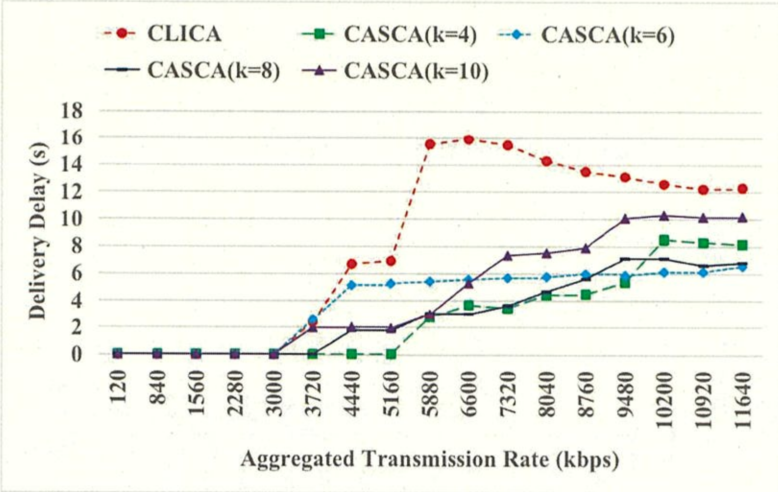


Fig. 3.8 Grid Topology Communication Performance Evaluation Delivery Delay (Point-to-point Traffic)

Fig. 3.9 shows the frame drop for point-to-point traffic pattern. I see that CLICA is prominently the worst while all CASCA cases have low frame collision. Furthermore, the volume of collision is lower as k increases, and achieved almost zero collision when $k = 10$, in which zero-collision is achieved also in the optimization phase. This means that the collision reduction function in CASCA well works also in traffic simulation, and also that the interference model shown in chapter 2 (Sec.2.5.2) works reliably. It is worth noting that there is a trade-off between capacity and collision. Fig. 3.9 shows that the cases with larger k clearly reduce collision whereas larger k does not have high throughput because of the capacity consumption problem due to long forwarding paths shown in Fig. 3.7. Although Fig. 3.7 demonstrates that some random factor exists in making bottleneck links, this trade-off should be considered when CASCA is applied.

Fig. 3.10 shows the aggregated throughput with the offered traffic volume as its horizontal axis. However, I see that CASCA doesn't always have better performance than CLICA for Internet-oriented traffic pattern. The main reason is that in such traffic pattern all traffic flows converge to the central node, which easily forms a link bottleneck. But in general, CASCA has better performance than CLICA.

Fig. 3.11 shows the delivery delay for Internet-oriented traffic pattern. I see that all cases have points where the delay rapidly increases, where the traffic load of some links exceeds their capacity, resulting in large queuing delay. However, when $k = 6$, I see the delivery delay of CLICA is the wort on this capacity problem, and CASCA outperforms it.

Fig. 3.12 shows the frame drop for Internet-oriented traffic pattern. I see that CLICA is prominently the worst while all CASCA cases have low frame collision. Furthermore,

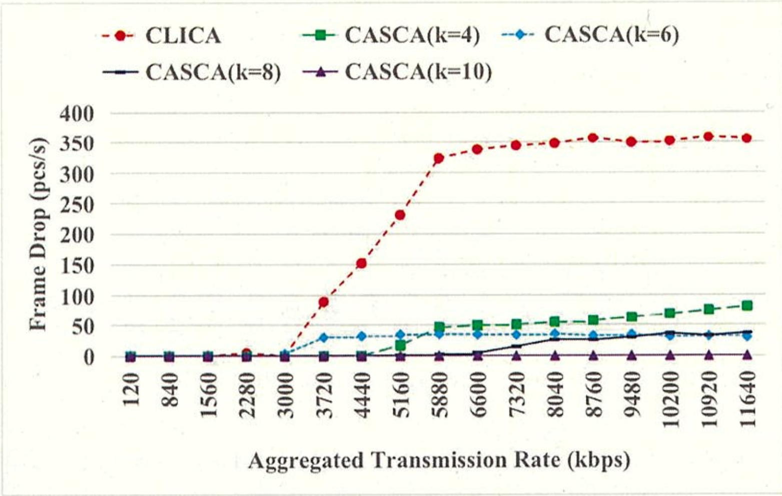


Fig. 3.9 Grid Topology Communication Performance Evaluation Frame Drop (Point-to-point Traffic)

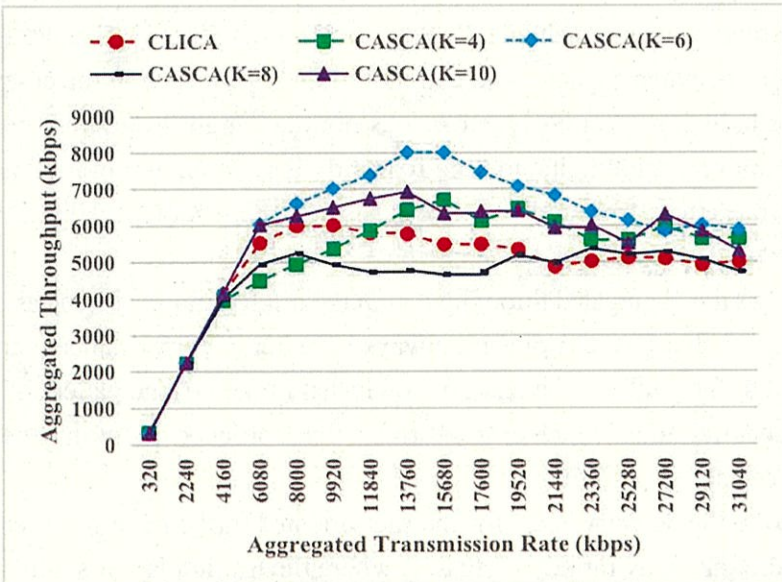


Fig. 3.10 Grid Topology Communication Performance Evaluation Throughput (Internet-oriented Traffic)

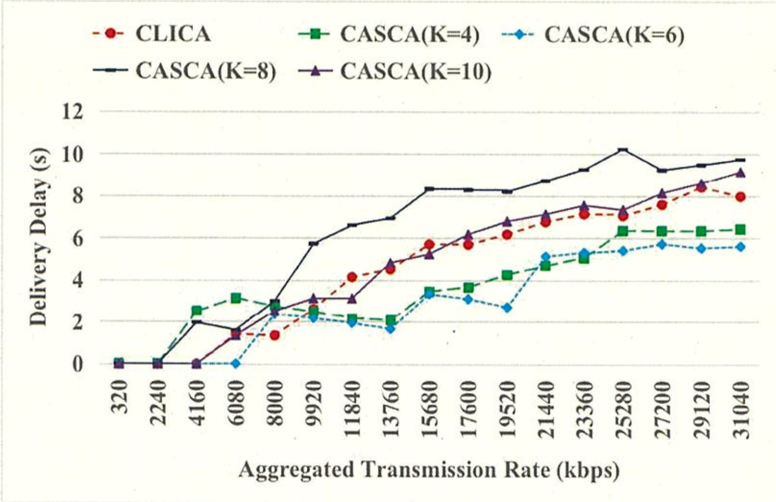


Fig. 3.11 Grid Topology Communication Performance Evaluation Delivery Delay (Internet-oriented Traffic)

the volume of collision is lower as k increases, and achieved almost zero collision when $k = 10$, i n which zero-collision is achieved also in the optimization phase. This means that the collision reduction function in CASCA well works also in traffic simulation.

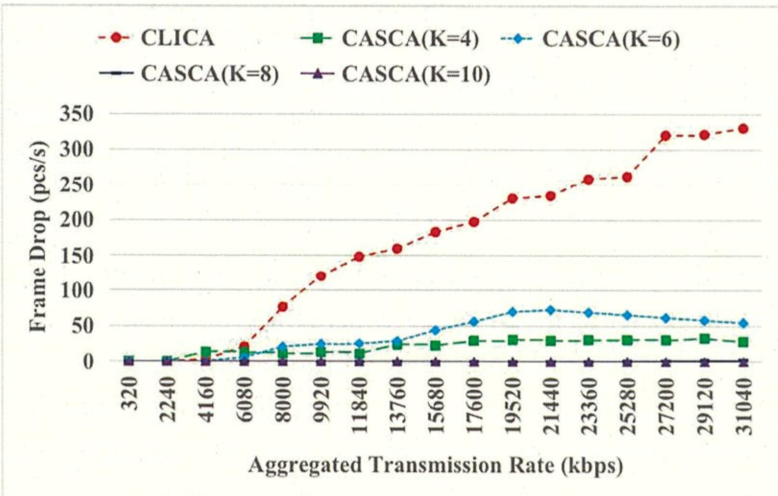


Fig. 3.12 Grid Topology Communication Performance Evaluation Frame Drop (Internet-oriented Traffic)

In general, Figs. 3.10, 3.11, and 3.12 show the results for the scenario of Internet-oriented traffic in the grid topology. Although the performances are a little different of the scenario of point-to-point traffic, the general trend is the same. In Figs. 3.10 and 3.11, I see that CLICA is not so bad compared with the point-to-point traffic case shown in Fig. 3.7, 3.8, and

3.9. This is because the links close to the gateway become bottleneck links and the effect degrades the relative performance of CASCA. However, in Fig. 3.12, I see that the frame drop performance is still good in CASCA, meaning that the result is due to the different balance of the above trade-off, i.e., in the gateway scenario, the capacity issue effects more than the collision issue on throughput performance.

Random topology: Fig. 3.13 plots the aggregated throughput versus the offered traffic volume for point-to-point traffic pattern. I see when $k = 5$ and $k = 7$, CASCA has worse performance than CLICA. It was confirmed that CASCA met a bottleneck link which traffic load exceeded its capacity, a lot of frames are dropped by queue.

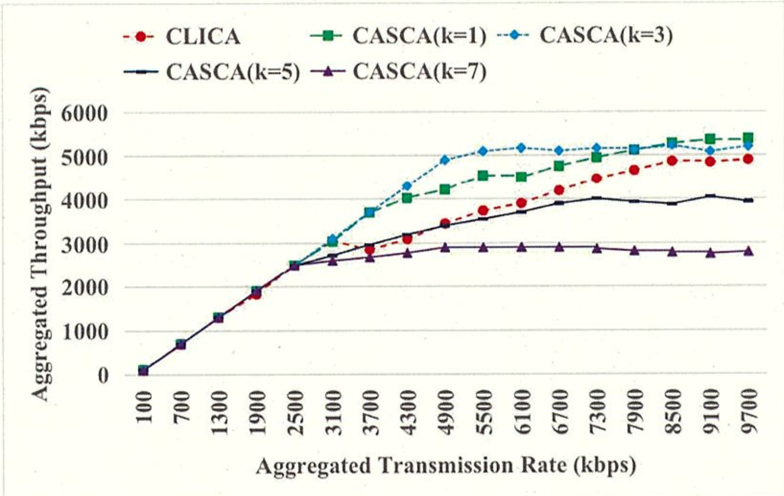


Fig. 3.13 Random Topology Communication Performance Evaluation Throughput (Point-to-point Traffic)

Fig. 3.14 shows the delivery delay for point-to-point traffic pattern. I see that all cases have points where the delay rapidly increases, where the traffic load of some links exceeds their capacity, resulting in large queuing delay. However, when $k = 1$ and $k = 3$, I see the delivery delay of CLICA is the worst on this capacity problem, and CASCA outperforms it.

Fig. 3.15 shows the frame drop for point-to-point traffic pattern. I see that CLICA is prominently the worst while all CASCA cases have low frame collision except $k = 1$. Furthermore, the volume of collision is lower as k increases, and achieved almost zero collision when $k = 7$, in which zero-collision is achieved also in the optimization phase. This means that the collision reduction function in CASCA well works also in traffic simulation.

Fig. 3.16 shows the aggregated throughput with the offered traffic volume as its horizontal axis. I see that CASCA doesn't always have better performance than CLICA for Internet-oriented traffic pattern. The main reason is that all traffic flows converge to the central node, which easily forms a link bottleneck.

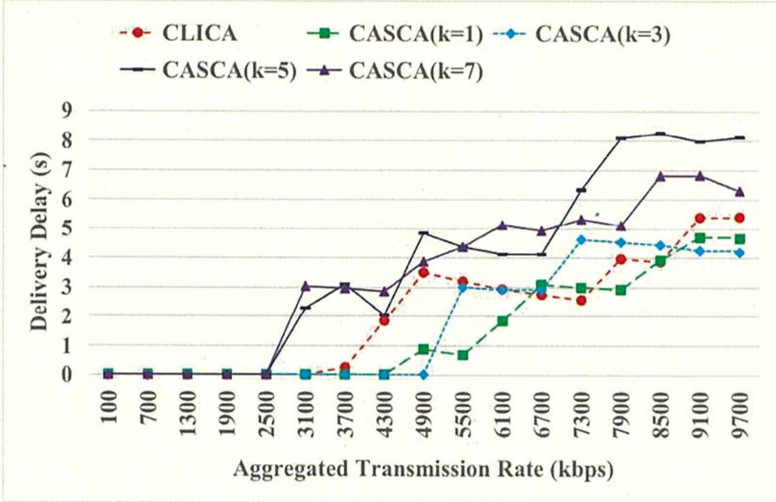


Fig. 3.14 Random Topology Communication Performance Evaluation Delivery Delay (Point-to-point Traffic)

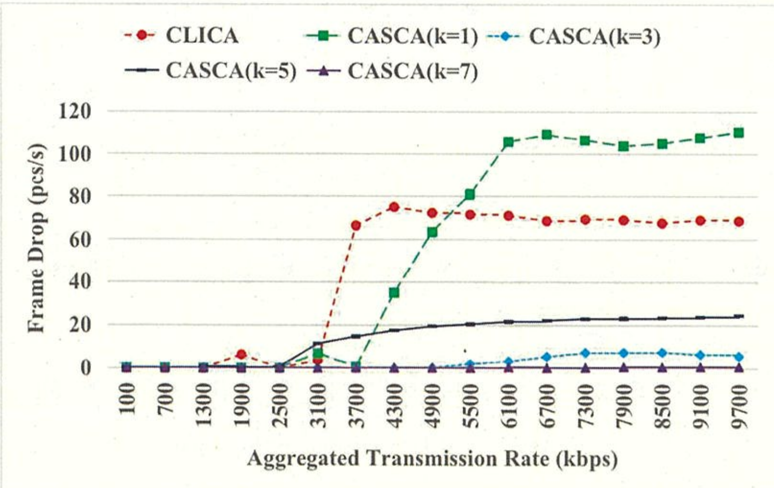


Fig. 3.15 Random Topology Communication Performance Evaluation Frame Drop (Point-to-point Traffic)

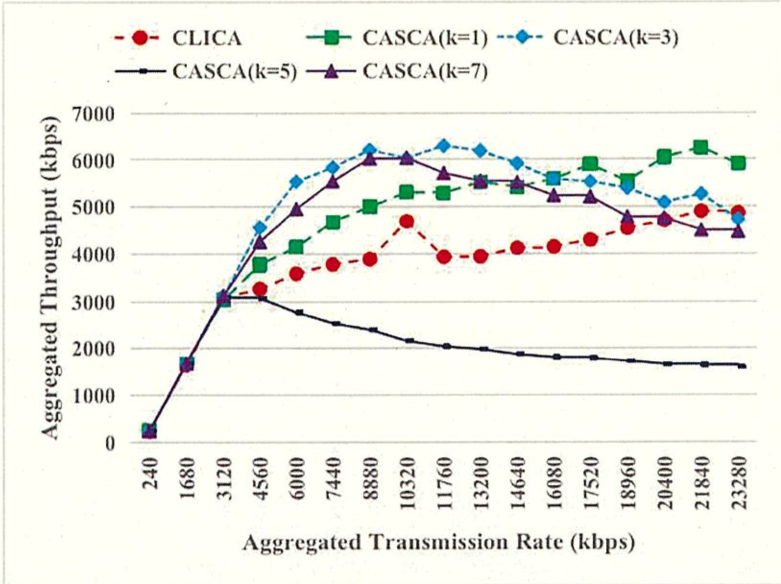


Fig. 3.16 Random Topology Communication Performance Evaluation Throughput (Internet-oriented Traffic)

Fig. 3.17 shows the delivery delay for Internet-oriented traffic pattern. I see that all cases have points where the delay rapidly increases, where the traffic load of some links exceeds their capacity, resulting in large queuing delay.

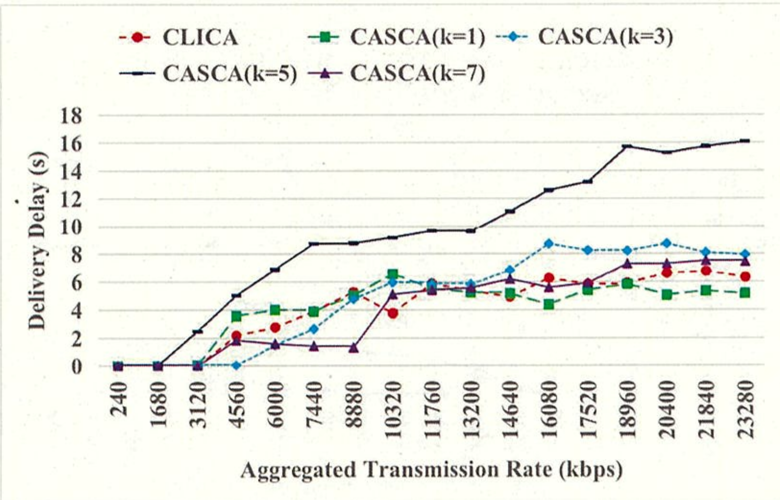


Fig. 3.17 Random Topology Communication Performance Evaluation Delivery Delay (Internet-oriented Traffic)

Fig. 3.18 shows the frame drop for Internet-oriented traffic pattern. I see that CLICA is prominently the worst while all CASCA cases have low frame collision. Furthermore, the volume of collision is lower as k increases, and achieved almost zero collision when $k = 10$, in which zero-collision is achieved also in the optimization phase. This means that the collision reduction function in CASCA well works also in traffic simulation.

