On Cross-Layer Design of Distributed MIMO Spatial Multiplexing Compliant Wireless Ad hoc Networks

by

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A thesis submitted to the Department of Electrical and computer Engineering

In conformity with the requirements for

The degree of Doctor of Philosophy

Queen’s University

Kingston, Ontario, Canada

September 2013

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Abstract

IEEE 802.11n Wireless Local Area Networks (WLANs) employ Multiple-Input-Multiple-Output (MIMO), which significantly boosts the raw data rate at the Physical layer (PHY). But the potential of enhancing Medium Access Control (MAC) layer efficiencies by MIMO is still in its early stage and is the aim of the research in this thesis. Many existing works in this field mainly employ distributed MIMO spatial multiplexing/Multi-User Detection (MUD) technique and stream sharing to enable multiple simultaneous transmissions. Most works require synchronization among multiple transmissions, split the channel, and aim for single-hop networks. In this thesis, a novel Hybrid Carrier Sense (HCS) framework is proposed, mainly at the MAC layer to exploit the power of MIMO. HCS senses the channel availability jointly by the virtual carrier sense and physical carrier sense. HCS does not require synchronization among nodes; each node independently and locally determines when to start its transmission. HCS not only shares the channel, but also exploits the bi-directional handshakes of the wireless transmissions and increases the number of simultaneous stream transmissions. For a network with $M$ antennas in each node, HCS can accommodate $2x(M-1)$ streams instead of $M$ streams achieved by all other existing works. Moreover, HCS is aimed for multi-hop wireless ad hoc networks, in which the hidden terminal, exposed terminal, and deafness problems greatly degrade network performance. The HCS framework incorporates solutions to these problems. HCS is implemented in an NS2 network simulator and the performance evaluation shows that HCS significantly outperforms MIMO-enabled IEEE 802.11 (in which MIMO is only used for enhancing the raw data
rate in the physical layer), resulting in higher aggregate throughput, packet delivery ratio and fairness in multi-hop wireless ad hoc networks. The HCS framework will be in wide use in the future generation of wireless networks and opens up more research possibilities. Some ideas in the HCS framework can be applied not only for MIMO, but also for many other techniques surveyed in this thesis; or we may combine them with HCS to further boost the network performance.
**Acknowledgements**

I would like to thank my thesis supervisor Professor Ahmed Safwat. He has been a great advisor and mentor, providing me with enormous support and encouragement. I am also grateful to Professor Il-Min Kim, Professor Hossam Hassanein, and our graduate secretary Debra Fraser. Without their help and support, this thesis would never be completed.

My wife Angela Zhu and my eleven-month-old son Jeremy have brought incredible joy to my life and provided me the most loving encouragement. Jeremy brought me many sleepless nights, but his smile is always my best inspiration and refreshment. In addition, I would like to thank my father Jue Li, my mother Shuhua Wang, my little sister Yujia Li, my father-in-law Yizhong Zhu and my mother-in-law Huiqin Zhang for their love, care, and encouragement.

Last but not least, my deepest gratitude goes to all my colleagues and friends at Queen’s, especially Quanhong Wang, Kean Xu, Yugang Zhou, Jun Yuan and Amr El Mougy. Their advice, collaboration and friendship have made my study and research more fruitful and enjoyable.
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<th>Description</th>
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<tr>
<td>ACK</td>
<td>Acknowledgement</td>
</tr>
<tr>
<td>AIFS</td>
<td>Arbitration InterFrame Space</td>
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<tr>
<td>BEB</td>
<td>Binary Exponential Backoff</td>
</tr>
<tr>
<td>BER</td>
<td>Bit-Error Rate</td>
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<tr>
<td>CA</td>
<td>Collision Avoidance</td>
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<tr>
<td>CBR</td>
<td>Constant Bit Rate</td>
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<tr>
<td>CD</td>
<td>Collision Detection</td>
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<tr>
<td>CDR</td>
<td>Circular Directional Request-To-Send</td>
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<tr>
<td>CS</td>
<td>Carrier Sense</td>
</tr>
<tr>
<td>CSMA</td>
<td>Carrier Sense Multiple Access</td>
</tr>
<tr>
<td>CSMA/CA</td>
<td>Carrier Sense Multiple Access with Collision Avoidance</td>
</tr>
<tr>
<td>CSMA/CD</td>
<td>Carrier Sense Multiple Access with Collision Detection</td>
</tr>
<tr>
<td>CTS</td>
<td>Clear-To-Send</td>
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<tr>
<td>CW</td>
<td>Contention Window</td>
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<tr>
<td>DA</td>
<td>Deafness Avoidance</td>
</tr>
<tr>
<td>DCF</td>
<td>Distributed Coordination Function</td>
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<tr>
<td>DD</td>
<td>Directional-Directional</td>
</tr>
<tr>
<td>DIFS</td>
<td>Distributed InterFrame Space</td>
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<tr>
<td>DNAV</td>
<td>Directional Network Allocation Vector</td>
</tr>
<tr>
<td>DO</td>
<td>Directional-Omni</td>
</tr>
<tr>
<td>DV</td>
<td>Deafness Vector</td>
</tr>
<tr>
<td>DVCS</td>
<td>Directional Virtual Carrier Sense</td>
</tr>
<tr>
<td>FIFO</td>
<td>First-In-First-Out</td>
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<tr>
<td>FSM</td>
<td>Finite State Machine</td>
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<tr>
<td>HCS</td>
<td>Hybrid Carrier Sense</td>
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<tr>
<td>HCS-MAC</td>
<td>Hybrid Carrier Sense Medium Access Control</td>
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<tr>
<td>HCS-PHY</td>
<td>Hybrid Carrier Sense Physical</td>
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<tr>
<td>HT</td>
<td>High Throughput</td>
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<tr>
<td>Acronym</td>
<td>Definition</td>
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<tr>
<td>IALT</td>
<td>IntrA-Layer Transition</td>
</tr>
<tr>
<td>ICT</td>
<td>Inter-Component Transition</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>IELT</td>
<td>IntEr-Layer Transition</td>
</tr>
<tr>
<td>IFS</td>
<td>InterFrame Space</td>
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<tr>
<td>LOS</td>
<td>Line Of Sight</td>
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<tr>
<td>MAC</td>
<td>Medium Access Control</td>
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<tr>
<td>MIMO</td>
<td>Multiple-Input Multiple-Output</td>
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<tr>
<td>MUD</td>
<td>Multiple User Detection</td>
</tr>
<tr>
<td>NAV</td>
<td>Network Allocation Vector</td>
</tr>
<tr>
<td>OD</td>
<td>Omni-Directional</td>
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<tr>
<td>OST</td>
<td>One Stream Transition</td>
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<tr>
<td>PCF</td>
<td>Point Coordination Function</td>
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<td>PCS</td>
<td>Physical Carrier Sense</td>
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<tr>
<td>PDR</td>
<td>Packet Delivery Ratio</td>
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<td>PHY</td>
<td>Physical</td>
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<tr>
<td>RTS</td>
<td>Request-To-Send</td>
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<tr>
<td>SB</td>
<td>Stream Bit</td>
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<tr>
<td>SBC</td>
<td>Stream Bit Correction</td>
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<tr>
<td>SIFS</td>
<td>Short Interframe Space</td>
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<tr>
<td>SST</td>
<td>Same-State Transition</td>
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<tr>
<td>UDP</td>
<td>User Datagram Protocol</td>
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<tr>
<td>VBLAST</td>
<td>Vertical Bell Labs Layered Space Time</td>
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<tr>
<td>VCS</td>
<td>Virtual Carrier Sense</td>
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<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
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<tr>
<td>ZOST</td>
<td>Zero-or-One Stream Transition</td>
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<td>ZST</td>
<td>Zero Stream Transition</td>
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Chapter 1
Introduction

1.1 Motivation

Today, multi-hop wireless ad hoc networks are very attractive to researchers. Unlike the conventional, infrastructure-based wireless networks, such as cellular networks, a multi-hop wireless ad hoc network is an autonomous and distributed system consisting of wireless nodes that do not rely on any fixed network infrastructure or central administration. A node communicates directly with nodes within the wireless range and indirectly with other nodes using a dynamically computed, multi-hop route via the other nodes of the ad hoc networks.

