MEDIUM ACCESS CONTROL FOR INTER-GATEWAY HANDOFF SUPPORT IN MULTI-HOP WIRELESS MESH NETWORKS

by

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ABSTRACT

HAOPENG LI. Medium access control for inter-gateway handoff support in multi-hop wireless mesh networks.
(Under the direction of DR. JIANG (LINDA) XIE)

Wireless mesh networks (WMNs) have emerged to be a key wireless technology to support large-scale wireless Internet access. Seamless inter-gateway handoff support is an essential issue to ensure continuous communications in multi-hop WMNs. When the movement of a mobile mesh node (MN) causes its attachment point change in the Internet, the complete handoff process may include two steps: the link-layer handoff and the network-layer handoff. During the network-layer handoff, network-layer signaling packets need to be transmitted between the MN and the Internet via the multi-hop wireless mesh backbone. Due to the multi-hop transmission of network-layer handoff signaling packets, the handoff performance in WMNs can be largely degraded by the long queueing delay and medium access delay at each mesh router, especially when the backbone traffic volume is high. However, this critical issue is ignored in existing handoff solutions of multi-hop WMNs. In addition, the channel contention between data packets and handoff signaling packets is not considered in existing medium access control (MAC) designs.

In this research, the seamless handoff support is addressed from a different perspective. By eliminating channel contentions between data and handoff signaling packets, the queueing delay and channel access delay of signaling packets are reduced, while data throughput is maintained. Since various WMNs have different channel resources and hardware cost requirements, four MAC schemes are proposed to improve the multi-hop handoff performance in single-channel single-radio, single-channel multi-radio, multi-channel single-radio, and multi-channel multi-radio WMNs. With the proposed MAC schemes, the inter-gateway handoff performance can be improved significantly in multi-hop WMNs.

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LIST OF ABBREVIATIONS

ConT	Contention-based Time Division
ChaS	Channel Splitting
GaS	Gateway Scheduling-based
HiCA	Hierarchical Channel Allocation
MAC	Medium Access Control
ETE	End-To-End
ACU	Average Channel Utilization
SCT	Separate Channel Transmission
CCT	Combined Channel Transmission
DD	Directional-Directional
OO	Omnidirectional-Omnidirectional
MN	Mobile Mesh Nodes
MR	Mesh Router
BMR	Border Mesh Router
CH	Cluster Head
GW	Gateway
AP	Access Point
CN	Correspondent Node
VoIP	Voice-over-IP
IETF	Internet Engineering Task Force
CoA	Care-of Address
HA	Home Agent
FA	Foreign Agent
WLAN	Wireless Local Area Network
WMN	Wireless Mesh Network
RSS	Received Signaling Strength

DRP	Double Reservation Period
SRP	Signaling Reservation Period
FRP	Free Contention Period
STP	Signaling Transmission Period
RTS	Request-To-Send
CTS	Clear-To-Send
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
ACL	Available Channel List
CST	Channel State Table
SST	Signaling Schedule Table
TDMA	Time Division Multiple Access
FDMA	Frequency Division Multiple Access
DCC	Dedicated Control Channel

CHAPTER 1: INTRODUCTION

Wireless mesh networks (WMNs) have emerged to be a key wireless technology to support ubiquitous coverage of wireless Internet access [1, 2, 3]. The basic characteristic of WMNs is the capability of self-forming, self-healing, and self-organization, so nodes deployed in the network can automatically establish and maintain wireless mesh connectivity among themselves. Nowadays, a large variety of applications of WMNs have been implemented in personal, local, campus, and metropolitan areas, such as broadband Internet access, enterprise networking, building automation, and intelligent transportation systems.

1.1 Introduction to Wireless Mesh Networks

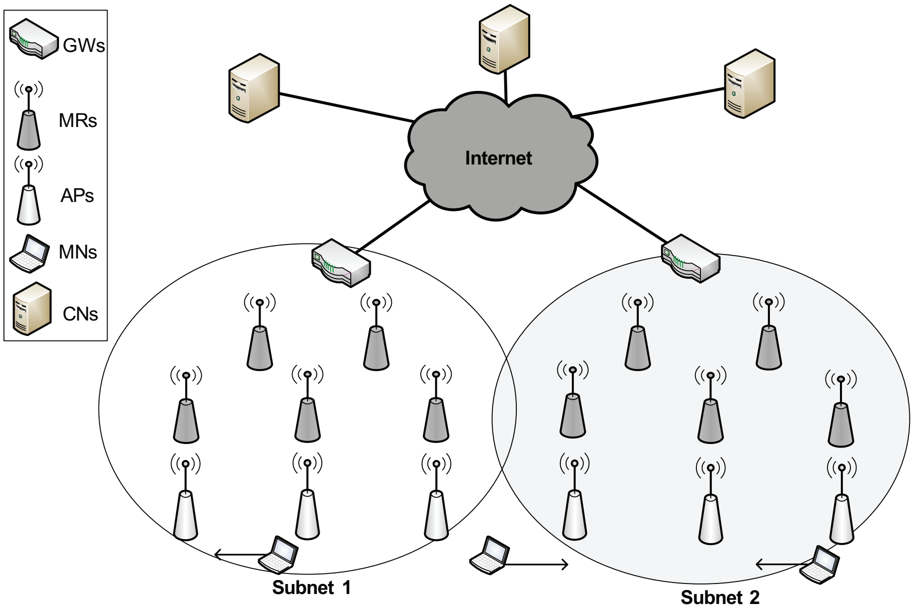


Figure 1.1: Architecture of infrastructure wireless mesh networks.

As shown in Figure 1.1, an infrastructure WMN is composed of a combination of static mesh routers (MRs) and mobile mesh nodes (MNs). In a typical WMN, MRs form a multi-hop wireless backbone network. Data packets can be forwarded among MRs deployed in the WMN via the multi-hop wireless mesh backbone without the assistance of wired connections. In order to provide wireless Internet service to MNs, some MRs serve as the wireless access points (APs) to offer wireless mesh backbone entries to MNs. Some MRs, called gateway MRs (GW), are connected to the Internet via wired links and serve as the Internet entry points to other MRs via multi-hop wireless links. MNs can move freely in WMNs when communicating with correspondent nodes (CNs) located in the Internet by means of handoffs between different APs.

Fast handoff support is a basic requirement for an Internet-based WMN. It aims to provide MNs with continuous connections to the Internet, regardless of their physical locations or moving trajectory. When the movement of an MN causes its attachment point change in the Internet, i.e., the MN accesses the Internet via a different gateway, the complete handoff process may include two steps: the link-layer handoff (which takes care of the switch of the communication channel) and the network-layer handoff (which takes care of the change of the IP address and/or routing path). During the handoff process, due to the attachment point change of MNs, data packets sent from CNs in the Internet may not be successfully received by MNs within a short time, which will significantly degrade the quality of end-to-end (ETE) service between MNs and CNs, especially for those delay-sensitive applications, such as video conference, Voice-over-IP (VoIP), and online games. In addition, long handoff delay may also lead to a considerable packet loss in the multi-hop wireless mesh backbone. Therefore, exploring effective handoff schemes is particularly necessary in multi-hop WMNs.

1.2 Handoff Management in Wireless Networks

1.2.1 Handoff Management in Mobile Internet

In order to provide handoff support in the Internet, Mobile IP [4] has been proposed by Internet Engineering Task Force (IETF) as a network-layer handoff solution in the Internet which allows MNs to move from one subnet to another without losing connectivity to CNs.

In Mobile IP, an MN has two addresses: a permanent home address and a care-of address (CoA) which are related to its home network and the current foreign network it is visiting, respectively. The home address never changes during the movement of an MN. However, the CoA changes each time when the MN moves to a new subnet. The home agent (HA) is located in the home network and always keeps the up-to-date locations of MNs. The foreign agent (FA) located in each subnet maintains the location information about MNs visiting its network and provides CoAs to MNs. Since an MN always uses its permanent home address to interact with CNs, data packets destined to an MN are firstly intercepted by its HA which then redirects them towards the CoA of the MN by encapsulating the original packets with a new IP header using the CoA of the MN. Hence, when an MN roams from one foreign network to another, it only needs to notify its new CoA to the HA during the handoff process. On the other hand, when acting as a sender, the MN directly sends packets to its CN without following the same path as the packets from the CN to the MN. The routing process is known as triangular routing, as explained in Figure 1.2.

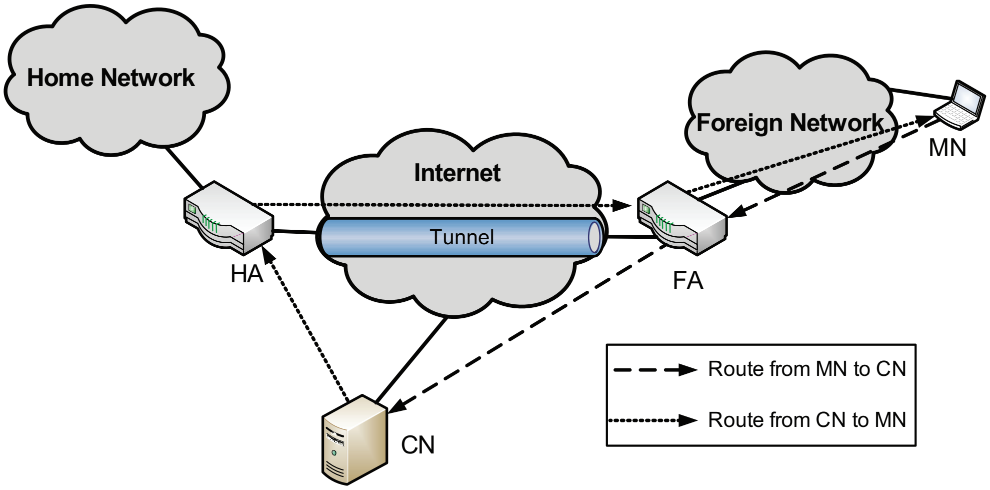


Figure 1.2: Triangular routing in Mobile IP.

The handoff process is triggered when an MN moves out of its previous subnet and enters a new subnet with a different network prefix. The *Agent Advertisement* message is periodically broadcasted by an FA to advertise its service on a wireless link. By receiving the *Agent Advertisement* message, an MN can obtain a new CoA of the new subnet from the FA. On the other hand, an MN may also actively solicit an *Agent Advertisement* message from the FA through an *Agent Solicitation* message to speed up this process. In order to maintain the connectivity with its CN, the MN should notify its HA about its latest location in the foreign network. Mobile IP defines that the MN needs to send a *Registration Request* message to its HA containing its new CoA. If the HA is willing to accept the MN's new CoA registration, it sends back a *Registration Reply* to the MN. Then, the HA redirects packets to the new CoA of the MN. However, the CN still sends packets to MN's permanent home address without knowing that the MN has moved to a new subnet. The Internet-based handoff process defined in Mobile IP is explained in Figure 1.3.

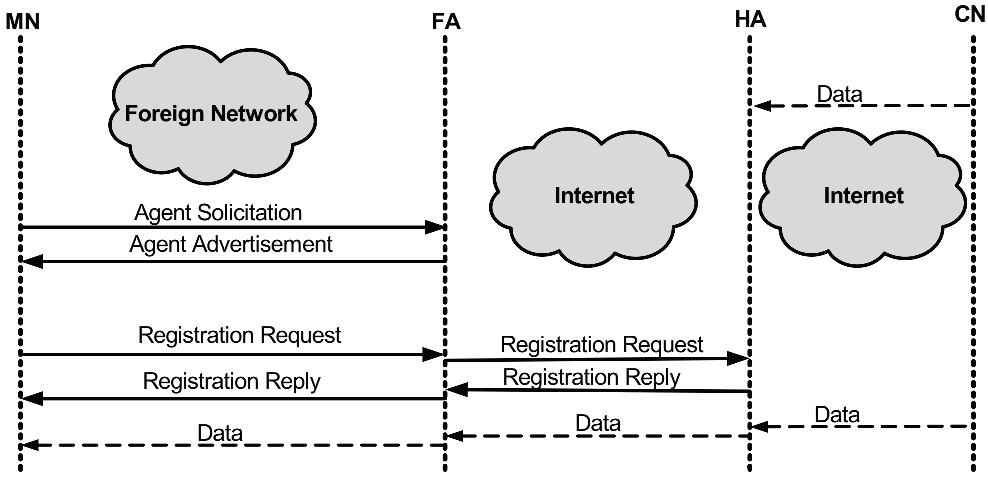


Figure 1.3: Handoff procedures in Mobile IP.

In conclusion, Mobile IP allows mobile users to move among different subnets without losing connectivity with the Internet. Since the HA needs to maintain the up-to-date locations of MNs, some handoff signaling packets, such as *Registration Request* and *Registration Reply*, are exchanged via wired links between the FA and the HA.

1.2.2 Handoff Management in Wireless Local Area Networks

Wireless local area networks (WLANs) have been widely deployed in recent years. Due to the growing popularity of WLANs, the IEEE 802.11 specification [5] provides a link-layer handoff solution to maintain the connectivity between roaming MNs and APs. In IEEE 802.11-based WLANs, a link-layer handoff occurs when an MN moves out of the transmission range of its old AP, and enters the transmission range of other APs. Figure 1.4 shows the scenario when an MN handoffs from AP1 to AP2 which are deployed in the same subnet. Since the link-layer handoff does not cause the IP address change of the MN in the Internet, the routing path from the CN to the MN in the Internet remains the same before and after the link-layer handoff.

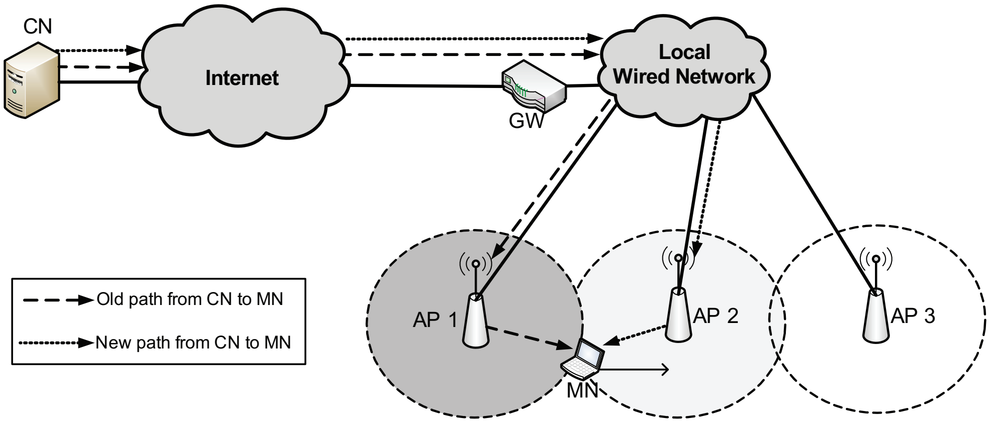


Figure 1.4: A handoff in WLANs.

The link-layer handoff procedures defined in IEEE 802.11 are summarized in Figure 1.5. When an MN moves out of the transmission range of its old AP, the weak received signal strength and the low signal-to-noise ratio cause it to loose connectivity from the old AP. Then, the link-layer handoff process is initiated. As defined in the IEEE 802.11 specification, the MN may either actively broadcast a *Probe Request* message on a wireless access channel (active mode) or passively listen to beacon messages from potential APs on that channel (passive mode). Meanwhile, it starts the *ProbeTimer* to control the waiting time on that channel. In the active mode, when an AP operating on the access channel receives the message, it replies a *Probe*

Response message to the MN. When the *ProbeTimer* expires, the MN proceeds to probe the next access channel. After probing all available channels, the MN creates a list of APs prioritized by the received signal strength and determines the new AP it is going to handoff. Then, the MN switches to the new AP's access channel and sends an *Authentication Request* message to the new AP requesting for connection. After receiving the *Authentication Request* message, the new AP replies an *Authentication Response* message to the MN. If the connection request is approved by the new AP, the MN sends a *Reassociation Request* message to the new AP and then receives a *Reassociation Reply* message from the new AP to complete the link-layer handoff.

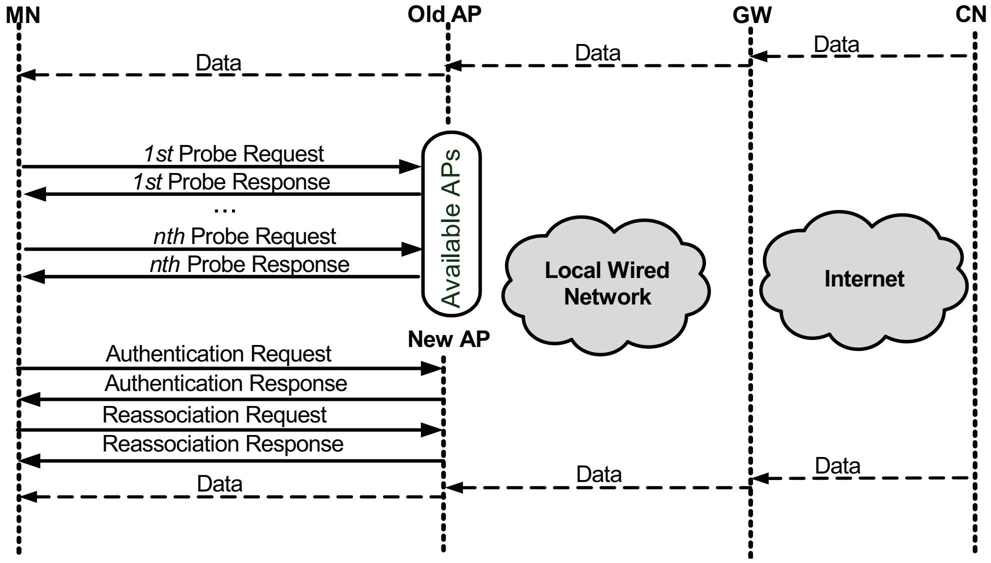


Figure 1.5: Handoff procedures in WLANs.

1.2.3 Inter-gateway Handoff Management in Wireless Mesh Networks

As discussed before, Mobile IP provides a network-layer handoff solution for the Internet-based handoff. However, the link-layer handoff procedures are not defined in Mobile IP. On the other hand, the IEEE 802.11-based handoff solution assumes that an MN's IP address remains the same when it changes its attachment point in the Internet, so the network-layer handoff is not needed during the WLAN handoff process. Different from Mobile IP and WLAN-based handoffs, both the link-layer and network-layer handoff procedures are required to maintain the connectivity between MNs and CNs during the inter-gateway handoff process in WMNs.

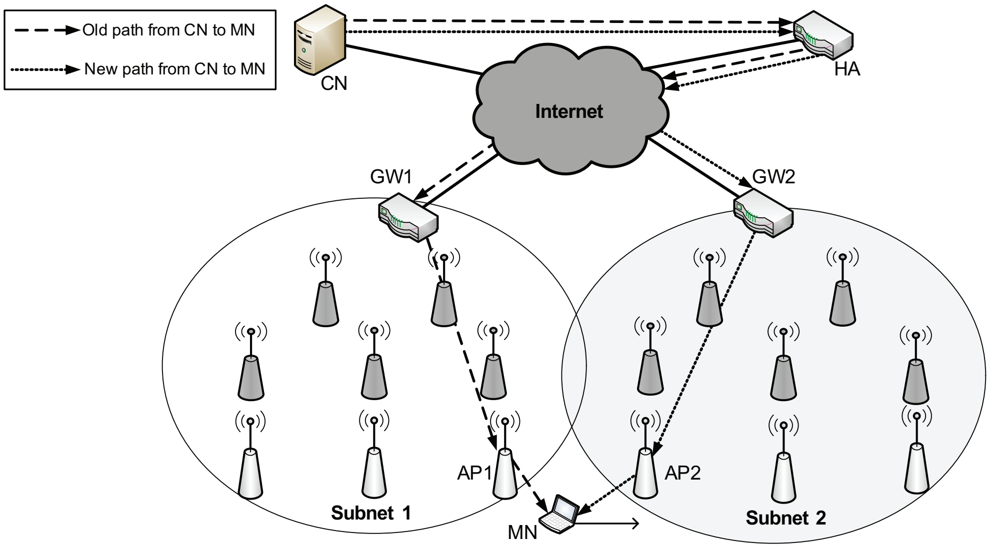


Figure 1.6: An inter-gateway handoff in wireless mesh networks.

Assume that each subnet deployed in the wireless mesh backbone has a gateway as its Internet portal, as shown in Figure 1.6. Initially, an MN receives data traffic from the CN via the multi-hop wireless mesh backbone of subnet 1 during its movement. When the MN moves out of the transmission range of AP1 and enters the transmission range of AP2 which is deployed in subnet 2, it needs to initiate the inter-gateway handoff in WMNs to keep the connectivity with the CN. Since both the wireless link and IP address of the MN need to be changed, the inter-gateway handoff includes both the link-layer and network-layer handoffs. During the link-layer handoff process, the MN executes the channel scanning, authentication, and reassociation procedures to connect to the new AP with the best received signaling strength (RSS). During the network-layer handoff process, the MN first gets a new IP address from the new AP. Then, it finds a new route to the new gateway. Finally, it registers the new IP address with its HA according to Mobile IP.

Figure 1.7 summarizes the link-layer and network-layer handoff procedures in IEEE 802.11-based WMNs by extending the Mobile IP scheme to multi-hop wireless networks.

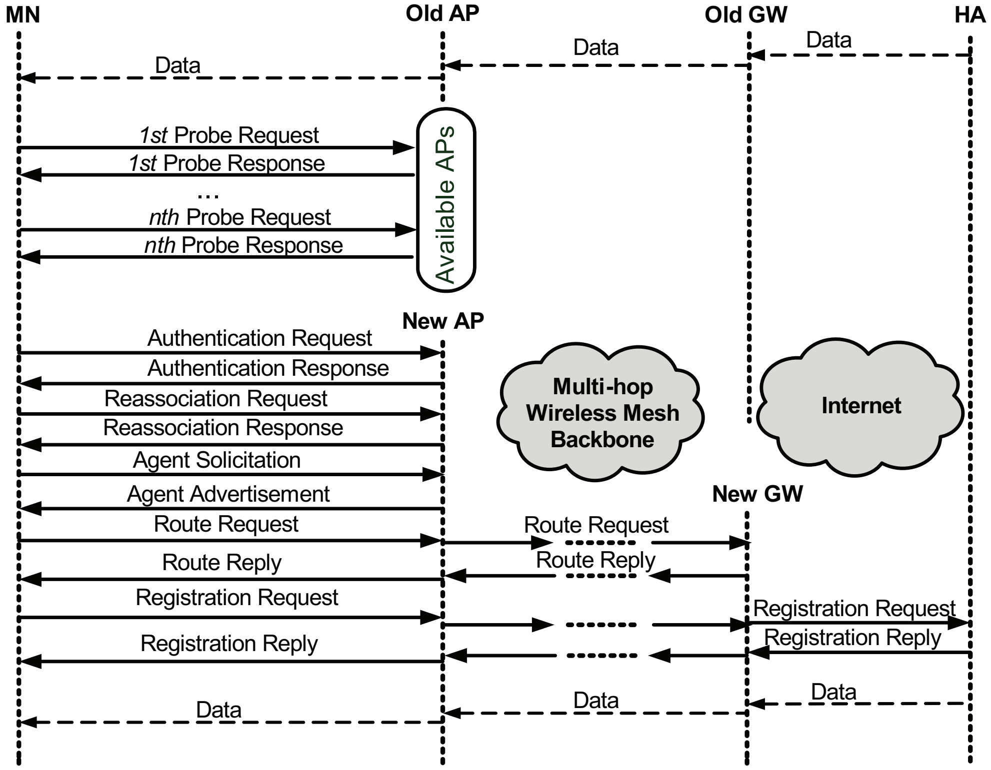


Figure 1.7: Inter-gateway handoff procedures in wireless mesh networks.

When an MN detects that the RSS from the current AP is below a certain threshold, the channel scanning process of finding a new AP begins. In order to find a new AP, the MN switches its radio to one of the access channels and broadcasts a *Probe Request* message. Meanwhile, it starts the *ProbeTimer* to control the waiting time on that channel. When an AP operating on the access channel receives the *Probe Request* message, it replies a *Probe Response* message to the MN. When the *ProbeTimer* expires, the MN proceeds to scan the next access channel. Having finished scanning all channels, the MN processes all the received *Probe Response* messages and determines the AP with the best RSS value as its new AP. Then, the MN switches to the new AP's access channel and sends an *Authentication Request* message to the new AP requesting for connection. After receiving the *Authentication Request* message, the new AP replies an *Authentication Response* message to the MN. If the connectivity request is approved by the new AP, the MN sends a *Reassociation Request* message to the new AP and then receives a *Reassociation Reply* message from the new AP to complete the link-layer handoff. Since the MN has moved to a new subnet, a network-layer handoff is also needed to update the new CoA and/or the routing path between the new gateway and the MN. To initiate the network-layer handoff, the MN first obtains a new IP address either from the new AP or the new gateway. Figure 1.7 shows the case that the MN obtains a new CoA from the new AP by exchanging *Agent Solicitation* and *Agent Advertisement* messages with its new AP. Then, the MN needs to establish a route to the new gateway by exchanging *Route Request* and *Route Reply* messages with its new gateway. After establishing the route to the new gateway, the MN sends a *Registration Request* message to its home agent (HA) in the Internet for CoA update. The HA updates the new CoA of the MN in its database and sends a *Registration Reply* message to the MN. The whole handoff process is finished when the MN receives data packets from the new AP via the new gateway.