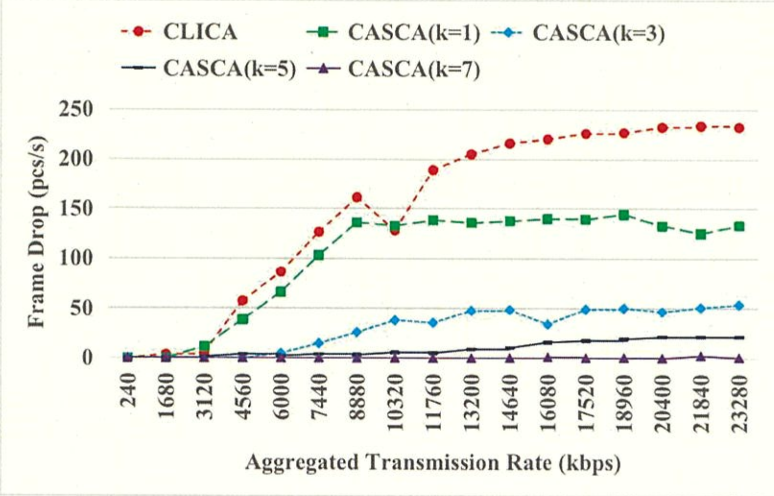


Fig. 3.18 Random Topology Communication Performance Evaluation Frame Drop (Internet-oriented Traffic).

In summary, Figs. 3.13, 3.14, 3.15, and Figs. 3.16, 3.17, 3.18 show the results of the random topology, which also have the similar trend to the grid topology. I see that, in the random topology, there is a trend that smaller k is better than larger k in both point-to-point and Internet-oriented traffic patterns, although CASCA still has better performance than CLICA. This would be because the distance variation between nodes in random node location reduces the frame loss rate between the interference link pairs, which changed the above trade-off balance between collisions and paths length.

3.4 Chapter Summary

In this Chapter, I extensive evaluation and simulation of CASCA. My evaluations confirmed that CASCA achieves collision-free channel assignment with 3-4 channels in IEEE 802.11-based wireless MRMC WMNs. Simulation results prove that the channel assignment of CASCA is mostly collision free if wireless interference model is up-to-date. The simulation results also showed that CASCA outperforms the conventional channel assignment method CLICA, and revealed several specific properties of CASCA. However, I also see that collision-freedom does not always lead to maximization in throughput because of the trade-off between collisions reduction and capacity occupation due to longer forwarding paths.

Therefore, next chapter, the work is to implement load balancing in CASCA, which mitigate the effect of bottleneck link and reduce the random effect on performance in CASCA.

Chapter 4

Traffic-demand-aware Collision-free CA with OCs in MRMC WMNs

4.1 Introduction

As described in Chapter 2 and 3, CASCA introduces a CSMA-aware interference model which allows two links located within the carrier-sense range to share the same channel, whereas making two links that invoke hidden-terminal problem use different channels. To eliminate harmful effect of hidden terminal problem, CASCA partially introduces routing function, i.e., excluding a part of links from a set of links that forward packets, while simultaneously guaranteeing feasible paths for any pair of source-destination nodes. However, CASCA does not treat full-routing function so that it lacks flexibility in terms of traffic engineering, meaning that it can not cope with variation of traffic patterns, and it easily leads overload of some links under variation of input traffic demands.

In this chapter, I propose a new joint static channel allocation and routing method TACCA (Traffic-demand-Aware Collision-free Channel Assignment) that achieves collision-free channel assignment with 3-5 orthogonal channels while considering traffic demand and traffic engineering. Because of the NP-hardness of the problem [92], CASCA formulates the problem as a PMAX-SAT (Partial MAXimum SATisfiability) problem. However, PMAX-SAT handles 0/1 values and can not handle real values. Therefore, to treat the traffic demands, I mathematically formulate the problem as a MILP (mixed-integer linear optimization problem) and incorporate the link capacity, interference, the number of available radios, and channels, etc.

The rest of this chapter is organized as follows. I describe the system model, interference model, shared link capacity model, and some assumptions in Sec. 4.2. I formulate the

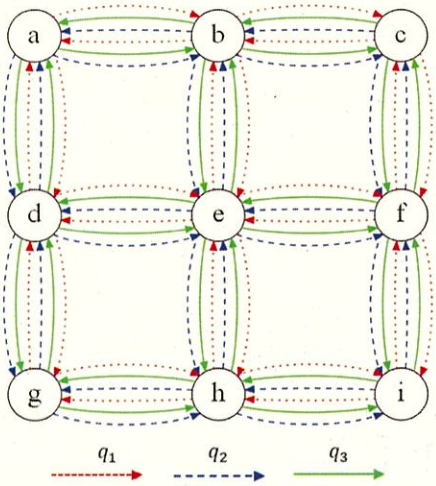


Fig. 4.1 One Network Model

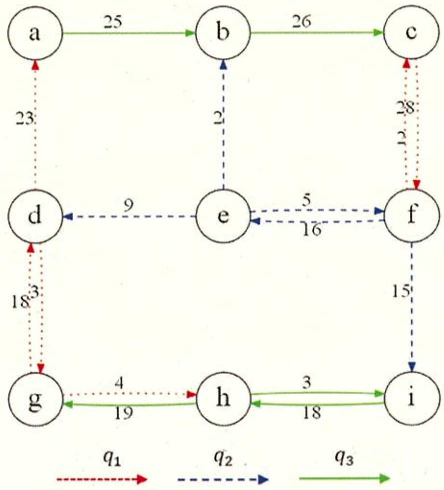


Fig. 4.2 An Optimization Result

problem in Sec. 4.3. Performance evaluations are given in Sec. 4.4. Conclusions are given in Sec. 4.5.

4.2 System Model

In this section, I introduce the network model, CSMA-aware interference model, and shared link capacity model, which specifies the key characteristics my scheme TACCA.

4.2.1 Network Model and Assumptions

I model a MRMC network as a set of stationary nodes V connected by a set of directed links E. Then, digraph $G = (V, E)$ represents a network. Each node in V is equipped with multiple classic NICs built on IEEE 802.11 technology, and each NIC operates on frequency channel. A link $\ell \in E$ that goes from node u to node v using channel $q \in Q$ is written as $\ell = (u, v, q)$, where Q is a set of orthogonal channels and $|Q|$ represents the number of the channels. Subsequently, I sometimes use the term (u, v, q) in place of link ℓ, where u and v are the terminal nodes of link ℓ. As described, $|Q|$ independent orthogonal channels are available for communications between every pair of nearby nodes u and v in V. Fig. 4.1 illustrates the model network G in case of $|Q| = 3$, in which $2|Q|$ links are defined between neighboring nodes.

In addition, I am given a traffic demand matrix D, which represents the amount of traffic demand from node s to d for each pair $(s, d) \in V \times V$. The demand from s to d is written as

$D(s,d)$. In order to represent the amount of traffic each link can afford, I assume each link has capacity C.

To introduce the collision-free and capacity constraint, I give additional definitions in the following sections.

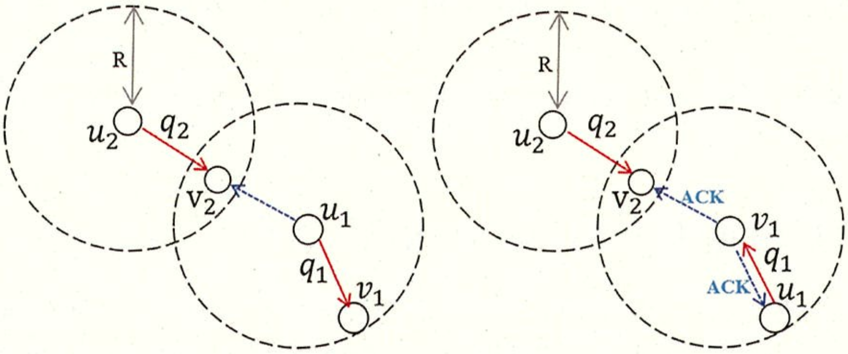
4.2.2 CSMA-aware Interference Model

To achieve collision-free transmission on the commodity 802.11 hardware, accurate interference model is very important. Therefore, I use the CSMA-aware interference model introduced in CASCA [95]. The CSMA-aware interference model is built on top of the single disk model, in which both the communication range and the interference range are the same, and is denoted by R. Therefore, given the 2D coordination of nodes in V, link $(u,v,q) \in E$ exists if the distance between nodes u and v is smaller than R, and both u and v have a NIC assigned with channel q. As is known, CSMA is a MAC protocol in which a node verifies the absence of other traffic before transmitting on a shared transmission medium. If a carrier is sensed, the node waits for the on-going transmission to end before initiating its own transmission. Basically in CSMA, multiple nodes would send and receive frames in turn on the same medium without collision unless hidden terminals exist. Therefore, in this study, I assume that the collision between links within carrier-sensing range are avoided due to CSMA, and regard that the two directed links interfere with each other only if they are located in the hidden-terminal position.

Let $\ell_1 = (u_1, v_1, q_1)$ and $\ell_2 = (u_2, v_2, q_2)$ be a pair of two links in E. Then, transmission on ℓ_1 prevents ℓ_2 due to collision of the hidden terminal effect if the following conditions are met.

Case 1: Collision of two Data frame.
(1) $q_1 = q_2$,
(2) $(u_1, u_2, q_1) \notin E$,
(3) $(u_1, v_2, q_1) \in E$.
Case 2: Collision of Data and Ack frame.
(1) $q_1 = q_2$,
(2) $(u_1, v_2, q_1) \notin E$,
(3) $(v_1, v_2, q_1) \in E$.

Case 1 defines the conditions where the transmission of data frame on ℓ_1 interferes the reception of data frames on ℓ_2. See Fig. 4.3 (a). Node v_2 is within the transmission range of both nodes u_1 and u_2, but nodes u_1 and u_2 are without the transmission range of each other, which results in collision because nodes u_1 and u_2 may simultaneously transmit frames to node v_1 and v_2, respectively, and they collide at v_2. Note that nodes v_1 and v_2 may be



(a) Collision of two Data frames (b) Collision of Data and Ack frames

Fig. 4.3 Two Cases of Interference

the same node. I regard such links ℓ_1 and ℓ_2 as an interference link pair, e.g., in Fig. 4.1, link (a,b,q_1) and (c,b,q_1), as well as link (a,b,q_1) and (c,f,q_1) are interference link pairs, respectively.

Fig. 4.3 (b) illustrates the case 2 where the transmission of ACK frames on ℓ_1 interferes the reception of data frames on ℓ_2. As we know, CSMA attempts to assure frame delivery by using explicit acknowledgment (ACK), which means an ACK frame is sent by the receiving node to confirm that the data frame arrived intact. This ACK frame may cause collision. See Fig. 4.3 (b). Node u_1 and u_2 can not sense each other. So, when they simultaneously use the same channel to deliver frame to node v_1 and v_2, respectively, the ACK frame from node v_1 and the data frame from node u_2 may collide at node v_2. Also in this case, I regard such links ℓ_1 and ℓ_2 as an interference link pair. In the example in Fig. 4.1, a pair of link (a,b,q_1) and (f,c,q_1) is an interference link pair in Case 2.

I suppose interference is asymmetric: a transmission on link $\ell_1 \in E$ prevents communication of $\ell_2 \in E$ under this interference model. In this case, I regard that ℓ_1 interferes ℓ_2 and write $\ell_1 \to \ell_2$. Accordingly, I define a set of interference link pairs as follow,

$$I_G = \{(\ell_1,\ell_2) | \ell_1,\ell_2 \in E, \ell_1 \to \ell_2\}. \tag{4.1}$$

I_G is computed from the given network topology. Under the interference model given above, I compute a collision-free joint channel assignment and routing. Note that, in the CSMA-aware interference model, collisions due to neither simultaneous backoff expiration nor due to simultaneous transmission of two ACK frames are ignored because of low occurring probability. If I obtain the collision-free channel assignment and routing under this interference model, collision probability in real WMNs would be expected to be in sufficiently low level.

4.2.3 Shared Link Capacity Model

In wireless networks, a frequency channel is shared by nodes within the carrier-sense range, and so the links around the nodes share a capacity. See Fig. 4.2, for an example of optimization results. Links (e,b,q_2), (e,d,q_2), (e,f,q_2), (f,e,q_2), and (f,i,q_2) share the capacity since transmitting nodes e and f are within their carrier sense range with each other. Therefore, a wireless link in a MCMR WMN does not have dedicated bandwidth since neighboring node's transmissions contends for the same bandwidth. To ensure high network performance, the amount of traffic loads through all these shared capacity links should not exceed the capacity C. As aforementioned, links (e,b,q_2), (e,d,q_2), (e,f,q_2), (f,e,q_2), and (f,i,q_2) in Fig. 4.2 are shared capacity links.

I define the set of shared capacity links in terms of node v and a frequency channel q as follows,

$$\begin{aligned} S_v^q = \{(v,u,q)|(v,u,q) \in E\} \cup \{(u,v,q)|(u,v,q) \in E\} \cup \\ \{(u,a,q)|(u,v,q) \in E, (u,a,q) \in E, a \neq v\}. \end{aligned} \tag{4.2}$$

See Fig. 4.4, where $u \in V$ is a node within the sensing range of node $v \in V$, and $a \in V$ is excluded from the sensing range of v while included in the sensing range of u. Then, if the links $(v,u,q), (u,v,q), (u,a,q)$ are assigned with the same channel q, they will share the link capacity C under CSMA. Note that S_v^q is defined for each node $v \in V$ because all nodes in v's collision domain do not always share capacity (Imagine that node u' such that $(v,u',q) \in E$ exists in Fig. 4.4. Then, u' is in a carrier sense range of v, but may not in that of u. Therefore, u and u' may not share capacity). Note also that links such as (a,u,q) is not included in S_v^q because they collide with (v,u,q) etc. Due to hidden terminal effect, and the interference constraint described in following Section does not allow those collision links to be active simultaneously.

4.3 Problem Formulation

In this section, I formulate a joint channel allocation and routing problem in MILP, and show the whole formulation.

I first provide basic variable definitions. Due to the structure of MRMC networks, I assume each node v is equipped with N_v NICs and each NIC on a node operates on a distinct frequency channel in Q. Two nodes must be assigned with same channel to communicate with each other. Therefore, if a link $\ell = (u,v,q)$ is used to transmit frames, I call it is active,

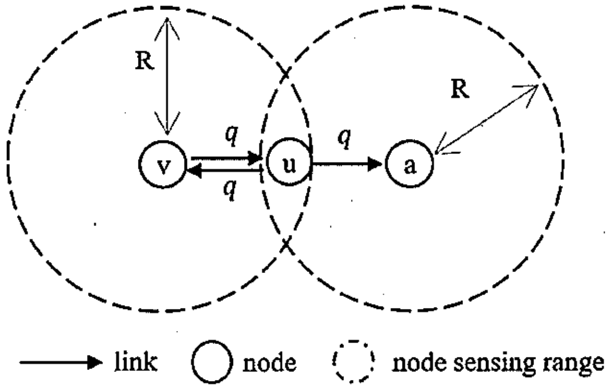


Fig. 4.4 Shared Capacity Schematic Diagram.

channel q must be assigned to a NIC of both u and v. I define a variable $F_v^q \in \{0,1\}$ indicating whether node v is assigned with frequency channel q or not, i.e., $F_v^q = 1$ if there is a NIC on node v assigned with frequency channel q, and $F_v^q = 0$ otherwise.

As previously described, I make a channel assignment for a given traffic demand D. Therefore, for each non-zero demand $D(s,d)$, I set a path to forward the traffic from s to d. With each pair (s,d) and each link ℓ, I associate a variable $P_\ell^{(s,d)} \in \{0,1\}$ that indicates whether the traffic flow for demand (s,d) goes through link ℓ or not, i.e., $P_\ell^{(s,d)} = 1$ if the routing path from s to d includes link ℓ, and $P_\ell^{(s,d)} = 0$ otherwise.

If link ℓ is included in some routing path from s to d, i.e., $P_\ell^{(s,d)} = 1$ for at least one pair of s and d, I call link ℓ is active as it is used for packet transmission. A variable $A_\ell \in \{0,1\}$ is defined, where $A_\ell = 1$ indicates link ℓ is active and $A_\ell = 0$ is inactive.

Our optimization objective is to make the maximum link utilization in the network minimized. The link utilization is the ratio of traffic amount over the link capacity C, i.e., the utilization of link $\ell \in E$ is expressed as $\sum_{(s,d)\in V\times V} D(s,d)P_\ell^{(s,d)}/C$. Thus, I define a variable U_{max} ($0 \leq U_{max} \leq 1$) represents the maximum link utilization among all links. When the maximum of link utilization is minimized, the percentage of the residual bandwidth on links, i.e., unused bandwidth, is maximized. Therefore, the growth in traffic in the future is more likely to be accommodated and can be accepted without requiring the re-arrangement of assigned paths. To summarize the definition above all, I give a table of the notations in Table 4.1.

With those notations, given the network topology and the expected traffic demand matrix, the general routing and channel assignment problem can be formulated in MILP framework as follows,

$$\min \quad U_{max} \tag{4.3}$$

Subject to

$$\sum_{q\in Q} F_v^q \leq N_v, \qquad \forall\, v \in V \tag{4.4}$$

$$F_v^q \leq \sum_{(v,u,q)\in E} A_{(v,u,q)} + \sum_{(u,v,q)\in E} A_{(u,v,q)}, \forall\, q \in Q\,,\ \forall\, v \in V, \tag{4.5}$$

$$A_{(u,v,q)} \leq F_v^q,\ A_{(u,v,q)} \leq F_u^q,\ \forall\ (u,v,q) \in E, \tag{4.6}$$

$$\sum_{(u,v,q)\in E} P_{(u,v,q)}^{(s,d)} D(s,d) - \sum_{(v,w,q)\in E} P_{(v,w,q)}^{(s,d)} D(s,d) = \begin{cases} -D(s,d), \text{if}\, v = s, \\ D(s,d), \text{if}\, v = d, \\ 0, \text{otherwise}, \end{cases} \quad \forall (s,d) \in V \times V, \tag{4.7}$$

$$\sum_{(s,d)\in V\times V} P_\ell^{(s,d)} \leq MA_\ell, \quad \forall\, \ell \in E, \tag{4.8}$$

$$\sum_{(s,d)\in V\times V} P_\ell^{(s,d)} \geq A_\ell, \quad \forall\, \ell \in E, \tag{4.9}$$

$$\sum_{(s,d)\in V\times V, \ell\in S_v^q} D(s,d) P_\ell^{(s,d)} \leq U_{max}C + (1 - F_v^q)W, \qquad \forall\, v \in V,\ \forall\, q \in Q, \tag{4.10}$$

$$A_{\ell_1} + A_{\ell_2} \leq 1, \qquad \forall\, (\ell_1, \ell_2) \in I_G, \tag{4.11}$$

$$\sum_{\ell\in E} P_\ell^{(s,d)} \leq \delta_{s\to d} + k, \quad \forall\, (s,d) \in V \times V, \tag{4.12}$$

Where

$$0 \leq U_{max} \leq 1, \tag{4.13}$$

$$F_v^q \in \{0,1\}, \qquad \forall\, q \in Q, \quad \forall\, v \in V, \tag{4.14}$$

$$A_\ell \in \{0,1\}, \qquad \forall\, \ell \in E, \tag{4.15}$$

$$P_\ell^{(s,d)} \in \{0,1\}, \quad \forall\,(s,d) \in V \times V, \ \ \forall\,\ell \in E. \tag{4.16}$$

Formula (4.3) is my objective function. I try to minimize the maximum of link utilization in all the network. Therefore, (4.3) makes traffic flows move from congested hot spots to less utilized parts of the network, and leaves more space for future traffic growth or fluctuation.