Wireless ad hoc networks are suited for use in situations where an infrastructure is unavailable or when deploying one is not cost effective, or avoiding the single-point failure is vital. By using a wireless ad hoc network, a network could be set up in hours instead of weeks, as required in the case of wired line communication. Moreover, without depending on the fixed infrastructure and central control, there is no single-point failure and the network will automatically adjusted and keep functioning if any node fails. Wireless ad hoc networks are expected to play an important role in the future generation of wireless networks, encouraging many emerging applications, such as wireless sensor networks, wireless mesh networks, vehicular ad hoc networks, nano networks, and cognitive networks to name a few. Potential applications for this class of network include, but are not limited to, an instant network infrastructure to support collaborative computing in temporary or mobile environments; military networks where soldiers relaying information for situational awareness on battlefields; emergency rescue networks in disasters where the entire communication infrastructure is destroyed and restoring communication quickly is crucial; communication systems for intelligent transportation system such as inter-vehicle...
communications, and mobile access to the global Internet. Moreover, with the popularity of more powerful smart devices such as smart phones, tablets, smart TVs etc., the smart homes and smart offices will become a reality. Wireless ad hoc networks will be good candidate for these types of networks.

In wireless networks, the primary goal of MAC sub-layer is to coordinate the channel access among multiple nodes to achieve high channel utilization. While wireless ad hoc networks exhibit unique advantages compared with conventional wireless networks, such as cellular networks and WLANs, they do impose several challenges on MAC protocol design.

The foremost challenge is that central control is not available in wireless ad hoc networks due to the lack of infrastructure support. Without perfect coordination, collisions can take place when multiple nodes simultaneously access the shared medium. The popular Carrier Sense Multiple Access (CSMA) and its variants such as CSMA with Collision Detection (CSMA/CD) developed for wired networks cannot be used directly in wireless networks as a node in the wireless medium cannot immediately detect collisions during its own transmissions. Also, a node cannot determine whether the receiver receives the packet successfully by simply monitoring the channel. Thus the receiver has to generate an acknowledgement frame and send it back to confirm the reception of a packet, such as the ACK frame employed in IEEE 802.11 [1]. This bidirectional frame exchange of the DATA and ACK frames between the sender and the receiver further complicates the protocol design because the failure of either frame at either end of the link will render a transmission unsuccessful.

Secondly, in a multi-hop wireless ad hoc network, the collisions are often much more severe than in a single-hop network, resulting from the transmissions that are a few hops away. Due to the multi-hop communication, nodes may experience different degrees of channel contention and collision. Besides the ad hoc nature of a multi-hop wireless ad hoc network, a node in such a
network will often relay the packets for many other nodes over multiple multi-hop routes. Thus the topology and data traffic of a multi-hop wireless ad hoc network is very dynamic and can change dramatically from time to time.

These ad hoc and multi-hop constraints, along with the requirement for the positive acknowledgement frame, impose significant challenges to the MAC sub-layer design for wireless ad hoc networks and introduce several serious problems to the MAC sub-layer in a multi-hop wireless ad hoc network, namely hidden terminal, exposed terminal and deafness problems, which will be discussed below with Figure 1-1.

While node A is transmitting to node B, node D is considered as the exposed terminal; node C is the hidden terminal; and nodes E and F are the deaf terminals.

**Figure 1-1. An illustration of the hidden terminal, the exposed terminal and deafness problems**

In Figure 1-1, it is assumed that node A is sending to node B and the circles illustrate the communication range of wireless nodes. Link A→B is the target of our study. We will investigate how it affects other surrounding links and vice versa.
First, we examine the hidden terminal problem. Node C is out of the communication range of node A and is unaware of node A’s transmission. Node C is hidden from node A in this situation. If the hidden terminal C starts a new transmission to another node, such as node E, it will cause the ongoing transmission from node A to node B to fail because a collision will occur at node B. The hidden terminal problem describes the impact on an ongoing transmission imposed by other neighboring nodes.

Next, we investigate the exposed terminal problem. In a carrier-sensing scheme, due to sensing the sender node A’s signal, node D is not allowed to send to other nodes, such as node F, although this transmission might not collide with the receiver node B’s reception. Node D is the exposed terminal to node A and this problem is referred to as the exposed terminal problem. The rationale behind suppressing the transmission of the exposed terminal D is due to the bidirectional DATA and ACK frames exchange; the ACK frame to be transmitted at a later time from node B to node A will be collided at node A if the exposed terminal D is allowed to transmit.

Lastly, we study the deafness problem. When node A is transmitting to node B, node D will not receive the frames transmitted by node F due to the ongoing transmission from node A. In a carrier-sensing scheme, node F interprets this as a collision and triggers a collision resolution mechanism to decrease the possibility for further collisions, such as enlarging the contention window as employed in the Binary Exponential Backoff (BEB) mechanism in the IEEE 802.11 standard. This results in an unfairness issue because node F will have a much less opportunity to capture the channel. Moreover, unaware of (deaf to) node D’s status of being unable to receive, node F will pointlessly keep trying to connect with node D. The packets at node F will be dropped when it concludes that node D is unreachable after several consecutive failed attempts. A similar situation may occur at node E if it initiates a packet to node C. Even though node C may receive the frame from node E, node C may not be allowed to respond to node E to avoid
colliding with node B’s reception (thanks to some floor reservation mechanisms such as the
Clear-To-Send frame transmitted by node B as employed in the IEEE 802.11 standard). Node E
and node F are called deaf nodes because they are unaware of the fact that their destination nodes
are unable to receive or respond.

The hidden terminal problem characterizes the impact on an ongoing link imposed by other
nodes in the surrounding area and the exposed terminal and deafness problem represent the
impact on other nodes imposed by an ongoing link. These three problems are not isolated, but
rather related to each other. Due to the bidirectional frame exchange of the DATA and ACK
frames, a sender’s exposed terminal could become a receiver’s hidden terminal, and a sender’s
hidden terminal could become a receiver’s exposed terminal. For example, as it was shown in
Figure 1-1, when node B is transmitting an ACK frame to node A, node D becomes the hidden
terminal of node B, although it was the exposed terminal of node A. Moreover, the hidden
terminal and deafness problem can be related. If the hidden terminal C transmits to node E, it will
cause a collision with the ongoing transmission between nodes A and B, which, in turn, will
result in the deafness problem at the link between nodes A and B; node A will pointlessly send to
the unavailable receiver node B, which will not receive due to the ongoing transmission from
node C to node E.

In summary, the hidden terminal problem causes collisions; the exposed terminal problem
decreases spatial reuse; and the deafness problem elevates unfairness. An efficient MAC protocol
for multi-hop wireless ad hoc networks must address these problems to achieve high throughput
and great fairness.

There are many approaches towards to solving these problems — in the form of the controlled
communication distance, leading to transmission power control protocols; in the form of the
disjointed frequencies, leading to multi-channel protocols; in the form of narrowed
communication directions, leading to directional antennas protocols; or in the form of utilizing multi-path propagation, leading to the schemes employing MIMO distributed spatial multiplexing. MIMO as a powerful technique has been widely used in wireless networks to boost the raw data rate, and this makes it a strong candidate and competitor for the future wireless networks compared to other techniques. Although it has become a hot topic, the research of enhancing MAC layer efficiencies by MIMO for wireless ad hoc networks is still in its early stage and its full potential is yet to explore. In this thesis, we will propose the Hybrid Carrier Sense (HCS) framework that utilizes MIMO distributed spatial multiplexing to solve the MAC problems and inefficiencies in multi-hop wireless ad hoc networks.

1.2 Contributions of the thesis

MIMO as a powerful technique has been widely used in wireless ad hoc networks and other wireless networks. Compared to other techniques, MIMO significantly boosts the raw data rate, which is a great advantage. Although it has drawn more and more research interest, the potential of enhancing MAC layer efficiencies by MIMO is still in its early stage and is the aim of the research in this thesis. There are many existing works in this area [65] — [83] (a thorough review is provide in chapter 2.8), mainly through distributed MIMO spatial multiplexing/MUD technique and stream sharing to enable multiple simultaneous transmissions. Most works require synchronization among multiple transmissions and split the channel but without considering the potential of expanding the channel capacity, and aim for single-hop networks.

In this thesis, a novel Hybrid Carrier Sense – HCS framework is proposed, mainly in the MAC layer to exploit the power of MIMO and enhance the network efficiencies. HCS senses the channel availability jointly by the virtual carrier sense and physical carrier sense, and a finite state machine is devised to model the HCS states and decision-making. HCS does not require the synchronization among nodes; each node independently and locally makes its own decision when
to start its transmission. HCS not only shares the channel, but also exploits the bi-directional handshakes of the wireless transmissions and increases the number of simultaneous stream transmissions. For a network with $M$ antennas in each node, HCS can accommodate $2 \times (M - 1)$ streams, a significant increase compared to $M$ streams seen by all other existing works. Moreover, HCS is aimed for multi-hop wireless ad hoc networks, in which the hidden terminal, exposed terminal, and deafness problems greatly degrade the network performance. These problems are thoroughly studied with a unified treatment in this thesis. The HCS solves these problems simultaneously. HCS is implemented in NS2 network simulator and the performance evaluation shows that HCS significantly outperforms MIMO-enabled IEEE 802.11 (in which MIMO is only used for enhancing the raw data rate in the physical layer), resulting in significantly higher aggregate throughput, packet delivery ratio, and fairness in multi-hop wireless ad hoc networks.