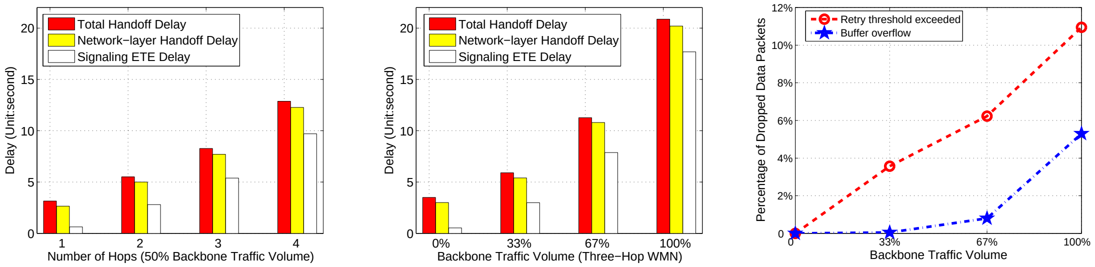
In conclusion, as shown in Figure 1.7, during the entire inter-gateway handoff process in WMNs, several network-layer signaling packets, such as *Route Request/Response* and *Registration Request/Reply*, need to be exchanged between the MN and the GW/HA via multi-hop transmissions, which may potentially compete with the data packets generated by backbone MRs to access the channel resource in the multi-hop wireless mesh backbone.

1.3 Research Motivation

Fast handoff support in WMNs has been investigated in existing papers which mainly focus on shortening the link-layer channel scanning delay, optimizing the WMN architecture for better handoff support, and improving multi-hop routing in the wireless mesh backbone. To some extent, these handoff solutions can alleviate the long handoff delay problem in WMNs under certain scenarios, e.g. the number of wireless hops from the AP of an MN to the GW is small or the backbone data traffic volume is low. Unfortunately, the essence of causing the long handoff delay in multi-hop WMNs has not been captured by these existing handoff solutions under which the handoff delay may still increase substantially as the growing number of wireless hops or the increasing volume of the backbone data traffic. To fill this gap, this research considers to reduce the multi-hop handoff delay in WMNs from a more ambitious and creative perspective and focus on exploring efficient medium access control (MAC) for facilitating fast handoff support to MNs.

During the network-layer handoff process in WMNs, network-layer signaling packets, such as *Route Request/Response* and *Registration Request/Reply*, need to be transmitted between the MN and the Internet via the multi-hop wireless mesh backbone. If the network-layer signaling packet ETE delay is short enough, the movement of MNs can be transparent to applications. However, the existence of multi-hop wireless links in the mesh backbone network can degrade the throughput significantly due to the delay of channel access over multi-hop links [6, 7], which results in very long inter-gateway handoff delay in multi-hop WMNs. As shown in Figure 1.8(a) and 1.8(b), OPNET [8] simulation results also indicate that the inter-gateway handoff performance in WMNs can be largely degraded, especially when the number of wireless hops connecting the MN and the Internet grows or the backbone traffic volume increases. In particular, the upsurge of the network-layer handoff delay is fueled by the soar of signaling packet ETE delay, which can account for up to 80% of the total inter-gateway handoff delay. Hence, the multi-hop ETE delay of signaling packets is a main component of the long inter-gateway handoff delay in Internet-based WMNs, especially when the backbone traffic volume is high, as shown in Figure 1.8(b).

In addition, in a multi-hop WMN, as can be seen in Figure 1.8(b), MNs may suffer a long inter-gateway handoff delay when a high traffic volume exists in the wireless mesh backbone. In Figure 1.8(b), the signaling ETE delay is composed of signaling queueing delay and channel access delay. If a First-In-First-Out (FIFO) queue is



(a) Delay vs. number of hops (b) Delay vs. data traffic volume (c) Percentage of dropped packets

Figure 1.8: Handoff delay in 802.11-based WMNs.

used at each MR, a handoff signaling packet may experience very long queueing delay when the data traffic volume at each MR is high, because it has to wait in the queue until the data packets which arrived earlier are successfully transmitted. Even if signaling packets were given a higher transmission priority at each MR, MRs in charge of forwarding these signaling packets would still need to compete with other MRs to access the same channel resource. Since the growing data traffic volume may also increase the number of MRs competing the limited channel resource, the channel access delay of handoff signaling packets can be lengthened significantly at each MR along the established route from the handoff MN to its new GW. Even worse, as shown in Figure 1.8(c), some packets, including handoff signaling packets, may be dropped by MRs due to buffer overflow or retry threshold exceed, leading to the failure of handoffs.

To sum up, due to the competition for accessing the channel resource among several MRs in the wireless mesh backbone, the handoff performance can be largely degraded by the long queuing delay and channel access delay of handoff signaling packets at each MR. Therefore, the medium access control (MAC) design for both data and handoff signaling packet transmissions in the wireless mesh backbone is crucial to the inter-gateway handoff performance in WMNs.

1.4 Overview of Proposed Research

In this research, the seamless WMN handoff support is considered from a different prospective which focuses on reducing the long queueing delay and channel access delay of handoff signaling packets on the multi-hop wireless mesh backbone. Since various WMNs may have different channel resources and hardware cost requirements, four MAC schemes are proposed to improve the multi-hop handoff performance in single-channel single-radio, single-channel multi-radio, multi-channel single-radio, and multi-channel multi-radio WMNs. An overview of the proposed designs is shown in Figure 1.9.

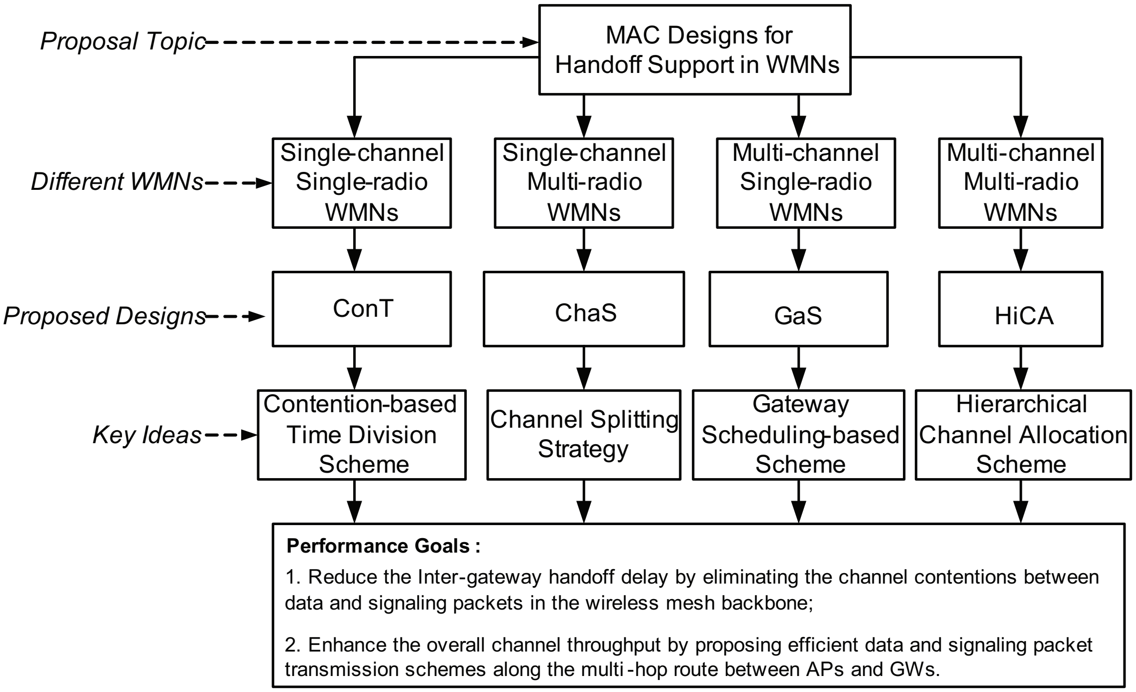


Figure 1.9: Overview of the proposed research.

1.5 Dissertation Organization

The rest of the dissertation is organized as follows. In Chapter 2, related work on handoff solutions and MAC designs in wireless networks are surveyed. In Chapter 3, a contention-based time division (ConT) scheme is proposed in single-radio single-channel WMNs. In Chapter 4, a channel splitting (ChaS) strategy is introduced in multi-radio single-channel WMNs. In Chapter 5, a gateway-based scheduling (GaS) scheme is proposed in single-radio multi-channel WMNs. In Chapter 6, a hierarchical channel allocation (HiCA) scheme is proposed in multi-radio multi-channel WMNs. In Chapter 7, this dissertation is concluded and future works are considered.

CHAPTER 2: RELATED WORK

Seamless handoff support is an essential issue to ensure continuous communication in single/multi-hop wireless networks for mobile users. However, the channel resource contentions existing in the wireless mesh backbone of WMNs may lead to very long queueing delay and channel access delay of handoff signaling packets, especially when the data traffic volume is high. Although a large amount of handoff and MAC solutions have been proposed in the literature, the channel contention issue between signaling and data packets are ignored in existing works.

2.1 Existing Handoff Solutions

Various solutions on WMN handoff management have been proposed to optimize the handoff process in order to shorten the handoff latency [9]. [10] points out that the channel scanning delay accounts for more than 90% of the overall link-layer handoff delay in IEEE 802.11-based wireless networks. Hence, different link-layer handoff schemes [11, 12, 13, 14, 15, 16, 17] are proposed on improving the channel scanning process to reduce the link-layer handoff delay. In order to reduce the network-layer handoff delay, [18, 19, 20] take advantage of the hierarchical network topology to facilitate the handoff process. [21, 22, 23] exploit the two-channel transmission technology to schedule the transmission of signaling and data packets using multiple radios; [24, 25, 26, 27] propose new network infrastructures to facilitate the overall handoff process; [28] introduces the concept of temporary IP addresses to shorten the delay of applying a new CoA; [29, 30] provide solutions to reduce the route discovery delay in the network-layer handoff process; and [31, 32] presents mobility management schemes to shorten the handoff delay by reducing the signaling cost. In addition, [33] takes advantage of the priority-queue solution to improve the performance of delay-sensitive applications. However, the channel contention issue between signaling and data packets, which essentially results in long multi-hop handoff delay, are ignored in all existing handoff schemes [9].

The IEEE 802.11e standard [34] provides quality of service (QoS) based solutions to different types of applications. However, the short channel access delay of delay-sensitive applications is realized at the expense of the undermined performance of applications with low transmission priority. Furthermore, when the backbone traffic load is very high, IEEE 802.11e is not able to guarantee the real-time transmission of delay-sensitive packets, because high data traffic volume significantly increases the packet queueing delay at each MR.

To sum up, existing WMN handoff schemes do not consider resolving the wireless channel access contentions between handoff signaling packets and data packets during a handoff process. Since the network-layer handoff process generates network-layer handoff signaling traffic that needs to be delivered over the multi-hop wireless mesh backbone, the handoff delay is affected by the volume of the data traffic competing the wireless channels with the handoff signaling traffic in the wireless mesh backbone. When the backbone data traffic volume is heavy, the overall handoff delay could be very long due to the long queuing delay and channel access delay of handoff signaling packets. Therefore, efficient MAC schemes, including channel resource allocation, packet transmission scheduling, and mobility management, are required in WMNs in order to address this issue.

2.2 Existing WMN MAC Solutions

There are many existing MAC solutions for single-channel-based wireless networks. The IEEE 802.11 specification [5] defines a carrier sense multiple access with collision avoidance (CSMA/CA) scheme as the wireless transmission standard in single-channel-based WLANs. [35, 36] propose contention-free MAC solutions which focus on allocating the wireless channel to a set of non-interfering transmission pairs in the network to maximize the data throughput. However, the delay-sensitive feature of the handoff signaling packets is still ignored by these works.

On the other hand, various multi-channel MAC schemes for WMNs have been proposed in the literature. They can be classified into two categories: single and multiple rendezvous approaches.

The single rendezvous approaches include dedicated control channel (DCC) approach [37, 38, 39, 40], split phase approach [41, 42], and common hopping approach [43, 44]. The MAC schemes for data packet transmissions are well designed in these works. [37, 38, 39, 40] propose to utilize a dedicated control channel to reserve other data channels dynamically for data transmissions so that the channel reservation and data transmission can be carried out separately and simultaneously. [41, 42] propose a time division multiple access (TDMA) based channel allocation scheme in which the channel reservation and data transmission can be finished in an alternating sequence of control and data phases. [43, 44] propose to make use of common channel hopping to avoid collisions so that a pair of devices can stop hopping and remain on the same channel to transmit data packets after making an agreement.

However, due to the multi-hop transmission of handoff signaling packets which are much shorter than data packets but require very short ETE delay, the single rendezvous approaches are questionable. First, [43, 44] suffers a channel switching delay at the beginning of every time slot, so the channel utilization and packet ETE delay largely depend on the hardware performance [45]. In addition, the control channel defined in DCC-based approaches [37, 38, 39, 40] is dedicated for the transmission of request-to-send (RTS) and clear-to-send (CTS) for reserving data channels, as shown in Figure 2.1. Similarly, the control phase defined in split phase approaches [41, 42] is also only dedicated for exchanging RTS/CTS packets. However, how to transmit handoff signaling packets in these approaches in an efficient way is still an open issue. Even if the signaling packets can be transmitted in either the control channel/phase or data channels/phase, the channel contention problem between signaling packets and data packets is still a serious issue in existing multi-channel MAC schemes. Take the DCC-based channel allocation scheme as an example. As shown in Figure 2.2 and 2.3, no matter which channel is used for signaling transmissions, the channel contention between data and signaling packets always exists, resulting in the under utilization of data channels, especially when signaling packets are transmitted in the control channel.

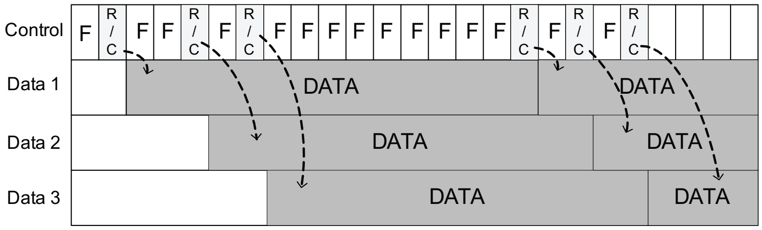


Figure 2.1: No signaling transmission.

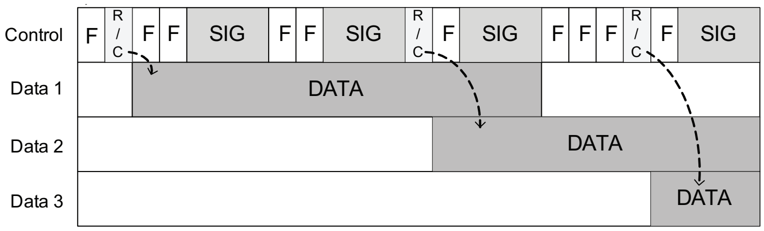


Figure 2.2: Signaling in the control channel.

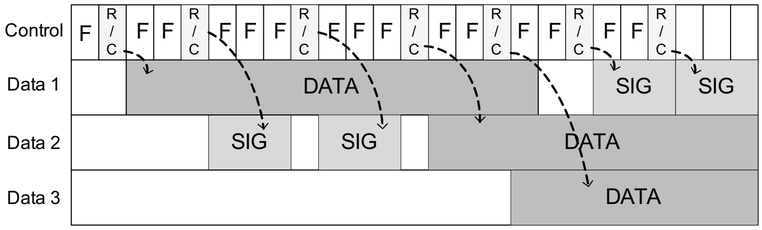


Figure 2.3: Signaling in data channels.

Although multiple rendezvous approaches [46, 47] can achieve high data throughput by distributing parallel data packet transmissions on multiple channels simultaneously, they are still not appropriate for the delay-sensitive signaling packet transmissions over multi-hop wireless links. Take the MAC scheme proposed in [46] as an example. As shown in Figure 2.4, a handoff signaling packet needs to be delivered through a newly established route (MR A → MR B → MR C) and the channel hopping sequence of the MRs are listed in Figure 2.4. Assume that time is slotted and starts from the first slot shown in Figure 2.4. It takes at least 2 slots for MR A and MR B to rendezvous on the same channel (Channel 2) and another 3 slots for MR B and MR C to hop on the same channel (Channel 0). Hence, the signaling ETE delay from MR A to MR C is at least 5 slots, even if the signaling packet is assigned with a higher transmission priority. In addition, multiple rendezvous approaches usually require the length of a time slot long enough for dozens of data packet transmissions to guarantee the data throughput. However, handoff signaling packets are usually much shorter than data packets. As a result, the signaling ETE delay is considerable and this delay will be further prolonged when the number of rendezvous channels is large. Similarly, although the MAC scheme proposed in [47] defines that a source MR can temporarily follow its destination MR's hopping sequence to initiate a packet transmission, the destination MR is not guaranteed to always stay on its original sequence and wait to receive from the source MR. For example, as shown in Figure 2.4, assume that MR A temporarily follows MR B's sequence in order to transmit a signaling packet to MR B. However, MR B may already follow another MR's hopping sequence to initiate its own data transmissions. If MR B has many data packets destined to other MRs, MR A may wait for a long time to be able to transmit out the signaling packet.

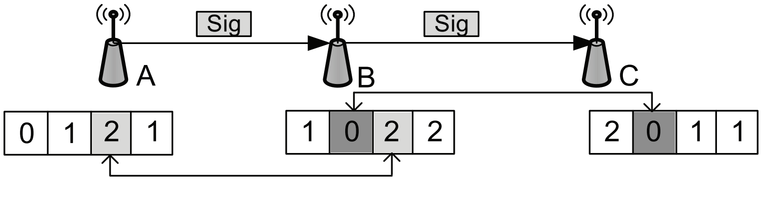


Figure 2.4: Signaling transmissions using multiple rendezvous approaches.

Therefore, since the channel resource competition between signaling packets and data packets always exists in existing single-channel and multi-channel MAC schemes, long handoff delay and low channel utilization may occur if existing MAC solutions are directly applied to handoff scenarios in WMNs.

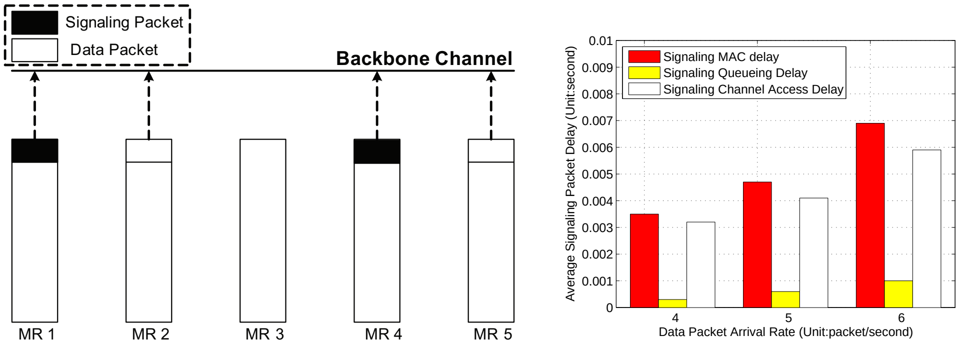
2.3 Summary

In conclusion, neither the existing handoff solutions nor MAC schemes can solve the long handoff delay problem in WMNs which mainly derives from the channel resource contentions between signaling and data packets in the wireless mesh backbone. To achieve a significant breakthrough on the WMN handoff delay reduction, in this research, four different MAC schemes are proposed to provide seamless handoff support by eliminating channel resource contentions between handoff signaling and data packets in Internet-based Infrastructure WMNs with different hardware and channel resources.

CHAPTER 3: CONT: CONTENTION-BASED TIME DIVISION SCHEME

In single-radio single-channel WMNs, all backbone MRs are only configured with one wireless radio operating on the same backbone channel. When multiple MRs in an interference area have data/signaling packets to transmit at the same time, they need to access the same backbone channel via contentions before the transmission. Only one transmission on the backbone channel can be initiated within an interference area at any time. Therefore, the limited hardware and channel resource of single-radio single-channel WMNs inherently prolongs the MAC delay of handoff signaling packets at each MR, including the channel access delay and queueing delay.

In this chapter, a contention-based time division (ConT) scheme is proposed to reduce the MAC delay of handoff signaling packets at each MR for guaranteed handoff performance. Though the proposed ConT scheme focuses on providing a MAC solution for handoff support in WMNs, it is different from the existing collision-free MAC schemes [35, 36] which concentrate on scheduling simultaneous transmission pairs in each transmission slots and the IEEE 802.11e standard [34] which provides QoS solutions by assigning applications with different channel access priorities. In particular, the contributions of this work lie in the following points: (1) we propose a ConT scheme to improve the handoff performance in single-radio single-channel WMNs; (2) we estimate the optimal ratio of the data period length to signaling period length to balance the tradeoff between the handoff delay and channel utilization; and (3) we evaluate the performance of the proposed ConT scheme using OPNET simulations.



(a) Low data traffic volume (b) Result

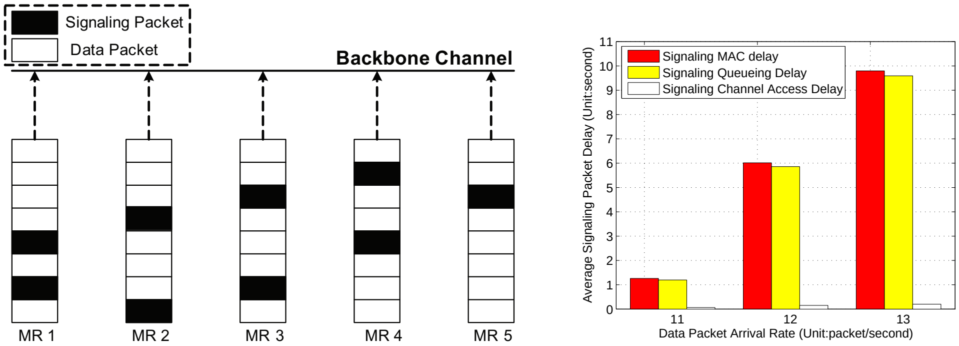
Figure 3.1: Low data traffic volume scenario

3.1 Problem Description

In 802.11-based single-channel single-radio WMNs, data and signaling packets are transmitted on the same backbone channel. The signaling queueing delay and channel access delay may vary as the backbone traffic volume changes.

3.1.1 Channel Access Delay

The channel access delay of each packet is defined as the interval from the moment when a packet arrives at the head of the queue to the moment when the MR successfully transmits out the packet to its next hop neighbor. When the backbone data traffic volume is low, a packet can be transmitted without waiting a long time in the queue. As a result, the channel access delay is the main component of the overall MAC delay under such scenarios. As shown in Figure 3.1(a), there are five routers share the same backbone channel and their transmissions influence each other. Since the data packet arrival rate is low, a signaling packet experiences very low or zero queueing delay. Under such situations, the channel access delay is the dominant delay of the overall MAC delay. The simulation result shown in Figure 3.1(b) also confirms that the channel access delay accounts for more than 90% of the total MAC delay when the data packet arrival rate is low at each MR.



(a) High data traffic volume (b) Result

Figure 3.2: High data traffic volume scenario

3.1.2 Queueing Delay

The queueing delay of each packet is defined as the interval from the moment when a packet is generated at the MAC layer to the moment when it arrives at the head of the queue. As shown in Figure 3.2(a), the high data packet arrival rate leads to a very long packet queue at each MR. Under such scenarios, signaling packets often suffer long queueing delay before they can reach the head of the queue. This will result in a significantly long MAC delay, as shown in Figure 3.2(b). When the data packet arrival rate is high at each MR, the queueing delay becomes the dominant delay of the total MAC delay and consequently, the MNs' handoff delay can be very long.

3.1.3 Summary

As discussed above, the backbone data traffic volume has a great impact on the signaling MAC delay at each MR. Therefore, when the data traffic congestion occurs at backbone MRs, the MNs' handoff performance will be largely undermined by the long signaling MAC delay. Considering this point, the motivation of this work is to reduce the signaling MAC delay at each MR which includes the channel access delay and queueing delay. Specifically, our proposed ConT scheme emphasizes on reducing the long queueing delay when the backbone data traffic volume is very high.

3.2 Proposed ConT Scheme

Different from existing time division multiple access (TDMA) designs which focus on scheduling multiple packet transmissions in the same transmission slot to maximize the channel utilization, our proposed ConT scheme emphasizes on reducing the signaling MAC delay without undermining the channel utilization, especially when the backbone traffic volume is very high. In the proposed ConT scheme, time is divided into slots and each slot contains a data period and a signaling period. Data packets and signaling packets can be transmitted only in the data period and signaling period, respectively. Although existing multi-channel TDMA-based MAC solutions [41] also define a control phase and a data phase to utilize multiple channels efficiently, the control phase defined in these works is dedicated for exchanging request-to-send (RTS) and clear-to-send (CTS) packets to determine the transmission pairs in the next data phase. The delay-sensitive feature of handoff signaling packets is ignored in these solutions. In addition, since we focus on designing a MAC scheme based on a single backbone channel, the channel switching delay in time-slotted multi-channel MAC schemes [43] does not exist in our proposed ConT scheme.

Time synchronization is required for all MRs deployed in the same network. Thus, MRs can transmit different types of packets according to different time periods. In order to realize separate transmissions in the time domain, two queues, signaling and data packet queues, are maintained by each backbone MRs in our proposed ConT scheme. When signaling and data packets are generated in the MAC layer, they are placed in the corresponding queue.