Constraint (4.4) denotes the relationship between NICs and channels. To decrease the interference, I allow to assign no channel for some NICs. Therefore, the number of distinct frequency channels q allocated to one node must be less or equal to the number of NICs on each node N_v.

Constraint (4.5) and (4.6) denote the relationship between links and channels. For each node v, $(v,u,q) \in E$ denotes the output links of node v, and $(u,v,q) \in E$ denotes the input links. Node u is the other terminal node of links (v,u,q) and (u,v,q). See Fig.4.1, network topology is defined as a multiple graph in which neighboring two nodes may have multiple links corresponding to each channel in Q. Therefore, as indicates in (4.5), if a NIC on node v is assigned with channel q, i.e., $F_v^q = 1$, then $\sum_{(v,u,q)\in E} A_{(v,u,q)} + \sum_{(u,v,q)\in E} A_{(u,v,q)} \geq 1$, this means at least one connecting link (no matter output or input link) must be activate. Conversely, as indicated by (4.6) if none of the NICs on node v is assigned with channel q, i.e., $F_v^q = 0$ and $F_u^q = 0$, then $A_{(u,v,q)} = 0$, it means none of the connecting links is active.

Constraint (4.7) denotes the traffic flow conservation. Traffic flows in the network must meet the conservation conditions. In (4.7), $P_{(u,v,q)}^{(s,d)}$ and $P_{(v,w,q)}^{(s,d)}$ denote whether the route of traffic demand (s,d) goes through the input link (u,v,q) and output link (v,w,q) of v, respectively. For each traffic demand pair (s,d), I refer to s and d as the source and destination nodes of the demand. From the viewpoint of flow conservation, the total volume of flows sent by s must be equal to that received by d. Also, the total input and output volume of flows on every intermediate node must be equal. If node v is the source node, i.e., $v = s$, the value of (4.7) equals to $-D(s,d)$. If node v is the destination node, i.e., $v = d$, the value of (4.7) is equal to $D(s,d)$. Otherwise, the node is intermediate node, and the value of (4.7) equals to 0. This constraint not only ensures that the traffic flow is properly routed from s to d, but also ensures that each demand is satisfied with a single explicit route.

Constraint (4.8) and (4.9) denote the relationship between traffic flows and links. Activated link must be traffic flows whose route go through it. Conversely, inactivated link has no traffic flow going through. In (4.8), M is a constant whose value is large enough. When at least one traffic flow goes through link ℓ, i.e., $\sum_{(s,d)\in V\times V} P_\ell^{(s,d)} \geq 1$, then the link ℓ must be activated, i.e., $A_\ell = 1$, we get $1 \leq \sum_{(s,d)\in V\times V} P_\ell^{(s,d)} \leq M$. Formula (4.9) means that if there is no traffic flow through link ℓ, the link ℓ must be inactivated, i.e., $A_\ell = 0$, then

Table 4.1 Notations for TACCA

Symbol	Description
V	A set of stationary nodes (routers)
E	A set of directed links
G	A directed network
C	Link capacity (common with all links)
Q	A set of orthogonal channels
D	A traffic demand matrix
$D(s,d)$	A traffic demand from s to d
$\ell/(u,v,q)$	A link
I_G	A set of interference link pairs
S_v^q	A set of shared capacity links
F_v^q	Binary variable indicating node v is assigned channel with q or not
$P_\ell^{(s,d)}$	Binary variable indicating whether path of $D(s,d)$ includes link ℓ or not
A_ℓ	Binary variable indicating link ℓ is active or not
U_{max}	Real variable indicating maximum link utilization

$\sum_{(s,d)\in V\times V} P_\ell^{(s,d)} = 0$. Both formula (4.8) and (4.9) keep the relationship between traffic flows and link activeness.

Constraint (4.10) is the constraint on link capacity. Recall that in CSMA-based wireless networks, links within the carrier-sensing range are regarded to share the link capacity as described (4.2). Therefore, the total traffic loads within one node's transmission range can not exceed the link capacity C. In (4.10), W is a constant whose value is large enough. If channel q is assigned to node v, then $F_v^q = 1$, and (4.10) is valid, i.e., I get $\sum_{(s,d)\in V\times V,\ell\in S_v^q} D(s,d)P_\ell^{(s,d)} \leq C$, which ensures the total traffic loads of the all shared capacity links of node v do not exceed the link capacity C. Otherwise, if channel q is not assigned to node v, then I get $\sum_{(s,d)\in V\times V,\ell\in S_a^q} D(s,d)P_\ell^{(s,d)} \leq C+W$, meaning that there are no capacity constraints on these links. Note that, in (4.10), we replace C with $U_{max}C$ where U_{max} is the maximum utility in the whole network. This is because we aim at optimizing the maximum utility to provide the load balancing function.

Constraint (4.11) is the interference constraint which ensures that interfering links are not assigned with the same channel. Recall to (4.1), links $(\ell_1,\ell_2) \in I_G$ can not be activated simultaneously, i.e., if $A_{\ell_1} = 1$, then there must be $A_{\ell_2} = 0$, and vice versa.

Constraint (4.12) is on path length. In my scheme, I allow each of the traffic flows from s to d to be detoured. $\delta_{s\to d}$ indicates the minimum hop count to reach d from s, i.e., the shortest-path length from s to d in G. $k \geq 0$ is a path stretch in integer, then $\delta_{s \to d} + k$ means that length of every path is limited by the shortest path length plus k. Length of all paths are controlled by adjusting the value of k.

Constraints (4.13), (4.14), (4.15), and (4.16) define the domains of variables described previously.

With above formulation, my problem assigns a single path for every non-zero traffic demand pair (s,d) in D, where both the link capacity constraint and the collision-free constraint are fulfilled, and the link utilization is minimized. Note that my idea to utilize the property of CSMA is included in constraint (4.10) and (4.11) where CSMA-based link-capacity sharing model is applied in (4.10) and CSMA-aware interference model is used to compute I_G in (4.11). See Fig. 4.2 again, which is an example of optimization results under the traffic demand matrix D that offers flows from every node to all the other nodes. In this schedule, I assume $D(s,d) = 1$ for all pairs of s and d, link capacity is $C = 60$ (unit), and $N_v = 2$ for every $v \in V$. I also assume that each radio reaches and interferes the neighbor nodes in vertical and horizontal direction. I see that each node is assigned with no more than two channels, e.g., except node e being assigned with 1 channel, all other nodes are assigned with 2 distinct channels, respectively. The numbers given on each link indicates the amount of traffic loads through it, e.g., the route from d to e is $d \to a \to b \to c \to f \to e$, and the number 16 on link (e, f, q_2) means that there are 16 flows like this that goes through this link. As I will describe in Section 4.2.3, the sum of the traffic flow rates going over each link does not exceed the link capacity $C = 60$, and $U_{max} = (25 + 26)/60 = 0.85$ regarding the links (a,b) and (b,c). It is clear that there is no collision among links that have flows travelling on them.

4.4 Evaluation

I evaluate the performance of my method TACCA with two different network topologies, i.e., a grid topology and a random topology. I evaluated both the optimization performance through a MILP solver, and the communication performance through simulation. In the former part, I computed the channel assignments with various parameter settings to show the property of the formulated problem. As for the latter, I made a traffic simulation using an up-to-date network simulator. I describe the detail in the following sections.

4.4.1 Optimization Performance Evaluation

In this evaluation, I see the performance of TACCA under various values of the parameters such as offered traffic load, the number of channels, and path stretch k. One of the important viewpoints is whether collision-free channel assignment with 3-5 orthogonal channels is possible or not with the CSMA-aware interference model. Another concern is the load-balancing performance against traffic demands with various values of path stretch k. Both are examined in two scenarios with grid and random topologies.

(1) Method

I solved my MILP problem with MATLAB R2019b with the optimization toolbox [117], which was executed on a computer with Intel (R) Xeon (R) CPU E3-1280 (3.70 GHz), 64 GB memory. As typical scenarios in WMNs, I suppose two different types of network topologies, i.e., grid and random layout of wireless nodes. As for grid topology, I designed a 5×5 square grid with 400 m interval in both horizontal and vertical directions. On the other hand, as a random topology, I located 30 nodes with random coordination in a $1,200 \times 1,200$ m square field. I assume that each node has 2 NICs, and the communication range is 530 m that corresponds to 20 dBm Txpower. Each NIC operates IEEE 802.11g with 6 Mbps communication speed so that the link capacity C is also 6 Mbps.

As the traffic demand given, I generate flows intending highly collided traffic that covers a certain area of field; I generate 12 bi-directional Constant Bit Rate (CBR) flows in the grid topology, and in the random topology, I generate 10 CBR flows with randomly selected source and destination nodes. In both scenarios, I test variation of flow volume to see the capacity of the networks. I show the grid topology and flows in Fig. 4.5, and the random topology in Fig. 4.6.

Note that the MATLAB computation would take for very long time because of the NP-hardness of the problem. Thus, in my evaluation, I set the maximum execution time limited to 7,200 sec. Namely, I obtain the best solution found within the time limitation. The whole configuration described above is summarized in Table 4.2.

(2) Result

I begin with the results of the grid topology. Fig. 4.7 shows the relationship between the optimization function U_{max} and the offered traffic load in the demand matrix with path stretch $k = 10$. Note that the horizontal axis represents the aggregated traffic volume, i.e., the total offered load of 12 bi-directional flows. First, I found that the collision-free solution surely exists even when the number of channels is 3. Next, I see that the link utilization U_{max} gradually increases as the offered load increases. This means that the network utilization U_{max} is in proportion to the amount of offered load, which implies that traffic load is well

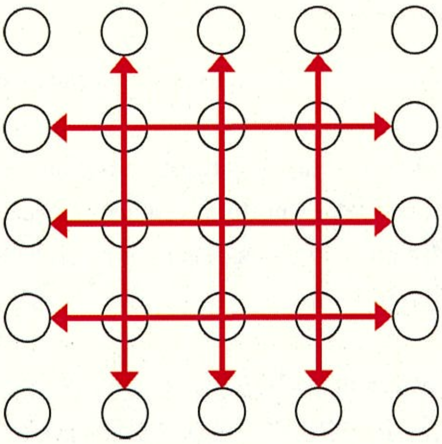


Fig. 4.5 Traffic pattern (5×5 grid topology)

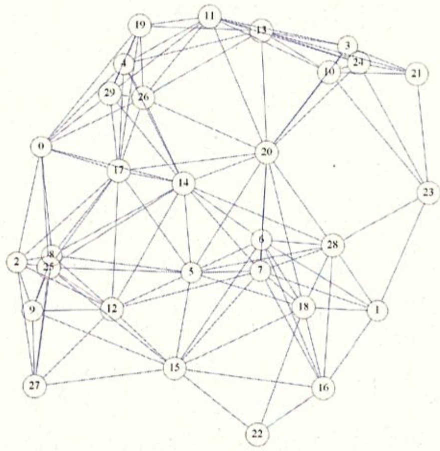


Fig. 4.6 30 nodes random topology

balanced with $k = 10$. On the other hand, I do not see the effect of the number of channels with 3-5 channels; This point would be mentioned later in Fig. 4.9.

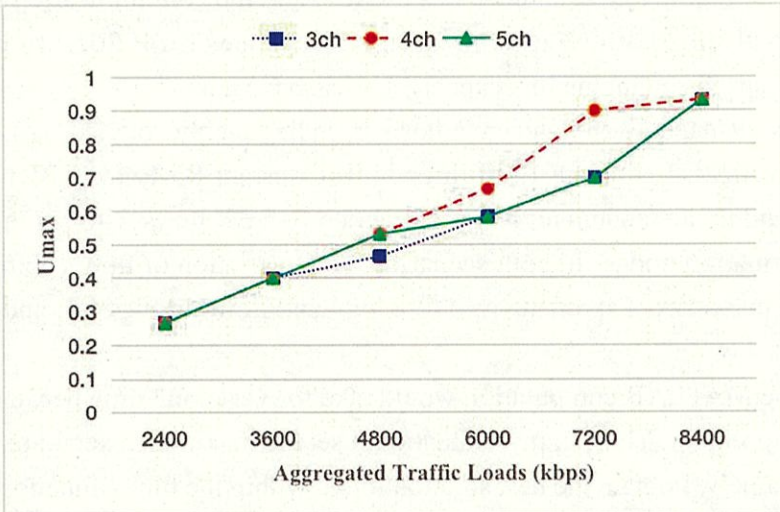


Fig. 4.7 Maximum Link Utilization with Traffic Load (Grid Topology)

Fig. 4.8 shows the effect of path stretch k with the maximum network link utility U_{max}. I see that U_{max} decreases as k increases. This again shows that the load balancing function works, and the effect increases as k increases.

Fig. 4.9 shows the result on supportable offered load with $k = 10$ under variation of the number of channels. The vertical axis represents the total offered load of the traffic demand so that the figure indicates the maximum volume of traffic demand that MATLAB could compute within the configured limited time. From the result, I see that the supportable traffic volume does not change with 3-5 channels as I have already seen in Fig. 4.7, whereas the

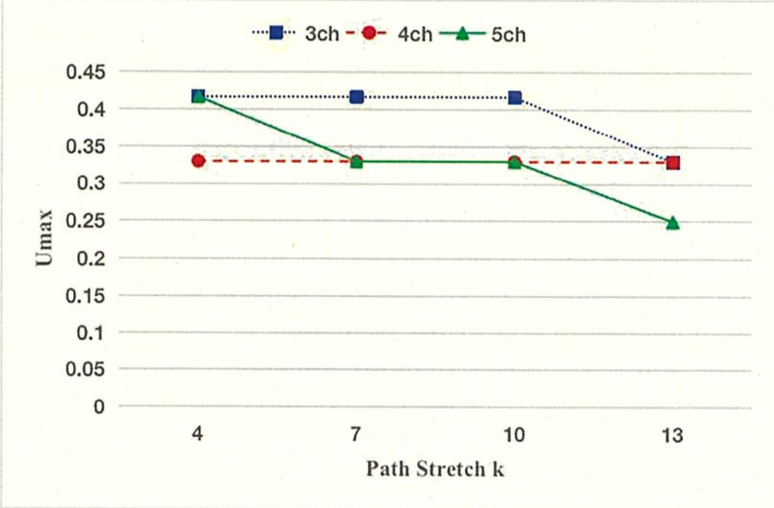


Fig. 4.8 Maximum Link Utilization with Path Stretch k (Grid Topology)

supportable traffic volume rapidly increases with 6-8 channels. This means that the number of channels has a large effect on the network capacity, but unfortunately the effect is not seen with 3-5 channels in the grid scenario.

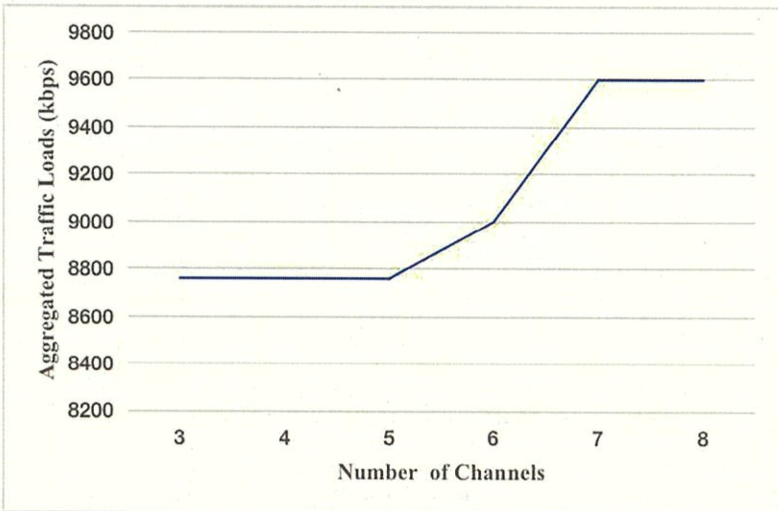


Fig. 4.9 Supportable Traffic Loads (Grid Topology)

I show the results of the random topology in Figs. 4.10, 4.11, and 4.12. Those results present the similar trend as the grid topology. Namely, the effect of load balancing is seen in Fig. 4.10 the effect of path stretch k is seen in Fig. 4.11, and the effect of the number of channels is seen in Fig. 4.12. Note that the effect of the number of channels on the supportable traffic volume is seen even for 3-5 channels in the random scenario in Fig. 4.12.

Table 4.2 Configuration in Optimization Evaluation

Items	Values
Solver	Matlab2019b with the optimization toolbox
Number of Channels	≥ 3
Number of Interfaces	2 for each node
Link Capacity	6 Mbps
Communication Range	530 m
Network Topology	Grid and Random
Number of Nodes	25 (Gird), 30 (Random)
Traffic Demands	12 CBR flows (Grid) 10 CBR flows (Random)

As above, in the optimization evaluation, I confirmed the property of TACCA under parameter variations. TACCA computes a collision-free channel assignment combined with routing configuration with 3-5 channels, and its load balancing effect is clearly seen depending on k and the number of channels.