The following is a brief list of HCS framework and the contributions of this thesis:

i) Proposed HCS-MAC with the following features:

a) Hybrid Carrier Sensing, which senses channel availability jointly by physical carrier sense and virtual carrier sense;

b) Multiple simultaneous transmissions among the wireless nodes;

c) Solving hidden terminal, exposed terminal, and deafness problems for multi-hop and ad hoc networks;

d) Sharing the channel and exploiting the bi-directional handshakes of the wireless transmissions while increasing the number of simultaneous stream transmissions. $M - 1$ antennas are used for DATA frame transmissions whenever deemed feasible, while control frames are transmitted using a single antenna. For a
network with $M$ antennas in each node, HCS can accommodate $2 \times (M - 1)$ streams, a significant increase compared to $M$ streams generated by other existing works. The Stream Bit Negotiation and Correction mechanisms are devised to determine the number of antennas used to transmit the DATA frames in a MIMO system;

e) Modeling HCS-MAC as a Finite State Machine (FSM), which defines the HCS-MAC states and decision-makings rules:

- The Inter-Component Transitions (ICT) that describe the rules of Hybrid Carrier Sensing;
- The IntrA-Layer Transitions (IALT), IntEr-Layer Transitions (IELT) and Same State Transitions (SST) that update and maintain the HCS-MAC states at each node;

f) The study of new types of deafness problem arising in HCS-enabled networks and deafness avoidance mechanism.

ii) Proposed a cross-layer design of HCS-Physical Carrier Sense (HCS-PCS) that provides a practical solution to determine the number of streams currently in transmission.

iii) Conducted extensive performance study:

a) Implemented HCS-MAC with C++ programming language in NS2 simulator;

b) Thoroughly studied the performance of HCS-MAC, MIMO IEEE 802.11 and Legacy IEEE 802.11 in terms of throughput and fairness for various antenna deployments in several fundamental scenarios of wireless ad hoc networks;

c) Thoroughly studied the performance of HCS-MAC, MIMO IEEE 802.11 and Legacy IEEE 802.11 in terms of throughput and packet delivery ratio in large-
scale multi-hop ad hoc networks with various traffic loads and numbers of antenna deployments;

d) Studied the performance of proposed deafness avoidance mechanism for HCS-enabled wireless networks.

iv) Studied hidden terminal, exposed terminal, and deafness problems in a unified context. These problems are the major factors that degrade the performance and efficiencies of MAC protocols in multi-hop ad hoc networks.

v) Conducted a thorough review of MAC protocols proposed for wireless ad hoc networks, including: a) BEB refinement; b) frame aggregation; c) rate adaptation; d) power control; e) multiple channels; f) directional antennas; and g) MIMO. Some of the ideas proposed in the HCS framework can be applied not only for MIMO, but also over many other surveyed techniques, taking multiple channels as an example. We may use HCS with other techniques and dynamically switching between them, such as spatial multiplexing and directional antennas; or we may even integrate HCS with some of the techniques to further enhance the performance, such as BEB refinement, frame aggregation, rate adaptation, power control, or multiple channels.

vi) Three conference papers [56], [57] and [66] and one journal paper [61] are produced related to the thesis research.

Nowadays, the prevalence of multimedia and many other data consuming applications mandates that wireless networks provide higher throughput and spatial efficiency. The HCS framework can significantly improve the throughput and the fairness of wireless ad hoc networks and is anticipated to be in wide use in the future generation of wireless networks. It can be used in mesh networks, cognitive networks, vehicular networks, military networks, rescue or emergency networks, and in many other situations where an infrastructure is unavailable or when deploying
one is not cost effective. Moreover, with the popularity of more powerful smart devices, such as smart phones, tablets, smart TVs etc., the smart homes and smart offices will become a reality. Wireless ad hoc networks with HCS framework can be a very good candidate for such networks.

There are some limitations of the HCS solution proposed in this thesis and this subject will continue to be researched. Mobility, energy conserving, QOS, and some other aspects of MAC layer issues in wireless ad hoc networks are not considered in this thesis. These are promising topics for future research. This thesis assumes all the nodes in the networks have $M$ antennas. The extension of HCS framework with cooperative networks in which each node may have different number of antennas or a single antenna would be interesting. Applying HCS to cognitive networks would be a good area to explore as well. The more research on the PHY, routing layers and the cross layers design and optimization with HCS framework would be desired. Moreover, it would be very beneficial and practical to build a HCS test-bed.

1.3 Thesis outline
The rest of this thesis will be organized as follows:

Chapter 2 provides a thorough literature review of the MAC protocols proposed for wireless ad hoc networks. For the single-hop wireless ad hoc networks, the key is to improve the utilization of the channel and reduce the overhead, which leads to the approaches such as refining backoff mechanism, frame aggregation, and rate adaptation. For the multi-hop wireless ad hoc networks, the hidden terminal, the exposed terminal, and deafness problems significantly limit the network performance. There are many approaches for solving these problems — in the form of the controlled communication distance, leading to the transmission power control protocols; in the form of the disjointed frequencies, leading to the multi-channel protocols; in the form of the narrowed communication directions, leading to the directional antennas protocols; or in the form of utilizing the multi-path propagation, leading to the schemes employing MIMO distributed
spatial multiplexing. Compared to other approaches, MIMO can significantly boost the raw data rate, which is a great advantage. Although this has drawn more and more research interest, the potential of enhancing MAC layer efficiencies by MIMO is still in its early stage and is the aim of the research in this thesis.

Chapter 3 provides an overview of the HCS Framework. First we briefly review the limitations of current protocols that employ MIMO distributed spatial multiplexing. Then we discuss the idea of using $M-1$ antennas to transmit DATA frames and a single antenna to transmit control frames, and how this design can solve the hidden terminal, exposed terminal and deafness problems. There is a discussion of applying HCS to other techniques, such as multiple channels and why the MIMO is preferred. This is followed by presenting the motivations of hybrid carrier and a brief description of HCS-PCS.

Chapter 4 is pertinent to the HCS-MAC design. HCS-MAC utilizes complete random access among the nodes. Each HCS-enabled node dynamically maintains its HCS-MAC state information and determines, independently of its neighbors, whether to access the channel. When deemed feasible based on channel conditions, $M-1$ antennas are used for DATA frame transmissions, while control frames are transmitted using a single antenna. Consequently, HCS enables simultaneous medium access among neighboring nodes and maximizes the data rate in a single-hop, thereby achieving both high aggregate throughput and fairness. In this chapter, we first introduce the notations that will be used in the HCS-MAC scheme and then propose the basic scheme for a 2I2O system. The basic HCS-MAC scheme will be modeled by a multi-component and multi-layered Finite State Machine (FSM). Four types of transitions will be presented. Inter-Component Transitions (ICT) is the decision making transition that depicts the rules of hybrid-carrier sensing, IntrA-Layer Transitions (IALT), IntEr-Layer Transitions (IELT) and Same State Transitions (SST) are the supporting transitions that update and maintain the HCS-MAC state.
information at each node. The scheme for more general MIMO systems, where $M > 2$, will be followed with some modifications and add-on mechanisms to the basic HCS-MAC. Lastly, the design of HCS-PCS will be presented, which provides a practical solution to determine the number of streams currently in transmission.

Chapter 5 conducts computer simulations to study the performance of the proposed HCS framework. The HCS-MAC is implemented in the NS2 network simulator. We study the performance of HCS-MAC with three fundamental scenarios to examine and validate the design of HCS-MAC and compare its performance to Legacy IEEE 802.11 and MIMO IEEE 802.11, in which all available antennas are used to transmit. The aggregate throughput and fairness for each scenario will be studied. Then we study another two deafness scenarios to investigate the effectiveness of the DA mechanism. Finally, we run the simulations of the large scale multi-hop wireless ad hoc networks with random topology and various data traffic loads. We compare the performances of HCS-MAC and MIMO IEEE 802.11 with respect to the aggregate throughput and Packet Delivery Ratio (PDR). The simulation results show that HCS-MAC significantly outperform MIMO IEEE 802.11 in terms of all the simulated metrics.

Chapter 6 will conclude the thesis. The contributions, limitations, and some future works of the HCS framework will be discussed in this chapter.
Chapter 2  
Background and Literature Study

In this chapter, we will review the MAC protocols proposed for the wireless ad hoc networks. First, we will first present the IEEE 802.11 Distributed Coordination Function (DCF), the most fundamental and widely used MAC protocol for wireless ad hoc networks. Most MAC protocols proposed for wireless ad hoc networks are, more or less, based on IEEE 802.11 DCF. Then, we will categorize the MAC protocols proposed for wireless ad hoc networks and survey the representative protocols in each category.