As shown in Figure 3.3, when the backbone data traffic volume is high, the data packet queue maintained by each MR will be long. However, this long data packet queue does not affect the signaling MAC delay, because data and signaling packets are placed in separate queues and transmitted in different time periods. On the other hand, since handoffs do not occur all the time and the channel access time of signaling packets is much shorter than that of data packets due to their small packet size, the number of signaling packets buffered in the signaling queue is low. Therefore, signaling packets do not experience very long queueing delay. In addition, since the MRs with an empty signaling queue do not participate in the backbone channel access competition during the signaling period, the average channel access delay of all signaling packets can also be reduced.

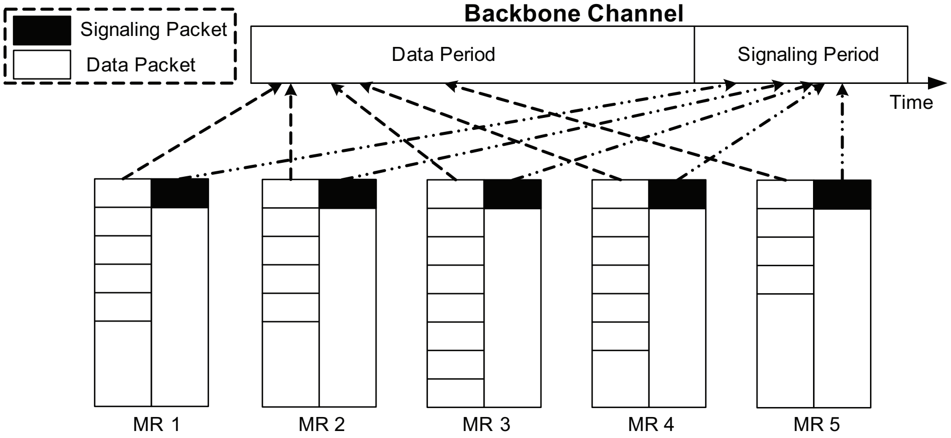


Figure 3.3: Proposed ConT scheme.

In our proposed ConT scheme, each MR has two network allocation vectors (NAVs), *NAV_data* and *NAV_sig*, and two backoff counters, *counter_data* and *counter_sig*, for the transmission of data packets and signaling packets, respectively. When a data period begins, the *NAV_data* and *counter_data* are activated at each MR. During the data period, each MR transmits data packets if its data packet queue is not empty. Based on the 802.11 CSMA/CA contention-based MAC scheme, MRs can transmit an RTS after sensing the channel idle for a distributed coordination function interframe space (DIFS) duration. After receiving the RTS, the destination MR replies a CTS to confirm the future communication. Other MRs receiving the RTS/CTS update their *NAV_data* according to the *Duration* field in the RTS/CTS. When the *NAV_data* expires, MRs with a data packet to transmit generate a random value *counter_data* and begins the backoff stages.

When the RTS/CTS reservation completes, the MR begins to transmit after confirming that the data transmission can be finished in the current data period. However, if the data transmission cannot be finished in the current data period, i.e., the length of the data packet is longer than the remaining time of the data period, the MR does not transmit this data packet at the present time. When the next data period comes, the MR can directly transmit this data packet without the need of experiencing the backoff stage and making the RTS/CTS reservation. When the signaling period starts, MRs in the backoff stage first freeze the *counter_data* and *NAV_data*, and then activate the *counter_sig* and *NAV_sig* to start the signaling packet transmission. The *counter_data* and *NAV_data* of each MR are resumed at the beginning of the next data period and their values do not change during the signaling period.

When the signaling period starts, MRs initiate signaling packet transmissions, if their signaling packet queues are not empty. The signaling packet transmission scheme also follows the IEEE 802.11 CSMA/CA scheme. When the signaling period expires, MRs first freeze the *counter_sig* and *NAV_sig*, and then resume the *counter_data* and *NAV_data* to start the next data period.

To sum up, in our proposed ConT scheme, since data packets are not transmitted during the signaling period, the channel access delay and queueing delay of signaling packets can be greatly reduced. Consequently, the handoff performance is improved significantly, especially when the data traffic volume is high. On the other hand, MRs with an empty data packet queue do not compete with other MRs to access the backbone channel during the data period, even if they have signaling packets to transmit. This potentially reduces the channel access delay and improves the backbone channel utilization. In addition, since our proposed ConT scheme is based on the 802.11 CSMA/CA MAC scheme during each period, it can be easily applied to existing 802.11-based WMNs after small modifications.

3.3 Performance Evaluation

We first analyze the performance tradeoffs between the data throughput and handoff delay. Then, we determine the optimal length of the data period and signaling period. Finally, we compare the handoff performance of our proposed ConT scheme with existing handoff solutions.

3.3.1 Tradeoff Discussions

In the proposed ConT scheme, how to determine the optimal length of the data and signaling periods is a challenge. The benefit to the handoff performance should not be obtained at the expense of sacrificing the performance of data packets, which may undermine the data packet throughput.

There is a tradeoff between achieving a short signaling MAC delay and a high data throughput in the proposed ConT scheme. Longer signaling period is beneficial to achieving a short signaling MAC delay, because more signaling packets can be transmitted in one signaling period. However, this may lead to longer waiting time of data packets. Therefore, the data throughput may be undermined if the signaling period length is not properly designed. On the other hand, if the signaling period is too short, less signaling packets can be successfully transmitted in the current signaling period, leading to long signaling MAC delay. Similarly, the design of the data period length also has the same problem. Longer data period can improve the data throughput, because more data packets can be successfully transmitted in one data period, but at the same time, it increases the signaling MAC delay.

Since the purpose of this work is to reduce the handoff delay without undermining the data throughput in single-backbone-channel based WMNs, the performance of the handoff delay and data throughput needs to be taken into account at the same time in the proposed ConT scheme. Therefore, the optimal length of the data period and signaling period needs to be determined first to guarantee the performance of signaling MAC delay and data throughput simultaneously.

3.3.2 The Optimal Length of Data and Signaling Periods

In order to evaluate the optimal length of data and signaling periods, we establish a simulation scenario in which 10 MRs are deployed in a network and share the same backbone channel for the transmission of data packets and signaling packets. In order to prove that the signaling MAC delay is not affected by the backbone data traffic volume in our proposed ConT scheme, a very heavy data traffic volume is added on each MR. As discussed before, since handoffs do not occur very frequently in a network, a small amount of handoff signaling traffic is added on each MR. The inter-arrival time of data and signaling packets used in the simulation is geometrically distributed.

Time is divided into slots and a mini-slot is considered as the basic unit for evaluating the length of the channel access delay and queueing delay in the simulation. One transmission cycle is defined as a super slot which contains a data period and a signaling period. One super slot is composed of a certain amount of mini-slots, as shown in Figure 3.4. The parameters used in the simulation are listed in Table 3.1.

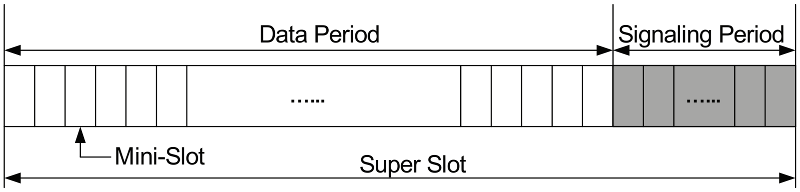


Figure 3.4: Slot definitions in the simulation.

In the simulation, the data throughput is defined as the ratio of the number of slots used for transmitting data packets to the total simulation time. Figure 3.5 shows the simulation results on the relationship among the average signaling MAC delay, data throughput, and the ratio of the signaling period length to the data period length. As shown in Figure 3.5, when the ratio of signaling to data period length increases, the signaling MAC delay is reduced because more transmission slots are assigned for signaling packet transmissions. On the other hand, the increasing of the ratio

Table 3.1: System Parameters in ConT

Parameter Explanation	**Values**
Number of MRs	10
Length of a mini-slot	50 μs
Data packet arrival rate	15 packets/second
Data packet size	164 mini-slots
Signaling packet arrival rate	3 packets/second
Signaling packet size	10 mini-slots
Initial size of the backoff window	32
Maximum backoff stage	5
Average signaling MAC delay requirement	0.1 second

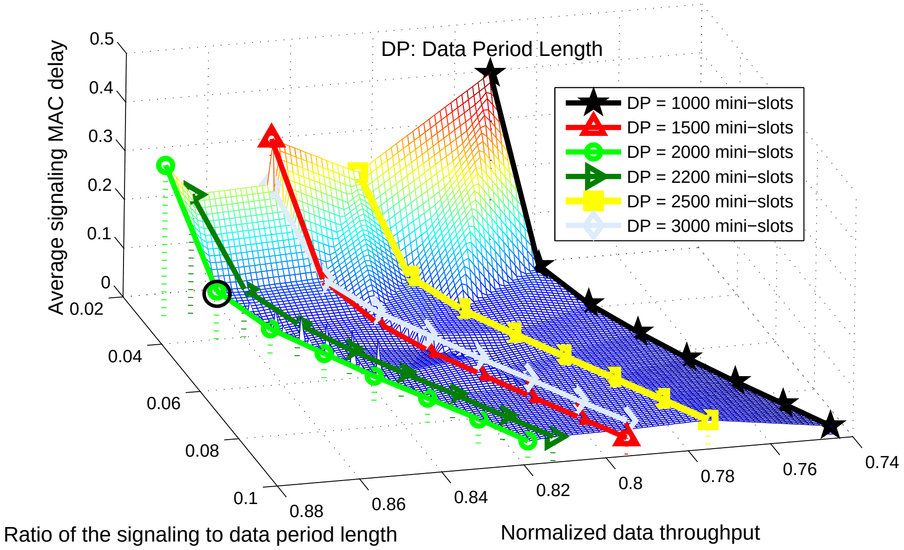
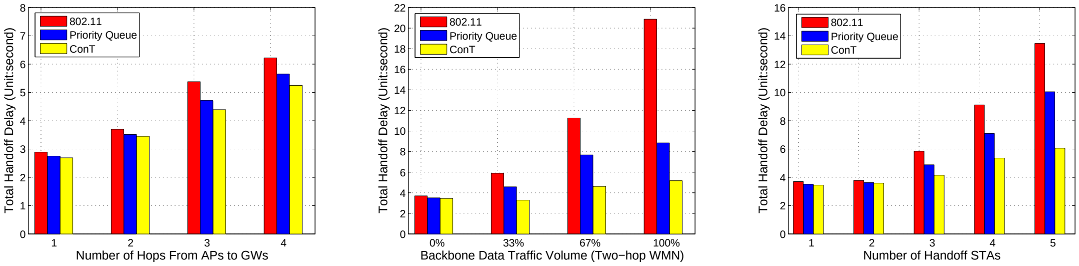


Figure 3.5: Evaluation of data and signaling period length.

also reduces the data throughput, because less transmission slots are assigned for data packet transmissions. Therefore, the performance of the signaling MAC delay is inversely proportional to the data throughput, when the ratio of the signaling period to data period length varies. Considering this, we try to find the optimal length of data and signaling periods in order to maximize the data throughput under the condition that the signaling MAC delay requirement is satisfied. We assume that requirement of the average signaling MAC delay is 0.1 second, which means that



(a) Handoff delay vs. number of hops (b) Handoff delay vs. traffic volume (c) Handoff delay vs. number of MNs

Figure 3.6: Multi-hop WMN handoff performance in ConT.

signaling packets should be successfully transmitted within 0.1 second on average. Under such a condition, the optimal ratio of the signaling to data period length can be found in Figure 3.5, when the maximum data throughput is achieved given that the signaling MAC delay requirement is satisfied, under fixed data period length. As shown in Figure 3.5, the maximum data throughput can be achieved when the data period length is 2000 mini-slots, and the average signaling MAC delay is guaranteed at the same time if the ratio of the signaling to data period length is 0.04. Hence, the data period length, signaling period length, and super slot length are determined as 0.1 second, 0.004 second, and 0.104 second in the simulations, respectively.

3.3.3 Handoff Performance Evaluation

We compare the multi-hop handoff performance under the proposed ConT scheme with existing MAC solutions for single-radio single-backbone-channel WMNs using the OPNET simulator [8]. In the simulation, three different packet scheduling schemes are implemented: 802.11-based scheme, priority-queue-based scheme, and the proposed ConT scheme.

In the 802.11-based scheme, data and signaling packets are transmitted in the same queue via the same backbone channel, so the signaling MAC delay largely depends on the backbone traffic volume, as described previously. In the priority-queue-based scheme, data packets and signaling packets are transmitted in different queues at each MR via the same backbone channel and the signaling queue has a higher priority than the data packet queue. Hence, data packets can be transmitted only when the signaling packet queue is empty. However, channel contentions between data and signaling packets from different MRs still exist in the priority-queue-based scheme. In our proposed ConT scheme, data and signaling packets are transmitted in different time periods, so channel contentions only exist among the same type of packets.

In the simulation, a few MNs move from one AP to another when communicating with their CNs. APs are deployed in different subnets, so the inter-gateway handoff is triggered when an MN moves from one AP to another. Every MN sends a data packet flow to their CNs. Similarly, CNs located in the Internet send the same amount of data traffic to MNs. When the background data traffic is added in the wireless mesh backbone, every AP generates two, four, and six such data packet flows to its gateway via the data channel which are considered as 33%, 67%, and 100% background data traffic, respectively. The data traffic between CNs and MNs starts at 100 second. The Internet has a constant latency of 0.1 second. The simulation lasts for 30 minutes and the data traffic between CNs and MNs ends at the end of the simulation.

Figure 3.6 shows the handoff performance of the three packet scheduling schemes under different handoff scenarios. As shown in Figure 3.6(a), the handoff delay increases with the increasing number of the backbone hops when the backbone data traffic volume is zero. In this scenario, the handoff delay of the ConT scheme is lower than the other two transmission schemes. However, the handoff performance can be improved significantly, as compared to the 802.11 and priority-queue-based schemes, when the backbone data traffic volume or the number of handoff MNs increase, as shown in Figure 3.6(b) and (c). This is because that the growing data traffic volume increases the signaling MAC delay in the 802.11 and priority-queue-based schemes. On the other hand, since channel contentions only exist among the same type of packets, the handoff delay is not affected by the growing data traffic volume much in our proposed ConT scheme.

CHAPTER 4: CHAS: CHANNEL SPLITTING STRATEGY

In multi-radio single-channel WMNs, although backbone MRs are configured with two or more wireless radios, they cannot transmit and receive packets simultaneously because only one backbone channel can be used among MRs in the same interference area. In this chapter, we propose a channel splitting (ChaS) strategy to address the long handoff delay issue in multi-radio single-channel WMNs by maximizing the utilization of the hardware and channel resources. In the ChaS scheme, we first propose novel handoff procedures in which data and signaling packets can be transmitted separately by means of a frequency division multiple access (FDMA) scheme. Then, two packet transmission schemes are proposed in the wireless mesh backbone to enhance the backbone channel utilization. Since the proposed ChaS scheme exploits the usage of a portion of the channel bandwidth to transmit handoff signaling packets in the wireless mesh backbone during the whole handoff process, it is different from the multi-channel protocols that require an additional full channel for control messages [21, 22, 23]. In addition, the additional full control channel usually has low traffic volume, which may cause the under-utilization of the channel bandwidth. However, the split control channel bandwidth in this design is determined with the goal of not causing channel congestion or under utilization as well as balancing the tradeoff between handoff delay and data packet ETE delay.

In particular, the contribution of this work mainly lies in the following points: (1) we design a channel splitting strategy to shorten both the link-layer and network-layer handoff latency; (2) we propose two transmission designs for the splitting channel medium access control in the wireless mesh backbone network to improve the performance of both handoff and data throughput; and (3) we evaluate the performance of the proposed ChaS scheme using OPNET simulations.

4.1 Proposed Handoff Procedures Based on ChaS

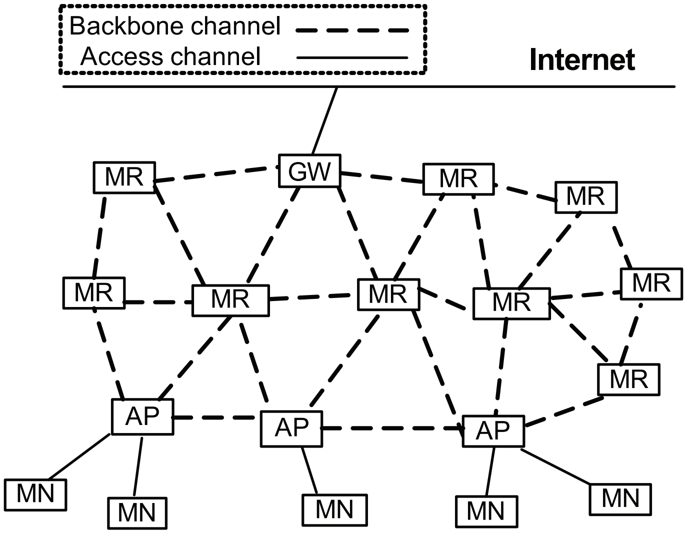


Figure 4.1: Traditional WMN architecture.

In a traditional 802.11-based WMN, as can be seen in Figure 4.1, every AP has two wireless channels: one serves as the access channel supplying the wireless interface to MNs; the other is the backbone channel providing connections to the mesh backbone. In our design, as shown in Figure 4.2, the access channel remains the same, only for the transmission of data packets between an MN and its AP. The backbone channel is split into two channels: a data channel and a control channel, dedicated for the data and signaling communications, respectively. MRs deployed in the wireless mesh backbone are configured with two radios: one radio always works on the control channel for transmitting/receiving signaling packets; the other is used to transmit/receive data packets on the data channel. When an MN performs a handoff, it directly sends signaling packets on the backbone control channel to communicate with its new AP and new gateway without causing contentions with the data packets. Based on this channel splitting design, we propose (1) selective control channel scanning to reduce the link-layer handoff delay and (2) separate channel transmissions to shorten the network-layer handoff delay.

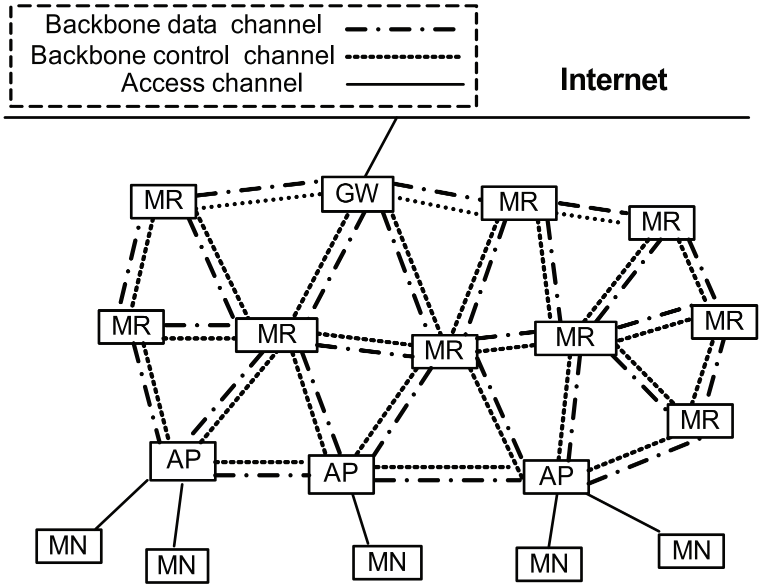


Figure 4.2: WMN architecture based on split channels.

When an MN moves between different APs, it needs to know the control channel information of the possible APs it may be handed off to. To address this issue, we propose that APs are configured with a control channel list containing the control channel information of neighboring APs. The control channel list can be provided to an MN in a handoff signaling message. On the other hand, MNs can have either one or two radios. Therefore, the handoff procedures for the scenarios when an MN has one radio or two radios are different. Since our work mainly focuses on reducing the handoff delay by using split channels, we consider that there is only one backbone channel to split in a WMN. The detailed proposed handoff procedures are explained as follows.

4.1.1 An MN with One Radio

In this scenario, each MN is configured with only one radio. Thus, the data reception and handoff process at an MN cannot be executed at the same time. However, MRs deployed in the WMN have two split backbone channels. We propose two improvements for the overall handoff process, as compared to the traditional method:

- By using the selective control channel scanning, the total channel scanning delay can be reduced in the link-layer handoff.

- Both the link-layer and network-layer handoff signaling traffic is delivered in a separate control channel without competing with the data traffic.

Figure 4.3 shows the proposed handoff procedures for this scenario. When an MN detects that the RSS is less than a certain threshold, it sends a *Handoff Request* message to its current AP informing that it needs a handoff. Having received the *Handoff Request* message, the AP sends a *Handoff Reply* message to the MN containing the control channel information of the surrounding APs. The number of the channels in the list is usually less than the total number of available channels. Then, the MN first switches its radio to one of the channels in the control channel list. After sensing the control channel idle, the MN broadcasts a *Probe Request* message and starts the *ProbeTimer* simultaneously. When receiving the *Probe Request* message on the control channel, in order to avoid collisions, APs reply the *Probe Response* messages to the MN after waiting for a random time interval. When the *ProbeTimer* expires, the MN continues to scan the next control channel in the list. After finishing scanning all channels in the list, the MN processes all the received *Probe Response* messages to choose the AP with the best RSS value as its new AP. Then, the MN switches its radio to the control channel of the new AP and continues to proceed the authentication and reassociation processes of the link-layer handoff as in the traditional design. It is worth mentioning that the access channel information can be obtained from the *Reassociation Reply* message from the new AP on the control channel. If a network-layer handoff is necessary, the MN needs to obtain a new IP address from the new subnet. To get a new Care-of Address, the MN sends an *Agent Solicitation* message to the new AP which replies an *Agent Advertisement* message containing the new IP address. After getting the new IP address, the MN first finds an available route to the new gateway using the multi-hop routing protocol adopted in the mesh backbone and then sends a *Registration Request* message which is delivered through the split control channel by mesh routers in the wireless mesh backbone to the HA in the Internet. When getting this *Registration Request* message, the HA updates the binding information of the MN and sends a *Registration Reply* message to the MN. When receiving the *Registration Reply* message, the MN switches its radio to the access channel of the new AP. Finally, the HA forwards all the data packets through the split data channel to the MN's new Care-of Address.

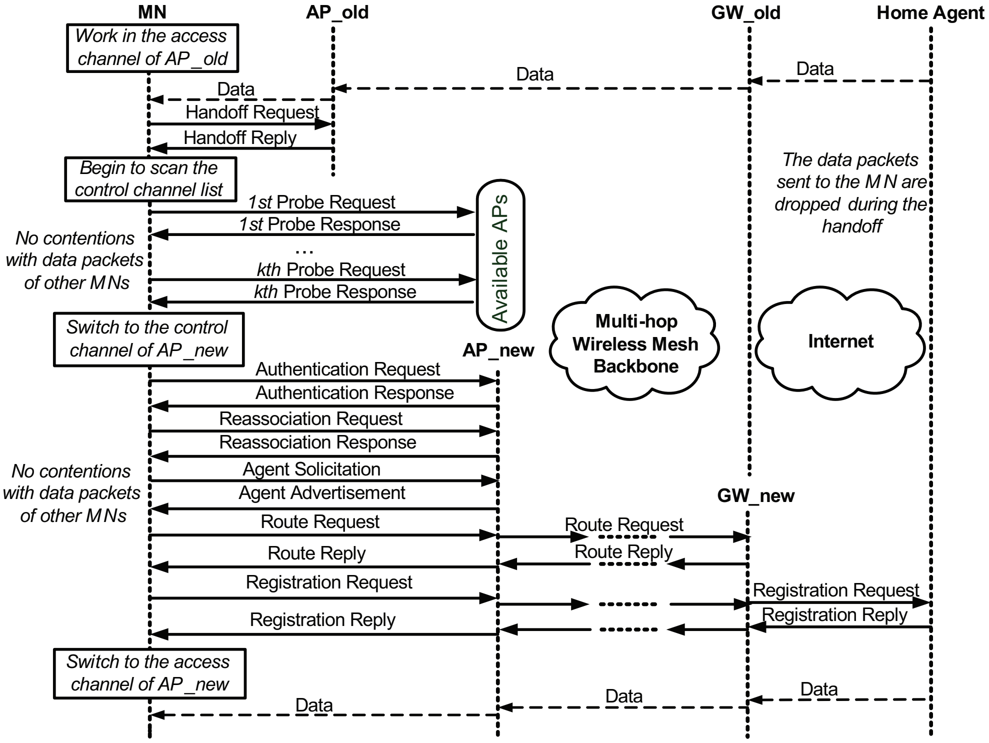


Figure 4.3: Proposed handoff procedures when an MN has one radio.

To sum up, as shown in Figure 4.3, since the MN only probes the channels in the control channel list to determine the new AP, its probe delay can be reduced. If there is only one backbone channel in the same WMN, the MN only needs to probe one control channel when it moves inside the WMN. In addition, since the handoff signaling packets are delivered in a separate control channel, the channel access contentions between the handoff signaling packets and data packets of other MNs are eliminated during both the link-layer handoff and the network-layer handoff.

4.1.2 An MN with Two Radios

In this scenario, since each MN is configured with two radios, data packets and signaling packets can be delivered in separate channels simultaneously without competing and interfering with each other during the handoff process. The proposed handoff procedures for this scenario are shown in Figure 4.4.