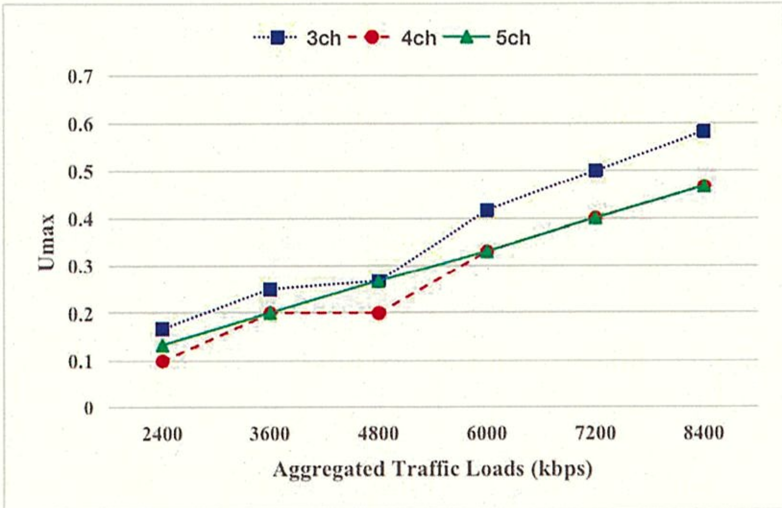


Fig. 4.10 Maximum Link Utilization with Traffic Load (Random Topology)

4.4.2 Communication Performance Evaluation

(1) Method

I made simulations using a commercial network simulator Scenargie version 2.1 [116], which implements up-to-date PHY and MAC models. Note that Scenargie adopts equivalent-level models with popular network simulators ns-3 and Qualnet, and the simulation perfor-

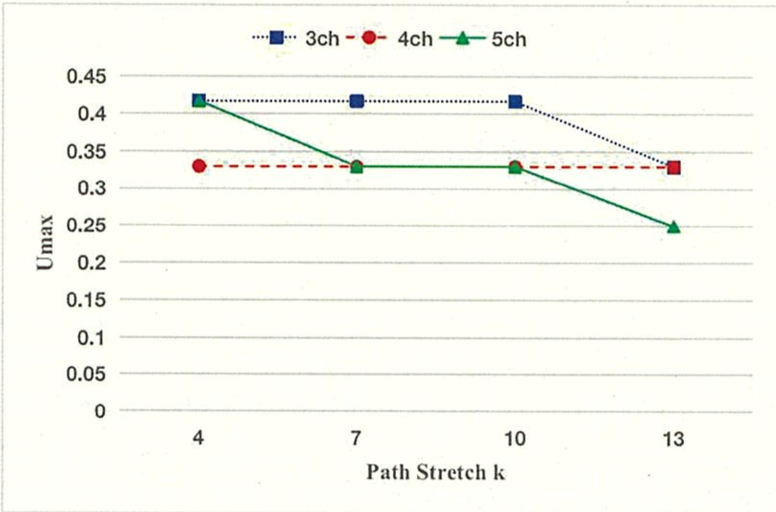


Fig. 4.11 Maximum Link Utilization with Path Stretch *k* (Random Topology)

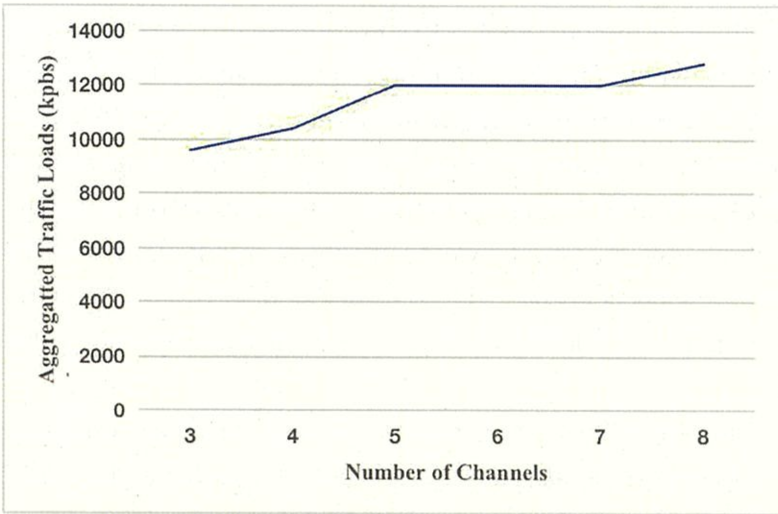


Fig. 4.12 Supportable Traffic Loads (Random Topology)

mance have been verified through calibration among them. The simulation configuration is almost the same as optimization evaluation, as shown in Table 4.3. Each node is equipped with 2 NICs which operates IEEE 802.11g in 6 Mbps speed with 20 dBm transmission power. I use the two-ray-ground model as the radio propagation model. I use the same topologies as the optimization evaluation; the 5×5 grid topology with 400 meters interval, and the random topology in a 1200×1200 m square field. I generate 12 bi-directional CBR flows in the grid topology, and 10 flows with a random source and destination selection in the random topology.

I use a channel assignment and routing schedule obtained in the optimization evaluation. Specifically, I chose the schedule with 3 orthogonal channels, $k = 10$, and the offered traffic load is 500 kbps per flow. As mentioned earlier, I am targeting on the mesh networks built with IEEE 802.11 technologies. Generally, 2.4 GHz band is regarded as more useful than 5 GHz band for mesh infrastructure in many cases. Note that 3 is the minimum number of channels with which I got collision-free schedules, and also 3 is a practically useful number of channels since I can take only 3 orthogonal channels in 2.4 GHz band in IEEE 802.11, $k = 10$ is a value with good load balancing performance.

I compare the performance of TACCA with CASCA and TiMesh. Recall that there is a few schemes that achieves collision-free schedule with 3-5 channels in CSMA-based MCMR WMNs. Thus, most of the past schemes in the literature are not comparable in performance. Actually, as shown later, TACCA achieves almost 100% packet delivery unless the traffic volume exceeds the network capacity, and so the schemes with considerable collisions with 3 channels are not suitable to compare. Since CASCA achieves a collision-free schedule but does not consider traffic demands, I can see the performance gain of TACCA coming from considering traffic demands. Therefore, the CASCA schedule with the same parameters, i.e., 3 channels and $k = 10$ is used in the comparison. TiMesh has a close strategy to TACCA as it aims at minimizing network utility for a given traffic demand, and uses a path stretch parameter. However, it applies traditional RTS/CTS handshakes instead of interference models to cope with collisions among frames. Through comparison, I would see the performance of our CSMA-aware interference model compared with RTS/CTS handshakes.

I ran the simulator for 5000 sec and measure the average of the communication performance with five repeated executions, and compare those three schemes in terms of throughput, packet delivery ratio, end-to-end delivery delay, and frame drop, which because collisions continue on a regular basis and so do the MAC layer retransmission with the final result effecting throughput, delivery, latency, and frame drop. Here, frame drop is included to show the state of collision and interference in the network. Since frame loss invokes frame retransmissions in MAC layer, it effects on the performance in throughput, delivery delay, and delivery ratio.

(2) Results

Grid Topology: We show the results of the grid topology in Figs. 4.13, 4.14, 4.15, and 4.16.

Fig. 4.13 shows the aggregated throughput of the three schemes with the offered traffic volume as its horizontal axis, where the aggregated throughput is the sum of the data rates delivered to all terminals in a network. I see that all performs good when the offered load is low, but the performance of TiMesh and CASCA drop down with smaller offered load than TACCA. It was confirmed that CASCA met a bottleneck link, i.e., the link whose traffic load exceeded its capacity, with lower offered load than TACCA, proving that the load balancing function in TACCA well worked to enhance network capacity. In TiMesh, a considerable number of packets got stuck at source nodes. This is due to overhead of RTS/CTS handshake. Although TiMesh has the load-balancing function, the overhead of RTS/CTS due to exposed terminal problem extremely degrades the network capacity. As a result, TACCA outperforms the others in network capacity.

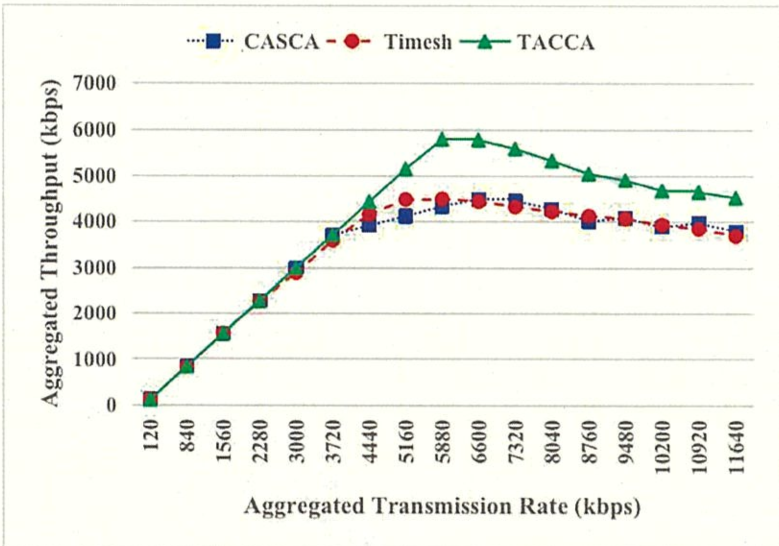


Fig. 4.13 Throughput (Grid Topology)

Fig. 4.14 shows the packet delivery ratio with the offered traffic volume. Here, I see that TACCA keep almost 100% packet delivery unless the traffic volume reaches their network capacity, meaning that the collision-freedom property in the schedule lives in the simulation. In contrast, in TiMesh, delivery ratio gradually decreases as traffic volume increases even when the traffic volume is relatively low. I confirmed this is mainly caused by the collision of

RTS/CTS frames due to hidden terminal problem. TiMesh still suffers from hidden terminal problem even under RTS/CTS mechanisms.

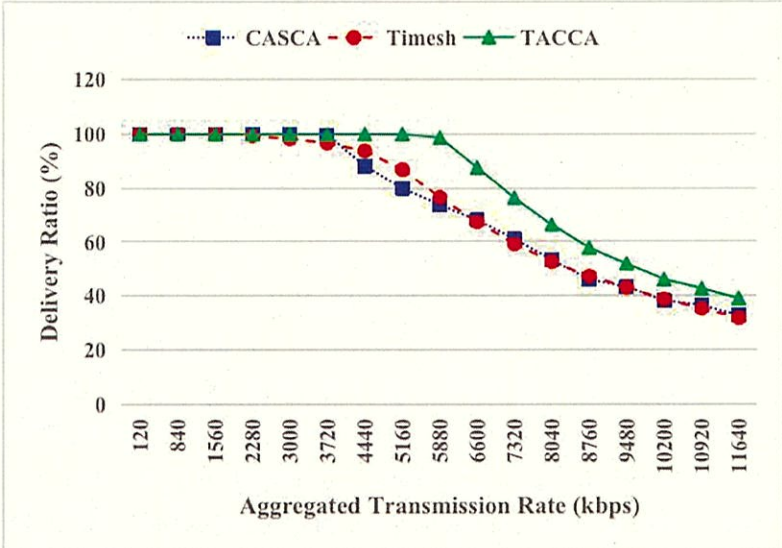


Fig. 4.14 Delivery Ratio (Grid Topology)

I show the packet delivery delay in Fig. 4.9, I see the delivery delay rapidly increases when the network saturates (i.e., when the traffic load exceeds the capacity of some links) in all of CASCA, TiMesh, and TACCA.

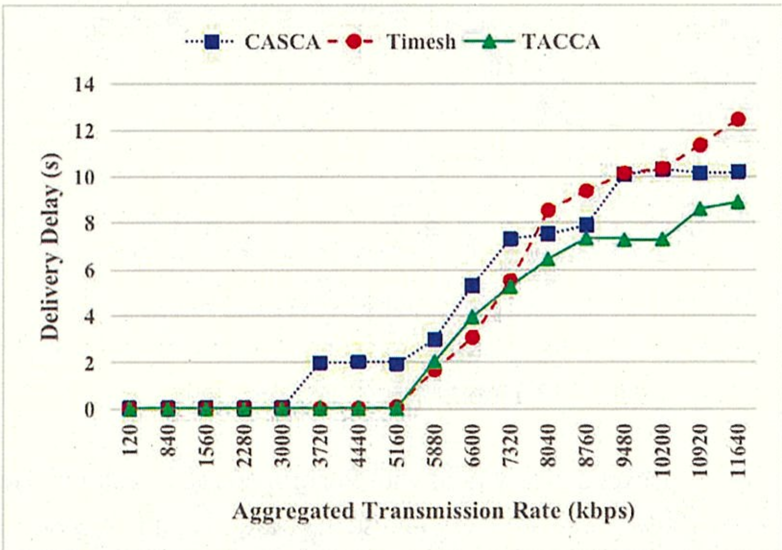


Fig. 4.15 Delivery Delay (Grid Topology)

Fig. 4.16 shows the status of frame loss in MAC layer due to collisions or interference. It is shown that, in TiMesh, the loss of frames increases as the volume of traffic increases. I observed a large number of RTS/CTS frames dropped because of exceeding the limit of retransmission counts, and most of them were due to collision of the hidden terminal problem. In contrast, in CASCA and TACCA, the number of dropped frames is very small; I observed only a few frame drops, which were due to interference or simultaneous backoff expiration, and they all were recovered by CSMA's frame retransmission.

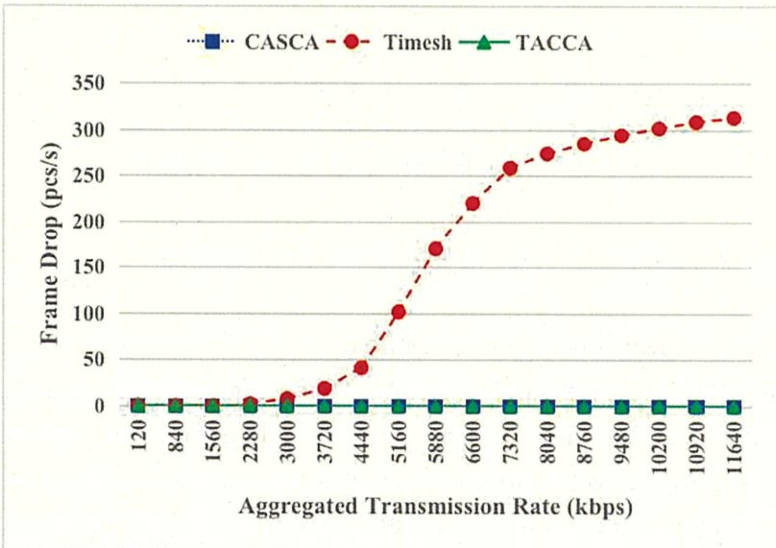


Fig. 4.16 Frame Drop (Grid Topology)

Random Topology: In Figs. 4.17, 4.18, 4.19, and 4.20, I show the same set of results in the random topology scenario. Note that the result is the average of 4 different random topologies.

Fig. 4.17 shows the aggregated throughput of the three schemes with the offered traffic volume as its horizontal axis, where the aggregated throughput is the sum of the data rates delivered to all terminals in a network. Same as grid topology, I see that all performs good when the offered load is low, but the performance of CASCA drop down with smaller offered load than TACCA. It was confirmed that CASCA met a bottleneck link, i.e., the link whose traffic load exceeded its capacity, with lower offered load than TACCA, proving that the load balancing function in TACCA well worked to enhance network capacity. Although TiMesh has the load-balancing function, the overhead of RTS/CTS due to exposed terminal problem extremely degrades the network capacity. As a result, TACCA outperforms the others in network capacity.

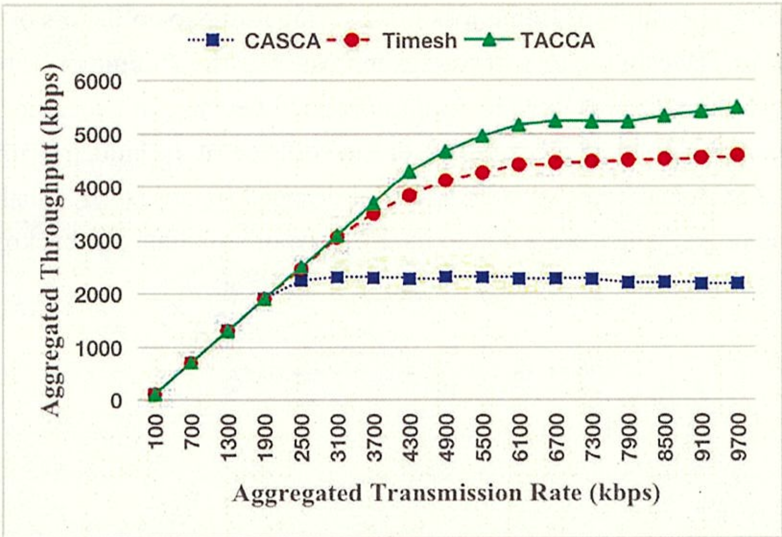


Fig. 4.17 Throughput (Random Topology)

Fig. 4.18 shows the packet delivery ratio with the offered traffic volume. Here, I see that TACCA keep almost 100% packet delivery unless the traffic volume reaches their network capacity, meaning that the collision-freedom property in the schedule lives in the simulation. In contrast, in CASCA, delivery ratio gradually decreases as traffic volume increases even when the traffic volume is relatively low. I confirmed this is mainly caused by some links are overloaded. TiMesh still suffers from hidden terminal problem even under RTS/CTS mechanisms.

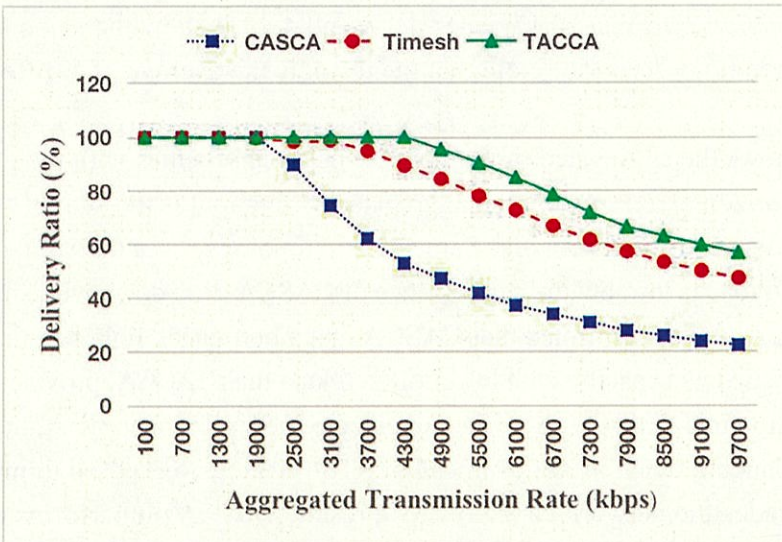


Fig. 4.18 Delivery Ratio (Random Topology)

Fig. 4.19 shows the status of the packet delivery delay. I see the delivery delay rapidly increases when the network saturates (i.e., when the traffic load exceeds the capacity of some links) in all of CASCA, TiMesh, and TACCA.