2.1 Fundamental MAC protocol: IEEE 802.11 DCF

IEEE 802.11 [1] is the most widely used MAC scheme in wireless ad hoc networks research. In IEEE 802.11, there are two mechanisms to access the medium: Distributed Coordination Function (DCF) and Point Coordination Function (PCF). The DCF is designed for the ad hoc mode.

In DCF, the default scheme is a two-way handshaking characterized by the transmission of a positive acknowledgement (ACK) frame by the destination station to confirm the successful reception of a DATA frame. The explicit transmission of an ACK frame is required because in the wireless medium a transmitter cannot determine whether a packet is successfully received simply by listening to its own transmission. If a sender node does not receive the ACK frame correctly, it regards its recent DATA frame transmission as failed. It is important to note that, acknowledgements for successful transmissions are necessary due to the unreliable wireless communication environment; even if the transmission of DATA frames is collision-free, it may still be corrupted by short-term channel fading.

DCF is a random-access scheme based on the Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) scheme. A node has to sense that the channel is free for a period defined
as the Distributed InterFrame Space (DIFS) before it can start its transmission attempt. However, several nodes may start to transmit at the same time after they sense the channel for a DIFS period and collisions will occur. To address this problem, DCF adds a CA mechanism on the top of the CSMA scheme – a Binary Exponential Backoff (BEB) – to resolve channel contention. Before initiating a transmission, a node S chooses a random backoff interval from a range of $[0,CW - 1]$, where $CW$ is referred to as the contention window. Node S then decrements the backoff counter by 1 after each idle time slot. This is called counting down. When the backoff counter reaches zero, node S transmits the packet. If the transmission from node S collides with other transmissions (detected by the absence of an ACK frame after a timeout), node S doubles its $CW$ until reaching a maximum value, randomly chooses a new backoff interval according to the newly enlarged $CW$, and then retransmits. During the period of counting down, if node S senses the channel as busy, it freezes the backoff counter, and resumes counting down from the last frozen backoff counter value if it senses the channel as idle again for another DIFS period.

DCF also defines an optional four-way handshake with an exchange of Ready-To-Send (RTS) and Clear-To-Send (CTS) control frames preceding DATA and ACK transmissions to resolve the collision among longer data frames. This four-way handshake can also be used to solve the collisions due to the hidden terminal problem. There is a Short Interframe Space (SIFS) period between each handshake to allow the transceiver to switch from receiving mode to transmission mode. The SIFS period is shorter than the DIFS period to grant the ongoing transmissions higher priority to acquire the channel than a new transmission, therefore protecting the ongoing transmission from being interrupted. Both RTS and CTS frames advertise the duration needed for completing the rest of the four-way handshake. Nodes located in the vicinity of the communicating nodes overhear either or both of RTS and CTS frames have to defer their transmissions for the period advertised by the overheard control frames. To enable this Virtual Carrier Sensing (VCS), each node maintains a variable called Network Allocation Vector (NAV)
and updates its NAV upon overhearing an RTS or CTS frame. Through VCS mechanism, a larger area in which nodes can interfere with the current sender or receiver nodes has been reserved. Figure 2-1 and Figure 2-2 illustrate an example scenario and the corresponding timeline diagram of the four-way handshake and the NAV setup.

Although VCS addresses the hidden terminal problem, it significantly decreases the spatial reuse. As shown in Figure 2-1, node A is transmitting to node B. All the nodes in two grey circles can neither send nor receive. It will be even worse in a multi-hop ad hoc network. All the transmission requests initiated by the nodes in the plain circles such as nodes D and F to the nodes in the grey circles such as nodes C and E will not be granted. To protect a single transmission, the whole area that spans as many as five hops has to be blocked.

**Figure 2-1. Addressing the hidden terminal problem with RTS/CTS**
2.2 Protocols refining backoff

Although BEB is widely used in many contention based MAC protocols for its simplicity and good performance, it suffers from both fairness and efficiency. In BEB, each station resets its $CW$ to the minimum value after a successful transmission, and doubles its $CW$ after a failed transmission. Therefore, it is very likely that a node that has gained the channel and transmitted successfully will gain the channel in the successive channel contentions. On the other hand, BEB is also diagnosed with low efficiency when there are many active nodes [2], [3], and hence severe contentions for the channel. Analysis shows that after reaching its peak, the aggregate throughput decreases along with the input traffic. In addition, the aggregate throughput decreases with the number of active stations under saturated status.

A multiplicative increase and linear decrease (MILD) was proposed in the MACAW protocol [4] to address the large variation of the contention window size and the unfairness problem of BEB. In MILD, the backoff interval is increased by a multiplicative factor (1.5) upon a collision.
and decreased by 1 step upon a successful transmission, where step is defined as the transmission
time of an RTS frame. MILD works well when the traffic load is steadily heavy. However, the
linear decrease sometimes is too conservative, and suffers performance degradation when the
traffic load is light or the number of active nodes changes sharply [5]. To overcome these
problems, the exponential increase exponential decrease (EIED) backoff algorithm has been
studied in [5], [6]. In the EIED algorithm, the contention window size is decreased by a factor $r_D$
upon a successful transmission, and increased by a factor $r_I$ upon a collision, where $r_D$ and $r_I$ are
customizable parameters. As a result, EIED is not as conservative as the linear decrease of MILD
and not as progressive as the reset of BEB. On the other hand, in light of there is a different
optimal contention window size for different number of active nodes, some studies focused on
adaptive contention window schemes [2], [3], [7]. By collecting observed collision statistics,
these schemes estimate the number of currently active nodes and calculate a new contention
window size to schedule the next transmission. Note that in these schemes, timely and accurate
estimate of the number of active stations, which is not easy [8], is a prerequisite to improve the
performance. A fast collision resolution (FCR) algorithm was proposed in [9] with the following
characteristics: (1) using much smaller initial (minimum) and much larger maximum contention
windows; (2) increasing the contention window size when a node is in either collision or
deferring state; (3) reducing the backoff timers at an exponential rate when a prefixed number of
consecutive idle slots has been detected; (4) assigning the maximum successive packet
transmission limit to achieve good fairness performance. The purpose of FCR is to develop a
contention based MAC algorithm that assigns a backoff timer 0 to the station in transmission
while assigning all other stations’ backoff timers to $+\infty$ for each contention cycle, so as to achieve
the perfect scheduling and lead to the maximum throughput and good fairness performance.
2.3 Protocols using frame aggregation

The IEEE 802.11, 802.11b [10], and 802.11a/g [11], [12] specifications provide up to 2 Mb/s, 11 Mb/s, and 54 Mb/s data rates, respectively. It follows that increasing the data rate will lead to increasing the throughput. However, as proved in [13], a theoretical throughput limit exists due to MAC and PHY overheads, which include headers (MAC header, frame check sequence, and PHY header), interframe spaces, backoff time slots, and ACKs. For example, for IEEE 802.11a with a payload size of 1500 bytes, the theoretical throughput limit about 75 Mb/s is the upper bound of any obtained throughput even when the data rate goes infinitely high [13]. Moreover, the normalized overhead is extremely large when either the data rate is high or the frame is small [14]. Both reducing overhead and pursuing higher data rates are therefore necessary and important. Some works [14] - [19] proposed frame aggregation concept for the purpose of reducing overhead. In the new 802.11n standard [20], frame aggregation is used as the main mechanism to reduce the MAC overhead, aimed toward achieving a higher throughput.

The idea of frame aggregation is to aggregate multiple shorter MAC/PHY frames/ payloads into a longer single transmission. The frame aggregation mechanisms can be performed at both PHY and MAC levels. At the PHY level, after acquiring the channel, a node can transmit several PHY frames consecutively without the need to compete the channel again. At the MAC level, several MAC frames are aggregated into a single PHY or MAC frame, thus only one PHY or one MAC header is required. For the PHY level aggregation, each sub frame in an aggregated frame can be acknowledged individually via separate ACK frames immediately after a SIFS period, or altogether through a single delayed block ACK frame that will be transmitted until the whole aggregated frame transmission is complete. With the block ACK frame, two consecutive aggregated PHY frames may be separated by nothing or a SIFS period. If taking the former approach, a mechanism to enable the receiver to separate the aggregated frames is required, such as the delimiter implemented in IEEE 802.11n, which is inserted into the aggregated frame to
indicate the length of each sub MAC frame. Note that there is a tradeoff between the overhead and robust. Figure 2-3 illustrates different types of frame aggregation.