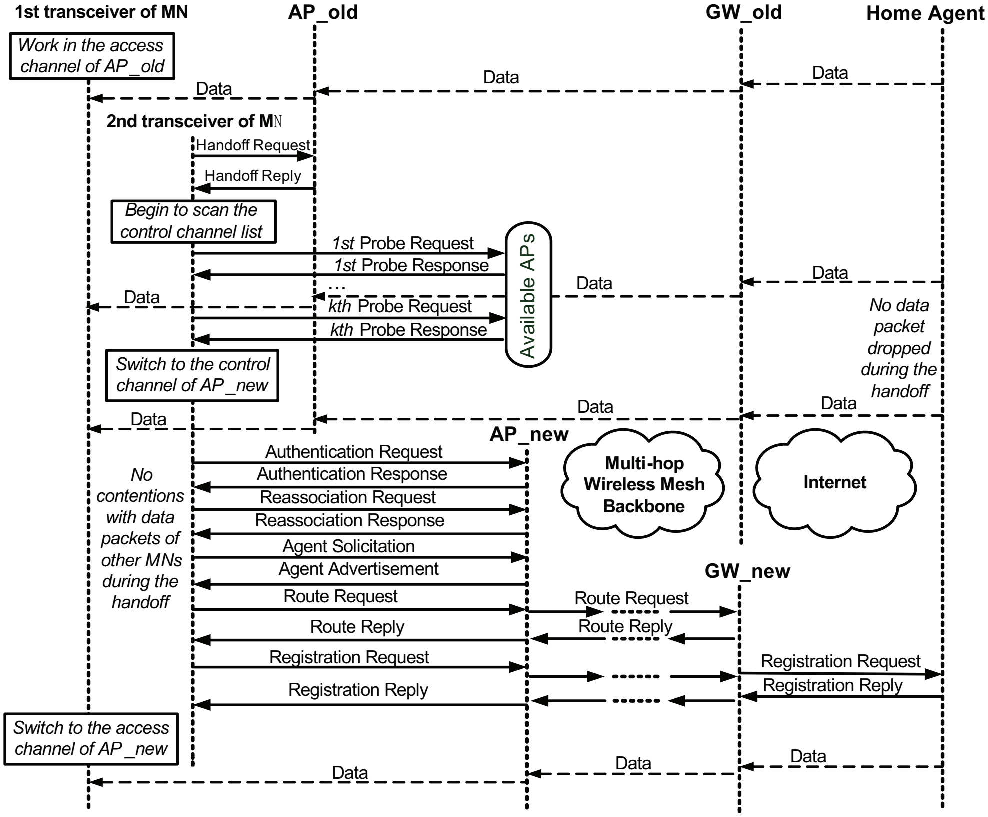


Figure 4.4: Proposed handoff procedures when an MN has two radios.

When an MN detects that the RSS from the current AP is less than a certain threshold, it sends a *Handoff Request* message to its current AP on the control channel. The current AP replies a *Handoff Reply* message containing the control channel list of the surrounding APs. Then, the MN switches its control channel radio to one of the control channels in the list, and at the same time, the data channel still receives data packets from the current AP. After sensing the control channel idle, the MN broadcasts a *Probe Request* message and starts the *ProbeTimer* simultaneously. APs receiving the *Probe Request* message reply the *Probe Response* messages to the MN after waiting for a random time interval. When the *ProbeTimer* expires, it proceeds to scan the next control channel in the list. After finishing the scanning, the MN processes all the received *Probe Response* messages to determine the new AP. Then, the MN switches its control channel radio to the control channel of the new AP and continues to proceed the authentication and reassociation processes of the link-layer handoff. The access channel information can be obtained from the *Reassociation Reply* message from the new AP on the control channel. Then, the MN starts the network-layer handoff as in the traditional design. After receiving the *Registration Reply* message from the HA, the MN directly switches its data channel radio to the new AP's access channel and gets ready to receive data packets forwarded from the HA.

In this scenario, as shown in Figure 4.4, since the MN has two radios, it can manage data traffic and control traffic at the same time. Thus, while the MN performs the link-layer and network-layer handoffs using the control channel via the new AP, it can still receive data packets destined to it on the data channel via the old AP. Therefore, in the ideal situation, the total handoff delay is only a channel switching time and the packet loss during a handoff is minimized.

In conclusion, the handoff performance of an MN can benefit from our proposed channel splitting strategy under both one- and two-radio scenarios. Moreover, it is also worth mentioning that traditional link-layer handoff procedures are still supported by our proposed design to avoid the compatibility problem on the client side. Therefore, MNs only designed for standard channels can still execute the traditional handoff procedures if the selective control channel scanning is not supported. However, the network-layer handoff delay for these MNs can still be greatly reduced due to the separate transmission of signaling packets in the wireless mesh backbone.

4.2 Proposed Packet Transmission Designs Based on Channel Splitting

Since the IEEE 802.11 CSMA/CA does not provide an effective solution to multi-channel models, it is necessary to find an efficient mechanism to schedule the delivery of data and signaling packets in the split channels. Although various multi-channel MAC protocols are proposed [48, 49, 37], they cannot be applied to the handoff scenarios in WMNs, because the control channel in the existing multi-channel MAC protocols is only for the transmission of the request-to-send (RTS) and clear-to-send (CTS) packets to reserve the data channel. Other signaling messages including handoff messages are not considered. Accordingly, the handoff signaling messages can be either transmitted on the data channel or on the control channel in the existing designs. However, since handoff signaling packets are very small, it is inefficient to transmit them in the same way as in the transmission of data packets by means of RTS/CTS reservations on the control channel. On the other hand, if the handoff signaling messages are directly transmitted on the control channel without RTS/CTS reservations, they may compete with the RTS/CTS packets of the data packets to access the control channel. When the signaling traffic load on the control channel is very high, the RTS/CTS packets of data packets cannot be transmitted in time on the control channel, which may result in long idle periods on the data channel. Therefore, existing multi-channel packet transmission designs [48, 49, 37] are not applicable under handoff scenarios in multi-hop WMNs.

In this section, we propose separate channel transmission (SCT) and combined channel transmission (CCT) for the scheduling of the transmission of data packets and signaling packets. This issue has not been well considered in other papers. We assume that data packets are transmitted based on the IEEE 802.11 CSMA/CA access mechanism with the RTS/CTS option which is not required in the transmission of handoff signaling packets with small packet size.

4.2.1 Separate Channel Transmission (SCT)

In this design, both the RTS/CTS reservation and the transmission of data packets are carried out on the data channel. The control channel is only used to transmit signaling packets, such as *Agent Solicitation*, *Agent Advertisement*, *Registration Request*, and *Registration Reply*. Assume that Router A and B are connected by the same split data channel and control channel. As shown in Figure 4.5, the contention to access the control channel is only among the signaling packets. All the data packets only compete on the data channel. Therefore, the two types of packets no longer affect each other. This method is applicable to the situation when the total number of handoffs in the WMN is high and a separate split channel is required to deliver the high volume of signaling packets to guarantee the handoff delay. In addition, if the channel utilization of both channels is high, a high network throughput can be achieved.

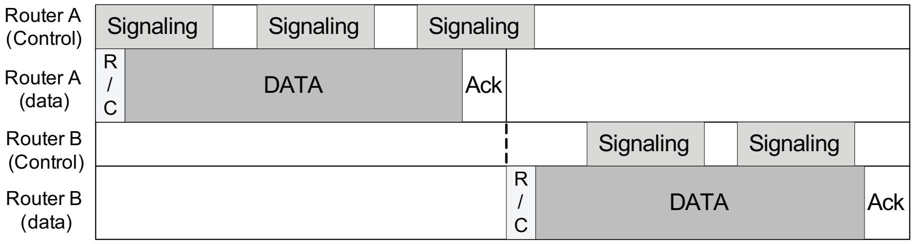


Figure 4.5: Separate channel transmission (R/C: RTS/CTS).

4.2.2 Combined Channel Transmission (CCT)

When an MR has a data packet to send, the MR first checks the state of the data channel. If the data channel is idle, the MR performs the RTS/CTS reservation process on the data channel. However, when the data traffic load is high in the wireless mesh backbone, the data channel may be in the busy state most of the time. Under such situations, our proposed CCT scheme is designed to make use of the idle periods on the control channel to finish the RTS/CTS reservation in advance, so the next data transmission can be executed right after the previous data transmission. In our proposed CCT design, MRs can determine to deliver the RTS/CTS reservation packets either on the control channel or on the data channel dynamically depending on the backbone traffic load, thereby improving the overall channel utilization and data packet ETE delay.

To realize this design, three network allocation vectors (NAVs) are proposed for MRs in the scheduling of data packet transmission: *NAV_data*, *NAV_control*, and *NAV_backup*. *NAV_data* is maintained for the data channel indicating the expiration time of the data channel busy state. It is dynamically updated when receiving RTS/CTS packets in both channels. *NAV_control* is obtained from the RTS/CTS packets transmitted on the control channel. It provides the time required for the next data packet transmission. *NAV_backup* is used to save the value of *NAV_data* each time before it is updated. In addition, *reservation_time* denotes the time required for an RTS/CTS reservation on the control channel. We use a *reserved_flag* to indicate whether the next data channel transmission has already been reserved or not. In order to avoid idle periods on the data channel, the next RTS/CTS reservation should be finished before the completion of the current data transmission (i.e., $NAV\_data - current\_time > reservation\_time$). The proposed protocol details of the CCT design are shown in Algorithm 1, 2, and 3.

Algorithm 1 MRs which want to transmit a data packet

```
if (data channel is idle)
   Send RTS containing NAV_data on the data channel;
else if (data channel is busy and control channel is idle)
 and (reserved_flag == FALSE)
  and ($NAV\_data - current\_time > reservation\_time$)
    Send RTS containing NAV_control on the control channel;
else
    Wait until NAV_data expires;
    Send RTS containing NAV_data on the data channel;
end if
```

Figure 4.6 shows that Router A and Router B, connected with the same data channel and control channel, can determine to deliver the RTS/CTS of data packets

Algorithm 2 MRs already sent RTS on the control channel

```
if ($reserved\_flag$ == TRUE)
    Wait until $NAV\_backup$ expires;
    $reserved\_flag$ = FALSE;
    Transmit the data packet on the data channel;
else
    Wait until receiving CTS containing $NAV\_control$;
    $NAV\_backup = NAV\_data$;
    $NAV\_data = NAV\_data + NAV\_control$;
    $reserved\_flag$ = TRUE;
    Wait until $NAV\_backup$ expires;
    $reserved\_flag$ = FALSE;
    Transmit the data packet on the data channel;
end if
```

Algorithm 3 Other MRs with the same backbone channel

```
if (receiving RTS containing $NAV\_control$)
    $NAV\_backup = NAV\_data$;
    $NAV\_data = NAV\_data + NAV\_control$;
end if
if (receiving CTS containing $NAV\_control$)
    $NAV\_backup = NAV\_data$;
    $NAV\_data = NAV\_data + NAV\_control$;
    $reserved\_flag$ = TRUE;
end if
if ($NAV\_backup$ expires)
    $reserved\_flag$ = FALSE;
end if
```

either on the control channel or on the data channel dynamically according to the current channel status. Initially, since the control channel and data channel are idle, the signaling packet of Router A and the kth data packet of Router B can be transmitted simultaneously in separate channels. After finishing the transmission on the control channel, Router A needs to send its ith data packet to Router B. At

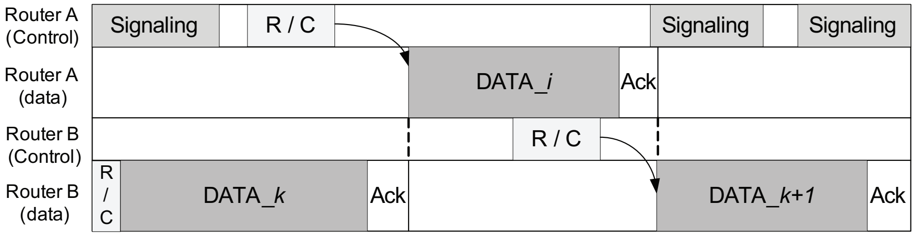


Figure 4.6: Combined channel transmission (R/C: RTS/CTS).

this moment, since Router B still has not finished its kth data packet transmission, the data channel is still busy, but the control channel is idle. After checking that the *reserved_flag* is FALSE and the reservation of its ith data packet on the control channel can be finished before the completion of the kth data packet of Router B on the data channel, Router A sends an RTS packet to Router B on the control channel containing *NAV_control* to reserve its ith data packet transmission. Other neighboring APs receiving this RTS packet save the current value of *NAV_data* to *NAV_backup*, update the value of *NAV_data*, and then set their *reserved_flag* to be TRUE, meaning that the data channel has been reserved. Similarly, when receiving a CTS packet from Router B containing *NAV_control* on the control channel, other neighboring APs as well as Router A set their *reserved_flag* to be TRUE, save the current value of *NAV_data* to *NAV_backup*, and then update the value of *NAV_data*. Once *NAV_backup* expires, Router A transmits its ith data packet on the data channel. Other neighboring APs with no transmission reset their *reserved_flag* to be FALSE, meaning that the next data channel transmission can be reserved at this moment. During the transmission of the ith data packet of Router A, Router B needs to send its $(k+1)$th data packet. At this moment, the data channel is busy while the control channel is idle. Hence, Router B repeats the steps as in the ith data packet transmission of Router A. Later during the transmission of the $(k+1)$th data packet of Router B, since the control channel is idle, Router A starts to transmit a handoff signaling packet on the control channel.

In conclusion, this design can utilize the data channel with high efficiency, because the time required to reserve the data channel is consumed in the idle period of the control channel. Therefore, the RTS/CTS overhead on the data channel is reduced and the overall channel throughput is improved. However, this design may be unfair to signaling packets, because it brings more contentions on the control channel, as compared to the SCT design. Therefore, the CCT design can be applied to the WMN where the handoff traffic volume in the mesh backbone is low, leaving sufficient idle periods on the control channel for the data channel reservation.

4.3 Performance Evaluation

In this section, we assess the performance of the packet transmission designs proposed in Section 4.2 based on the channel splitting strategy using the OPNET [8] simulator. Since OPNET 14.5 does not provide multi-radio MR models, we implement new AP and MR models to support our proposed transmission designs. In the simulation, APs and MRs are configured with three and two wireless radios, respectively, and each radio has one IP address.

4.3.1 Simulation Setup

We implement handoffs in multi-hop WMNs using five different channel transmission methods: traditional single-channel-based method, priority-queue-based method, proposed SCT method based on split channels, proposed CCT method based on split channels, and two-channel-based method.

In the traditional single-channel-based method, MRs are configured with one radio operating on a single backbone channel. Data packets and signaling packets are transmitted in the same queue via the same backbone channel. In the priority-queue-based method, MRs are configured with one radio operating on one backbone channel. However, data packets and signaling packets are transmitted in different queues via the same backbone channel and the queue for signaling packets has a higher priority than the data packet queue. Hence, data packets can be transmitted only when the signaling packet queue is empty. In our proposed SCT and CCT methods, MRs are configured with two radios operating on one backbone channel which is split into a data channel and a control channel. Data packets and signaling packets are transmitted separately via the split data channel and control channel. In the two-channel-based method, MRs are configured with two radios operating on two full backbone channels. Data packets and signaling packets are transmitted separately via different channels. In addition, APs in all transmission methods have one additional radio operating on a standard access channel to provide wireless services to MNs.

Two 4 × 4 grid topology WMNs are deployed in the simulation. Each WMN contains 4 APs, 1 gateway, and 11 backbone MRs. The three non-overlapping IEEE 802.11b standard channels are used in the simulation and the data rate is set to be 1 Mbps. In the SCT and CCT simulation scenarios, the backbone channel in each WMN is split into a control channel and a data channel. MRs have two radios for the split data channel and control channel separately. APs are configured with three radios. One radio is for the access channel to provide wireless services to clients; the other two radios are for the split data channel and control channel in the wireless mesh backbone. MNs move from one AP in one WMN to another AP deployed in a different WMN. Hence, both link-layer and network-layer handoffs are needed during the movement of MNs. The moving speed of MNs is randomly selected between 3 miles/hour and 6 miles/hour. The HA of MNs is located in the Internet, so signaling packets need to be delivered from MNs to the HA via multi-hop wireless transmission during the network-layer handoff.

The average data packet size is set to be 8184 bits [50] in the simulation. Every MN sends a data packet flow (10 packets/second) to their CNs. Similarly, CNs located in the Internet send the same amount of data traffic to MNs. When the background data traffic is added in the wireless mesh backbone, every AP generates additional two, four, and six such data packet flows to its gateway via the data channel which are considered as 33%, 67%, and 100% background data traffic, respectively. The signaling packet size is set based on the size of *Registration Request* and *Registration Reply* messages defined in Mobile IP [4]. When the background signaling traffic is added in the wireless mesh backbone, every AP generates additional one, two, and three signaling packet flows to its gateway via the control channel which are considered as 33%, 67%, and 100% background signaling traffic, respectively. The data traffic between CNs and MNs starts at 100 second. The Internet backbone network has a constant latency of 0.1 second. The simulation lasts for 20 minutes and the data traffic between CNs and MNs ends at the end of the simulation. The simulation results are obtained from the average of 30 simulation trials with different seeds and based on a 90% confidence interval.

4.3.2 Result Analysis

4.3.2.1 Tradeoff Discussion

We first compare the network performance with different bandwidth ratios of the split data channel to control channel. There is a tradeoff between achieving a faster network-layer handoff and a shorter data packet ETE delay, given fixed total channel bandwidth. The handoff delay can be reduced by assigning larger bandwidth to the split control channel, but meanwhile, the data packet ETE delay will be undermined due to the reduced bandwidth of the split data channel. However, the data packet ETE throughput can be affected by both the handoff delay and data packet ETE delay. On the one hand, if the handoff delay is reduced, packet loss during the handoff is also reduced, resulting in the improvement of data packet ETE throughput. On the other hand, if the data packet ETE delay is reduced, more data packets can be received by clients in a certain time interval and the data packet ETE throughput can also be improved. Considering the above interrelation between the handoff delay, data packet ETE delay, and data packet throughput, we choose the handoff delay and data packet ETE delay as the criteria for evaluating the optimal bandwidth ratio of the data channel to control channel.

4.3.2.2 Bandwidth Ratio of the Split Data Channel to Control Channel

In the simulation, two wireless hops from the AP of the MN to the gateway are implemented in each WMN. Each AP also has 33% background data traffic. As shown in Figure 4.7, when the bandwidth ratio of the data channel to control channel is greater than $7:3$ and less than $9.5:0.5$, the tradeoff between the total

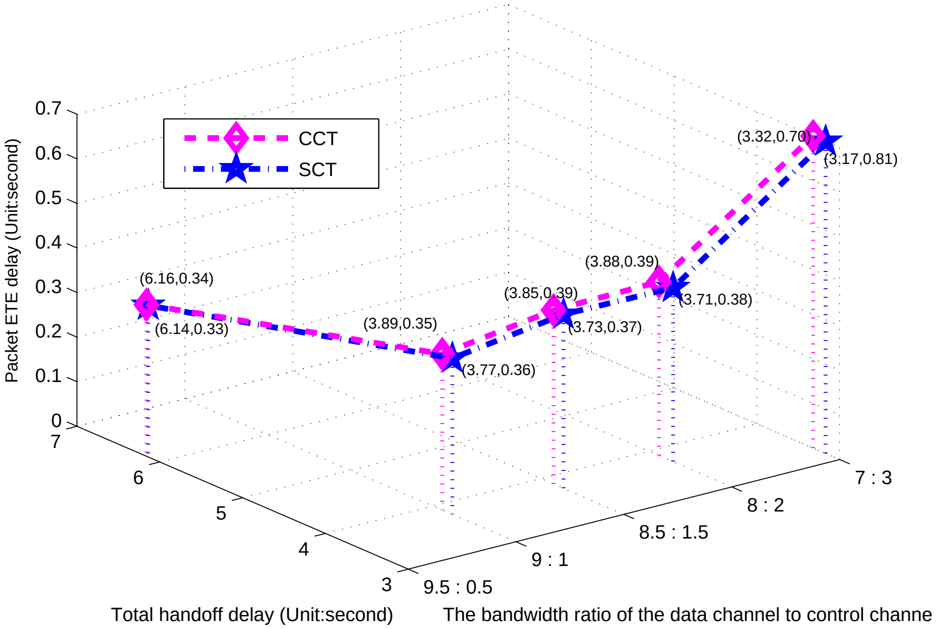


Figure 4.7: Performance with different split channel bandwidth ratios.

handoff delay and data packet ETE delay can be well balanced. However, in order to maximize the data traffic capacity in the mesh backbone, it is reasonable to allocate more bandwidth to the data channel, if the total handoff delay is not compromised. Based on this analysis, the channel bandwidth ratio of 9 : 1 is implemented in our channel splitting strategy in the simulation.

4.3.2.3 Handoff Performance with No Background Traffic

Figure 4.8 shows the link-layer, network-layer, and total handoff delay under different number of hops between the AP of the MN and the gateway, when there is no background data traffic. Since an MN only scans the split control channel in the control channel list during the link-layer handoff using the channel splitting strategy, the link-layer handoff delay is significantly reduced, as compared to the traditional and priority-queue-based methods. In addition, the network-layer handoff delay can also be reduced by using the improved SCT and CCT designs in the no background traffic environment. As shown in Figure 4.8, since the network-layer handoff delay accounts for a large percentage in the overall handoff delay, our proposed channel splitting strategy can reduce the overall handoff delay by up to 20.3%, as compared to the traditional method in the no background traffic scenario.

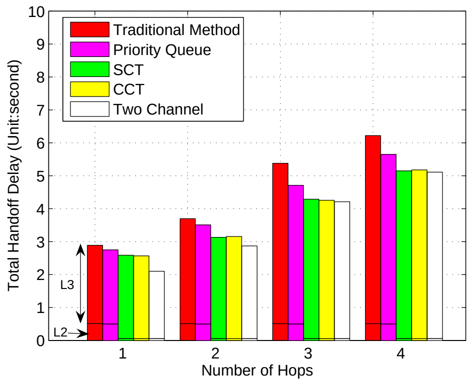


Figure 4.8: No background traffic scenario.

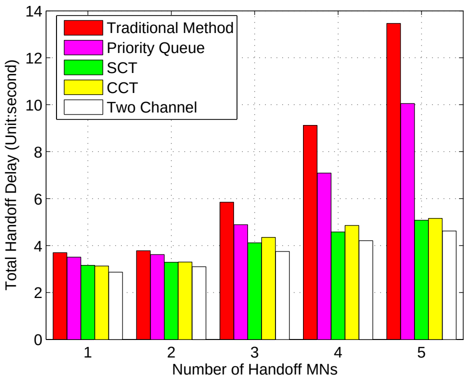
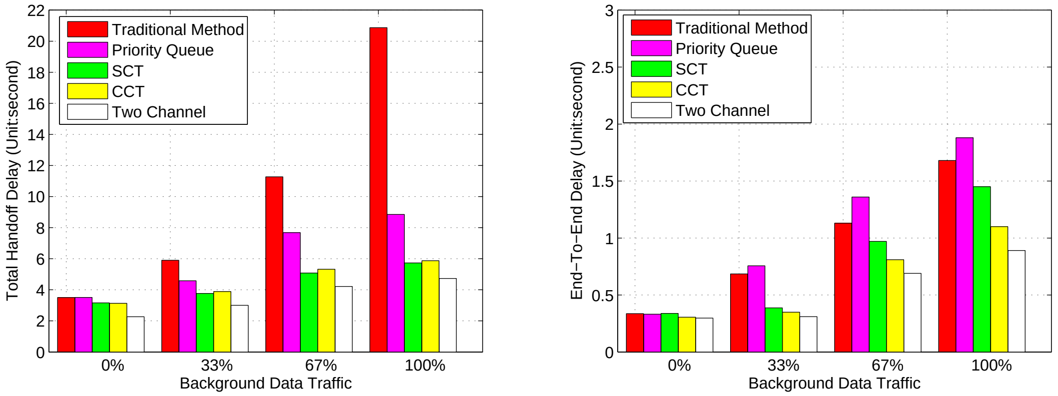


Figure 4.9: Multi-handoff scenario.

Figure 4.9 shows the handoff performance in two-hop WMNs with different number of handoff MNs. Since the growing number of the handoff MNs increases the volume of signaling traffic in the wireless mesh backbone, the handoff delay rises as the number of handoff MNs increases in all methods. However, for the traditional and priority-queue-based method, when some clients finish their handoffs, they continue to receive data packets from their CNs, which potentially increases the channel access delay of handoff signaling packets of other clients who have not finished their handoffs. On the other hand, the same problem does not exist in the SCT, CCT, and two-channel-based methods, so they have better handoff performance as compared to the traditional and priority-queue-based methods.

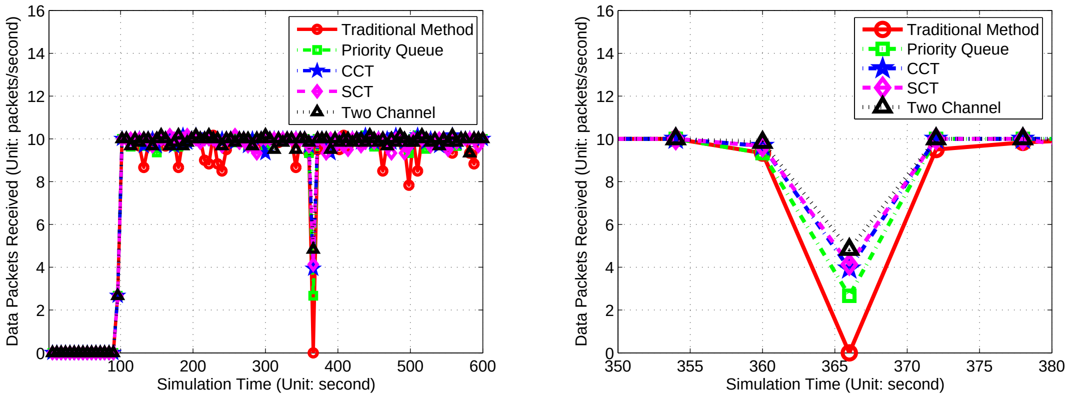
4.3.2.4 Handoff Performance with Background Traffic

Figure 4.10 demonstrates the handoff performance in two-hop WMNs with different percentage of background *data* traffic. As shown in Figure 4.10(a), the handoff delay sharply increases along with the background data traffic using the traditional single-channel-based handoff design. However, it can be maintained within a certain range using our proposed channel splitting design. In other words, the handoff delay



(a) Total handoff delay (b) Data packet ETE delay

Figure 4.10: Handoff performance with background *data* traffic.