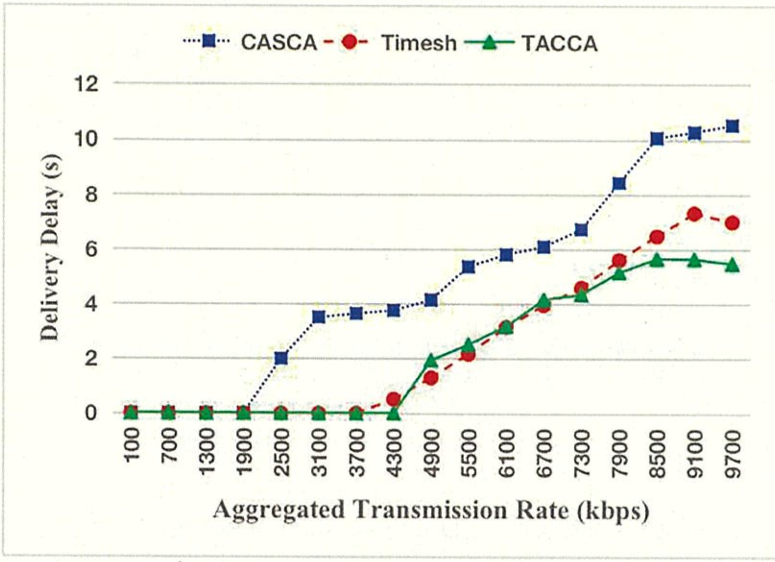


Fig. 4.19 Delivery Delay (Random Topology)

Fig. 4.20 shows the status of frame loss in MAC layer due to collisions or interference. It is shown that, in TiMesh, the loss of frames increases as the volume of traffic increases. I observed a large number of RTS/CTS frames dropped because of exceeding the limit of retransmission counts, and most of them were due to collision of the hidden terminal problem. In contrast, in CASCA and TACCA, the number of dropped frames is very small; I observed only a few frame drops, which were due to interference or simultaneous backoff expiration, and they all were recovered by CSMA's frame retransmission.

Although the performance of CASCA and TACCA degrades compared with the grid scenario, the general trend is the same as the grid scenario. Namely, TACCA has the highest network capacity under the given traffic demand, and keep almost 100% packet delivery with higher offered load than CASCA and TiMesh. As above, I conclude that TACCA outperforms CASCA and TiMesh in both grid and random scenarios, and has an ability to keep collision-freedom with high offered load even if the number of available channels is as small as 3. Because of the collision freedom property with 3 channels, TACCA would naturally achieve collision freedom with more than 3 channels, and consequently outperform the others.

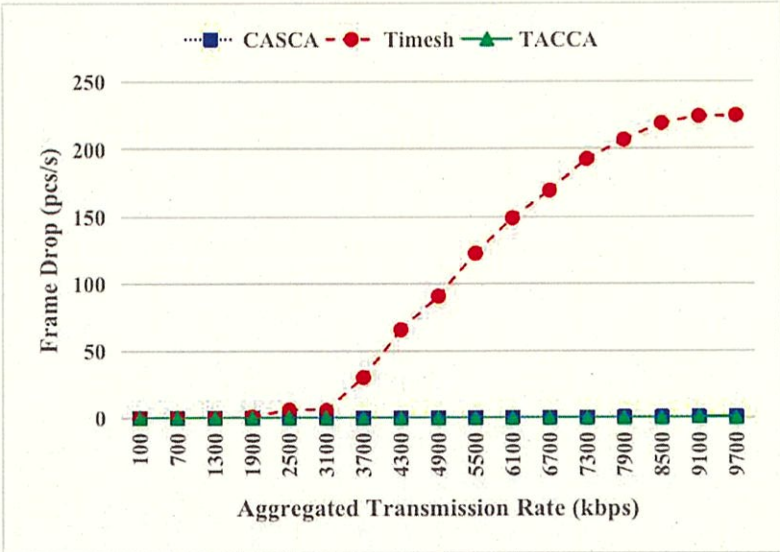


Fig. 4.20 Frame Drop (Random Topology)

Table 4.3 Configuration in Traffic Simulation

Items	Values
Simulator	Scenargie version 2.1
PHY and MAC Protocols	IEEE 802.11g
Propagation Model	Two ray ground
Link Capacity	6 Mbps
Transmission Power	20 dBm
Number of Interfaces	2 for each node
Number of Channels	3
Communication Range	530 m
Network Topology	Grid and Random
Traffic Demands	12 CBR flows (Grid) 10 CBR flows (Random)
Payload Size	1472 bytes
Number of Nodes	25 (Grid) and 30 (Random)
Simulation Time	5000 seconds

4.4.3 Discussion

In theory, CASCA, TiMesh, and TACCA are all collision-free transmission schemes, which achieves 100% packet delivery without collision under their own interference model. However, in the simulation running with SINR interference model, I observed a certain level of collision caused by interference.

In TiMesh, except the loss due to queue overflow that occurs when traffic volume exceeds link capacity, the main cause of frame loss is the collision of RTS/CTS frames due to interference among hidden terminal nodes. This sort of frame loss increases as the volume of traffic increases, and is reflected on the decrease of delivery ratio seen in low-traffic-volume cases. In contrast, in CASCA and TACCA, I observed only a few frame drops, which were due to interference or simultaneous backoff expiration, and they all were recovered by CSMA's frame retransmission. As a result, CASCA and TACCA have almost no frame loss due to interference, shown as Fig. 4.16, and 4.18, This shows that the interference model in TACCA and CASCA well performed to reduce the interference among nodes.

The typical pattern of performance degradation in TACCA is seen when the distance between two nodes assigned with the same channel is slightly larger than the communication range R. See Fig. 4.6 again. A Node Pair 0 and 9 is the case, in which a link between them does not exist while radio of a node interferes the other. In this case, for instance, a transmission on link $(0,26)$ would prevent successful transmission on link $(15,9)$. In my simulation, I observed the case in each random topology although the frame drops due to this were all recovered by retransmission of frames. Here, I must notice that this case degrades the load balancing performance. If the radio of one of the node pair is sensed by the other, it introduces error in the capacity estimation of TACCA because the assumption in shared link capacity model is violated. This inconvenience in load balancing were also seen in our random topology simulations, which was the main cause of performance degradation of TACCA in random scenario compared with grid scenario.

4.5 Chapter Summary

In this chapter, by incorporating the CSMA-aware interference model introduced in CASCA, I proposed TACCA, which is a new joint channel assignment and routing scheme that achieves collision-freedom with 3-5 OCs, which also minimizes the network-wide utility under a given traffic demand matrix. Different from CASCA, I formulated the optimization problem as MILP to introduce a traffic engineering function under the CSMA-aware link capacity sharing model, which enables capacity management in MRMC WMNs under traffic demand. Through evaluation with the MATLAB MILP solver, I confirmed that TACCA achieves collision-freedom with 3 channels in both scenarios, and has good traffic engineering performance brought from the parameter called path stretch k. Results of traffic simulations show that the schedule computed by TACCA works without major collision under the up-to-date simulation models, and TACCA clearly outperforms the conventional schemes in them. To the best of my knowledge, TACCA is the first joint channel assignment and routing scheme that enables capacity management in MCMR WMNs under collision-freedom with 3-5 orthogonal channels. Note that collision-freedom is a key issue for the reliable capacity management. I believe that TACCA would provide an important contribution toward realizing practical IEEE 802.11-based MCMR WMNs.

Chapter 5

Traffic-demand-aware Collision-free CA with POCs in MRMC WMNs

5.1 Introduction

In chapter 4, I proposed the joint channel assignment and routing scheme TACCA that achieved collision-free transmission in 802.11-based MRMC WMN. However, TACCA deals with channel assignment with OCs, resulting in low spatial utilization. On the other side, due to the difference in interference estimation between OCs and POCs, TACCA does not work with POCs. Therefore, in this chapter, I propose a new scheme TAC-POCA (Traffic-Demand-Aware Collision-free Partially Overlapping Channel Assignment), which newly introduce POCs into a CSMA-aware interference model and CSMA-aware shared capacity model to achieve collision-free transmission while considering traffic engineering. By exploiting the good property of POC's spatial reuse in combination with route optimization, I achieve a higher number of simultaneous transmissions than merely using OCs.

The rest of this chapter is organized as follows. I describe the system model, interference model, shared link capacity model, and some assumptions in Section 5.2. I formulate the problem in Section 5.3. Performance evaluations are given in Section 5.4. Conclusions are given in Section 5.5.

5.2 System Model

In this section, I first introduce our network model and assumptions. After that, basic interference model among POCs are defined. Then, I extend the CSMA-aware interference

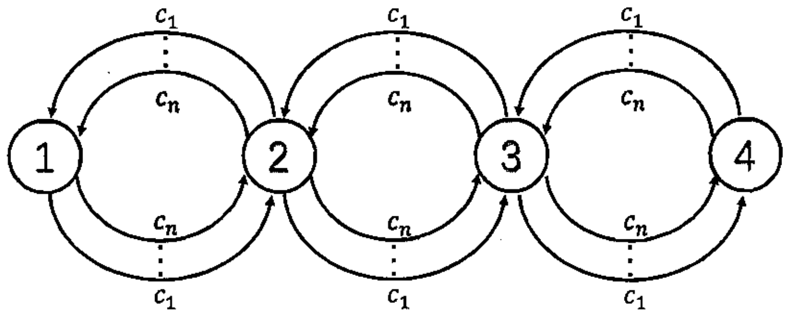


Fig. 5.1 Network Model

model and shared link capacity model by introducing POCs into them, which specifies the key characteristics of our scheme TAC-POCA.

5.2.1 Network Model and Assumptions

I model a MRMC WMN as a set of nodes V connected by a set of directed links E. Then, digraph $G = (V, E)$ represents the network. I assume each node in V is equipped with N_v classic NICs that are built on IEEE 802.11 technology, and each NIC operates on a distinct frequency channel. A link $l \in E$ that goes from node u to node v using channel $c \in C$ is written as $l = (u, v, c)$, where C is a set of channels. Then, there are potentially $2|C|$ available links for communications between every pair of neighboring nodes u and v in V. Fig.1.2 illustrates the model of our network G, where $c_1 \dots c_n$ represents the channel of the $n(n = |C|)$ potential links from a sender node to receiver.

I am given a traffic demand matrix D, which represents the amount of traffic demand from node s to d for each pair $(s,d) \in V \times V$. I write $D(s,d)$ to denote the amount of traffic demand from s to d. For each non-zero demand $D(s,d)$, I set a path to forward the traffic. Then, with each pair (s,d) and each link l, I associate a variable $P_l^{(s,d)} \in \{0,1\}$ that indicates whether the traffic flow for demand (s,d) goes through link l or not, i.e., $P_l^{(s,d)} = 1$ when the routing path from s to d includes link l, and $P_l^{(s,d)} = 0$ otherwise.

As is well known, neighbor nodes must be assigned with the same channel to communicate with each other. Then, if a link $l = (u, v, c)$ is used to transmit frames, the channel c must be assigned to one of the NICs of both u and v. I call the link used as a path of some flow *active link*. To represent this, a variable $A_l \in \{0,1\}$ is defined, where $A_l = 1$ indicates link l is active and $A_l = 0$ inactive. Meanwhile, I define a variable $R_v^c \in \{0,1\}$ indicating whether a NIC on node v is assigned with frequency channel c or not, i.e., $R_v^c = 1$ if there is a NIC on node v assigned with frequency channel c, and $R_v^c = 0$ otherwise. Naturally, if $A_{(u,v,c)} = 1$, then $R_u^c = R_v^c = 1$.

In this study, I minimize the maximum link utilization to achieve good load balancing in the network. I assume that all links communicate in the same speed, and have the same capacity defined as Θ. Then, the link utilization of a link is the ratio of traffic amount over the link capacity Θ, i.e., the utilization of link $l \in E$ is expressed as $\sum_{(s,d)\in V\times V} D(s,d)P_l^{(s,d)}/\Theta$. Thus, I define a variable U_{max} where $0 \leq U_{max} \leq 1$, which represents the maximum link utilization among all links.

I sometimes use the term (u,v,c) in place of link l, where u and v are the terminal nodes of link l, and c is the assigned channel with link l. To introduce the collision-free and capacity constraint, I give additional definitions in the following sections. Problem formulation will be given in Sec.5.3.

5.2.2 Interference among POCs

As is well known, on the IEEE 802.11 2.4 GHz band, there are 13 available channels, each of which has a spread of about 22 MHz and the center frequencies of channels are 5 MHz apart, which is shown as Chapter 1 Fig. 1.2. Therefore, any two channels with a separation over 5 (channels) are called OCs, e.g., channels 1, 6, and 11 are OCs, among which signals do not overlap with one another. Otherwise, they are POCs; Their signals overlap with each other, e.g., channel 1 and 3 are POCs. Hoque et al.[28] classified the interference of IEEE 802.11-based MRMC WMNs into three types: (i) When two in-range transmitters operate on the same channel, they interfere with each other, and such interference is called as co-channel interference (CCI). (ii) When two transmitters operate on relatively close channels that partially overlap, they cause lesser degree of interference, which is referred to as adjacent channel interference (ACI). (iii) Transmissions on a NIC at a node interferes with another NIC at the same node if those two nodes are assigned with the same, or non-orthogonal channels, it is defined as self-interference (SI). To achieve collision-free transmission, all of these three types of interference have to be eliminated. It's known that interference model is utilized as the technique for estimating interference level among nodes. Therefore, to achieve collision-free transmission, designing accurate interference model is important.

In this study, interference is modeled based on the simple disk model (or called protocol model) [27], i.e., *interference range* $(1+\Delta)R$ is defined, and nodes within the range $(1+\Delta)R$ of a transmitter fails to receive any frame. This disk model is defined for CCI, and I extend it extended for POCs.

See Fig.5.2 in which two links (u_1,v_1,c_1) and (u_2,v_2,c_2) are located closely. If $c_1 = c_2$, then it is a CCI case; transmission on (u_1,v_1,c_1) collides with (u_2,v_2,c_2) and v_2 fails to receive frames because the distance between u_1 and v_2 is smaller than $(1+\Delta)R$. If the channel separation of c_1 and c_2 is 1, i.e., $|c_1 - c_2| = 1$, then it is an ACI case, and the interference

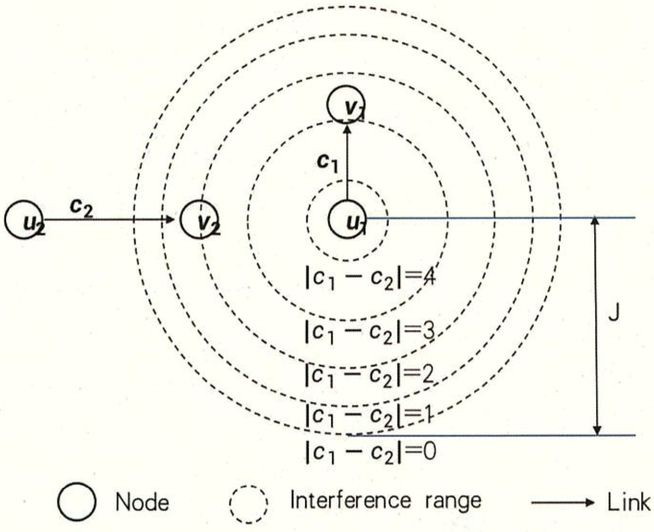


Fig. 5.2 Interference Ranges Depending on The Channel Distance

Table 5.1 Reduce Interference Range Ratios

Channel Distance	**0**	**1**	**2**	**3**	**4**	≥ 5
$I_{rrr}(c_, c_2)$	1	0.8667	0.6928	0.4739	0.1882	0

range shrinks a little than J, where $J = (1+\Delta)R$. However, since v_2 is still within the interference range, v_2 still fails to receive frames. Similarly, as the channel separation of c_1 and c_2 gets smaller, the interference range shrinks accordingly, and v_2 is able to receive frames when the channel separation is 3. Finally, when the channel separation is larger than 4, the interference range is 0, and even SI does not happen. To express the reduction of the interference range along with the level of channel separation, the range reduction ratio $I_{rrr}(c_1, c_2)$ is introduced, which takes range [0,1] that indicates the reduction ratio of interference range, i.e., $JI_{rrr}(c_1, c_2)$ is the interference range under two channels c_1 and c_2. This means that, when a node receives signal with channel c_2, the interference ranges from other nodes depend on the transmitting channel c_1. Specifically, the interference range gets smaller as the distance in frequency between c_1 and c_2 gets larger, and the range is zero (i.e., no interference) when the channel distance is larger than 4. This interference model is introduced by [118], and similar models are commonly used in many studies. Values of $I_{rrr}(c_1, c_2)$ are set as shown in Table 5.1.

5.2.3 CSMA-Aware Interference Model with POCs

The CSMA-aware interference model was proposed in chapter 4, which significantly reduce collisions among frames in CSMA-based WMNs by considering the behavior of CSMA. However, it assumes to use OCs, and the performance is limited. In this section, I introduce POCs into the CSMA-aware interference model to further improve the spatial reuse in WMNs.

Recall that the interference distance depends on both physical distance and channel separation distance as described in the previous section. In our new CSMA-aware interference model, we simply apply this considering of the property of CSMA. Specifically, we regard J as the *interference range* of the CCI case. Using the definition of the disk model, we also regard R as the *communication range* of the CCI case, within which two nodes can exchange frames with each other, and as the *carrier-sense range* of the CCI case, within which a node senses the other node's transmission in CSMA. As for the *carrier-sense range*, we apply a special treatment that the *carrier-sense range* is assumed to be far smaller than the *interference range* in the ACI case. This is our own heuristic approach consider for the real difference between the *carrier-sense range* and the *interference range*; when the signal received is weak, the interference is effected markedly by the nature of the SINR-based reception. Because we designed our model on the basis of the disk model and the reduced interference range ratio $I_{rrr}(c_1, c_2)$ introduced from [118] is designed on the basis of the interference effect, this heuristic approach is effective and makes capacity sharing more efficient.