Figure 2-3. Frame aggregation [14]
Frame aggregation brings many benefits. First, since transmitting longer frames can lead to better throughput than transmitting shorter frames when the data rate is high, and frame aggregation is a way to merge multiple shorter frames to a longer one. Secondly, frame aggregation can reduce overhead. Without frame aggregation, each frame transmission needs a separate set of overhead (headers, interframe spaces, backoff period, ACKs or RTS/CTS frames if VCS is employed). Rather, only one set of overhead will be necessary for using frame aggregation.

One issue is how long the total length of aggregated frames should be. One possible solution is that the number of aggregated frames should not be larger than a threshold, and the total length of aggregated frames should be smaller than another threshold, which is smaller than or equal to the fragmentation threshold. The purpose is to build a reasonably sized frame rather than a long frame, since long frames may cause fairness problems and are prone to transmission errors. Note that frame aggregation is not a reversed mechanism of fragmentation.

Frame aggregation is effective to increase the throughput for a single hop link by reducing the MAC overhead, but it may not necessarily lead to a significant throughput improvement in multi-hop wireless ad hoc networks, in which the hidden terminal, exposed terminal, and deafness problems greatly limit the achievable throughput. Moreover, the frequent collisions attributed to the multi-hop communication may even undermine the benefit from frame aggregation, because the cost of the collisions becomes higher when the frame is longer.

2.4 Protocols using rate adaptation

Wireless channel is time varying and location dependent due to path loss, shadowing, small-scale fading as well as interference. Rate adaptation is a powerful way to overcome channel variations. Unlike the original IEEE 802.11 protocol that only supports a single base rate, the
IEEE 802.b and 802.11a/g PHY/MAC standards have incorporated physical-layer, multi-rate capability and support multiple data rates. By adapting modulation and error-coding schemes to channel conditions, both throughput and energy efficiency are expected to improve.

The first MAC scheme that utilizes rate adaptation was the Auto Rate Fallback (ARF) protocol [21]. In ARF, senders attempt to use higher transmission rates after consecutive transmission successes, which indicates a high channel quality, and revert to lower rates after failures. Under most channel conditions, ARF provides a performance gain over pure single rate IEEE 802.11. However, ARF cannot adapt to fast multipath fading. In Reference [22], Receiver-Based Auto Rate (RBAR) was proposed. In RBAR, receivers measure the channel quality using physical-layer analysis of the RTS frames, and then accordingly determine the highest available transmission rate for the upcoming DATA frame transmission. As Figure 2-4 shows, the sender Src chooses a data rate based on some heuristic and then stores the rate and the size of the DATA frame into the RTS frame. Node A, which overhears the RTS frame, calculates the duration of the requested reservation $D_{\text{RTS}}$ and updates its NAV. Upon receiving the RTS frame, the receiver Dst generates an estimate of the channel conditions based on the SINR of the RTS frame, selects the appropriate rate based on that estimate, and then transmits it in the CTS frame back to the sender. Finally, the sender Src transmits the DATA frame at the rate chosen by the receiver Dst. In the case that the sender and receiver choose different rates, the reservation $D_{\text{RTS}}$ calculated by node A will no longer be valid and need to be corrected. The final reservations are confirmed by the presence or absence of a special subheader called the Reservation SubHeader (RSH) embedded in the MAC header of the DATA frame. As channel condition is evaluated per DATA frame transmission based, the estimation of the channel condition is quite accurate, so that RBAR yields significant throughput gains as compared to ARF (as well as compared to the single-rate IEEE 802.11).
Typically, channel coherence time exceeds multiple packet transmission time for both mobile and non-mobile users. It is wise to let a user transmit more packets when in good channel condition and transmit fewer packets when in bad channel condition. In RBAR, only one packet is allowed to transmit each time, which is not efficient, especially when channel is good. To better exploit the durations of high-quality channels conditions, researchers [23], [24] introduce the Opportunistic Auto Rate (OAR) protocol to opportunistically send multiple back-to-back data packets whenever the channel quality is good. Basically, this protocol aggregates the packets according to the channel quality. By exploiting good channel condition and reducing overhead for competing channel through fame aggregation, OAR achieves significant throughput gains as compared to RBAR.

Till now, the schemes being studied only consider the time diversity and mitigate channel variations rather than utilizing it. In wireless LANs or wireless ad hoc networks, it is usual that a node needs to communicate with several neighbors. Since channel quality is often time-varying......
and independent across different neighbors, this provides a node with an opportunity to choose one of its neighbors with good channel quality to transmit data, if the First-In-First-Out (FIFO) service discipline is not strictly enforced. In other words, multiuser diversity may be exploited. To exploit the multiuser diversity in a distributed fashion, [28] presents the Opportunistic Packet Scheduling and Auto Rate (OSAR) protocol. The basic idea of OSAR is to extend the functionality of the RTS/CTS handshake to probe channel conditions of several candidate receivers simultaneously. In the beginning, the intended sender multicasts RTS message to a selected group of candidate receivers. Each candidate receiver evaluates the instantaneous link quality based on the RTS. The candidate receiver with channel quality better than a certain level is allowed to access the medium. Considering more than one candidate receiver may have good channel quality and are ready to receive data, a coordinating rule is applied to avoid collision. The RTS includes a list of the media access priority of each candidate receiver through the ordering of the receiver address carried in the RTS. According to the priority list, the higher priority a node has the smaller IFS value it will be assigned to – a mechanism similar to the IEEE 802.11e Arbitration IFS (AIFS). The qualified candidate receiver with the highest priority is ensured to access the channel first. After that, rate adaptation and packet bursting technique are employed to utilize high-quality channel.

It is worthwhile to point out that the rate adaptive mechanisms are closely coupled with routing. Usually, the shorter distance between the sender and the receiver, the higher data rate can be applied. However, for a multi-hop wireless ad hoc network, it may result in finding a longer route across more hops. This issue was investigated in [29].

2.5 Protocols using transmission power control

In the CSMA/CA, all nodes transmit control and data frames at a fixed (and maximal) power level, and any node that senses signal with power level higher than a certain threshold, the carrier
sense threshold, or overhears the RTS or the CTS frame, defers its transmission until the ongoing transmission is complete. This mechanism can be overly conservative since many times the maximal power may not be needed for a communication pair, leading to low spatial reuse and low energy efficiency. Figure 2-5 illustrates the benefit of the power control. In Figure 6, the dashed circles indicate the maximum transmission ranges, while the dotted ones indicate the minimum transmission ranges needed for coherent reception at the respective receivers. If all nodes communicate with the maximum transmission ranges (using the maximum transmission power), nodes D and E are not allowed to transmit when nodes A and B are communicating with each other. However, it shows that the three transmissions: A → B, D → C, and E → F can overlap in time if nodes are able to select their transmission powers and control their transmission ranges appropriately, such as the dotted cycles as shown in Figure 6, consequently increasing network throughput and possibly reducing overall energy consumption.

Figure 2-5. Benefit of the power control [36]

Power control was initially used for energy conservation. In [30], nodes exchange their RTS and CTS frames at the maximum allowable power $P_{\text{max}}$ to reduce the collision probability of the DATA and ACK frames, but send their data and ACK frames at the minimum power $P_{\text{min}}$. 
necessary for reliable communication. However, as shown in [31], [32], [35] and [36], it may also degrade network throughput; reducing power for data transmission also reduces carrier-sensing range so that DATA and ACK are more likely to collide. In [31], [32], the authors enhanced this approach by periodically increasing the transmission power of the data frame to $P_{\text{max}}$, allowing for enough time to protect the frame reception. While this class of power control schemes achieves good reduction in energy consumption, it contributes little to improving the throughput because RTS and CTS frames are still transmitted with the maximum transmission power to silence neighboring nodes, preventing concurrent transmissions from taking place over the reserved area.