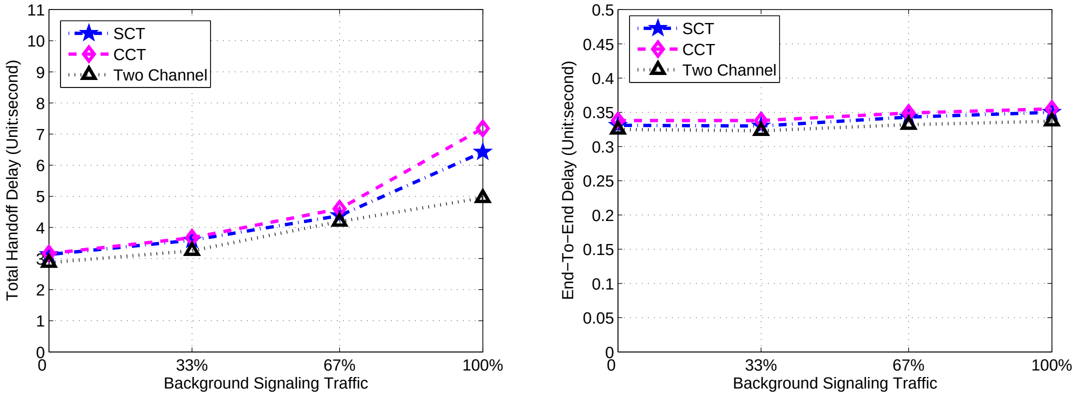
(a) Number of data packets received per second (b) Handoff period

Figure 4.11: Time-based overall handoff process.

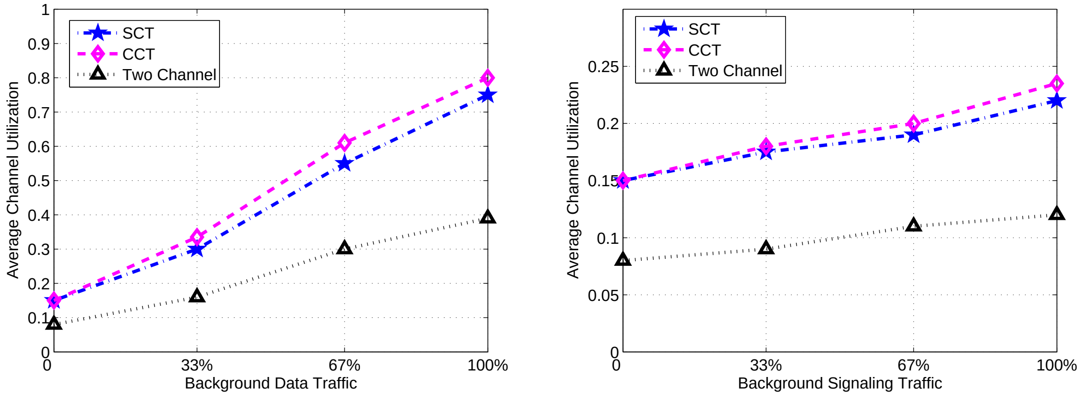
is relatively independent of the background data traffic volume under our proposed channel splitting design. In addition, the handoff delay under the two-channel-based design has no big difference from the delay under our channel splitting design. This is because when the background data traffic volume is high, the main reason for the long handoff delay is the channel access delay, not the channel bandwidth. Moreover, since signaling packets have a higher transmission priority, as compared to data packets, the priority-queue-based method has improved handoff performance as compared to the traditional method. However, when the background data traffic volume becomes higher, the handoff performance of the priority-queue-based method turns worse because signaling packets of one node still need to compete with data packets of other nodes to access the channel. Figure 4.10(b) shows that the data packet ETE delay can also be improved using the proposed SCT and CCT methods. Since the data packets can be sent only when the signaling packet queue becomes empty, the priority-queue-based method shows the worst performance in data packet ETE delay.

Figure 4.11 presents the time-based overall handoff process in two-hop WMNs with 33% background data traffic. In the overall handoff process, as shown in Figure 4.11(a), the traditional single-channel method has the worst data packet reception performance, because the collisions between data packets and signaling packets may occur among different backbone MRs on the same channel. In addition, as shown in Figure 4.11(b), since the traditional method suffers long handoff delay, it drops the largest number of data packets during the handoff process, as compared to other handoff schemes. The two-channel-based design show the best performance of data reception during the handoff process, because a dedicated control channel with full bandwidth is used for the delivery of handoff signaling packet. In addition, since the SCT and CCT designs can benefit from the channel splitting strategy in the wireless mesh backbone, they can also achieve similar data performance to the two-channel-based design.

Since the SCT, CCT, and two-channel-based methods all require two radios for separate transmissions of data and signaling packets in the backbone network, we compare the handoff performance of these three two-radio methods when background signaling traffic on the control channel exists. In addition, we also compare their performance of average channel utilization under different percentage of background *data* and *signaling* traffic. As shown in Figure 4.12(a), the handoff delay increases slowly when the percentage of background signaling traffic is under 67%. However, when the percentage of background signaling traffic reaches 100%, the handoff delay



(a) Total handoff delay (b) Data packet ETE delay



(c) Channel utilization under background *data* traffic (d) Channel utilization under background *signaling* traffic

Figure 4.12: Network performance with background traffic.

of both SCT and CCT sharply increases due to the high traffic volume on the control channel. When the background signaling traffic is very high, it means that a large amount of clients execute handoffs in the same place and at the same time. However, this situation seldom happens in real networks. In addition, the RTS/CTS packets of data packets may compete with handoff signaling packets to access the control channel in the CCT design, resulting in longer channel access delay, as compared to the SCT design. Hence, the total handoff delay of the CCT method is longer than that of the SCT method in this scenario. The two-channel-based method has similar handoff performance as compared to the proposed SCT and CCT designs, when the background signaling traffic is under 67%, but better handoff performance when the background signaling traffic reaches 100% because of the larger control channel bandwidth used. Figure 4.12(b) shows that the three two-radio methods have a similar data packet ETE delay under different percentage of background *signaling* traffic. However, as can be seen in Figure 4.12(c) and (d), since small signaling packets are delivered using full channel bandwidth, channels cannot be utilized efficiently in the two-channel-based design. On the other hand, when the background *signaling* or *data* traffic increases, the average channel utilization can be significantly improved by our proposed SCT and CCT designs, as compared to the two-channel-based design.

4.3.2.5 Summary

From Figure 4.8 to Figure 4.11, we conclude that the inter-gateway handoff performance can be significantly improved using our proposed SCT and CCT designs, as compared to the traditional single-channel-based and priority-queue-based methods, especially under the situation when background data traffic is high in the wireless mesh backbone. In addition, the performance of the CCT design is better than that of the SCT design in this scenario. On the other hand, when the background signaling traffic is added on the control channel, the performance of the SCT method becomes better than the CCT method, as shown in Figure 4.12(a) and (b). Therefore, the CCT design can be applied to the WMN where the handoff traffic volume is low but the background data traffic volume is high, while the SCT design is applicable to the WMN with high handoff frequency requiring a separate control channel to deliver these handoff signaling packets. Moreover, from Figure 4.12(c) and (d), we can see that the two-channel-based scheme, which requires double full channel bandwidth at each MR, has very low average channel utilization under different handoff scenarios. However, the average channel utilization can be greatly improved using our proposed channel splitting design.

CHAPTER 5: GAS: GATEWAY SCHEDULING-BASED HANDOFF SCHEME

In this chapter, we propose a gateway scheduling-based (GaS) handoff scheme to reduce the ETE delay of handoff signaling packets in single-radio multi-channel WMNs without degrading the data performance. In the proposed GaS scheme, signaling transmissions over multiple hops can be reduced to a single-hop by means of periodically establishing directional-directional (DD) transmission links between APs and GWs. The DD signaling transmissions and data transmissions are scheduled on different channels, so the channel contention between data and signaling packets is eliminated. In addition, due to the single-hop signaling transmission, the signaling overhead in the wireless mesh backbone can also be reduced significantly. To the best of our knowledge, this design is the first WMN fast handoff scheme exploiting the virtues of directional antennas.

5.1 Feasibility Analysis and Contributions

5.1.1 Feasibility Analysis

In the proposed GaS scheme, we utilize the virtues of directional antennas in the handoff process to address the multi-hop signaling transmission issue. In previous directional-antenna-based MAC designs [51, 52], since directional antennas only radiate power in one direction, they are used for building multiple DD transmissions in different directions in order to enhance the channel capacity. Different from previous directional antenna works which mainly focus on reducing the interference area, in our design, the advantage of directional antennas is taken from a novel viewpoint. Since the DD transmission pair has a much longer transmission range than the omnidirectional-omnidirectional (OO) transmission pair given the same transmission power, it is possible that a GW can always be reached by APs via only one wireless hop by means of a DD transmission link, if this link is well scheduled between them.

As long as the DD transmission link is successfully established, the handoff process has the following benefits: (1) since GWs can be reached by APs via only one wireless hop, handoff signaling packets used for finding a new route to the GW, such as *Route Request/Response*, are no longer needed. (2) Other handoff signaling packets, such as *Registration Request/Reply*, do not need to be transmitted via the multi-hop wireless mesh backbone during the network-layer handoff process; and (3) the signaling overhead in the wireless mesh backbone can be greatly reduced.

In order to validate the possibility of establishing DD transmission links between APs and GWs, we first derive the attainable DD transmission distance between a sender and a receiver. According to [53], the reception power P_r at a receiver can be expressed as

$$P_r = \frac{P_t G_t G_r}{K D^{\alpha}}, \tag{5.1}$$

where G_t is the transmitter gain, G_r is the receiver gain, P_t is the transmission power, D is the transmission range, α is the path-loss factor, and K is a constant.

Denote G_{d_t} and G_{d_r} as the DD transmitter and receiver gain, G_{o_t} and G_{o_r} as the OO transmitter and receiver gain, and D_{dd} and D_{oo} as the DD and OO transmission ranges, respectively. Then, given the same transmission power P_t and reception power P_r, the relationship between D_{dd} and D_{oo} is

$$D_{dd} = D_{oo} \left(\frac{G_{d_t} G_{d_r}}{G_{o_t} G_{o_r}} \right)^{1/\alpha}. \tag{5.2}$$

In addition, assume that the power of the OO transmission and DD transmission is uniformly distributed on the surface of a sphere and a spherical crown, respectively. The relationships between OO and DD transmitter and receiver gains are

$$G_{d_t} = G_{o_t} \frac{2}{1 - cos\frac{\theta}{2}} \quad \text{and} \quad G_{d_r} = G_{o_r} \frac{2}{1 - cos\frac{\gamma}{2}}, \tag{5.3}$$

where θ and γ are the DD transmission and reception angles, respectively.

As shown in 5.2 and 5.3, the ratio of D_{dd} to D_{oo} is determined by the path-loss factor α and the DD transmission/reception angles, θ and γ. The value of the path-loss factor α is normally from 2 to 6 depending on different scenarios [53]. Considering the worst path-loss scenario when α equals 6, D_{dd} can be 3 to 5 times longer than D_{oo}, if proper DD transmission and reception angles are selected. This conclusion is consistent with [54] which also takes advantage of the long transmission distance of DD transmission pairs. Therefore, we conclude that GWs can be reached by APs in multi-hop WMNs via a single-hop if a DD transmission link can be established between them.

5.1.2 Contributions

In this chapter, we propose a gateway scheduling-based handoff scheme to reduce the overall handoff delay in multi-hop WMNs by resolving the two essential issues, the multi-hop transmission of handoff signaling packets and the channel contentions between data and signaling packets, which lead to considerable handoff signaling ETE delay. The contributions of the proposed GaS scheme are summarized as follows.

(1) We propose a directional-directional (DD) transmission design dedicated for signaling packet transmissions. The signaling transmissions over multiple hops can be reduced to a single-hop by means of periodically establishing DD transmission links between APs and GWs. Therefore, the multi-hop signaling transmission problem is resolved. In addition, due to the single-hop signaling transmission, the signaling overhead in the wireless mesh backbone can also be reduced significantly.

(2) We propose a MAC design in GaS to provide fast handoff support in which the DD signaling transmissions and data transmissions can be executed simultaneously on different channels. Therefore, the channel contention between data and signaling packets is eliminated. In addition, this benefit can be realized by using only one-radio MRs, so the hardware cost is also minimized.

(3) We propose an analytical model to evaluate the signaling throughput of the GaS scheme and implement simulation scenarios to evaluate the optimal length of the DD signaling transmission period as well as the handoff delay. OPNET simulation results show that handoff performance can be significantly improved by the proposed GaS scheme without degrading the data throughput.

5.2 Proposed GaS Handoff Scheme

5.2.1 Network Architecture of GaS

In order to maintain the compatibility to existing WMNs, as shown in Figure 5.1, the proposed GaS scheme does not change the traditional WMN architecture. Particularly, the improvements mainly lie in the newly proposed transmission links: the DD transmission link and OO transmission link. These two types of transmission links are designed based on the different characteristics of signaling packets and data packets.

Considering the special features of handoff signaling packets, such as delay-sensitive, small-size, and low-volume, we propose to use the DD transmission link dedicated for signaling transmissions so that signaling packets can be delivered from APs to the GW/HA rapidly via only one wireless hop. However, as shown in Figure 5.1, since the DD transmission link is based on a hub-and-spoke topology which can only be established between an AP and its GW, the capacity of the DD transmission link is low. Hence, the DD transmission link is not appropriate for the transmission of data packets with a large packet size and high traffic volume. Therefore, we propose to use traditional OO transmission links for data packet transmissions, because the OO transmission link is based on the mesh topology and multiple OO links can be established at the same time to achieve a high throughput.

To minimize the hardware cost, all MRs and APs are configured with only one radio in the wireless mesh backbone. The radio of each MR along with an omnidirectional antenna is dedicated for data packet transmissions. The radio of each AP

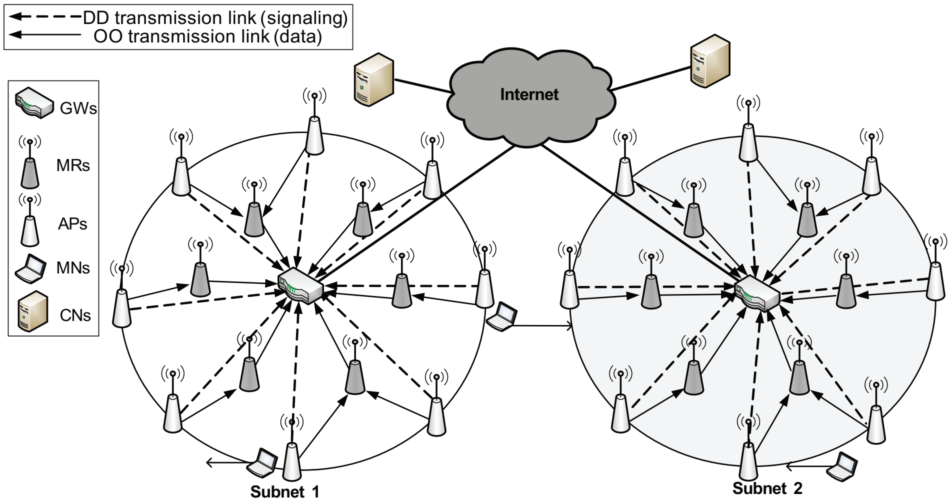


Figure 5.1: Network architecture of GaS.

is used together with a directional antenna which works under either the DD or OO transmission mode depending on the transmission requirements. At each AP, data packets are transmitted omnidirectionally to its next-hop MRs/APs, while signaling packets are transmitted directionally to the GW. GWs are configured with two radios. One radio together with an omnidirectional antenna is dedicated for data packet transmissions with MRs deployed one wireless hop away. The other radio of the GW along with a directional antenna is used only for signaling packet transmissions with APs which could be multiple hops away, as shown in Figure 5.1. In order to eliminate the channel contentions between data and signaling packets, we define that different channels should be used by the DD and OO transmission links. MRs with data packets to transmit stay on the data channels using the OO transmission link. When MRs have signaling packets to transmit, they can switch their radio to the signaling channel for DD signaling transmissions.

To sum up, two different types of transmission links, the DD transmission and OO transmission links, are proposed in the GaS scheme. The DD transmission link is dedicated for signaling packet transmissions and built only between APs and GWs. The OO transmission link is only for data transmissions and can be established between any two nodes among APs, MRs, and the GW.

5.2.2 The DD Transmission Link Establishment

5.2.2.1 Challenge

Although an AP and a GW can communicate with each other directly via a DD transmission link, a negotiation scheme is required in advance to make them beamform in each other's direction. In addition, they also need to be synchronized so that the transmission and reception can start exactly at the same time. This issue becomes more challenging when the sender and receiver are deployed multiple hops away. [54] proposes that a DD transmission link can be established by sending an RTS from the sender to the receiver over multiple wireless hops. However, this design is not appropriate for DD signaling transmissions, because the multi-hop RTS negotiation process may take a long time, especially when the data traffic volume is high along the multi-hop route from the sender to the receiver. Moreover, if the RTS packet is lost during the multi-hop transmission process, the signaling overhead will be sharply increased by the retransmissions of the RTS over multiple hops.

5.2.2.2 How to establish a DD transmission link

To avoid considerable negotiation delay and signaling overhead, we propose a gateway-based synchronization scheme to build DD signaling transmission links. As shown in Figure 5.2, the coverage area of a WMN is divided into multiple sectors by the GW. The GW maintains a schedule of the signaling transmission service for each sector, including the signaling service start time, signaling service duration, and signaling service channel. According to this schedule, the GW periodically beamforms its directional antenna to different directions towards different sectors. When the GW beamforms its directional antenna towards a certain sector, a DD signaling transmission link can be established on the signaling channel when an AP deployed in the sector beamforms its directional antenna towards the GW with a proper angle. Since multiple APs in the same sector may transmit signaling packets at the same time to the GW, the signaling packet transmission follows the IEEE 802.11 CSMA/CA scheme to avoid collisions.

5.2.2.3 How to obtain the signaling transmission schedule

The GW's signaling transmission schedule can be acquired by APs/MRs during the initialization process. When an AP joins a WMN, it first sends a *Schedule Request* message containing its location information to the GW over the multi-hop wireless mesh backbone using its OO transmission link. After receiving the *Schedule Request* message, the GW calculates the AP's sector based on the AP's location information. Then, the GW replies a *Schedule Reply* message to the requested AP on its OO transmission link. The *Schedule Reply* message contains the GW's location, the AP's sector number, and the signaling service information of the sector, such as the service start time, service duration, and signaling channel schedule. After receiving the *Schedule Reply* message, the AP determines the DD transmission angle to the GW based on the location information of the GW and itself. Similarly, MRs deployed in the sector also need to get the GW's signaling transmission schedule in the same way as APs, because they should avoid to use the signaling channel to initiate any OO data transmission during the signaling service period. Note that the acquiring of the signaling transmission schedule is only needed during the initialization phase of an AP/MR in infrastructure WMNs.

5.2.2.4 Example

Figure 5.2 shows an example of the establishment process of the DD signaling transmission link. The WMN is divided into six sectors, so the GW's directional transmission angle is determined as 60 degree and the GW periodically beamforms its directional antenna towards sector 1 to 6. In Figure 5.2, the signaling service period 1 to 6 are scheduled for the signaling transmission of APs deployed in sector 1 to 6, respectively. At first, the GW beamforms its antenna to the direction of sector 1 and signaling period 1 begins. At this time, to avoid collisions, OO data packet transmissions cannot be initiated on the current signaling channel in sector

1. Assume that AP1 has signaling packets to transmit. It first switches its radio to the GW's current signaling channel, then beamforms its antenna with a proper angle towards the direction of the GW, and finally starts the back-off process to initiate signaling transmissions. When period 1 ends, AP1 switches its radio to its data channel and beamforms its antenna to the OO transmission mode to initiate data transmissions. Similarly, when the signaling service period 2 comes, AP2 deployed in sector 2 establishes a DD transmission link with the GW to initiate signaling transmissions in the same way as AP1.

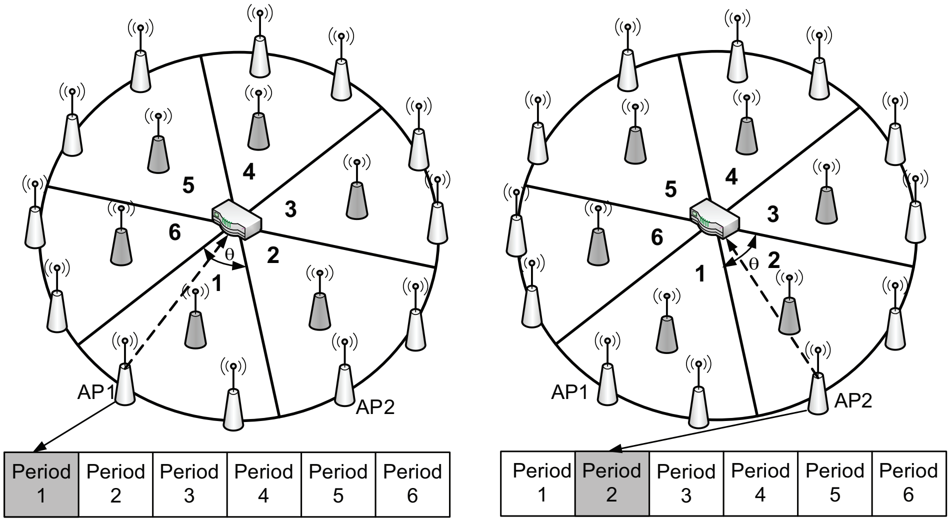


Figure 5.2: DD transmission link establishment.

5.2.3 MAC Design in GaS

5.2.3.1 Challenge

The proposed MAC design is based on the multiple channel rendezvous approach in which each MR/AP maintains its own channel hopping sequence to guarantee at least one time slot channel rendezvous with all its one-hop neighbors. However, different from existing multiple channel rendezvous approaches which only focus on data transmissions [46, 47], our MAC design emphasizes the coordination of signaling and data transmissions to eliminate the channel contentions between them. Meanwhile, the unfairness in per-flow data throughput should be avoided and the overall network data throughput cannot be degraded. Therefore, how to integrate the periodic signaling periods into the data transmission slots at each MR/AP is a challenging issue in our design.

5.2.3.2 Fixed channel integration

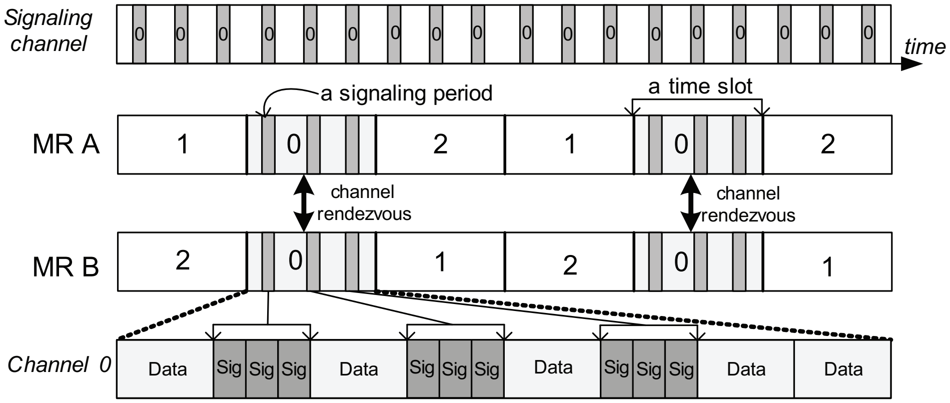


Figure 5.3: Fixed channel integration.

The signaling period can be incorporated on a fixed channel, so all APs can transmit signaling packets on this channel when their signaling periods come. However, since data transmissions in a particular sector need to be terminated on the fixed channel when the signaling period comes to that sector, the fixed channel integration may seriously degrade the per-flow throughput of some MRs. As shown in Figure 5.3, $(1, 0, 2)$ and $(2, 0, 1)$ are the channel hopping sequence of MR A and MR B, respectively. Hence, MR A and MR B can only initiate data transmissions between them when they both hop on channel 0 at the same time. If channel 0 is selected as the fixed signaling transmission channel, as shown in Figure 5.3, the OO data transmissions between MR A and B on channel 0 will always be interrupted by the periodic coming signaling period on channel 0, so the per-flow data throughput between MR A and B is largely degraded.