On the basis of these assumptions, we now introduce three cases in which frames collide in our CSMA-aware interference model with POCs. Let $d(u, v)$ be the Euclidean distance between nodes u and v. Also, let $l_1 = (u_1, v_1, c_1)$ and $l_2 = (u_2, v_2, c_2)$ be a pair of two directed links in E, i.e., both $d(u_1, v_1) < R$ and $d(u_2, v_2) < R$ hold. Then, transmission on l_1 prevents communication on l_2 owing to collision if either of the following cases are met:

Case 1: Data frames collided with Data frames.

(1) $d(u_1, v_2) < JI_{rrr}(c_1, c_2)$,

(2) $d(u_1, u_2) \geq JI_{rrr}(c_1, c_2)$.

Case 2: Ack frames collided with Data frames.

(1) $d(v_1, v_2) < JI_{rrr}(c_1, c_2)$,

(2) $d(u_1, u_2) \geq JI_{rrr}(c_1, c_2)$,

(3) $d(u_1, v_2) \geq JI_{rrr}(c_1, c_2)$.

Case 3: Data frames collided with Ack frames.

(1) $c_1 \neq c_2 \wedge u_1 \neq u_2$,

(2) $d(u_1,u_2) < JI_{rrr}(c_1,c_2)$.

Case 1 provides the conditions that the transmission of Data frames on l_1 interferes the reception of Data frames on l_2. See Fig. 5.3(a). Node v_2 is within the *interference range* of node u_1, but nodes u_1 and u_2 are not within the carrier-sense range of each other, which results in collision of Data frames when two Data frames are transmitted simultaneously on both l_1 and l_2. Note that nodes v_1 and v_2 may be the same node.

Case 2 shown in Fig. 5.3(b) is the case where the transmission of Ack frames on l_1 interfere the reception of Data frames on l_2. In this case, two reception nodes v_1 and v_2 are located within the *interference range*, while the distance of two node pairs (u_1,u_2) and (u_1,v_2) are both larger than the *carrier-sense range*. Then, u_1 and u_2 may transmit Data frames simultaneously, and Ack frames transmitted by v_1 interferes Data frame reception of v_2.

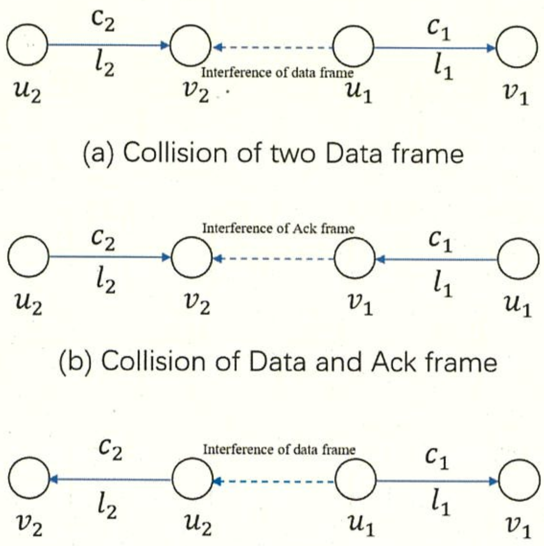
Case 3 shown in Fig. 5.3(c) is the case where Data frames on l_1 interfere the reception of Ack frames on l_2. This case occurs only in case of ACI (i.e., $c_1 \neq c_2$), and I assume $u_1 \neq u_2$ to exclude the case of Self-interference (SI). Note that, here, u_1 and u_2 are within the interference range $JI_{rrr}(c_1,c_2)$, but we assume they cannot sense carriers with each other according to the special treatment for POC stated in this section. In this case, both u_1 and u_2 transmit Data frames and the returned Ack frames are interfered by the Data frames.

Note that the fourth case where two Ack frames collide is ignored Because the probability of it happening is very low. Even if this case is included in our channel assignment results, its effect on communication performance is a sufficiently low level.

According to the above definition of interference, I introduce a set of interference link pairs S_{ILP} that should not appear in the solution of our channel assignment problem. Note that the interference is asymmetric, i.e., even if link l_1 prevents communication on l_2, l_2 may not prevent communication of l_1. Thus, I write an interference link pair under the above definition of three cases as $l_1 \to l_2$, and the set of interference link pairs in the network is defined as follows.

$$S_{ILP} = \{(l_1,l_2)|l_1,l_2 \in E, l_1 \to l_2\} \tag{5.1}$$

S_{ILP} is computed from the given network topology, and used in the MILP formulation of our joint channel assignment and routing problem.



(a) Collision of two Data frame

(b) Collision of Data and Ack frame

(c) Collision of Data frame or Ack frame

Fig. 5.3 Interference Model

5.2.4 Shared Link Capacity Model with POCs

The above CSMA-aware interference model enable me to avoid the collisions that occur under the system of CSMA. On the other hand, CSMA's carrier sensing behavior also avoids collisions of CCI and SI cases. With the combination of those two, all collisions are eliminated in my scheme TAC-POCA.

However, I must note CSMA's collision avoidance mechanism based on carrier sensing makes multiple links share the common communication resources. To make load balancing within the limited network resources, the total amount of traffic load on all the shared capacity links should not exceed the capacity Θ. In wireless networks, a channel as a resource is shared by nodes within the *carrier-sense range*, and so the links around the nodes share the capacity. Therefore, I define the set of shared capacity links for each combination of node v and frequency channel c as follows.

$$\begin{aligned} S_v^c = &\{(v,u,c')|(v,u,c') \in E, 0 < I_{rrr}(c,c')\} \\ &\cup \{(u,a,c)|(u,a,c) \in E, d(u,v) < R\} \end{aligned} \tag{5.2}$$

See Fig. 5.4, where $u \in V$ is a node within the *carrier-sense range* of node $v \in V$ under CCI, and $a \in V$ is within the *communication range* of u. Note that v and a may be the same

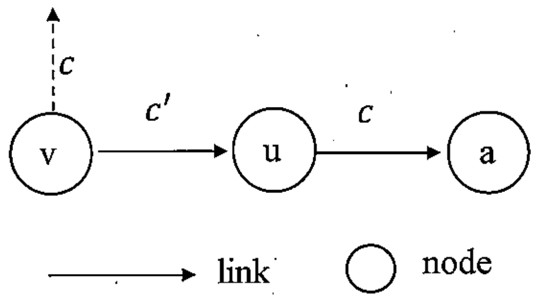


Fig. 5.4 Shared Link Capacity Model

node. The dotted arrow indicates that a NIC on node v is assigned with channel c. If another NIC on v is assigned with c' and link (v,u,c') exists, and c and c' are not orthogonal (i.e., $0 < I_{rrr}(c,c')$), they are the relationship of SI, and share the capacity Θ of S_v^c. Also, if link (u,a,c) exist, it also shares the capacity of S_v^c. Here, note again that the transmission of u on channel c' are not sensed by v on channel c due to the special treatment of POCs. Thus, if link (u,a,c') where $c \neq c'$ exists, it is not included in S_v^c. Rather, it is treated as the collision link by the Case 3 of the CSMA-aware interference model, and a channel that does not collide with v's links is assigned to the link as a result.

To summarize the definitions, I give a table of the notations in Table 5.2.

5.3 Problem Formulation

In this section, I formulate a joint channel assignment and routing problem in MILP based on the definition and assumptions provided in Sec.5.2.

$$\min \quad U_{max} \tag{5.3}$$

Subject to

$$\sum_{c \in C} R_v^c \leq N_v, \qquad \forall\ v \in V, \tag{5.4}$$

$$R_v^c \leq \sum_{(v,u,c) \in E} A_{(v,u,c)} + \sum_{(u,v,c) \in E} A_{(u,v,c)}, \forall\, c \in C\,,\ \forall\, v \in V, \tag{5.5}$$

$$A_{(u,v,c)} \leq R_v^c,\ A_{(u,v,c)} \leq R_u^c,\ \forall\ (u,v,c) \in E, \tag{5.6}$$

$$A_{l_1} + A_{l_2} \leq 1, \qquad \forall\,(l_1, l_2) \in S_{ILP}, \tag{5.7}$$

$$\sum_{(u,v,c)\in E} P^{(s,d)}_{(u,v,c)} D(s,d) - \sum_{(v,w,c)\in E} P^{(s,d)}_{(v,w,c)} D(s,d) = \begin{cases} -D(s,d), \text{if } v = s, \\ D(s,d), \text{if } v = d, \\ 0, \text{otherwise}, \end{cases} \quad \forall\,(s,d) \in V \times V, \tag{5.8}$$

$$\sum_{(s,d)\in V\times V} P^{(s,d)}_l \leq M A_l, \quad \forall\, l \in E, \tag{5.9}$$

$$\sum_{(s,d)\in V\times V} P^{(s,d)}_l \geq A_l, \quad \forall\, l \in E, \tag{5.10}$$

$$\sum_{(s,d)\in V\times V, l \in S^c_v} D(s,d) P^{(s,d)}_l \leq U_{max}\Theta + (1 - R^c_v)W, \forall\, v \in V, \ \forall\, c \in C, \tag{5.11}$$

$$\sum_{l\in E} P^{(s,d)}_l \leq \delta_{s\to d} + k, forall\ (s,d) \in V \times V, \tag{5.12}$$

Where

$$0 \leq U_{max} \leq 1, \tag{5.13}$$

$$R^c_v \in \{0,1\}, \forall\, c \in C, \forall\, v \in V, \tag{5.14}$$

$$A_l \in \{0,1\}, \forall\, l \in E, \tag{5.15}$$

$$P^{(s,d)}_l \in \{0,1\}, \forall\,(s,d) \in V \times V, \forall\, l \in E. \tag{5.16}$$

Load balancing is of utmost importance to avoid hot spots and to increase network utilization. In order to balance the traffic in the network and avoid overloading any link, I set (5.3) as the objective function, in order to minimize the largest of link utilization in the network.

As mentioned before, my network topology is defined as a multiple graph in which neighboring two nodes have multiple links corresponding to each channel in C. To decrease interference, we allow to remove (i.e., inactivate) some of the links from the topology.

Table 5.2 Notations for TAC-POCA

Symbol	Description
V	A set of nodes (routers)
E	A set of directed links
G	A directed network
Θ	Link capacity (common with all links)
N_v	The number of NICs on each node
C	A set of channels
R	Communication range of the same channel.
J	Interference range.
D	A traffic demand matrix
$D(s,d)$	A traffic demand from s to d
$l/(u,v,c)$	A link
S_{ILP}	A set of interference link pairs
S_v^c	A set of shared capacity links
R_v^c	Binary variable indicating node v is assigned with channel c or not
$P_l^{(s,d)}$	Binary variable indicating whether the path for $D(s,d)$ includes link l or not
A_l	Binary variable indicating link l is active or not
U_{max}	Real variable indicating maximum link utilization among all the links in the network.
$I_{rrr}(c_1,c_2)$	Reduce interference range ratio between transmission with channel c_1 and c_2.
$d(u,v)$	Euclidean distance between node u and v.

Therefore, the number of distinct frequency channels c allocated to one node must be less or equal to the number of NICs on each node. To represent this, I give the constraint (5.4). Next, I manage the relationship among channel assignment and active links. For each node v, $(v,u,c) \in E$ denotes the output links of node v, and $(u,v,c) \in E$ denotes the input links where node u is the other terminal node of links. Then, if a NIC on node v is assigned with channel c, i.e., $R_v^c = 1$, then $\sum_{(v,u,c)\in E} A_{(v,u,c)} + \sum_{(u,v,c)\in E} A_{(u,v,c)} \geq 1$. This means that at least one connecting link (no matter whether it is output or input link) must be activated. This constraint is given as (5.5). Conversely, as indicated by (5.6), if none of the NICs on node v is assigned with channel c, then $A_{(u,v,c)} = 0$, i.e., link (u,v,c) must be inactive. To achieve collision-free transmission I set (5.7) to ensure that the interfering links are not used for communication simultaneously. Specifically, links $(l_1,l_2) \in S_{ILP}$ cannot be activated simultaneously, i.e., if $A_{l_1} = 1$, then $A_{l_2} = 0$ must stand, and vice versa.

Traffic flows in the network must meet the conservation conditions. In (5.8), $P_{(u,v,c)}^{(s,d)}$ and $P_{(v,w,c)}^{(s,d)}$ denote whether the route of traffic demand (s,d) goes through the input link (u,v,c) and output link (v,w,c) of v, respectively. For each traffic demand pair (s,d), I refer to s and d as the source and destination nodes of the demand. In terms of flow conservation, the total volume of flows sent by s must be equal to that received by d. Also, the total input and output volume of flows on every intermediate node must be equal. Therefore, if node v is the source node, i.e., $v = s$, the value of (5.8) equals to $-D(s,d)$. If node v is the destination node, i.e., $v = d$, the value of (5.8) is equal to $D(s,d)$. Otherwise, the node is intermediate node, and the value of (5.8) equals to 0. This constraint not only ensures that the traffic flow is properly routed from s to d, but also ensures that each demand is satisfied with a single explicit route. In (5.9), when at least one traffic flow goes through link l, i.e., $\sum_{(s,d)\in V\times V} P_l^{(s,d)} \geq 1$, then the link l must be activated, where M is a constant whose value is large enough. Formula (5.10) means that if there is no traffic flow through link l, the link l must be inactivated. Those two formulas (5.9) and (5.10) keep the relationship between traffic flows and link activeness.

Recall my shared link capacity model described in Sec.5.2.4. The total traffic load on the links in S_v^c cannot exceed the link capacity Θ. Therefore, if channel c is assigned to node v, i.e., $R_v^c = 1$, then $\sum_{(s,d)\in V\times V, l\in S_v^c} D(s,d)P_l^{(s,d)} \leq \Theta$ must be satisfied. Otherwise, if channel c is not assigned to node v, there is no capacity constraint on these links, constraint (5.11) covers both of the cases. Namely, if $R_v^c = 1$, $(1-R_v^c)W$ equals to zero, and the capacity constraint is activated, and otherwise, $(1-R_v^c)W$ equal to W, where W is a constant whose value is large enough, meaning that the capacity constraint is inactivated. Here, I put $U_{max}\Theta$ in place of Θ to minimize the largest link utilization U_{max} in the network. Since $0 \leq U_{max} \leq 1$ assigned in (5.13), inserting U_{max} does not violate the capacity constraint.

Also, by minimizing U_{max} in (5.3), I can explore the solution for the best load balancing performance.

On the other hand, I allow to use longer routing paths to enhance load balancing performance. Longer paths enable me to compute more flexible path scheduling and improve optimality in load balancing. However, too long paths will waste the capacity and increase communication delay. Thus, I enforce each of the traffic flows from s to d to use relatively short path. Our path length constraint is (5.12), where $\delta_{s \to d}$ indicates the minimum hop count to reach d from s, i.e., the shortest-path length from s to d in G. $k \geq 0$ is a path stretch in integer, then $\delta_{s \to d} + k$ in (5.12) means that length of every path is limited by the shortest path length plus k. Length of all paths are controlled by adjusting the value of k.

Constraints (5.13), (5.14), (5.15), and (5.16) define the domains of variables described previously.

With above formulation, my problem is to assign a single path for every non-zero traffic demand pair (s,d) in D using all the available channels, where both the link capacity constraint and the collision-free constraint are fulfilled, and the link utilization is minimized.

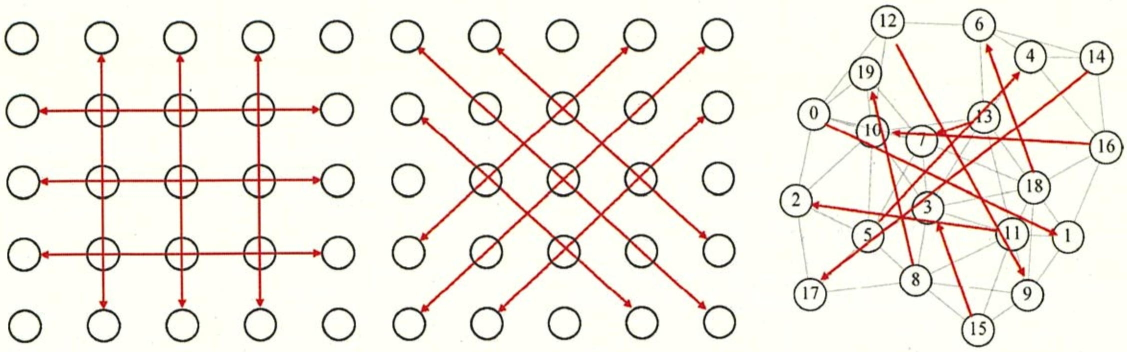
5.4 Evaluation

I evaluate the performance of our method TAC-POCA with two different network topologies, i.e., the grid topology and the random topology. In the former part, I evaluated the optimization performance through a MILP solver. As for the later, I made the traffic simulation using an up-to-date network simulator. I describe the detail in the following sections.

5.4.1 Optimization Performance Evaluation

In this evaluation, I test the optimization performance of TAC-POCA under various values of the parameters such as path stretch k, the number of NICs, and offered traffic load. One of the important viewpoints is to examine the effect of introducing POCs. Another concern is whether TAC-POCA has better performance than TACCA. Recall that there is no scheme that jointed routing and channel assignment with POCs, and even with OCs no schemes achieves collision-free transmission in MCMR WMNs. Thus, all of the past schemes except TACCA in the literature are not suitable to compare. Since TACCA achieves a collision-free schedule but only consider OCs, we can see the performance gain of TAC-POCA coming from considering POCs. Both are examined in two scenarios with grid and random topologies.

(1) Method



(a) Traffic Pattern 1 (Grid) (b) Traffic Pattern 2 (Grid) (c) Traffic Pattern (Random)

Fig. 5.5 Traffic Patterns

I solved our MILP problem with IBM CPLEX Optimizer version 12.10 ([119]), which was executed on a computer with Intel (R) Xeon (R) CPU E5-2698 (2.20 GHz), 265 GB memory. As typical scenarios in WMNs, I suppose two different types of network topologies, i.e., grid and random layout of wireless nodes. As for grid topology, I designed a 5×5 square grid with 400 m interval in both horizontal and vertical directions. On the other hand, as a random topology, I located 20 nodes with random coordination in a $1,500 \times 1,500$ m square field. I assume each node has a communication range of 530 m that corresponds to 20 dBm Txpower, and we assume $\Delta = \varepsilon$, where ε is an infinitesimal number. Each NIC operates IEEE 802.11g with 6 Mbps communication speed so that the link capacity Θ is also assumed as 6 Mbps. All of the 13 channels defined in IEEE 802.11 2.4 GHz are used for channel assignment.