To increase spatial reuse, researchers [33], [34] introduced the interference-limited media access control schemes. Concurrent data transmissions are allowed as long as the multiple access interference does not corrupt the ongoing neighboring transmissions. This is completely different from the idea of carrier sensing based media access control schemes, in which any node in the carrier sensing range of an ongoing transmission node pair should defer its intended transmission. A MAC protocol that combines the mechanisms of power control, RTS/CTS dialogue, and busy tones (based on DBTMA [38] which will be presented in next subsection) is proposed in [33]. The main idea is to use the exchange of RTS and CTS frames between two intended communicators to determine the relative channel gain (through the signal strength of RTS/CTS). This information is then utilized to derive the minimum power level necessary for the transmission of data frames. The power level used for RTS and data transmission should be less than the maximum allowable power level above which it may cause interference to the ongoing neighboring communication. The maximum allowable transmission power level (used to transmit RTS) is determined based on how strong the receiving busy tones (BTr) are around the intended sender. CTS and BTr are transmitted by receivers at the maximal power level. In addition, a sender sends transmission busy tone (BTt) during data transmission at the same power level as that of data. Any node that hears BTt should not agree to intended reception. The Power-
Controlled Multiple access (PCMA) protocol [34], similar to [33], generalizes the transmit-or-defer collision avoidance model of CSMA/CA to a more flexible variable bounded power collision suppression model, which uses the noise tolerance/interference margin to allow a greater number of simultaneous transmissions, thus increasing spatial reuse. The noise tolerance/interference margin is advertised by the receiver over a separate busy tone channel. To avoid using separate busy tone to locally broadcast the interference margin, the power-controlled dual channel (PCDC) protocol [35] advertises it by RTS and CTS, which are transmitted on a separate control channel. In addition, to further increase the spatial reuse and provide better protection of ACK frames than the schemes in [33], [34] (a problem inherited from the DBTMA, the base protocol of [33], [34]), researchers [35] proposed the use of a second control channel for sending ACK frames. Although the simulations of the above TPC schemes indicate impressive throughput performance, as [36] pointed out, there are several major design issues with these schemes. First, the channel gain is assumed to be the same for both the control (busy tone) and data channels, which, however, may not be true. Secondly, it is assumed that nodes are able to transmit on one channel and, simultaneously, receive on the other, which requires a node to equip with two transceivers. The complexity and cost of the additional hardware may not justify the increase in throughput. Finally, the optimal allocation of the total spectrum between the data and control channels is load dependent. For the allocation to be optimal under various traffic loads, it has to be adjusted adaptively. However, it is not feasible in practice. The power-controlled MAC (POWMAC) protocol proposed in [36] addresses all the above issues and provides a throughput oriented MAC solution for wireless ad hoc networks using a single transceiver and a single channel. Collision avoidance information is inserted into the control frames and is used to bound the transmission powers of potential interferers, rather than to silence such nodes. Instead of alternating between the transmission of control (RTS/CTS) and data frames, as done in the 802.11 scheme, POWMAC uses an Access Window (AW), which consists of an adjustable number of
fixed duration time slots, to allow for a series of RTS/CTS exchanges to take place before multiple concurrent power-controlled data frame transmissions. POWMAC does not require any synchronization since the size of a time slot is a fixed network-wide parameter and the AW length is embedded into the RTS/CTS frames. And because the AW slot is fixed, BEB is not proper for the contention resolution. Instead, a fixed single $CW$ is used, but a node decides whether to contend for the next slot with the probability of so-called network losses. Simulation results demonstrate the significant throughput and energy gains.

2.6 Protocols using multiple channels

In multi-hop wireless ad hoc networks, the hidden terminal problem is a main cause for collisions, and the exposed terminal problem limits spatial reuse. Out-of-band busy tone and multi-channel are widely used in many schemes to overcome the hidden terminal problem and/or the exposed terminal problem. Note that, because a busy tone is transmitted in a separate channel, we categorize this type of approaches into the multi-channel schemes.

In the Busy Tone Multiple Access scheme (BTMA) [37], a base station broadcasts a busy tone signal to prevent the hidden terminals from accessing the channel when it senses a transmission. The scheme relies on a centralized network infrastructure not available in wireless ad hoc networks. The Dual Busy Tone Multiple Access (DBTMA) [38] divides the channel into a DATA channel and a control channel; control channel is used for the transmission of the RTS or CTS frame. Moreover, on the control channel, DBTMA employs a transmit busy tone $BT_t$ at a transmitter, and a receive busy tone $BT_r$ at the receiver. $BT_t$ is used to prevent the exposed terminals from becoming new receivers and $BT_r$ is used to prevent the hidden terminals from becoming new transmitters. The exposed terminals are able to initiate data packet transmissions, and the hidden terminals can reply to RTS requests and initiate a data frame reception. However, in the DBTMA scheme, no ACK frame is sent to acknowledge a transmitted DATA frame, which
is clearly deficient for unreliable wireless links. Furthermore, potential collisions between the ACK frame and other frames could greatly degrade the performance. To address this problem, MAC with dual channels (DUCHA) [39] introduces the Negative Acknowledgment (NACK), a continuing receiver busy tone signal, when the receiver determines that the received DATA packet is corrupted and in error. Upon sensing the NACK tone, the sender will conclude that the data transmission is failed. The NACK signal is also exploited to alleviate the MAC contentions between the upstream nodes and the downstream nodes of a multi-hop path by allowing the receiver to contend for the channel after a successful reception while keeping the neighboring nodes silent during the NACK period. The busy tone technique provides a simple solution to the hidden terminal and exposed terminal problems, but it requires additional channels and transceivers. The busy tone channel must be close to the DATA channel and, hence, can have similar channel gain to that of the DATA channel, and there must also be enough spectral separation between these channels to avoid inter-channel interference. However, the bandwidth requirement of busy tone signal is small and the decoding is much simpler than that over the DATA channel; a node only needs to check the existence of the busy tone signal at certain frequency by the sensed power level.

Besides using busy tones, many studies employ multiple channels to alleviate the hidden and exposed terminal problems. In single-channel schemes, all types of frames, such as the RTS, CTS, DATA, and ACK frames in the IEEE 802.11 protocol, are transmitted on the same channel, and thus collisions between any two types of frames exist. One common approach to reduce collisions among different types of frames is to employ multiple channels, and transmit different types of frames over different channels.

Many schemes use a separate channel for the transmission of the RTS and CTS frames, and one or more channels for the transmission of the DATA and ACK frames. In the Dynamic
Channel Assignment (DCA) scheme [40], the overall bandwidth is divided into a single control channel and \( n \) equivalent data channels, each with the same bandwidth. The purpose of the control channel is to resolve the contention on data channels and assign data channels to mobile hosts. Each mobile host is equipped with two half-duplex transceivers. One is for control channel, and the other one is dynamically switched to one of the data channels to transmit or receive the DATA or ACK frame. A five-way handshake is used. An RTS frame that stores the sender’s Free Channel List (FCL) is transmitted by the sender and the receiver will select the channel for the upcoming data transmission according to the received FCL and its own Channel Usage List (CUL). Thereafter, CTS and RES (reservation) frames are transmitted to notify the neighbors of the receiver and the sender of the reserved data channel, respectively. The RTS, CTS, and RES frames are all transmitted over the control channel (for this reason, RES cannot be implemented as a sub-header of the DATA frame to reduce the overhead, a technique proposed in the RBAR [22] in Subsection 2.4). DCA follows an ‘on-demand’ style to assign channels to mobile hosts, and does not require clock synchronization. The collisions between data frames are alleviated due to the use of multiple data channels. IEEE 802.11s [41] proposed for mesh networks applies a similar mechanism called the Common Channel Framework (CCF). However, in these schemes, the common control channel may become the bottle neck when the traffic is heavy and the number of data channels is large.

MAC with a Separate Control Channel (MAC-SCC) [42] uses two channels, one control channel and one data channel, and the data channel is assigned more bandwidth than the control channel. Different from the previous schemes, the RTS and CTS frames are transmitted over the data channel if the data channel is idle or over the control channel otherwise. Because both data and control channels are used to resolve contentions, MAC-SCC requires two NAVs, one for each channel. While there is a data transmission over the data channel, MAC-SCC allows an
RTS/CTS dialogue over the control channel to schedule the next data transmission. In this way, the utility on the data channel is improved.

Figure 2-6 outlines the basic concepts of the multi-channel MAC protocols that use a common control channel and multiple transceivers.

Besides the common control channel approach, some other schemes do not rely on the control channel. Instead, they are flexible in arranging different channels for RTS, CTS, DATA, and ACK frames to reduce collisions. Both Interleaved CSMA (ICSMA) [44] and Jamming based MAC (JMAC) [45] divide the entire bandwidth into two channels and employ one half-duplex transceiver for each channel. ICSMA uses two channels of equal bandwidth. A node is permitted to originate transmission in either channel. The transmitter sends the RTS and DATA frames on one channel, and the receiver responds by sending the CTS and ACK frames on the other channel, thereby solving the hidden and exposed terminal problem. In JMAC, the medium is divided into two channels: an S channel for the transmission of the RTS and DATA frames, and an R channel for the transmission of the CTS and ACK frames; the bandwidth of the S channel is greater than that of the R channel. In JMAC, the carrier sensing is performed in one channel, but
blocks the channel access in another channel. In other words, a node that senses the carrier as busy in one channel is not allowed to transmit to the other channel, but may be allowed to transmit to the same channel. Therefore, a transmitter transmits jamming signals over the S channel to protect the present or upcoming CTS or ACK frame on the R channel. For a receiver, while it is waiting or receiving a DATA frame on the S channel, it jams the R channel to prevent neighboring nodes from transmitting RTS frames on the S channel. The so-called jamming signal is similar to a busy tone.