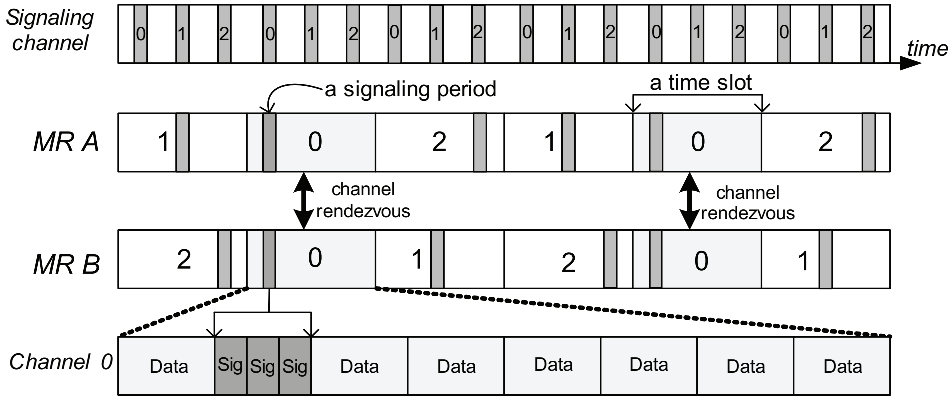


Figure 5.4: Dynamic channel integration.

5.2.3.3 Dynamic channel integration

To avoid the scenario in Figure 5.3, we propose a dynamic channel integration scheme in which all available channels in the network are sequentially selected by the GW as the signaling channel. For instance, assume that there are M available channels and the GW initially chooses the $1st$ channel as the signaling channel. When the GW finishes the signaling transmission service to all sectors using the $1st$ channel, it changes the signaling channel from the $1st$ channel to the $2nd$ channel in the next signaling transmission cycle. According to such channel selection sequence, the $1st$ channel will be selected as the signaling channel again right after the Mth channel. By means of the dynamic channel integration scheme, the unfairness in per-flow data throughput can be avoided, as shown in Figure 5.4.

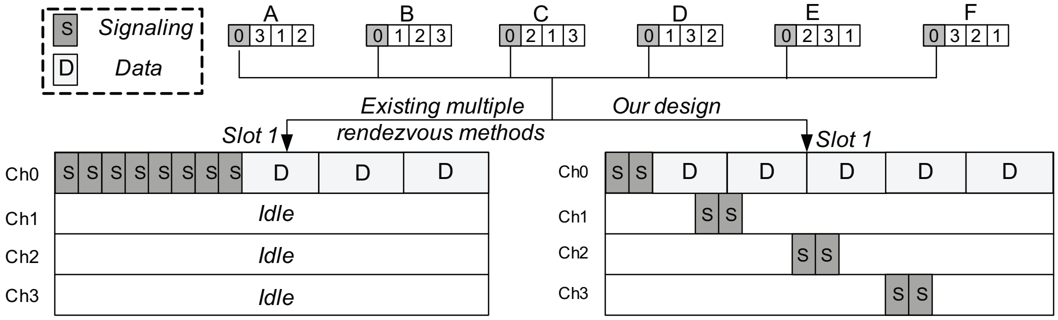


Figure 5.5: Temporary data transmission bottleneck scenario.

As compared to existing multiple channel rendezvous approaches, the dynamic channel integration scheme can also alleviate the temporary data transmission bottleneck problem brought by the randomness of the channel hopping sequences of MRs. In multiple channel rendezvous schemes, it is very possible that multiple transmission pairs deployed in an interference area rendezvous on the same channel during a time slot, leaving other channels idle. Under such scenarios, the contentions on this particular channel among multiple transmission pairs are fierce in that slot. This weak point can be offset by the proposed dynamic channel integration scheme, especially when the signaling arrival rate is high. As shown in Figure 5.5, six nodes deployed in the same interference area all hop on channel 0 at slot 1. Assume that signaling packets have a higher transmission priority. In existing multiple rendezvous approaches, since data packets need to wait until signaling transmissions are completed, data throughput is largely reduced in slot 1. In our design, all available channels are dynamically selected for signaling transmissions, so signaling traffic is distributed to all channels, which potentially alleviate the temporary data transmission bottleneck problem on channel 0.

5.2.3.4 Example

Figure 5.6 explains the details of the proposed MAC design. Two APs and four MRs are deployed in a sector and their hopping sequences are listed in Figure 5.6. Assume that the signaling period of the sector arrives during the second time slot, and at this time, AP1 has signaling packets to transmit, while AP2 does not. Since MR4 and MR5 hop on channel 2 simultaneously, they can initiate data transmissions via an OO transmission link on channel 2. In addition, since AP2 does not have a signaling packet to transmit at this time, it ignores the signaling period and stays on channel 0 to transmit data packets to MR2 via an OO transmission link. On the other hand, AP1 has signaling packets to transmit but its current channel is channel 0, so it switches its radio from channel 0 to the signaling channel, channel 1, and beamforms its antenna to a proper angle facing the direction of the GW to establish a DD signaling transmission link. During the signaling period, even if MR3 and MR1 rendezvous on channel 1 at the second time slot, they cannot establish an OO data transmission link until the signaling service period on channel 1 expires.

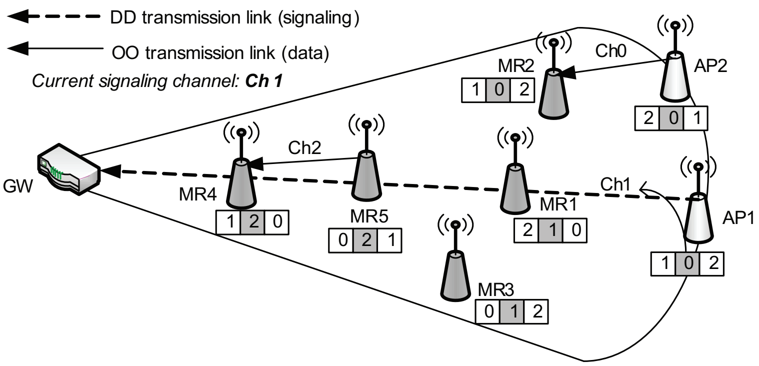


Figure 5.6: Working principles of the proposed MAC design.

5.2.4 Summary

Since the DD signaling transmission link can be established via our proposed GW synchronization scheme, the multi-hop signaling transmission can be reduced to a single-hop, so the signaling ETE delay will be reduced remarkably. On the other hand, DD signaling transmissions and OO data transmissions are scheduled in different time periods by means of the proposed MAC design, so channel contentions between data and signaling packets are completely eliminated. Moreover, due to the single-hop signaling transmission, the signaling overhead in the wireless mesh backbone can also be reduced significantly.

5.3 Performance Evaluation

In this section, we first propose an analytical model to evaluate the DD transmission throughput. Then, we evaluate the optimal length of a signaling service period that can guarantee the minimum signaling packet transmission delay. Finally, we compare the data throughput and handoff delay of the proposed GaS scheme with existing MAC schemes and handoff solutions using simulations.

5.3.1 Simulation Setup

We set up simulation scenarios to evaluate the DD transmission throughput, optimal signaling period length, and the data throughput of the proposed GaS scheme. In the simulations, time is divided into slots. A time slot contains 1000 mini-slots and a mini-slot is 50μs long. The data and signaling packet lengths are 180 and 15 mini-slots long, respectively. The number of channels is 3. The inter-arrival time of signaling packets follows the geometric distribution. The area covered by a GW is evenly divided into 6 sectors and 10 APs are deployed in each sector.

We also implement four different WMN handoff solutions in the OPNET simulator: 802.11-based handoff, priority-queue-based handoff, split-phase-based handoff, and the proposed GaS handoff. In the 802.11-based handoff, data packets and signaling packets are transmitted in the same queue via the same communication channel. In the priority-queue-based handoff, data packets and signaling packets are transmitted from different queues and the signaling packet queue has a higher transmission priority than the data packet queue. In the split-phase-based handoff, all MRs are synchronized to make reservations during the control phase and send signaling/data packets during the data phase. In the proposed GaS scheme, handoff signaling packets are transmitted to the GW via DD transmission links during the signaling service period. In order to capture the real network scenarios, we also add data traffic flows on each backbone MR as the backbone traffic which are destined to other MRs deployed in the same WMN. In addition, we use 33%, 67%, and 100% backbone traffic to simulate the growing volume of backbone traffic in which the full mesh flows among all MRs in the mesh backbone is considered as the 100% backbone traffic volume.

5.3.2 Evaluation of the DD Transmission Throughput

In order to verify the maximum bandwidth that can be used for signaling transmissions at each direction, we propose an analytical model to evaluate the normalized saturated signaling throughput of the DD transmission at one of the directions. During a signaling service period, an AP has the probability of p to transmit at the beginning of each mini-slot, if the remaining length of the current signaling period is long enough for a complete signaling transmission. Otherwise, all APs do not attempt to transmit because of the insufficient signaling transmission time left. Other parameters required in the analysis are defined in Table 5.1.

Table 5.1: System Parameters in GaS

Parameter	**Explanation**
N_m	Average number of MRs at each direction
p_s	Successful transmission probability
L	Length of the signaling transmission period (unit: mini-slot)
l	Average length of signaling packets (unit: mini-slot)
ρ	Normalized saturated signaling throughput
N_{sec}	Total number of sectors
k	Maximum number of transmissions in a signaling period
P_i	Probability of i signaling transmissions occurred during a signaling period
N_{sig}	Average number of signaling transmissions in a signaling period

Since only one MR can successfully transmit its signaling packet in a signaling transmission mini-slot, the successful transmission probability p_s is

$$p_s = N_m p(1-p)^{(N_m-1)}. \tag{5.4}$$

In Table 5.1, we assume $L > l$, so that at least one signaling packet is possibly to be transmitted during a signaling period. Then, the possible number of transmissions in a signaling period can be considered as an event dataset $\{X_1, X_2, ..., X_k\}$, where k is the divisor of L and l. Given the occurrence probability P_i of each event X_i, the average number of signaling transmissions in a signaling period is

$$N_{sig} = \sum_{i=1}^{k} i \cdot P_i. \tag{5.5}$$

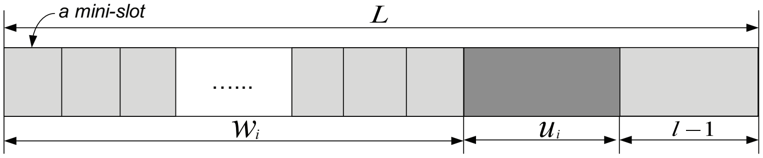


Figure 5.7: Signaling period analysis.

To calculate P_i, as shown in Figure 5.7, we consider the overall i possible signaling transmissions during a signaling period in two scenarios, when the maximum number of transmissions k is greater than 1: (1) all i transmissions *start* in the first w_i slots, where $w_i = L - u_i - (l-1)$; and (2) the first $i-1$ transmissions *end* within the first $w_i + j - 1$ slots and the last transmission *starts* at the jth slot among the u_i slots, where $j = 1, 2, ..., u_i$. As shown in Figure 5.7, u_i can be expressed as

$$u_i = \begin{cases} l-1, & i = 1,2,...,k-1; \\ d+1, & i = k, \end{cases} \tag{5.6}$$

where d is the reminder of L divided by l. Then, the occurrence probability of scenario (1), p_{w_i}, is

$$p_{w_i} = \begin{cases} \begin{pmatrix} w_i - (i-1)(l-1) \\ i \end{pmatrix}, & i = 1,2,...,k-1; \\ 0, & i = k; \end{cases} \tag{5.7}$$

The occurrence probability of scenario (2), $p_{u_{ij}}$, is

$$p_{u_{ij}} = \begin{pmatrix} w_i - (i-1)(l-1) + (j-1) \\ i-1 \end{pmatrix}. \tag{5.8}$$

Based on 5.7 and 5.8, P_i can be expressed as

$$P_i = \begin{cases} p_{w_i} p_s^i (1-p_s)^{w_i-(i-1)(l-1)-i} + \sum_{j=1}^{u_i} p_{u_{ij}} p_s^i (1-p_s)^{w_i-(i-1)(l-1)-i+j}, \\ \qquad\qquad\qquad\qquad \text{where } i \leq k \text{ and } k > 1; \\ \sum_{n=0}^{d} p_s(1-p_s)^n, \qquad\qquad \text{where } i = k \text{ and } k = 1; \end{cases} \tag{5.9}$$

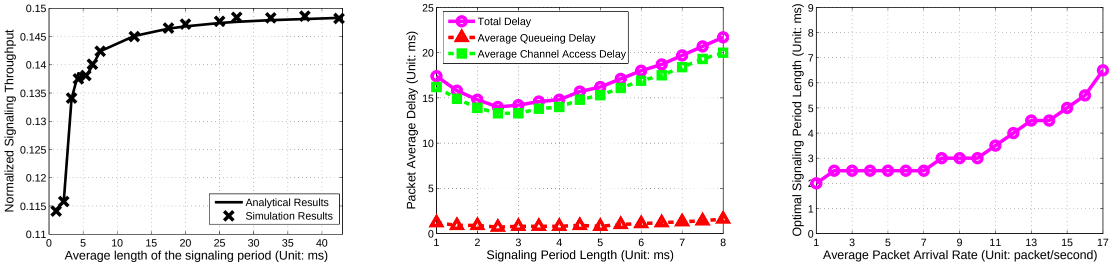
According to 5.5 and 5.9, the normalized signaling throughput ρ can be obtained as

$$\rho = \frac{N_{sig}}{N_{sec} \cdot L}. \tag{5.10}$$

We use simulations to validate the proposed analytical model. Similar to [45], we used $1/e$ as the saturated successful transmission probability p_s in the simulation. Figure 5.8(a) demonstrates that the analytical results of the saturated signaling throughput coincide with the simulation results under the variation of the signaling period length. As shown in Figure 5.8(a), the saturated signaling throughput is between 0.11 and 0.15, meaning that 11%∼15% of the channel resource is used for successful signaling transmissions at each direction. The previous studies show that 10% of the channel resource is needed for signaling transmissions in order to guarantee the overall handoff delay requirement in WMNs [55]. Therefore, under GaS, the channel resource used for signaling transmissions is enough to avoid signaling traffic congestions and guarantee the low handoff delay.

5.3.3 Evaluation of the Optimal Length of a Signaling Period

Figure 5.8(a) shows that a relative high signaling throughput requires a long signaling period under saturated scenarios. However, in real network environments, MRs may not always have handoff signaling packets to transmit. Therefore, a long signaling period may lead to considerable idle time slots due to the low arrival rate of signaling packets. In addition, signaling packets arrive randomly in real network scenarios. If the signaling period length is too long, signaling packets which arrive



(a) DD transmission throughput (b) Delay vs. signaling period length (c) Optimal signaling period length

Figure 5.8: Evaluation of DD transmission.

during the non-service period or during the last $l-1$ mini-slots of a signaling period as shown in Figure 5.7 need to wait until the next signaling period comes. On the other hand, a too short signaling period may not be long enough to satisfy the signaling packet arrivals in a certain direction. Under such scenarios, it is possible that a signaling packet needs to wait for several signaling period cycles before it can be successfully transmitted. Thus, we propose to explore the optimal signaling period length in order to obtain the minimum average signaling transmission delay.

In order to reap the full performance potential of the proposed GaS scheme, we evaluate the optimal length of a signaling period using simulations under different signaling packet arrival scenarios. In the simulation, signaling packets arriving during the signaling period can be transmitted immediately. On the other hand, if a signaling packet arrives during the non-signaling period, it will be cached in the queue until the next signaling period comes.

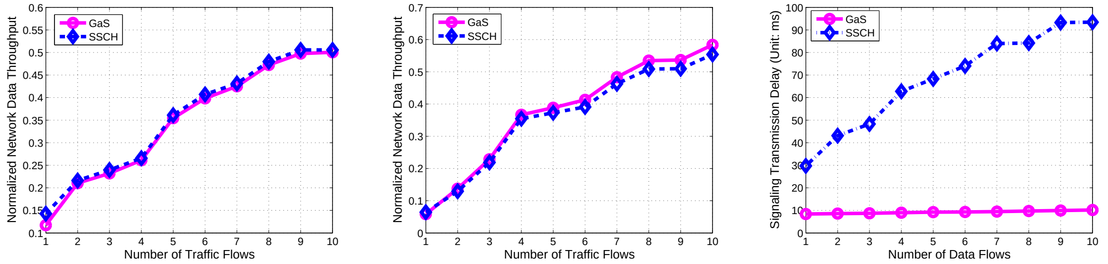
Figure 5.8(b) shows the relationship between the signaling period length and the average signaling delay when the signaling packet arrival rate equals 5 packets/second. As shown in Figure 5.8(b), the overall signaling delay is composed of the queueing delay (the time interval from the moment when a packet is generated at the MAC layer to the moment when it arrives at the head of the queue) and channel access delay (the time interval from the moment when a packet arrives at the head of the queue to the moment when it is successfully transmitted out) and it varies when the signaling period length increases. The signaling period length is considered optimal when the nadir of the overall signaling delay is reached. Therefore, as shown in Figure 5.8(b), we consider 2.5 ms as the optimal length of the signaling period when 5 signaling packets arrive at each MR every second.

To extensively exploit the optimal signaling period length under different scenarios, we summarize the optimal length of the signaling period under different signaling packet arrivals at each MR. As shown in Figure 5.8(c), the optimal signaling period length increases with the growing number of the signaling packet arrivals, because the increasing number of signaling packet arrivals at each MR requires longer signaling transmission period to avoid signaling traffic congestions in each sector.

5.3.4 Performance Results of GaS

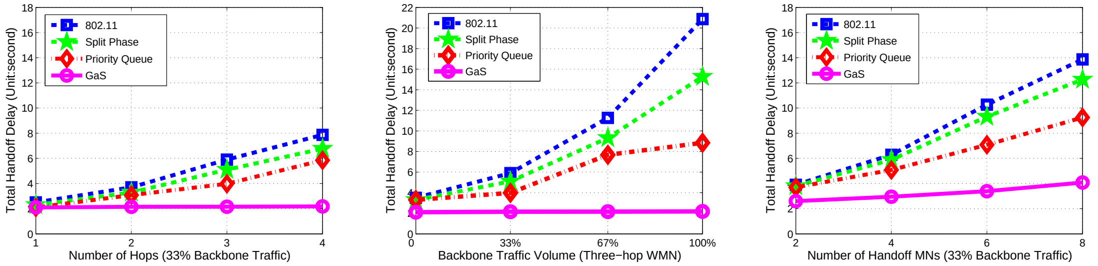
We first compare the data throughput and signaling transmission delay of the proposed GaS scheme with the SSCH multiple rendezvous approach proposed in [46]. As shown in Figure 5.9(a), the data throughput of the SSCH scheme slightly outperforms the GaS scheme, because signaling periods in the GaS scheme may be idle due to the low signaling packet arrivals. However, when the signaling packet arrival rate becomes high, the data throughput of the proposed GaS scheme outperforms SSCH, as shown in Figure 5.9(b). Moreover, as shown in Figure 5.9(c), since the source MR can transmit signaling packets when its signaling period comes without waiting for a long time to have the channel rendezvous with the destination MR, the average signaling transmission delay of the proposed GaS scheme is significantly lower than the SSCH scheme.

Figure 5.10 demonstrates the total handoff delay of different WMN handoff solutions. As shown in Figure 5.10(a) and (b), our proposed GaS scheme is not affected by the (1) growing number of wireless hops and (2) the increasing volume of backbone data traffic in the wireless mesh backbone. Hence, the handoff performance in GaS substantially outperforms the other three handoff solutions. As shown in



(a) Throughput (2 signaling packets/s)
(b) Throughput (8 signaling packets/s)
(c) Signaling transmission delay

Figure 5.9: Data throughput and signaling transmission delay.



(a) Handoff delay vs. number of hops
(b) Handoff delay vs. traffic volume
(c) Handoff delay vs. number of MNs

Figure 5.10: Handoff performance evaluation.

Figure 5.10(c), the handoff performance can be degraded by the growing number of handoff MNs in all schemes. However, due to the single-hop transmission of the handoff signaling packets, our proposed GaS scheme still outperforms the other handoff solutions.

CHAPTER 6: HICA: HIERARCHICAL CHANNEL ALLOCATION SCHEME

Various MAC solutions has been proposed in multi-radio multi-channel WMNs. Although there is no hardware cost and channel resource limitation for backbone MRs, existing MAC solutions cannot provide sufficient handoff support to mobile users. In this chapter, we first propose a channel reuse scheme by means of a novel hierarchical wireless mesh architecture. By doing this, the channel contention can be limited to a small area. Then, under such a network architecture, we propose a hierarchical channel allocation (HiCA) scheme to enhance the channel utilization and shorten the handoff delay simultaneously. In the proposed HiCA design, data packets and handoff signaling packets are delivered by MRs in separate time periods via different channels, without requiring time synchronization and channel hopping. In addition, since most backbone MRs are still configured with one wireless radio in HiCA, the hardware cost is much lower than existing multi-radio MAC solutions.

6.1 Problem Description

In the proposed HiCA scheme, we focus on reducing the handoff delay by eliminating channel contentions between signaling and data packets. However, the following issues existing in DCC-based channel allocation designs are also addressed in HiCA.

6.1.1 Multi-channel Hidden Terminal Problem

In DCC-based WMNs, a new type of hidden terminal problem exists called multi-channel hidden terminal problem. As illustrated in Figure 6.1, there are three available channels. Channel 3 is the control channel dedicated for RTS/CTS channel reservations. Channel 1 and 2 are for data transmissions. Initially, node A sends an RTS to node B on Channel 3 to request a data transmission. After receiving the RTS from A, B selects Channel 2 as the communication channel and informs A by replying a CTS. Then, both A and B switch to Channel 2 and start the data transmission. However, since C is transmitting to D on Channel 1 during the channel reservation of A and B, it cannot hear the CTS sent from B on Channel 3. Therefore, collisions may occur at B if C also selects Channel 2 for its next data transmission. This multi-channel hidden terminal problem should be resolved in DCC-based WMNs in order to reduce the number of collisions.

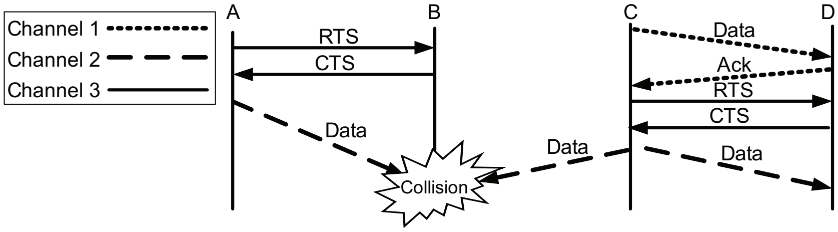


Figure 6.1: Multi-channel hidden terminal problem.

6.1.2 Channel Reuse Problem

As shown in Figure 6.2, node C is sending data packets to node D via Channel 2. Since nodes within the transmission range of node C and D, such as node B and E, can overhear the RTS and CTS sent from node C and D, respectively, they do not choose Channel 2 as their communication channel to avoid collisions. Under such situations, area 1 and 2 are considered as the contention area of Channel 2. Only the nodes deployed outside the contention area, such as node A, can reuse Channel 2 as their communication channel. Therefore, if the contention area can be reduced, more communication channels can be reused, thereby the overall channel utilization can be improved.

6.1.3 Channel Selection Problem

The data channel selection problem also often occurs in DCC-based multi-channel WMNs. As can be seen in Figure 6.2, every node maintains an available channel list (ACL) containing the current available channels. Node C may initiate a data packet transmission to D via either Channel 1 or Channel 2. When node C chooses Channel

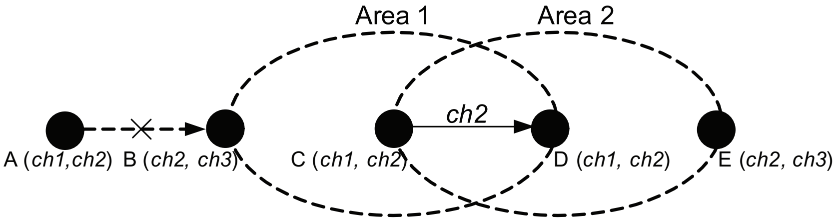


Figure 6.2: Channel reuse and selection problem.

2 as the communication channel regardless of its neighboring node B, node A and B cannot communicate with each other because Channel 2 is the only common channel between their ACLs. Hence, the performance of data channel utilization demands a good channel selection design.

6.1.4 Contributions

In this chapter, we consider to utilize the virtues of the hierarchical network architecture in mobility and resource management processes to address the above issues. In addition, based on the proposed architecture, the reservation/transmission of data and signaling packets can be scheduled in different time periods and on different channels, so the ETE delay of signaling packets is not affected by the data traffic volume in the wireless mesh backbone. Therefore, the handoff delay can be also greatly reduced by HiCA. The contributions of this design are explained as follows.

(1) We propose a directional antenna based hierarchical WMN architecture to reduce the channel contention area. By means of the cluster-based hierarchical network architecture, all channels can be reused in every mesh cluster.

(2) We propose an HiCA scheme to provide fast handoff support in multi-hop WMNs. In our proposed HiCA scheme, the reservations/transmissions of handoff signaling packets and data packets are coordinated in different time periods so that the channel contentions between them are eliminated. In addition, in HiCA, the usage of channel resources is managed by a cluster head (CH) in every mesh cluster. As a result, the multi-channel hidden terminal problem and channel selection problem

can also be solved. Moreover, an adaptive channel reservation design is proposed in HiCA to alleviate the channel reservation bottleneck problem.

(3) We propose an analytical model to evaluate the average channel utilization of HiCA and other existing channel allocation schemes. Both analytical results and OPNET simulation results show that HiCA can achieve high average channel utilization and short handoff delay under various handoff scenarios of WMNs.