Note that the number of nodes in this scenario may be relatively small compared to the network size expected in practice. However, we choose this network size in consideration of the large computational complexity, which requires considerable time to test a variety of parameter values. We believe that 20-25 nodes scenarios enable us to demonstrate all the principles and reveal the performance of our method. Additionally, it will be possible to apply our method into larger networks in practice using more capable computers in parallel.

As a traffic demand, I generate flows intending highly collided traffic that covers the whole area of field. I generate 12 bi-directional Constant Bit Rate (CBR) flows in the grid topology, and in the random topology, I generate 10 CBR flows with randomly selected source and destination nodes. I show the traffic pattern of grid topology in Fig. 5.5(a) (b), and the random topology in Fig. 5.5(c).

Note that the CPLEX computation for TAC-POCA would take longer time than TACCA because of its large number of variables in the MILP formulation. In order to obtain the best possible solution, we set the relative MIP gap tolerance to $1e-04$ (default value) and set the

Table 5.3 Configuration in Optimization Evaluation

Items	Values
Solver	IBM CPLEX Optimizer version 12.10
Number of Channels	3 for TACCA and 13 for TAC-POCA
Number of Interfaces	≥ 2 for each node
Link Capacity	6 Mbps
Communication Range	530 m
Δ	ε (an infinitesimal number)
Network Topology	Grid and Random
Number of Nodes	25 (Gird), 20 (Random)
Traffic Demands	12 CBR flows (Grid)
	10 CBR flows (Random)

limitation of computational time of CPLEX optimization to 48 h. The entire configuration described above is summarized in Table 5.3.

(2) Result

In Table 5.4, I show the effect of path stretch k with the maximum network link utility U_{max}, where each of the traffic flow volume equal to 500 kbps and each node is equipped with 2 NICs. I set $k = 0$, 2,4, 6 for grid topology and k= 0, 1, 2, 3 for random topology. Note that, for example, k=3 in grid topology is the same as k=2 because length of any detour path in grid topology is the length of the corresponding shortest path plus an even number of hops. All the results are average of 5 executions. I will discuss them separately in the following.

First, I focus on the grid topology. See Table 5.4 (a). When $k = 0$, both TACCA and TAC-POCA obtain no solution because of the tight constraint to find solution, which implies TAC-POCA has no obvious advantage in the shortest-path case. When $k = 2$, TAC-POCA obtains solution but TACCA cannot obtain solution, which implies that POC enable TAC-POCA to find solutions easier than TACCA under allowing detouring paths. When $k = 4$, I see TAC-POCA gets better solution than TACCA, which shows that traffic load is well balanced in TAC-POCA than TACCA, and the efficiency of POCs decrease the link utilization. Unfortunately, when $k = 6$, TAC-POCA did not get better solution than TACCA within the limited time because of its large computational complexity.

Next, see Table 5.4 (b) for random topology, I see TACCA can not get solution when $k = 0$. However, TAC-POCA gets solutions for each set value of k, which is because diversity in node distances in the random topology enable POCs to exploit more efficient spatial reuse of channels. We also see that TAC-POCA has better solutions (i.e., lower link utility U_{max}) than TACCA, which means the network capacity also can be improved by using POCs. Note that, in both grid and random topology, TAC-POCA with lower k sometimes obtain better solution than higher k cases. This is because the size of the problem (i.e., the number of variable in the MILP formulation) in TAC-POCA is larger than TACCA and near-optimal solution is not always obtained within the limited time.

Table 5.4 Path Stretch k with The Maximum Network Link Utility U_{max} (Avg.)

k	Grid	
	TACCA	TAC-POCA
0	-	-
2	-	0.5
4	0.5	0.3333
6	0.5	0.583

"-" indicates no solution be found.
(a) Grid topology

k	Random	
	TACCA	TAC-POCA
0	-	0.2916
1	-	0.3333
2	0.4583	0.3333
3	0.4583	0.3333

"-" indicates no solution be found.
(b) Random topology

To see the complexity of the problems, we show the relative MIP gap values at the end of each computation in Table 5.5. Here, "finished" means that the computation had finished within 48 h so that the gap value is small enough. We find that the gap value is generally smaller in TACCA than TAC-POCA, meaning that TAC-POCA is harder to solve than TACCA. Also, the gap values increase as k increases, which is because the search space expands as k increases to allow longer routing paths. Especially, in several cases the gap keeps 100%, which means that in TAC-POCA it is very hard to find the optimal solution even though better solutions (i.e., U_{max} values) than TACCA had been found in most of the cases.

Table 5.5 The value of relative MIP gap (Avg.) with path stretch k

k	Grid	
	TACCA	TAC-POCA
0	-	-
2	-	83.3%
4	50%	100%
6	72.9%	100%

"-" indicates no solution be found.
(a) Grid topology

k	Random	
	TACCA	TAC-POCA
0	-	finished
1	-	75.0%
2	finished	100%
3	finished	100%

"-" indicates no solution be found.
(b) Random topology

In Table 5.6, I show the effect of number of NICs with the maximum network link utility U_{max}, where each of the traffic flow volume equal to 500 Kbps. I set $k = 4$ for grid topology because this is the smallest value of k with which both TAC-POCA and TACCA obtained good solutions. In the same way, I set $k = 2$ for the random topology. From Table 5.6 I see that the number of NICs has no obvious effect on the performance, which means that 2 NICs are almost enough to achieve efficient spatial reuse of channels.

Table 5.6 Number of NICs with The Maximum Network Link Utility U_{max} (Avg.)

NICs	Grid		Random	
	TACCA	TAC-POCA	TACCA	TAC-POCA
2	0.5	0.3333	0.4583	0.3333
3	0.5	0.3333	0.4167	0.3333
4	0.5	0.3333	0.4167	0.3333
5	0.5	0.3333	0.4167	0.2916

As above, in the optimization evaluation, I confirmed the property of TAC-POCA under parameter variations. TAC-POCA computes a collision-free channel assignment combined with routing configuration. Compared with TACCA, TAC-POCA not only efficiently uses overall channels, but also improves the network capacity. Compared with the grid topology which has fixed node distance, TAC-POCA is more effective in random networks because the diversity in node distance leads to better spatial reuse of channels. On the other hand, I see that the performance of TAC-POCA has larger fluctuation as the complexity of the problem is larger. TAC-POCA needs more computational resources than TACCA to obtain stable results.

5.4.2 Communication Performance Evaluation

(1) Method

The simulation configuration is designed based on that of the optimization evaluation, as shown in Table 5.7. I equip each node with 2 NICs that operate IEEE 802.11g in 6 Mbps speed with 20 dBm transmission power. In my preliminary experiment, 2 NICs per node was enough to obtain good schedule. Moreover, I use IEEE 802.11g standard as it provides basic CSMA functions without additional mechanisms to enhance efficiency. I chose two-ray-ground model as the radio propagation model. The same topologies as the optimization evaluation are used, which are a 5×5 grid topology with 400 meters interval, and a $1,500 \times 1,500$ meters square field random topology with 20 nodes. I generated 12 bi-directional CBR flows in the grid topology, and 10 flows with a random source and destination selection in the random topology. A commercial network simulator Scenargie version 2.1 [116] is used for simulation, which implements up-to-date PHY and MAC models and adopts equivalent-level models with popular network simulators ns-3 and Qualnet, and the simulation performance have been verified through calibration among them.

I use a channel assignment and routing schedule obtained in the optimization evaluation. Specifically, I chose the schedule computed with $k = 4$ for grid topology, $k = 2$ for random topology, and with the offered traffic load 500 Kbps per flow. As mentioned earlier, I am targeting on the mesh networks built with IEEE 802.11 technologies, so all the 13 channels are used. Generally, 2.4 GHz band is regarded as more useful than 5 GHz band for mesh infrastructure in many cases. mainly because 2.4 GHz band radio is more robust against obstacles than 5 GHz band and easier to maintain wireless link connection.

I compare the performance of TAC-POCA with TACCA and [102] which I call Mohsenian-Rad-POCA (MR-POCA). Recall that there is no joint POCs assignment and routing scheme for CSMA-based MRMC WMNs. Thus, most of the past schemes in the literature are not comparable in performance. Since TACCA achieves a collision-free schedule but uses OCs, I can see the performance gain of TAC-POCA coming from considering POCs. Therefore, TACCA schedules with the same parameters is used in the comparison. In MR-POCA, I used the shortest path as its pre-determined routes and set the appropriate parameters of SINR-based interference model that matches our simulation parameters such as the transmission power and the IEEE 802.11 channel bandwidth.

I used different scenarios (shown as Fig.5.5 (a), (b), and (c)) and ran the simulator for 5000 seconds and measure the average of the communication performance with five repeated executions, and compare the performance in terms of packet delivery ratio, throughput, end-to-end delivery delay, and frame drop. Since collisions continue on a regular basis and so do the MAC layer re-transmission with the final result effecting throughput, delivery, latency, and frame drop. In this study, frame drop is included to show the state of collision and interference in the network. In both scenarios, I apply variation of flow volume to see the capacity of the networks.

(2) Results

Grid topology: I show the results of the grid topology in Figs. 5.6, 5.7, 5.8, and 5.9, Note that the result is the average of the two different scenarios shown in Fig. 5.5 (a) and (b).

Fig. 5.6 shows the packet delivery ratio along with the offered traffic volume as its horizontal axis. Here, I see that both TAC-POCA and TACCA keep almost 100% packet delivery unless the traffic volume reaches their network capacity, meaning that the collision-freedom property in the schedule lives in the simulation. I found that the delivery rate of TACCA decreases earlier, i.e., with lower traffic load, than TAC-POCA. This is because TAC-POCA has more efficient spatial reuse of channels, resulting in reducing the maximum link utilization. In contrast, in MR-POCA the delivery ratio gradually decreases as traffic volume increases even when the traffic volume is relatively low. I confirmed this is mainly caused by the collision of RTS/CTS frames due to hidden terminal problem.

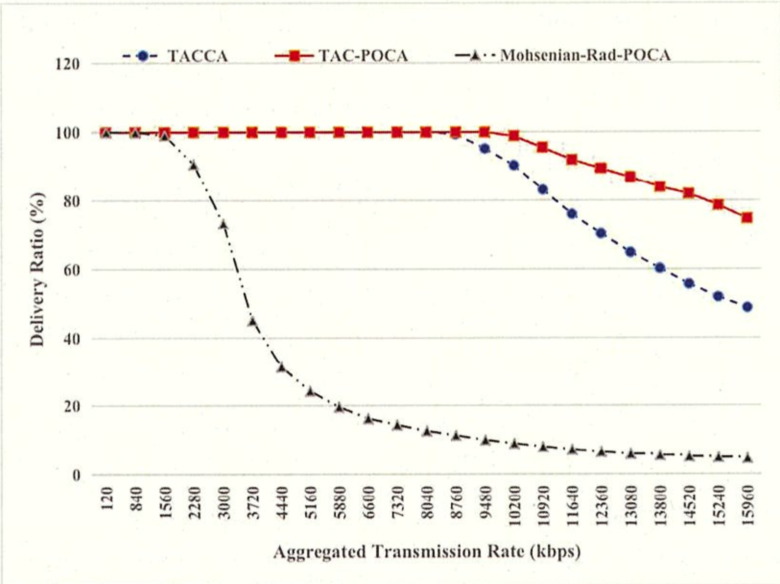


Fig. 5.6 Communication Performance Evaluation Delivery Ratio (Grid Topology)

Fig. 5.7 shows the aggregated throughput of the two schemes along with the offered traffic volume as its horizontal axis, where the aggregated throughput is the sum of the data rates delivered to all terminals in a network. I see that all perform good when the offered load are low in both TACCA and TAC-POCA, which proves that the load balancing function well worked to enhance network capacity. Due to the efficiency in channel utilization, TAC-POCA provided extra capacity space to support larger traffic, which improved the aggregate throughput. Therefore, unexpected growth in traffic often seen in real environment is more likely to be accommodated and can be accepted by TAC-POCA. In MR-POCA, a considerable number of packets got stuck at source nodes. This is because MR-POCA uses the shortest path routing. As a result, MR-POCA shows far less performance than TACCA and TAC-POCA in network capacity.

Fig. 5.8 shows the packet delivery delay. I see the delivery delay rapidly increases when the network saturates (i.e., when the traffic load exceeds the capacity of some links) in MR-POCA, this is due to the shortest path routing. In TAC-POCA and TACCA, the delay growth rate is relatively slow. However, more flexible channel assignment enables TAC-POCA to choose shorter paths, leading to less delay than TACCA.

Fig. 5.9 shows the status of frame loss in MAC layer due to collision or interference. It is shown that, in MR-POCA, frame loss increased as the volume of traffic increases. I observes a large number of frames dropped by of exceeding the limit of retransmission counts, and most of them were due to collision of the hidden terminal problem. In contrast,

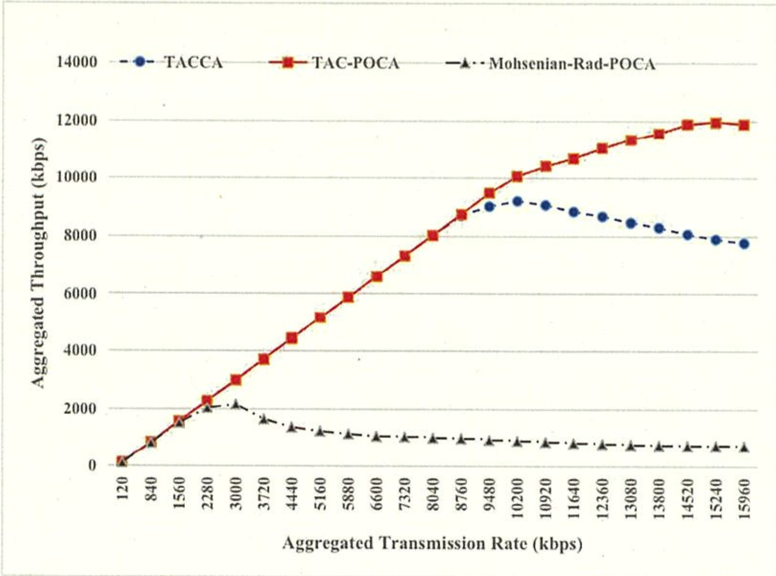


Fig. 5.7 Communication Performance Evaluation Throughput (Grid Topology)

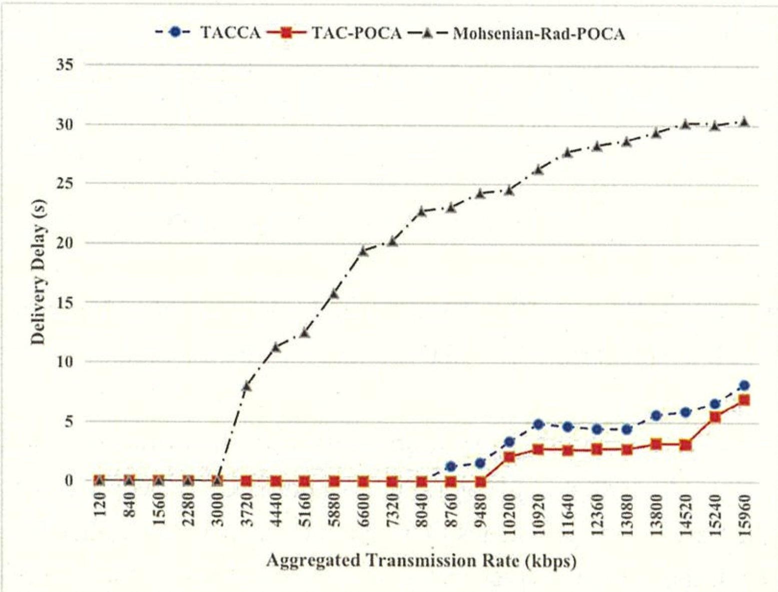


Fig. 5.8 Communication Performance Evaluation Delivery Delay (Grid Topology)

I see that the number of dropped frames are very small in both TAC-POCA and TACCA. Through the log files, I observed only a few frame drops; There were several interference or simultaneous backoff expiration among frames, but most of them were recovered by CSMA's frame retransmission. As a result, TAC-POCA and TACCA have almost no frame loss due to interference, shown as Fig. 5.9. It implies that the interference model in TAC-POCA well performed to reduce the interference among nodes. In theory, TAC-POCA and TACCA are all collision-free transmission schemes, which achieves 100% packet delivery without collision under their own interference model. On the other hand, in the simulation running with SINR interference model, although I observed a certain level of collision caused by interference, basically the collision among frames is eliminated.

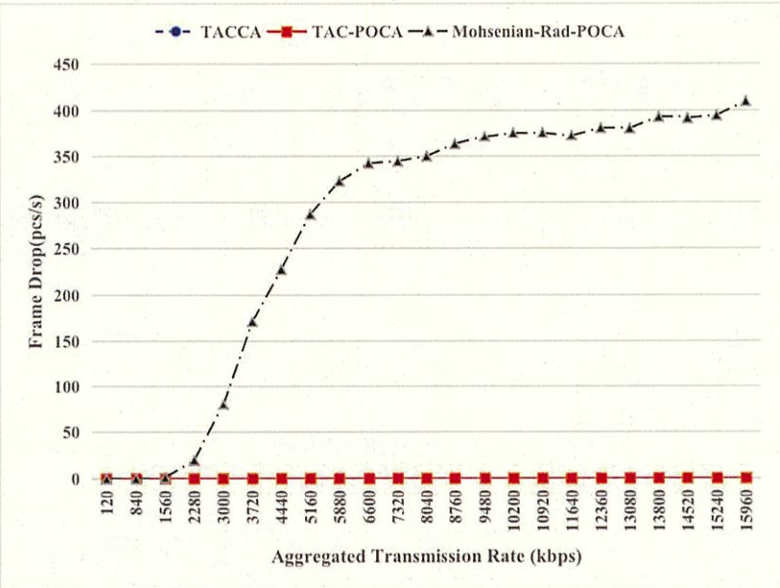


Fig. 5.9 Communication Performance Evaluation Frame Drop (Grid Topology)

Random topology: In Figs. 5.10, 5.11, 5.12, and 5.13, we show the same set of results in the random topology scenario. Note that the result is the average of 5 different random scenarios.