Finally, some protocols do not require multiple half-duplex transceivers. They only use a single half-duplex transceiver but require more complex negotiations and bookkeeping. The challenge is to ensure that the idle transmitter and receiver visit the same channel. This issue is studied in [46]. The solution could be the common hopping approach, in which devices do not exchange data hops through all channels synchronously; or the split phase approach, in which the time intervals is divided into an alternating sequence of control and data exchange phases. However, both approaches still belong to single rendezvous MAC protocols; the negotiations take place at a single channel, although this channel may not be fixed. One solution to allow parallel rendezvous is for each idle device to follow a “home” hopping sequence and for the sending device to transmit on that channel to find the intended receiver, such as SSCH [47] and McMAC [48], as discussed in [46]. Other than that, the single transceiver schemes are fundamentally similar to the schemes with multiple transceivers.

2.7 Protocols using directional antennas

In the study of wireless networks, the antenna model is often classified as omnidirectional or directional. Omnidirectional antennas, also known as isotropic antennas, radiate and receive equally well in all directions (although in reality, no antenna is perfectly omnidirectional). A directional antenna concentrates more energy in one direction compared to the others when
transmitting or receiving. Directional antennas can bring higher spatial reuse and a longer transmission range at the same time, as shown in Figure 2-7. When directional antennas are used, the transmission range not only depends on the type of antenna used by the sender, but also on the receiver’s antenna. Figure 2-7 illustrates four types of neighborhood relationships when directional antennas are used: Omni-Omni (OO) neighbors, Directional-Omni (DO) neighbors, Omni-Directional (OD) neighbors, and Directional-Directional (DD) neighbors.

![Figure 2-7. DO, OD, and DD neighbors](62)

In principle, most of the MAC protocols proposed for wireless ad hoc networks with directional antennas are based on the IEEE 802.11 four-way handshake. Some adaptations, such as Directional Virtual Carrier Sense (DVCS) and Directional Network Allocation Vector (DNAV) [54], [55], [58], are devised to take advantage of directional communications. DNAV – a directional version of NAV – is crucial to efficiently manage the directional transmission, avoiding collisions and meanwhile enabling spatial reuse. The DNAV is a table that keeps track of the directions and the corresponding periods during which a node must not initiate a transmission. If a node receives an RTS or CTS frame from a certain direction, it only updates its
DNAV and defers the transmissions associated with that direction. A transmission intended toward other directions may be initiated. Figure 2-8 illustrates the operation of DNAV.

![Figure 2-8. DNAV and simultaneous directional transmissions: S1-R1 and S2-R3 [62]](image)

In almost all of the proposed schemes, the DATA and ACK frames are transmitted directionally, while the transmission of RTS/CTS frames varies. [49], [50] assume directional transmission only. Consequently, although DATA and ACK frames are transmitted directionally, both RTS and CTS frames are transmitted omni-directionally because the DATA and ACK frame receptions are subject to the omni-directional interference. The benefits associated with the longer transmission range of the directional antennas are not realized. The authors in [51] examine many factors that affect network performance in wireless ad hoc networks with directional antennas, such as channel access, link power control, neighbor discovery, and multi-hop routing. The authors extend their work and propose a directional power-controlled MAC with a modified backoff procedure in [52]. In DVCS [54] and Directional MAC (DMAC) [55], [56], a node sends
the RTS and CTS frames directionally and maintains a DNAV. It is assumed that the transmitter knows the direction associated with the receiver before it starts to transmit. DMAC utilizes directional physical as well as virtual carrier sensing. [55], [56] also discuss the problems arising from the use of directional antennas, but do not provide any solutions. Instead, a multi-hop RTS MAC (MMAC) is proposed. It enables direct single-hop connections between DD neighbors by utilizing the extended transmission range of directional antennas. The challenge is that the receiver cannot receive the RTS frame from its DD neighbor when it is idle and in omni-directional mode. Via the established route to the DD neighbor, the sender node uses a multi-hop RTS frame through several (DO) transmissions to inform the intended DD neighbor to beamform to the sender. The CTS, DATA and ACK frames will be transmitted through this DD link directly over a single hop. The authors assume that the sender knows its DD neighbors beforehand.

Using directional antennas could greatly improve the performance of wireless ad hoc networks by means of the higher spatial reuse and longer transmission ranges. However, some problems, such as the deafness and hidden terminal problems, become more serious. The directional RTS/CTS handshake reserves a smaller area to enable a higher spatial reuse; however, in doing so, the neighbors out of the directional RTS/CTS scope are not being informed of the upcoming transmissions. These neighbors, although not the deaf nodes in the omni-directional communication, can become deaf nodes when directional antennas are used. There are two types of deafness problems. In the first one, the intended receiver is a transmitter or receiver of another transmission. In the second one, the intended receiver is neither a transmitter nor a receiver of another transmission, but is within the coverage area of another transmission. This area is called the deaf zone [57]. The second type of deafness problem is more serious than the first [57]. On the other hand, although the hidden terminal problem is a well-known problem in wireless ad hoc networks when using omni-directional antennas, two new types of hidden terminal problems are introduced when using directional antennas. The first type of hidden terminal problem is due to
the fact that RTS/CTS reservation only covers the DO neighbors but not the DD neighbors. These DD neighbors are the hidden terminals and can cause collisions when they beamform to the direction of an active receiver and transmit. Another type of hidden terminal problem occurs when a node is beamforming to other directions and cannot receive the directional RTS/CTS frames. Unaware of the current transmission, a node may transmit to the direction of a current receiver and result in a collision. The deafness problem is revealed to be much more serious than the hidden terminal problem [58].

ToneDMAC is proposed in [59] to address the first type of deafness problem. The protocol assumes a single transceiver with the capability to transmit or receive over multiple channels. A tone is transmitted omni-directionally through one of the control channels each time when a node successfully transmits or receives a data frame and multiple tones are required to identify each node. This requires a complicated tone assignment mechanism. It also assumes that a node is able to monitor both data and control channels at the same time. This work only addresses the first type of deafness problem. Another approach to address the hidden terminal problem, Circular Directional RTS MAC (CDR-MAC) is proposed in [60], [61]. Circular directional RTS frames are used to notify all the sender’s DO neighbors, including the receiver’s DD-range hidden terminals, of the upcoming transmission through several consecutive directional transmissions. In addition, a node maintains a location table for each neighbor that includes a pair of beam labels with which it and the corresponding neighbor can communicate with each other. The frame header in an RTS or a CTS frame contains the corresponding beam pair retrieved from the sender’s location table, so that a neighbor overhearing the RTS/CTS frames is able to determine whether its next transmission will interfere with the ongoing communication. A node always starts its first CDR at a fixed direction, and the CTS will be transmitted after the sender node covers all directions through $M$ CDRs transmissions. This requires an idle node to defer the
channel contention for a duration of $M \times l_{\text{RTS}}$ instead of a DIFS period, where $M$ is the number of antenna beams and $l_{\text{RTS}}$ is the transmission time of an RTS frame; this is a significantly longer delay.

To address both deafness and hidden terminal problems, researchers [58], [62] propose Directional MAC with Deafness Avoidance and Collision Avoidance (DMAC-DACA). DMAC-DACA uses sweeping RTS/CTS frames transmitted with several consecutive directional transmissions to inform DO neighbors in all directions of the upcoming transmission. With the information from the overheard packets, deafness avoidance and collision avoidance mechanisms have been proposed in DMAC-DACA. In the proposed mechanism for addressing the first type of deafness problem (DA1), a new network vector called Deafness Vector (DV) was introduced to indicate when the intended receiver will be available for receiving. Whether a transmission attempt is allowed will be determined by both DNAV and DV. Furthermore, with the aid of location information (can be acquired from the equipment such as GPS), DA2, and two Collision Avoidance (CA) mechanisms, CA1 and CA2, are proposed. In DA2, with the knowledge of the surrounding ongoing transmissions and the location information, a node could determine whether a neighbor is in the deaf zone and for how long it will remain deaf. Then the DV can be updated accordingly. In CA1, the DD neighbors of a receiver node can be reached by the sweeping RTS transmission from the transmitter node (the DD neighbors of a transmitter can be reached in a similar way through the sweeping CTS) and thus they are able to determine whether they could interfere with the ongoing reception according to their own locations and the locations of the transmitter and the receiver. The similar mechanism of CA1 also enables CA2. By the location information, a node is able to update its DNAV when receiving either a sweeping RTS frame or a sweeping CTS frame even if it has not received the previous basic RTS/CTS frames. Simulation
results show that DMAC-DACA significantly improves the throughput and that deafness problems have greater impact on the throughput than hidden terminal problems.