6.2 Proposed WMN Architecture and HiCA Scheme

6.2.1 Network Architecture

Hierarchical network architecture is a trend in WMN design owing to less overhead, shorter average routing path, and its advantages of organizing and maintaining the network [56]. In this chapter, we propose a cluster-based hierarchical WMN architecture to reduce the channel contention area. Although cluster-based WMN architectures have been studied previously [57], only partial communication channels can be used in each cluster and two or more radios for the backbone connections are required for all MRs in previously proposed cluster-based architectures. Different from [57], in our proposed architecture, all communication channels can be used by each MR within a cluster and most MRs deployed in the WMN only need one radio for communications in the wireless mesh backbone.

As shown in Figure 6.3, a WMN is divided into mesh clusters. Each cluster has a CH which can be reached by other MRs within the cluster with one wireless hop. Border MRs (BMRs) are used to connect two neighboring clusters. In our proposed network architecture, each CH has two radios with omni-directional antennas. Each MR is configured with only one radio and one directional antenna facing the direction of its CH. Each BMR has two radios with two directional antennas responsible for the communications between the two connected clusters. In addition, those MRs with AP functions need one more radio with an omni-directional antenna providing the wireless access to MNs. In Figure 6.3, 180 degree directional antennas ($\alpha = 180^o$) are

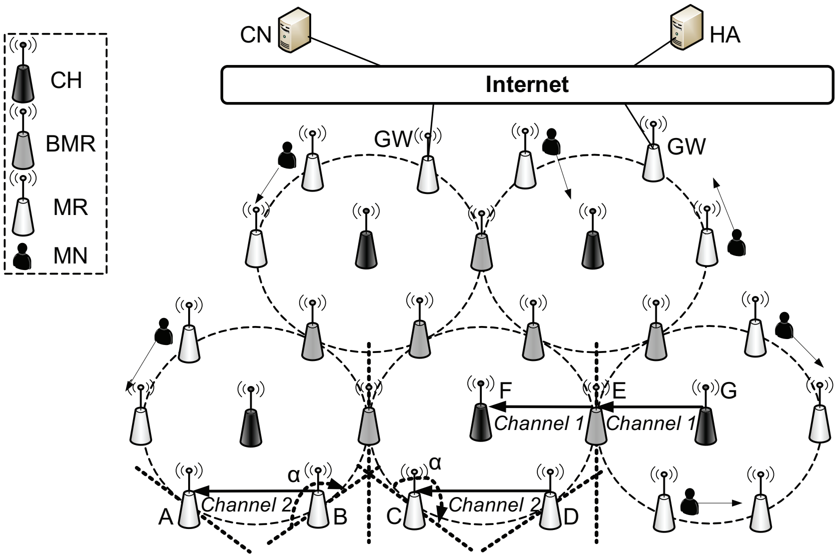


Figure 6.3: Proposed hierarchical WMN architecture.

used for MR/BMRs deployed in mesh clusters.

Since the directional antennas of MR/BMRs face the direction of their CHs, the transmission of an MR in one cluster does not disturb the receptions of its one-hop neighbors in other clusters. As shown in Figure 6.3, when MR C is receiving from MR D on Channel 2, MR B can still initiate a transmission to MR A via the same channel without causing collisions to MR C. Meanwhile, since MR E is a BMR configured with two radios with two directional antennas, it can communicate with MR F and G deployed in two different clusters at the same time via Channel 1 without interference. In addition, although omni-directional antennas are used by the CH G, the transmission of CH G does not interfere the reception of MR F which is two hops away. Therefore, by means of directional antennas, the channel contention area is reduced to one cluster.

To sum up, under our proposed hierarchical WMN architecture, the transmission within one cluster does not interfere the transmission/reception in neighboring clusters. Hence, the channel contention area is reduced to a single cluster. That is to say, all channels can be reused by every cluster.

6.2.2 Proposed HiCA Scheme

Since the channel contention problem between signaling and data packets still exists within a cluster under our proposed WMN architecture, we propose an HiCA scheme to solve this problem by scheduling data and signaling packets to be transmitted in separate time periods without requiring time synchronization. In addition, data channel allocation is managed by the CH within a cluster based on our proposed HiCA scheme, so the channel selection problem and multi-channel hidden terminal problem can be avoided.

In our proposed HiCA scheme, one of the communication channels is considered as the control channel. Other channels are used as the data channels assigned to MRs by the CH for data/signaling transmissions within a cluster. CHs are configured with two radios: one radio always monitors the control channel for making channel assignments to other MRs; the other radio is for data/signaling transmissions on data channels. MRs have one radio and can switch back and forth between the control channel and different data channels. All routers maintain two packet queues for data and signaling packets, respectively. The two queues have the same transmission priority in order to be fair to different types of packets.

In order to make the channel assignment efficiently, a channel state table (CST) and a signaling schedule table (SST) are maintained and updated by each CH. The CST contains the current availability of each channel, while the SST contains the addresses of MRs which are authorized to transmit signaling packets. In addition, considering two packet queues are maintained by each MR, we modify the RTS/CTS frames to realize the double-reservation of a data packet and a signaling packet simultaneously using only one RTS/CTS exchange. As shown in Figure 6.4, the *Dur_Data* and *Dur_Sig* fields represent the time required for a data and signaling transmission, respectively. The *CH_Addr* field contains the address of the CH. The *Src_Addr* field is for the sender's address. The *Dst_Data* and *Dst_Sig* fields contain the destination addresses of the data and signaling transmissions, respectively. The *Ch_index* field denotes the data channel index assigned.

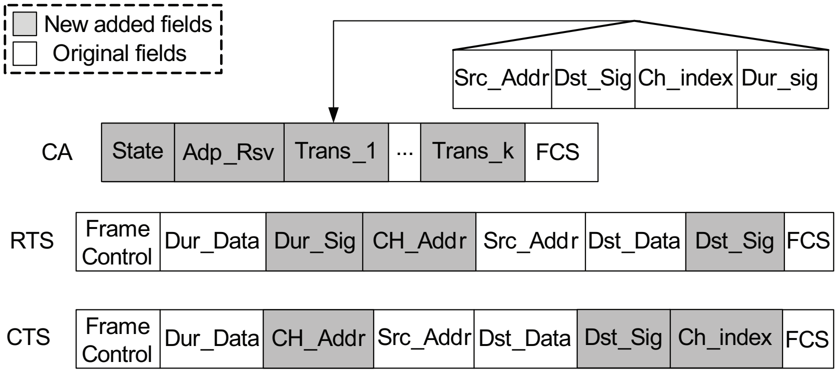


Figure 6.4: The CA frame and modified RTS/CTS frames.

In our proposed HiCA scheme, as shown in Figure 6.5, all data and signaling reservations and transmissions of MRs are divided into three time periods: double reservation period (DRP), free contention period (FCP), and signaling transmission period (STP). The switchover of MRs among different periods is controlled by the *CH_Announcement (CA)* messages broadcasted by the CH within a cluster. The format of the CA frame is shown in Figure 6.4. When the conditions of time period transitions are satisfied, as shown in Figure 6.6, CHs assign the *State* field of the *CA* message with the value 00, 01, or 10 to coordinate all MRs to switch to the double reservation period, free contention period, and signaling transmission period, respectively. The *Adp_Rsv* field defined in the CA frame is used to initiate the adaptive channel reservation process. The details of different periods defined in HiCA are described in the following.

6.2.2.1 Double Reservation Period (DRP)

During the double reservation period, only MRs with a non-empty data packet queue can initiate a data channel reservation. If the signaling queue of an MR is empty, the MR only initiates a channel reservation for its data packet. However, if an MR also has a non-empty signaling queue, it initiates a double-reservation for its

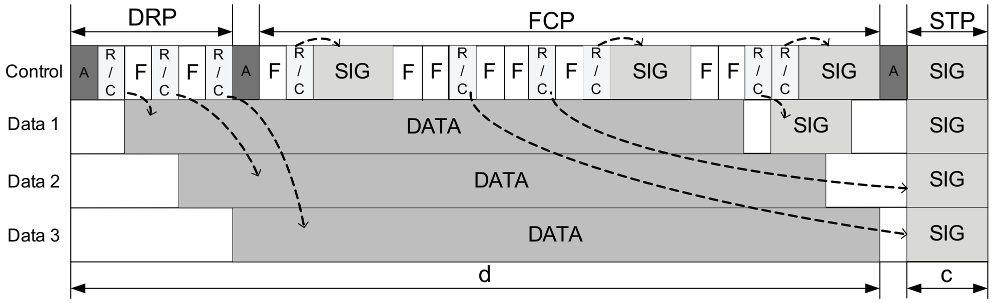


Figure 6.5: Transmission and reservation periods in HiCA.

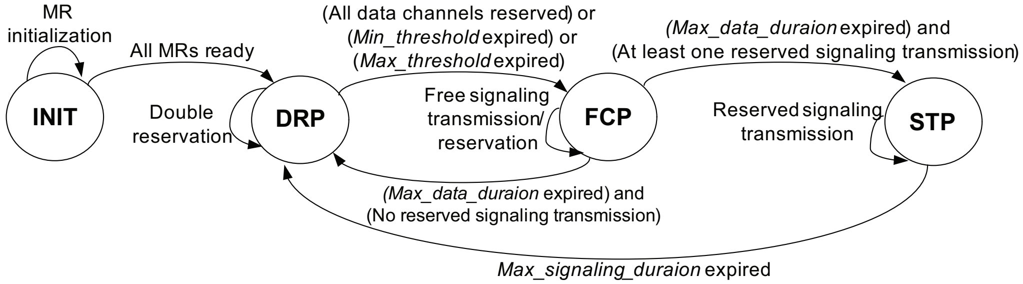
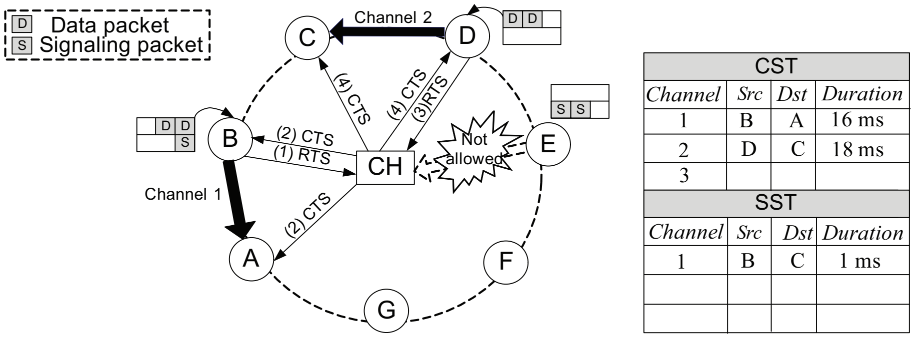


Figure 6.6: Time period transitions in HiCA.

data and signaling packets simultaneously. After filling out all the required fields of an RTS as defined in Figure 6.4, if any, the MR sends the RTS to its CH on the control channel. When receiving the RTS, the CH selects a free data channel in the CST and fills out all the required fields of a CTS as defined in Figure 6.4. In addition, if the field *Dst_Sig* in the RTS is not empty, meaning that a signaling reservation is also contained in the RTS, the CH records the addresses contained in *Src_Addr* and *Dst_Sig* to the SST and updates the CST accordingly. After that, the CH sends the CTS on the control channel to the requested MR and destined MR as the approval of the requested data transmission. When receiving the CTS, both MRs switch to the assigned data channel based on the *Ch_index* field of the CTS for the data transmission. When all data channels are assigned to MRs, the CH calculates the maximum duration time of the data transmissions on data channels, *Max_data_duration*, for the starting time of the signaling transmission period.

Figure 6.7 shows an example of the channel assignment during the double reser-



CST			
Channel	*Src*	*Dst*	*Duration*
1	B	A	16 ms
2	D	C	18 ms
3			

SST			
Channel	*Src*	*Dst*	*Duration*
1	B	C	1 ms

Figure 6.7: Double reservation period (DRP).

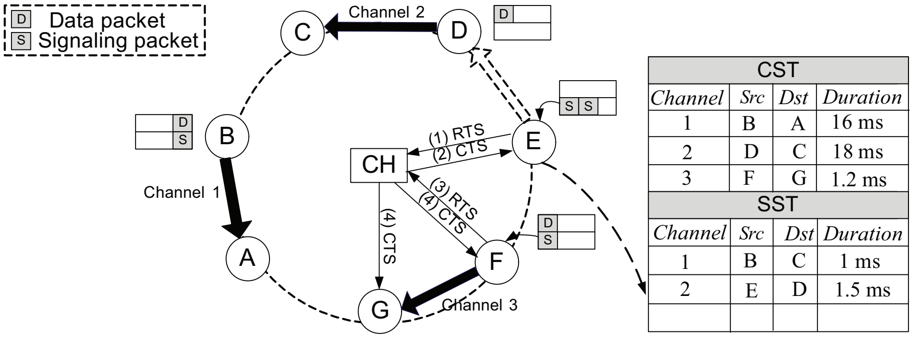
vation period based on the proposed HiCA scheme. MR A, B, C, D, E, F, and G are located in the same cluster and three channels are available within the cluster. Channel 3 is used as the control channel and Channel 1 and 2 are data channels. The CH always has a radio monitoring Channel 3 and all other MRs switch their radios to Channel 3 whenever they are idle.

At first, MR B needs to send a data packet to A. Since MR B still has a signaling packet to transmit destined to MR C, it sends an RTS containing the destination addresses of both MR A and C to the CH on Channel 3 to request an available data channel as well as to reserve a signaling transmission in the coming signaling transmission period. On receiving the RTS from MR B, the CH selects Channel 1 from the CST as the data channel for A and B and then updates the source, destination, and duration fields of Channel 1 in the CST, meaning that Channel 1 is no longer available for other MRs in the cluster. Then, the CH replies a CTS containing the information of Channel 1 to both B and A. After receiving the CTS from the CH, both A and B switch their radios from Channel 3 to Channel 1 to start the data communication. In addition, the CH also records the addresses of MR B and C to its SST and assigns Channel 1 as the signaling transmission channel for B and C in the coming signaling transmission period. Moreover, since MR D only has data packets to transmit, it sends an RTS to the CH to request a data transmission destined to C. Having checked the CST, the CH assigns Channel 2 to MR C and D for the requested data transmission. When MR C and D receive the CTS from the CH, they both switch to Channel 2 for the data transmission. As shown in Figure 6.7, although MR E has signaling packets in the queue, it is not allowed to make a channel reservation for signaling transmissions at this moment, because only the MRs with a non-empty data packet queue can make channel reservations during the double reservation period. Finally, all data channels are assigned to MRs and the duration time of Channel 2 (18 ms) is calculated by the CH as the *Max_data_duration*.

Our proposed double-reservation can enhance the reservation efficiency under our proposed architecture. Other channel allocation schemes can hardly realize this double-reservation even with two-radio MRs, because it is difficult to schedule another signaling transmission for the MRs currently involved in different data transmissions without coordination. The double reservation period is completed when one of the following conditions is satisfied: (1) all data channels have been successfully assigned to MRs; (2) no RTS reservation is received by the CH after a time interval *Min_threshold*; and (3) the duration of the double reservation period is greater than *Max_threshold*. Since the number of backbone MRs and available channels can vary for different WMNs, the value of *Min_threshold* and *Max_threshold* can be dynamically changed by the CH to adjust the length of the double reservation period.

6.2.2.2 Free Contention Period (FCP)

The free contention period is activated by the CH after the double reservation period. In this period, an idle MR who fails to reserve a channel for data transmissions or has new signaling packet arrivals during the double reservation period can transmit signaling packets on the control channel, if the destination MR is idle. However, if the destination MR is busy, e.g., the destination MR is transmitting/receiving on a data channel, the source MR can reserve a channel to transmit the signaling packet in the coming signaling transmission period. By doing this, all single-radio MRs have the opportunity to transmit/reserve their signaling transmissions during the free contention period.



CST			
Channel	*Src*	*Dst*	*Duration*
1	B	A	16 ms
2	D	C	18 ms
3	F	G	1.2 ms

SST			
Channel	*Src*	*Dst*	*Duration*
1	B	C	1 ms
2	E	D	1.5 ms

Figure 6.8: Free contention period (FCP).

In the example shown in Figure 6.8, assume that MR E has a signaling packet destined to MR D. It first sends an RTS to the CH to request a channel for its signaling transmission. Since the destination MR D is currently busy in the CST and Channel 2 has not been reserved for signaling transmissions in the SST, the CH assigns Channel 2 to MR E by replying a CTS so that MR E can initiate the signaling transmission when MR D becomes idle in the future signaling transmission period. After that, if MR F has a signaling packet destined to MR G, since the destination MR G is idle and all data channels are busy at the moment, the CH allows MR F to transmit the signaling packet to MR G on the control channel.

In addition, since a signaling packet is generally much shorter than a data packet, data channels which become idle during the free contention period can also be assigned by the CH to MRs with signaling packets, as shown in Figure 6.5.

By means of the free contention period, the idle time periods existing on the control channel and data channels can be well used for the signaling reservations/-transmissions. However, although these idle periods also exist in other multi-channel MAC solutions, they cannot be easily detected and used by MRs without notifications from a CH. The free contention period is completed when the value of *Max_data_duration* becomes zero, meaning that all data transmissions on the data channels are completed.

6.2.2.3 Signaling Transmission Period (STP)

When all the data transmissions on the data channels are completed, the MRs switch their radios back to the control channel. If there is no reserved signaling transmissions in the SST, the CH broadcast a *CA* message to start the next double reservation period. Otherwise, it broadcasts a *CA* message on the control channel to all MRs to start the signaling transmission period. The *CA* message contains the information of the scheduled signaling transmissions, including the source address, destination address, duration time, and channel index. When receiving the *CA* message, MRs with scheduled signaling transmissions switch to the assigned data channels for signaling transmissions. When the maximum duration time for signaling transmissions, *Max_sig_duration*, becomes zero, the next double reservation period starts. As shown in Figure 6.9, after sending the *CA* message, the CH flushes its CST and SST. Signaling transmissions are carried out from MR B to C on Channel 1 and MR E to D on Channel 2. Meanwhile, the time required for the signaling transmission from E to D (1.5 ms) is considered as the *Max_sig_duration*.

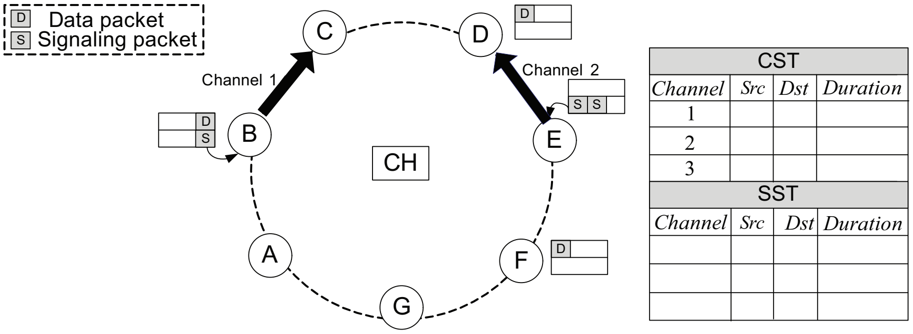


Figure 6.9: Signaling transmission period (STP).

6.2.2.4 Summary

Our proposed HiCA scheme can provide fast channel access for signaling packets by eliminating contentions between data and signaling packets (since data and signaling packet reservations/transmissions are carried out in different time periods) and utilizing all the possible idle periods in the control and data channels for signaling transmissions. Therefore, short signaling ETE delay can be achieved. In addition, HiCA considers the different lengths of data and signaling packets and explores the channel idle periods caused by the long transmission time of data packets on other channels for short signaling transmissions. Therefore, high channel utilization can be achieved. Moreover, due to the coordination of the CH, the multi-channel hidden terminal problem and channel selection problem will not occur and time synchronization for all MRs is not required in our proposed HiCA scheme.

6.3 Proposed Adaptive Channel Reservation Scheme in HiCA

In the previous section, three transmission periods, the double reservation period (DRP), free contention period (FCP), and signaling transmission period (STP), are designed in HiCA to eliminate the contentions between data and signaling packets. The transition from the DRP to FCP is triggered when all data channels are successfully reserved by MRs, meaning that the data channel reservation time on the control channel is a main factor determining the length of the DRP. Long DRP caused by the low channel reservation efficiency on the control channel may result in long idle time on data channels. To address this problem, we propose an adaptive channel reservation scheme to accelerate data channel reservations during the DRP.

6.3.1 Channel Reservation Bottleneck Problem

In DCC-based MAC schemes, when only one control channel is used for MRs to reserve data transmissions, data channels cannot be fully utilized if the data packet size is very small or the reservation on the control channel takes a long time, as shown in Figure 6.10. Previous works [41, 45] consider this problem as the control channel bottleneck problem. As shown in Figure 6.10, due to the reservation bottleneck on the control channel, data transmissions are executed on data channel 1, 2 and 3 only. Therefore, data channel 4 and 5 are idle all the time, resulting in low overall channel utilization.

In this section, this issue is further investigated and the control channel bottleneck

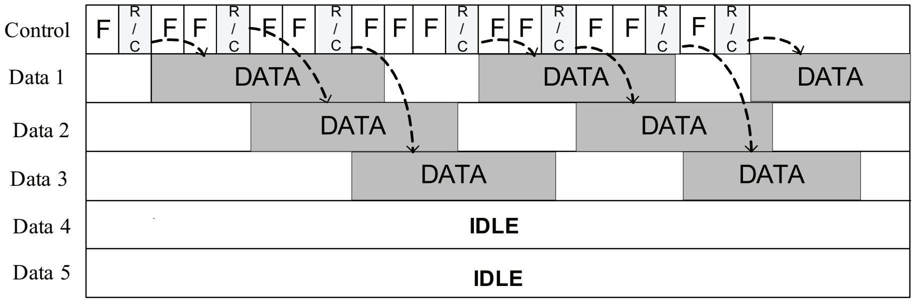
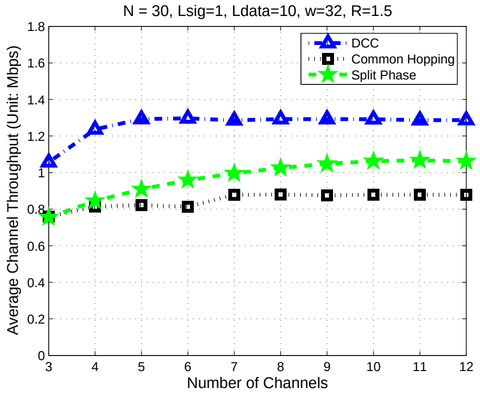


Figure 6.10: Control channel bottleneck problem.

problem mentioned in [45, 41] is extended to a channel reservation bottleneck problem. This problem exists in all contention-based channel reservation MAC schemes, including those schemes even without a dedicated control channel, such as the split phase and common hopping approaches. Through simulations, we find that the control channel reservation problem is caused by the following three scenarios: (1) due to the small data packet size, some reserved data channels may become idle again after short data transmissions, while other idle channels are still waiting to be reserved; (2) the number of channels is large; and (3) a large number of MRs compete on the control channel to reserve their packet transmissions, which results in a long reservation time. To summarize, the channel reservation bottleneck problem can be either caused by the small data packet size or the long channel reservation time. Therefore, given a fixed data packet size, the number of channels, and the number of MRs, the only way to mitigate the channel reservation bottleneck problem is to reduce the long data channel reservation time.

Simulation results in Figure 6.11 show the relationship between the average channel throughput and the total number of channels in the DCC approach, split phase approach, and common hopping approach. One control channel is defined in the DCC approach, while no common control channel is used in the split phase and common hopping approaches. The parameters used in the figures are explained in Section VI. As shown in Figure 6.11, when the total number of channels is greater than a certain threshold, the average channel throughput of these three MAC schemes does



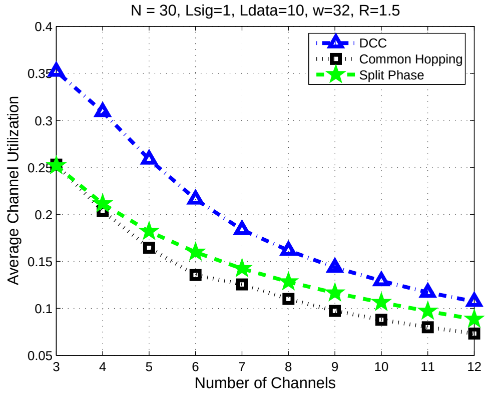


Figure 6.11: Average channel throughput. Figure 6.12: Average channel utilization.

not increase too much, even though the number of channels continues to grow. In addition, due to the channel reservation bottleneck problem, the overall channel utilization drops sharply when the total number of channels grows, as shown in Figure 6.12.

To sum up, due to the small data packet size and the long channel reservation time, existing contention-based channel reservation MAC schemes may suffer the channel reservation bottleneck problem, which leads to the channel throughput saturation and low channel utilization.

6.3.2 Adaptive Channel Reservation in HiCA

In order to solve the channel reservation bottleneck problem, [58] proposes that multiple control channels can be used by MRs to negotiate their sessions on data channels. By means of simultaneous reservations on different control channels, all data channels can be successfully reserved within a short time. However, [58] also points out that this solution is only suitable for networks with a high traffic load and a large number of channels. Since the network traffic load is time-variant, using multiple channels as the control channel is inefficient when the network traffic load is low. In addition, since the channel resource is limited in a real network, the implementation of multiple control channels is impractical.