Fig. 5.10 shows the packet delivery ratio along with the offered traffic volume as its horizontal axis. Here, I see that both TAC-POCA and TACCA keep almost 100% packet delivery unless the traffic volume reaches their network capacity, meaning that the collision-freedom property in the schedule lives in the simulation. I found that the delivery rate of TACCA decreases earlier, i.e., with lower traffic load, than TAC-POCA. This is because TAC-POCA has more efficient spatial reuse of channels, resulting in reducing the maximum link utilization. In contrast, in MR-POCA the delivery ratio gradually decreases as traffic volume increases even when the traffic volume is relatively low. I confirmed this is mainly caused by the collision of RTS/CTS frames due to hidden terminal problem.

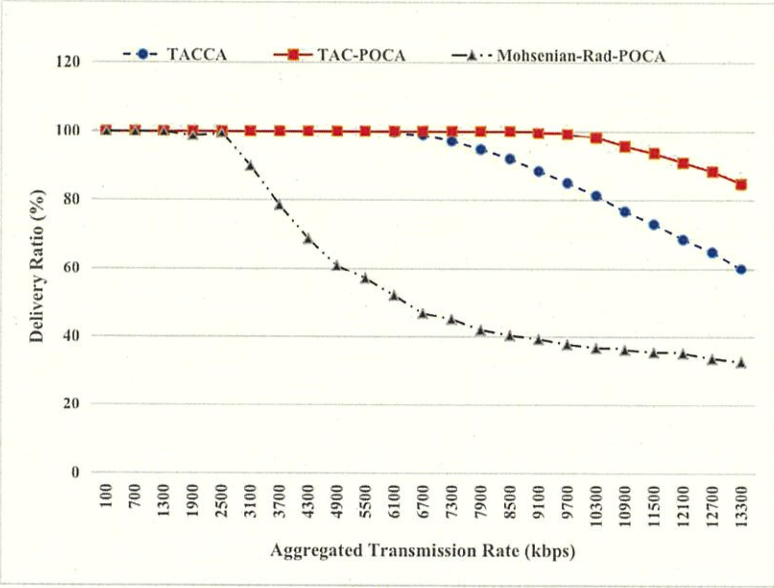


Fig. 5.10 Communication Performance Evaluation Delivery Ratio (Random Topology).

Fig. 5.11 shows the aggregated throughput of the two schemes along with the offered traffic volume as its horizontal axis. I see that all perform good when the offered load are low in both TACCA and TAC-POCA, which proves that the load balancing function well worked to enhance network capacity. Due to the efficiency in channel utilization, TAC-POCA provided extra capacity space to support larger traffic, which improved the aggregate throughput. Therefore, unexpected growth in traffic often seen in real environment is more likely to be accommodated and can be accepted by TAC-POCA. In MR-POCA, a considerable number of packets got stuck at source nodes. This is due to MR-POCA use the shortest path routing. As a result, MR-POCA outperforms TACCA and TAC-POCA in network capacity.

Fig. 5.12 shows the packet delivery delay. i see the delivery delay rapidly increases when the network saturates (i.e., when the traffic load exceeds the capacity of some links) in MR-POCA, this is because of the using shortest path routing. However, more flexible channel assignment enables TAC-POCA to choose shorter paths, leading to less delay than TACCA.

Fig. 5.13 shows the status of frame loss in MAC layer due to collision or interference. It is shown that, in MR-POCA, the loss of frames increased as the volume of traffic increases. I observes a large number of frames dropped because of exceeding the limit of retransmission

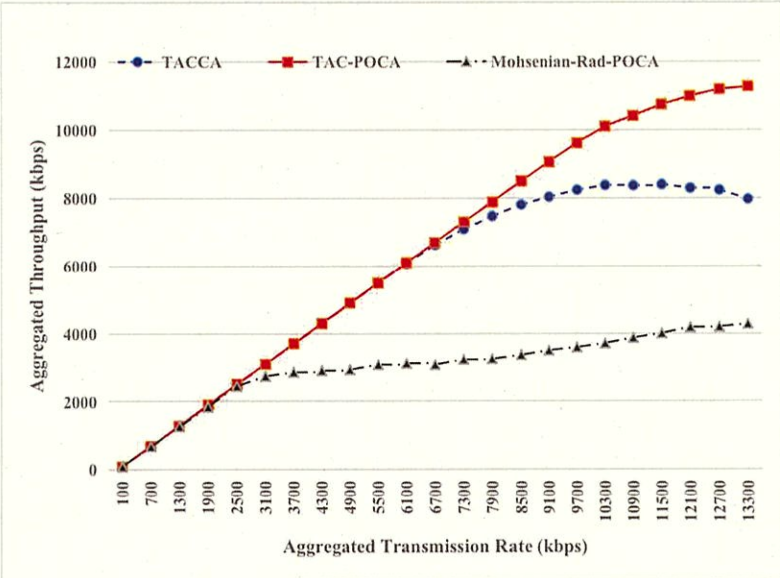


Fig. 5.11 Communication Performance Evaluation Throughput (Random Topology)

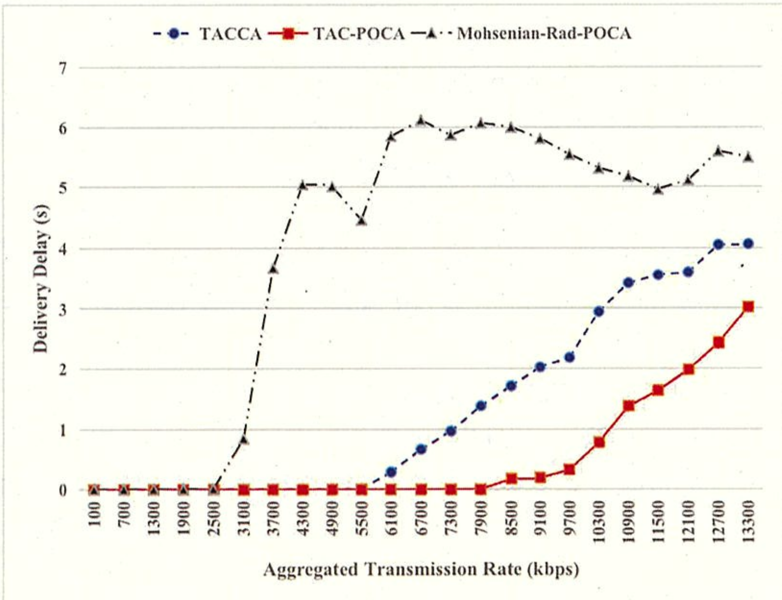


Fig. 5.12 Communication Performance Evaluation Delivery Delay (Random Topology)

counts, and most of them were due to collision of the hidden terminal problem. In contrast, I see that the number of dropped frames are very small in both TAC-POCA and TACCA.

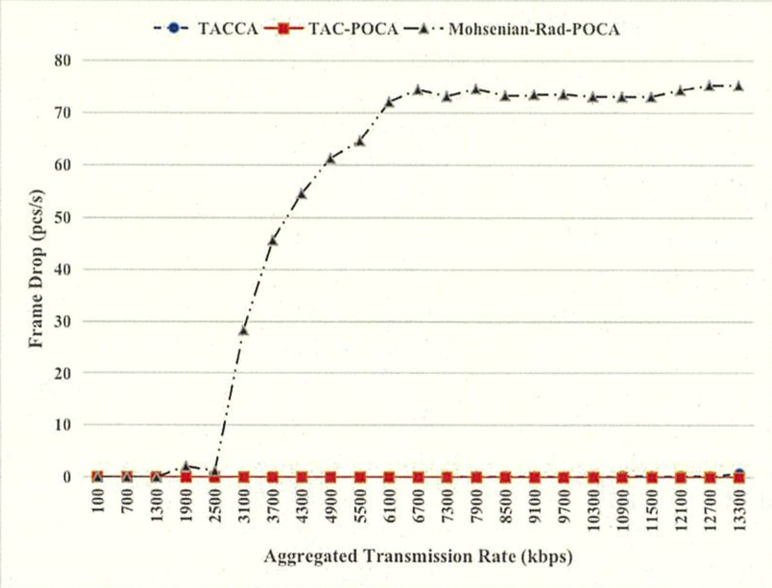


Fig. 5.13 Communication Performance Evaluation Frame Drop (Random Topology)

In general, although the performance of random scenario is a little better than grid scenario, the general trend is the same as the grid scenario. Namely, TAC-POCA has higher network capacity under the given traffic demand, and keeps almost 100% packet delivery with higher offered load than TACCA and MR-POCA. Take together, we conclude that TAC-POCA outperforms TACCA and MR-POCA in both grid and random scenarios, and it has the ability to keep the number of collisions very small with a higher offered load than TACCA.

Finally, we will discuss the value of Δ. In this study, we set a parameter value $\Delta = \varepsilon$, which means that the difference is very small between the communication range and the interference range in the protocol interference model. Generally, there is a trade-off with the value of Δ, which is caused by the difference between the protocol model and the SINR model, where SINR model is considered as the best interference model to explain reality. Here, if Δ is smaller, our optimization part will obtain better solutions because of the small interference range, while the simulation part will get lower performance because the interference range in simulation will be often larger than the values assumed in the optimization part. Conversely, if Δ is larger, the optimization part will be harder to obtain feasible solutions while simulation performance will be better. In this study, we set $\Delta = \varepsilon$ and showed that several feasible solutions are obtained in the optimization part, and simultaneously frame dropping is hardly observed in the simulation part. Since we had a very good result on packet drops, we can conclude that the value $\Delta = \varepsilon$ will be a good parameter value for our scheme with POCs.

Table 5.7 Configuration in Traffic Simulation

Items	Values
Simulator	Scenargie version 2.1
PHY and MAC Protocols	IEEE 802.11g
Propagation Model	Two ray ground
Link Capacity	6 Mbps
Transmission Power	20 dBm
Number of Interfaces	2 for each node
Number of Channels	3 for TACCA and 13 for TAC-POCA
Communication Range	530 m
Network Topology	Grid and Random
Traffic Demands	12 CBR flows (Grid)
	10 CBR flows (Random)
Payload Size	1472 bytes
Number of Nodes	25 (Grid) and 20 (Random)
Simulation Time	5000 seconds

5.5 Chapter Summary

In this chapter, by By exploiting all the channels defined in IEEE 802.11 2.4 GHz band channels, we designed a new joint channel assignment and routing scheme using POC interference models. The proposed scheme called TAC-POCA significantly improved the spatial reuse of radios, and achieved collision freedom in combination with the CSMA-aware interference model and the shared link capacity model extended for POCs. Although TACCA has already achieved a collision-free channel assignment and routing using OCs, TAC-POCA significantly improved the spatial reuse of radios and network capacity by applying POCs.

We conducted two evaluations, i.e., optimization and simulation evaluations, and showed that POCs significantly improve the spatial reuse in the context of joint channel assignment and routing. In particular, we found that the variations of distance in the random layout exploits the ability of POCs. Furthermore, we confirmed that TAC-POCA keeps a very low level of collision even in network simulations with the SINR-based interference model, and the proposed CSMA-aware interference model with POCs actually works in networks.

Chapter 6

Conclusion

6.1 Work Summary

Wireless mesh network is a communication network made up with radio nodes organized in a mesh topology. It is emerging as a promising technology for low-cost ubiquitous broadband Internet access with reduced dependency on the wired infrastructure. Collision due to radio interference is a main cause of performance degradation in wireless mesh networks, and it should be avoided in practice. With the development of advanced radio technologies, multi-radio multi-channel technology can greatly reduce the collision and enhance network performance in WMNs. In the architecture of MRMC WMNs, each router is equipped with multiple radios, and each radio can be operated on one of the several distinct channels. Compared with single-radio and single-channel case, MRMC settings significantly increase network capacity, provide flexible connectivity, and reduce interference among neighboring links. IEEE 802.11 standard is currently the most commonly used radio protocol for MRMC WMNs, and a MRMC WMN based on the IEEE 802.11 2.4 GHz standards can utilize 13 distinct channels, but these channels are partially overlapping channels rather than completely orthogonal, and only three channels out of them can be chosen as orthogonal channels . Therefore, to assign each radio on each node with an appropriate channel to maximize network performance is a great challenge. At present, there are tremendous amount of studies on channel assignment in MRMC WMNs, and routing configuration combined with channel assignment potentially reduces collisions, and it also contributes to the total network load balancing and controls. However, in the current state of the art, there is no joint channel assignment and routing scheme that achieves collision-freedom with 3-5 channels. Although Yoshihiro et al. proposed the first collision-free static channel assignment CASCA (CSMA-Aware Static Channel Assignment) for MCMR WMNs within 3-5 OCs, CASCA does not treat full-routing function so that it lacks flexibility in terms of traffic engineering, meaning that it can not cope with variation of traffic patterns, and it easily leads overload of some links under variation of input traffic demands. On other hand, POCs have not been applied to joint channel assignment and routing scheme completely, and the potential of the combination of channel assignment and routing under POC in MRMC WMNs has not been sufficiently explored.

Aiming at solving the problem stated above and improving network performance, in this thesis, joint channel assignment and routing to achieve collision-freedom is explored in MRMC WMNs. By incorporating a CSMA-aware interference model and a CSMA-shared capacity model, I formulate this problem as a MILP (Mixed Integer Linear Program), and achieve collision-free transmission under both the limited OCs and POCs in IEEE 802.11-based MRMC WMNs while considering traffic engineering. The main contributions of this thesis can be summarized in the following:

First, CASCA, which introduced CSMA-aware interference model, is analyzed in detail, and in-depth evaluation and simulation is conducted. Because the evaluation of CASCA is not enough (only optimization evaluation is done completely), whether it has good network performance or not is not clarified sufficiently. Therefore, I evaluate the performance of CASCA in both grid topology and random topology. The simulation results showed that CASCA outperforms the conventional channel assignment method CLICA (Connected Low Interference Channel Assignment), and revealed several specific properties of CASCA. However, I also see that collision-freedom does not always lead to optimal in throughput because of the trade-off between collisions reduction and capacity occupation due to longer forwarding paths.

Second, by incorporating the CSMA-aware interference model introduced in CASCA, I proposed TACCA, which is a new joint channel assignment and routing scheme that achieves collision-freedom with 3-5 orthogonal channels, which also minimizes the network-wide utility under a given traffic demand matrix. Different from CASCA, I formulated the optimization problem as MILP to introduce a traffic engineering function under the CSMA-aware link capacity sharing model, which enables capacity management in MCMR WMNs under traffic demand. Through evaluation with the MATLAB MILP solver, I confirmed that TACCA achieves collision-freedom with 3 channels in both scenarios, and has good traffic engineering performance brought from the parameter called path stretch k. Results of traffic simulations show that the schedule computed by TACCA works without major collision under the up-to-date simulation models, and TACCA clearly outperforms the conventional schemes in them. To the best of my knowledge, TACCA is the first joint channel assignment and routing scheme that enables capacity management in MCMR WMNs under collision-freedom with 3-5 orthogonal channels. Note that collision-freedom is a key issue for the reliable capacity management. I believe that TACCA would provide an important contribution toward realizing practical IEEE 802.11-based MCMR WMNs.

Third, by exploiting all the channels defined in IEEE 802.11 2.4 GHz band channels, I designed a new joint channel assignment and routing scheme using POC interference models. The proposed scheme called TAC-POCA (Traffic-Demand-Aware Collision-free Partially Overlapping Channel Assignment) significantly improved the spatial reuse of radios, and achieved collision-freedom in combination with the CSMA-aware interference model and the shared link capacity model extended for POCs. Although TACCA has already achieved a collision-free channel assignment and routing using OCs, TAC-POCA significantly improved the spatial reuse of radios and network capacity by applying POCs. I conducted two folds of evaluations, i.e., optimization and simulation evaluations. Through evaluation with the CPLEX MILP solver, I confirmed and showed that POCs improves the spatial reuse significantly in the context of joint channel assignment and routing. Especially, I found that the variation of distance in random layout exploits the ability of POCs. Furthermore, I confirmed that TAC-POCA keeps very low collision even in network simulation with SINR-based interference model, and the proposed CSMA-aware interference model with POCs actually work in networks.

6.2 Future Work

Several challenges remain for the future of MCMR WMNs. One of them is to apply improved interference models; Since TACCA's CSMA-aware interference model is based on single-disk model, the current schedule would not work efficiently with higher-speed links. Applying improved CSMA-aware interference models based on such as double-disk or SINR models would be important. On the other hand, exploring methods to coexist with other existing Wi-Fi APs and devices, or adapting to the dynamic transition of traffic demand would be other important future tasks.

One other problem found in our evaluation is the large complexity of TAC-POCA, which leads unstable (i.e., possibly less optimized) output of the optimization solver. One possible future work is to design a heuristic algorithm to obtain sub optimal solutions. Introducing SINR-based interference model to the joint routing and channel assignment schemes will be another interesting future task.

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Appendix A

List of Publications

Related International Journal Articles

1. Yi Tian and Takuya Yoshihiro, "Traffic-Demand-Aware Collision-Free Channel Assignment for Multi-Channel Multi-Radio Wireless Mesh Networks," in IEEE Access, Vol. 8, pp. 120712-120723, 2020, DOI: 10.1109/ACCESS.2020.3006275.

2. Yi Tian, Takahiro Noi, Takuya Yoshihiro, "Achieving Hidden-terminal-free Channel Assignment in IEEE802.11-based Multi-radio Multi-channel Wireless Mesh Networks," IEICE Transactions on Communications, Vol.E104-B, No.7, 2021, DOI:10.1587 /transcom.2020EBP3128.

3. Yi, Tian, and Takuya Yoshihiro. "Collision-free Channel Assignment with Overlapped Channels in Multi-Radio Multi-Channel Wireless Mesh Networks" (Under submission to IEEE Access).

Related International Conference Articles

1. Yi Tian and Takuaya Yoshihiro, "A Traffic-Demand-Aware Routing and Scheduling for CSMA-Based Wireless Mesh Networks," 2019 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom2019 Workshops), Kyoto, Japan, pp. 658-663, March 2019, DOI: 10.1109/PERCOMW.2019.8730587.

2. Yi Tian and Takuya Yoshihiro, "A Traffic-Demand-Aware Collision-free Channel Allocation for Multi-channel Wireless Mesh Networks," The Twelfth International Conference on Mobile Computing and Ubiquitous Network (ICMU2019), Kathmandu, Nepal, pp. 1-6, November 2019, DOI: 10.23919/ICMU48249.2019.9006629.