We propose an adaptive channel reservation scheme during the DRP in HiCA to accelerate data channel reservations. As defined in HiCA, the transition from the DRP to FCP is triggered when all data channels are successfully reserved once. When the DRP begins, data channels are reserved by MRs on the control channel one after another for their data packet transmissions. It is possible that some data transmissions are completed on certain data channels, while other data channels are still waiting to be reserved during the DRP, when the data packet size is small or the channel reservation time is long. Under such scenarios, the adaptive channel reservation process is automatically executed by the CH which dynamically allocates one or more idle data channels as additional control channels to accelerate data channel reservations. The utilization of one or more control channels does not require additional radios at MRs to monitor these new control channels. In our design, the only requirement to realize the adaptive channel reservation is to configure CHs with multiple radios and the number of configured radios determines how many new control channels can be used during the DRP.

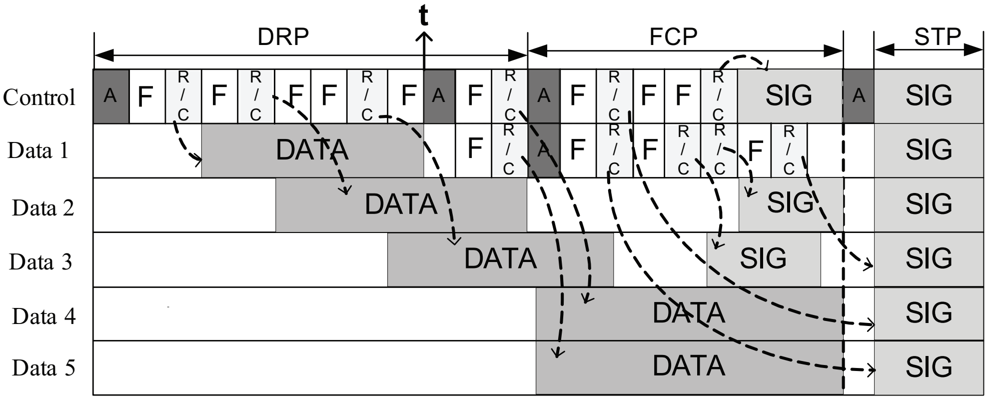


Figure 6.13: Adaptive channel reservation in HiCA.

Figure 6.13 shows an example of our proposed HiCA with adaptive channel reservation. As shown in Figure 6.13, the data transmission on data channel 1 finishes at time t. However, data channel 4 and 5 have not been successfully reserved. At this moment, the CH begins to use data channel 1 as an additional control channel to speed up the channel reservation. To realize this, it first divides the MRs in the cluster into two groups by advertising a *CA* message on the control channel. The information of the groups and their corresponding control channels are contained in the *Adp_Rsv* field of the *CA* message. Assume that the CH assigns data channel 1 as the new control channel for MRs in group 2. When receiving this CA message, MRs in group 2 switch their radios to data channel 1 and consider data channel 1 as their newly assigned control channel. On the other hand, MRs in group 1 still compete to reserve the remaining data channels on the original control channel. Meanwhile, the CH starts to use an additional radio monitoring data channel 1 and gets ready to receive RTS requests from MRs in group 2. By doing this, MRs in group 1 and group 2 can make data channel reservations on the original control channel and data channel 1, respectively, even though the sender and the receiver may belong to different groups. As shown in Figure 6.14, assume that MR A and MR B are assigned to group 1 and 2, respectively, and MR B needs to initiate a data transmission to MR A. Since MR B has already switched its radio to data channel 1 after receiving the CA message, it sends an RTS on data channel 1 to the CH. After confirming that MR A is idle and data channel 4 has not been reserved, the CH assigns data channel 4 to them by replying a CTS to MR A and B on the original control channel and data channel 1, respectively. When MR A and B receive the CTS, they switch their radios to data channel 4 and start the communication. Therefore, MRs in different groups can still exchange RTS/CTS with each other on different channels with the assistance of their CH.

Under our design, multiple control channels will be used until the next DRP starts. As shown in Figure 6.13, during the FCP, multiple control channels can be used for idle MRs to execute their signaling packet transmissions/reservations. MRs in different groups can use the same way to exchange RTS/CTS as described in Figure 6.14. When the current STP ends, all MRs switch their radios to the original control channel. Data channel 1 will no longer be used as an additional control channel,

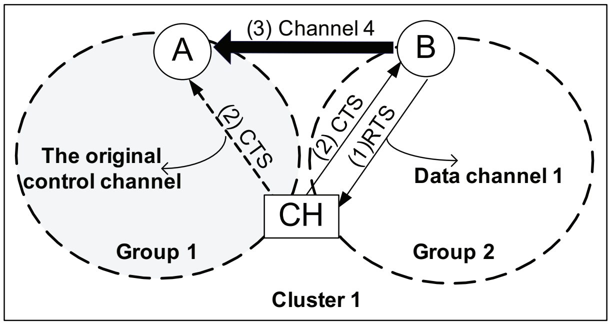


Figure 6.14: Channel reservation between MRs in different groups.

unless the channel reservation bottleneck problem is detected again by the CH in a future DRP.

6.3.3 Summary

In this section, an adaptive channel reservation scheme is designed in HiCA to solve the channel reservation bottleneck problem which is caused by the small data packet size and/or the long channel reservation time. By means of dynamically allocating one or more idle data channels as additional control channels during the DRP, the reservation process can be executed simultaneously on different channels, so the overall data channel reservation time can be greatly reduced, as compared to the single control channel scenario, especially when the number of channels is large. On the other hand, since the total number of MRs in a cluster are split into multiple groups, the number of competing MRs on the same channel is reduced, which also accelerates data channel reservations. In addition, since the network traffic volume varies over the time, the multiple channel reservation process is executed by the CH only when the channel reservation bottleneck problem is detected in a network. Therefore, a high overall channel throughput and utilization can be achieved by HiCA under different network scenarios.

6.4 Performance Evaluation

In order to evaluate the performance of our proposed HiCA scheme, we consider two performance metrics: (1) *average channel utilization (ACU)*: the average channel bandwidth used for packet transmissions (both data and signaling packets); and (2) *total handoff delay*: the time from an MN disconnects with its old AP until it receives data packets from its new AP which includes both the link-layer and network-layer handoff delay. We first propose an analytical model to analyze the ACU of HiCA and other existing multi-channel MAC schemes. Then, we compare the handoff delay of HiCA with existing handoff solutions using OPNET simulations.

6.4.1 Average Channel Utilization Analysis

We first propose an analytical method to evaluate the ACU of the DCC [37], common hopping [43], split phase [41], and our proposed HiCA schemes under handoff scenarios in WMNs. In order to make fair comparisons, the evaluation of all schemes is based on our proposed hierarchical WMN architecture in which the channel contention only exists within a cluster. Similar to [45], time is divided into slots and the time required for an RTS/CTS reservation is considered as one slot. Data and handoff signaling packets can be multiple slots long. We assume that each MR has two non-empty queues: a data packet queue and a signaling packet queue. An MR has the probability of p to transmit at the beginning of each slot. In addition, the total number of active transmission pairs on data channels is defined as the system state. Other parameters required in the analysis are defined in Table 6.1.

6.4.1.1 DCC approach

In DCC-based approaches, one of the communication channels is used as the control channel dedicated for RTS/CTS reservations, so only $M-1$ channels can be used for data/signaling transmissions. Since two packet queues are maintained, each MR randomly selects a queue to transmit with probability p at the beginning of each time slot. Then, T_k^j can be derived as

$$T_k^j = \binom{k}{j}(\frac{2}{L_{data}+L_{sig}})^j(1-\frac{2}{L_{data}+L_{sig}})^{k-j}. \tag{6.1}$$

Table 6.1: System Parameters in HiCA

Parameter	**Explanation**
N	Number of MRs in a cluster
M	Total number of channels
w	Initial size of the backoff window
S_k^i	Probability of i new reservations made in state k
T_k^j	Probability of j transmissions terminated in state k
p_{kl}	Transition probability from state k to l
L_{sig}	Signaling packet length (unit: slot)
L_{data}	Data packet length (unit: slot)
π_k	Steady-state probability of state k
ρ	Average channel utilization
R	Channel switch penalty factor
c	Average length of the control phase (unit: slot)
d	Average length of the data phase (unit: slot)

Since at most only one new reservation can be made during each slot, S_k^i is

$$S_k^i = \begin{cases} (N-2k)p(1-p)^{(N-2k-1)}, & i = 1; \\ 1 - S_k^1, & i = 0; \\ 0, & \text{otherwise.} \end{cases} \tag{6.2}$$

Then, p_{kl} can be described as

$$p_{kl} = T_k^{k-l} S_k^0 + T_k^{k-l+1} S_k^1, \tag{6.3}$$

where $T_k^j = 0$ when $j < 0$. The steady-state probability $\pi_k(k = 0, 1, 2, ..., M-1)$ can be derived based on 6.1, 6.2, and 6.3. Then, the ACU ρ is given by:

$$\rho = \frac{\sum_{k=0}^{M-1} \pi_k * k}{M}. \tag{6.4}$$

6.4.1.2 Common hopping approach

In common hopping approaches, all MRs are synchronized with the same hopping sequence. Since a pair of MRs can stop hopping and remain on any of the M channels to transmit data packets after making an agreement, all the M channels can be used as data channels. However, it suffers the channel switching delay at the beginning of each time slot. Then, T_k^j becomes

$$T_k^j = \binom{k}{j}(\frac{2R}{L_{data}+L_{sig}})^j(1-\frac{2R}{L_{data}+L_{sig}})^{k-j}. \tag{6.5}$$

where R is the channel switch penalty factor. In addition, an MR can transmit only when the current hopping channel is available and the destination MR is idle, so S_k^i becomes

$$S_k^i = \begin{cases} \frac{M-k}{M}\frac{N-2k-1}{N-1}(N-2k)p(1-p)^{(N-2k-1)}, & i=1; \\ 1-S_k^1, & i=0; \\ 0, & \text{otherwise.} \end{cases} \tag{6.6}$$

The steady-state probability $\pi_k(k = 0, 1, 2, ..., M)$ can be derived based on 6.3, 6.5, and 6.6. Then, the ACU ρ is given by

$$\rho = \frac{\sum_{k=0}^{M} \pi_k * k}{M}. \tag{6.7}$$

6.4.1.3 Split phase approach

The split phase approaches have two time phases: a control phase and a data phase. MRs make channel reservations during the control phase and send/receive packets during the data phase. In our analysis, we consider the average time required for reserving M channels as the length of the control phase c and the time required for transmitting a data packet as the length of the data phase d. In addition, an MR can only reserve one transmission during the control phase. The average length of the control phase c can be expressed as

$$c = \sum_{k=0}^{M-1} \frac{1}{(N-2k)p(1-p)^{(N-2k-1)}}. \tag{6.8}$$

The ACU ρ is

$$\rho = \frac{\sum_{k=0}^{M} \frac{\binom{M}{k}}{2^M}(kL_{sig} + (M-k)L_{data})}{M(c+d)}, \tag{6.9}$$

where the numerator denotes the average time slots utilized for signaling/data packet transmissions in the data phase.

6.4.1.4 HiCA

In our proposed HiCA scheme, two reservations via one RTS/CTS exchange is allowed during the double reservation period. As shown in Figure 6.5, we consider the time required for signaling transmissions as c. In addition, the total time required for the double reservation period, signaling reservation period, and free contention period are considered as the length of the data period d, which can be expressed as

$$d = L_{data} + \sum_{k=0}^{M-2} \frac{1}{(N-2k)p(1-p)^{(N-2k-1)}}. \tag{6.10}$$

In addition, the average number of signaling packets transmitted in the free contention period can be expressed as

$$n = \frac{L_{data} - 1}{L_{sig} + 1/((N-2(M-1))p(1-p)^{(N-2(M-1)-1)})}. \tag{6.11}$$

Then, the ACU ρ is

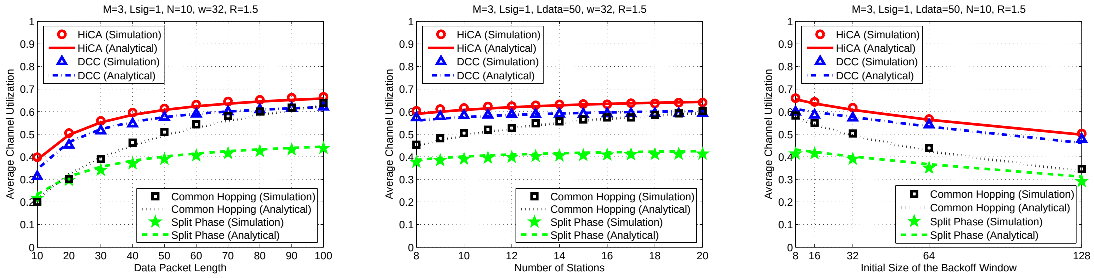
$$\rho = \frac{(L_{data} + L_{sig})(M-1) + nL_{sig}}{M(c+d+1)}. \tag{6.12}$$

6.4.2 Simulation Setup for Handoff Delay Analysis

We implement five different WMN handoff solutions in the OPNET simulator: 802.11-based handoff, split-phase-based handoff, DCC-based handoff, priority-queue-based handoff, and HiCA-based handoff.

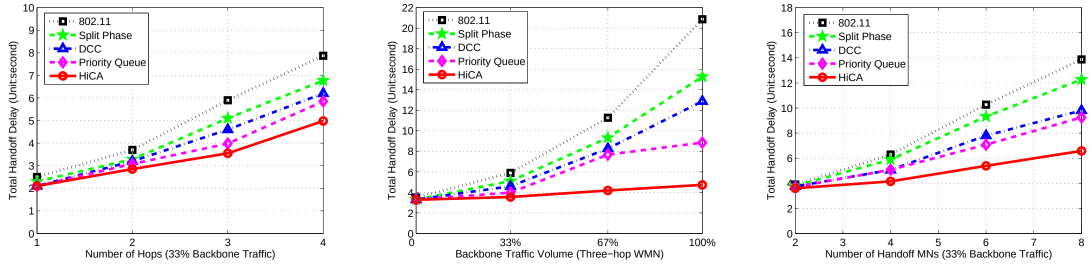
In the 802.11-based handoff, data packets and signaling packets are transmitted in the same queue via the same communication channel. In the split-phase-based handoff, all MRs are synchronized to make reservations during the control phase and send signaling/data packets during the data phase. In the DCC-based handoff, a dedicated control channel is used for RTS/CTS reservations and handoff signaling packets are transmitted in data channels. In the priority-queue-based handoff, data packets and signaling packets are transmitted from different queues and the signaling packet queue has a higher transmission priority than the data packet queue. Hence, data packets can be transmitted only when the signaling packet queue is empty. In our proposed HiCA-based handoff, the reservation/transmission of signaling and data packets are carried out in different time periods via the coordination of CHs. In all OPNET handoff simulations, $M = 3$ and $N = 7$.

We implement a WMN architecture in OPNET with multiple MRs and gateways to form a multi-hop wireless mesh backbone. In order to capture the real network scenarios, we add traffic flows on each backbone MR as the backbone traffic which are destined to other MRs deployed in the same WMN. In addition, we use 33%, 67%, and 100% backbone traffic to simulate the growing volume of the backbone traffic in which the full mesh flows among all MRs in the mesh backbone is considered as the 100% backbone traffic volume. MRs with AP functions are configured with one more radio. In our implemented handoff scenarios, MNs move from one AP to another which are deployed in two different WMNs. Hence, both link-layer and network-layer handoffs are needed during the movement of the MNs. The video streaming traffic from a CN to an MN starts at 60 second in the simulation. The Internet has a constant delay of 0.1 second. The simulation lasts for 20 minutes and the video traffic ends at the end of the simulation.



(a) ACU vs. data packet length (b) ACU vs. number of stations (c) ACU vs. initial backoff window

Figure 6.15: Average channel utilization.



(a) Handoff delay vs. number of hops (b) Handoff delay vs. traffic volume (c) Handoff delay vs. number of MNs

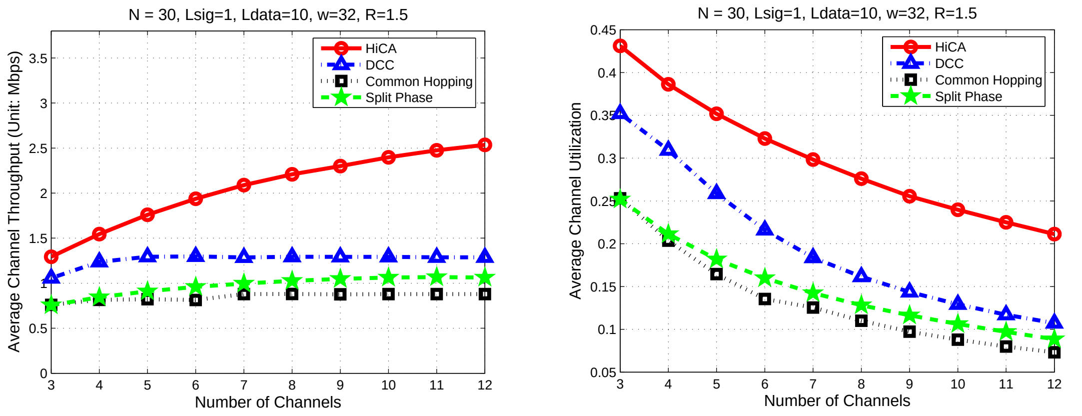
Figure 6.16: Total handoff delay.

6.4.3 Result Analysis

We validate our proposed analytical model using simulations. Figure 6.15 demonstrates that the analytical results of the average channel utilization coincide with the simulation results very well with a maximum difference 6.7%, under the variation of data packet length, L_{data}, number of MRs, N, and initial size of the backoff window, w. As shown in Figure 6.15(a), the growing of the data packet length can improve the average channel utilization, especially in our proposed HiCA scheme. This is because that long data packet transmissions can increase the length of the free contention period on the control channel but the channel reservation time stays the same, leading to the reduction of the ratio of idle periods to transmission periods. When the number of MRs and initial size of the backoff window increase, as shown in Figure 6.15(b) and (c), due to the coordination of CHs, the channel utilization of our proposed HiCA scheme still outperforms other channel allocation methods.

Figure 6.16 shows the total handoff delay of different WMN handoff solutions. As shown in Figure 6.16(a), the total handoff delay increases along with the number of hops in the wireless mesh backbone. Since the handoff signaling traffic does not compete channels with the backbone data traffic, our proposed HiCA scheme shows the best handoff performance. Figure 6.16(b) gives the total handoff delay under different percentage of backbone traffic volume. The handoff delay sharply increases with the growing of backbone traffic volume in the 802.11-based, split-phase-based, and DCC-based handoff solutions. However, it can be maintained within a certain range using our proposed HiCA design. In other words, the handoff delay is relatively independent of the backbone traffic volume in HiCA. In the priority-queue-based handoff solution, signaling packets have a higher transmission priority, so the queueing delay can be reduced. However, handoff signaling packets still need to compete with the backbone traffic from other MRs to access channels, so the total handoff delay still increases as the backbone traffic volume grows. Figure 6.16(c) shows the handoff performance when multiple MNs requiring handoffs. Since the handoff signaling traffic increases under this multi-handoff scenario, the total handoff delay increases with the number of the handoff MNs in all solutions. However, due to the separate transmissions of handoff signaling and data packets, our proposed HiCA scheme still outperforms other handoff solutions.

In addition, we also evaluate the performance of the average channel throughput and channel utilization using simulations under channel reservation bottleneck scenarios. In the simulation scenarios, each CH is configured with three radios, and can dynamically use one idle data channel as an additional control channel to accelerate data channel reservations, when the channel reservation bottleneck problem occurs. As shown in Figure 6.17(a), since the DCC, split phase, and common hopping approaches suffer from the long channel reservation time, the average channel throughput of these three schemes does not change too much as the number of chan-



(a) Average channel throughput vs. number of channels (b) Average channel utilization vs. number of channels

Figure 6.17: Channel reservation bottleneck scenario.

nels increases. However, since one additional control channel can be dynamically used for data channel reservations, the average channel throughput of HiCA continues to grow as the number of channels increases. Figure 6.17(b) shows that the performance of channel utilization of HiCA also outperforms the other three schemes when the number of channels grows.

CHAPTER 7: CONCLUSION

7.1 Completed Work

In this dissertation, four MAC schemes, contention-based time division (ConT) [59], channel splitting (ChaS) [55, 60, 61], gateway scheduling-based (GaS) [62], and hierarchical channel allocation (HiCA) [63, 64, 65], are proposed to reduce the inter-gateway handoff delay in single-channel single-radio, single-channel multi-radio, multi-channel single-radio, and multi-channel multi-radio WMNs, respectively.

The proposed ConT scheme focuses on reducing the channel access delay and queueing delay at each MR to shorten the overall handoff delay. A separate signaling queue is used to avoid the long queueing delay brought by the high backbone traffic volume. In order to reduce the channel access delay, the transmissions of handoff signaling packets and data packets are scheduled in different time periods. In addition, the optimal length of data and signaling periods is evaluated by means of simulations to achieve low signaling MAC delay and high data throughput. OPNET simulations are conducted to evaluate the handoff performance of the proposed ConT scheme. Simulation results confirm that the handoff performance of our proposed ConT scheme outperforms existing handoff solutions in single-channel single-radio WMNs under various scenarios.

In the proposed ChaS scheme, we split the single backbone channel to a data channel and a control channel, dedicated for the data and signaling communications, respectively, so the handoff signaling packets and data packets are transmitted separately in different frequency domains. Based on this, we propose (1) selective control channel scanning to reduce the link-layer handoff delay and (2) separate channel transmissions to shorten the network-layer handoff delay. In addition, two packet transmission designs, SCT and CCT, are proposed to enhance the channel throughput in the wireless mesh backbone. The optimal bandwidth ratio of the data channel to the control channel is evaluated in order to optimize the network performance. Under the optimal bandwidth ratio, the handoff performance, data packet ETE delay, and the channel utilization are evaluated under different traffic scenarios. Simulation results show that the handoff performance and channel utilization can be improved significantly, as compared to existing solutions in single-channel multi-radio WMNs.

The proposed GaS scheme is the first WMN fast handoff scheme exploiting the virtues of directional antennas. In the GaS scheme, signaling transmissions over multiple hops can be reduced to a single-hop by means of periodically establishing directional-directional (DD) transmission links between APs and GWs. Two MAC designs, fixed channel integration and dynamic channel integration, are proposed to schedule the transmission of handoff signaling packets so that the contentions between data and signaling packets can be eliminated. Both analytical model and OPNET simulations are conducted to evaluate the DD transmission throughput, optimal signaling period length, channel utilization, and handoff performance of the proposed GaS scheme. Simulation results show that the handoff delay can be largely reduced as compared to existing handoff solutions in multi-channel single-radio WMNs. Meanwhile, a high channel utilization can be achieved.

The proposed HiCA scheme addresses the long handoff delay issue by establishing a novel hierarchical network architecture. Under the new proposed WMN architecture, all MRs' transmissions are scheduled in three different time periods, double reservation period (DRP), free contention period (FCP), and signaling transmission period (STP), under the coordination of cluster heads, so the handoff signaling packets can be transmitted in separate time domains. In addition, the multi-channel hidden terminal problem, channel reuse problem, and channel selection problem can be well solved by the proposed HiCA scheme without requiring high hardware cost and time synchronization. Both analytical and OPNET simulation results show that the performance of the average channel utilization and total handoff delay can be improved significantly using our HiCA scheme under various scenarios, as compared to other existing channel allocation and handoff solutions in multi-channel multi-radio WMNs.

To sum up, since the contentions between data and signaling packets can be eliminated under the proposed MAC schemes, the inter-gateway handoff delay in multi-hop WMNs can be reduced significantly as compared to existing handoff solutions.

7.2 Future Work

Based on the proposed MAC designs, two issues can be considered in the future work.

In the hierarchical network architecture in HiCA, the handoff procedures can be improved to further reduce the handoff delay when an MN moves inside a cluster. In addition, some hierarchical routing schemes can be adopted to optimize the transmission route of handoff signaling packets between APs and GWs.

In the proposed GaS scheme, more radios can be used by GWs to operate the handoff signaling packet transmission in different directions, which can further reduce the signaling transmission delay and enhance the average channel utilization.

7.3 Published and Submitted Work

(1) H. Li and J. Xie, “A channel splitting strategy for reducing handoff delay in wireless mesh networks,” in *Proc. IEEE INFOCOM Student Workshop*, San Diego, CA, March 2010.

(2) H. Li and J. Xie, “A handoff solution in wireless mesh networks by implementing split channels,” in *Proc. IEEE GLOBECOM*, Miami, FL, December 2010.

(3) H. Li and J. Xie, “A channel splitting strategy for reducing handoff delay in internet-based wireless mesh networks,” *IEEE Transactions on Vehicular Technology*, vol. 61, July 2012.

(4) H. Li and J. Xie, “Novel channel assignment algorithm for handoff support in hierarchical wireless mesh networks,” in *Proc. IEEE GLOBECOM*, Houston, TX, December 2011.

(5) H. Li and J. Xie, “A low-cost channel scheduling design for multi-hop handoff delay reduction in internet-based wireless mesh networks,” in *Proc. IEEE INFOCOM*, Orlando, FL, March 2012.

(6) H. Li and J. Xie, “ConT: A contention-based time division scheme for handoff support in single-radio wireless mesh networks,” in *Proc. IEEE GLOBECOM*, Anaheim, CA, December 2012.

(7) H. Li and J. Xie, “An adaptive channel scheduling design for multi-hop handoff delay reduction in internet-based wireless mesh networks,” submitted to *IEEE Transactions on Vehicular Technology*, 2012.

(8) H. Li and J. Xie, “GaS: A gateway scheduling-based handoff scheme in single-radio infrastructure wireless mesh networks,” submitted to *IEEE INFOCOM*, 2013.

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