2.8 Protocols using MIMO

As it has been presented in the last subsection, using directional antennas can increase the spatial reuse and transmission range simultaneously, thereby significantly increasing the performance of wireless ad hoc networks. Nevertheless, directional antennas are suited for the line of sight (LOS) or near LOS environment, but will work poorly in the multi-path environment. MIMO, on the other hand, turns multi-path propagation, traditionally a pitfall of wireless transmission, into a benefit for the user. Given an arbitrary wireless communication system, MIMO defines a link for which the transmitter, as well as the receiver, is equipped with multiple antenna elements. In a MIMO system, the signals generated by the transmit antennas at one end and the signals recovered by the receive antennas at the other end are “combined” such that the quality (bit-error rate or BER) or the data rate (bits/sec) of the communication for each MIMO user is improved. The former is called spatial diversity and the latter is called spatial multiplexing.

MIMO channels offer a linear increase in capacity (in the order of $\min(M_T, M_R)$, where $M_T$ and $M_R$ are the numbers of antennas at the transmitter and the receiver respectively) for no additional power or bandwidth expenditure [62], [63], [64]. This gain, referred to as the spatial multiplexing gain, is achieved by transmitting independent streams or layers of data by all available transmit antennas simultaneously using the Vertical Bell Labs Layered Space Time (VBLAST) architecture [64], for example. More information about MIMO spatial multiplexing and other aspects of MIMO can be found in [62], [63], and the numerous references therein.

MIMO spatial multiplexing can significantly improve the raw rate, thus the throughput of the single-hop wireless LAN as in IEEE 802.11n, in which all available antennas are used for
transmissions. Nevertheless, it is not necessarily leading to a significantly performance improvement for multi-hop wireless ad hoc networks since the MAC inefficiencies associated with utilizing IEEE 802.11 and its variants in multi-hop wireless ad hoc networks – the hidden terminal, exposed terminal and deafness problems – remain unsolved. Fortunately, spatial multiplexing can be extended to a multi-user scenario, in which the multiple independent streams can be transmitted from multiple nodes rather than from a single user; the receivers that equip $M$ antennas successfully receive all the $K$ streams from $N$ nodes, provided that $N \leq K \leq M$. This is a distributed version of spatial multiplexing and can be exploited to solve the MAC inefficiencies in multi-hop wireless ad hoc networks. A node can use only a subset of the available antennas for the transmission and all the available antennas for the reception, thus multiple simultaneous transmissions can be carried out simultaneously.

In the example as shown in Figure 2-9, it is assumed that each node is equipped with two antennas. As shown in Figure 2-9 a), with distributed spatial multiplexing (each data and control frame contributes one stream), while node D is receiving from node C, the handshakes of other two links: A↔B and E↔F could be performed simultaneously, and all three transmissions will be successful. The spatial efficiency will be greatly improved because the hidden and exposed terminals transmit without harming the current transmission. The deafness and unfairness problems are resolved as well. Although one antenna is sacrificed to attain this, and the data rate in a single-hop transmission is halved accordingly, higher aggregate throughput (about 1 and a half times) may be achieved. On the other hand, as shown in Figure 2-9 b, if all the nodes use both antennas to transmit the DATA frames, the transmission of other two links, A↔B and E↔F, will not be permitted while node D is receiving from node C; thus only two streams will be transmitted.
The use of the multi-user or the distributed spatial multiplexing in MAC design for wireless ad hoc networks [65] — [83] has drawn more and more research interest but is still in its early stage.

Mitigating Interference using Multiple Antennas MAC (MIMA-MAC) [65] – motivated by distributed spatial multiplexing – is proposed for multi-hop ad hoc networks in which each node equips two antennas. In MIMA-MAC, a transmitter always uses one antenna to transmit and the receivers use two antennas for receiving. The proposed scheme assumes that all the nodes in the network are synchronized and the protocol divides the time into fixed-size MIMA-MAC frames. The MIMA-MAC frame is further divided into a negotiation period for two consecutive sets of RTS/CTS exchanges, and a contention-free period for two simultaneous DATA frame transmissions, each transmitted with a single stream. However, it is hard to achieve global synchronization in multi-hop ad hoc networks. The fixed-size frame design is not trivial and requires the DATA frame to be the same size. Also, if an RTS/CTS exchange does not take place in the negotiation period, or is unsuccessful, the following contention-free period will be wasted. As a result, only the nodes that manage to successfully carry out the negotiation phase are permitted to transmit.
A direct extension to MIMA-MAC, a MAC protocol for MIMO ad hoc networks with Parallel RTS Processing (PRP-MAC), is proposed in [67]. PRP-MAC is proposed to solve one problem of MIMA-MAC in which the DATA frame transmission period is not fully utilized if an RTS/CTS exchange does not take place or is collided in the negotiation period. Instead of immediately replying with a CTS frame to the first RTS frame, a receiver waits for another RTS frame. Therefore, it can determine the maximum allowable number of data streams after receiving up to 2 RTS frames. If it only receives one RTS frame by then, the DATA frame will be transmitted in the following contention free period with full antennas since there is only one transmission present.

A MAC/PHY cross-layer design of MIMO with layered multiuser detection is proposed in [68] for single-hop wireless ad hoc networks. It requires frame synchronization and each frame is divided into the RTS, CTS, DATA and ACK phases. All the nodes that have a packet to send transmit their RTS frames, which may contain multiple transmission requests, at the same time in the RTS phase. The RTS frames are not aimed to block transmissions, but rather are used for traffic load estimation. This strategy is highly relied on the findings that a rather powerful receiver is capable of decoding a large amount of incoming streams thanks to the advanced receiver derived in [69]. As reported in [68], a receiver with eight antennas is able to receive fourteen incoming streams with low probability of bit error. The contention resolution is performed in the frame level and a random backoff for a number of frames is needed for nodes that do not receive a CTS frame. The nodes that do not transmit in the RTS phase process all the received RTS frames and grant the transmission requests through the CTS frames according to one of the several CTS policies devised. As researchers found, the CTS policy that processes the RTS requests in the order of decreasing SNR achieves the best performance. In the CTS policy, a node not only processes the wanted RTS requests, but also the unwanted for the purpose of
interference cancellation. This protocol is capable of single-node to multi-nodes or multi-nodes to single-node communication.

Stream-Controlled Medium Access (SCMA) is proposed in [70]. In determining if the channel is busy and negotiating the number of streams to be assigned to each transmission link to achieve a fair share in a multi-hop wireless ad hoc network, SCMA estimates the resource availability at each node in its two-hop neighborhood. To facilitate this requirement, a node operates in the spatial diversity mode during an RTS/CTS frames exchange to extend the RTS/CTS frames transmission range. Thereafter, the two-hop neighbors switch to the spatial multiplexing mode and are scheduled (also through the range-extended RTS/CTS frames) to transmit simultaneously, each with the assigned number of streams. The RTS/CTS frames exchange with a double transmission range imposes a significant limitation to SCMA since as authors pointed out at least four antennas are required to double the transmission range, which may be infeasible for some mobile terminals such as a laptop or a PDA. Moreover, due to the share of streams in each link is determined through estimating the number of the neighboring transmission links, SCMA better fits a network with a stable traffic pattern and static topology, which often is not the case in a multi-hop wireless ad hoc network.

The Asynchronous Randomized Allocation Multi-antenna (ARAM) MAC protocol is proposed in [72] to achieve the fairness in asynchronous MIMO multi-hop networks. Different from other protocols, ARAM does not require the network-wide synchronization. The main idea is to prevent a flow from using all antennas for all time thereby leaving an SINR margin for other contending flows. ARAM contains two components: residual capacity estimation and randomized resource allocation. Residual capacity estimation is an interference measurement mechanism that estimates the current residual SINR margin at both the transmitter and receiver via a multi-bit quantization of the sensed interference. Randomized resource allocation is the decision-making
policy that randomly maps the residual capacity measurements into node resource allocations. Through such probabilistic antenna allocation mechanism, ARAM does not rely on the complete network topology and traffic information. However, to properly configure the many parameters in the randomized resource allocation policy is not easy although a formula of the average rate for two contending transmissions with random interferences is derived and can be used to estimate the parameters. Moreover, asynchronous MIMO networks require a more advanced design of MIMO transceiver, which is not addressed.

The MIMO-aware rate splitting (MRS) MAC protocol [73] is another protocol that does not require synchronization among nodes. The MRS protocol is a distributed MAC protocol that enables nodes to locally cooperate with other nodes in their vicinities to first estimate the spatial channels’ status, then to translate the required data rate into a number denoting spatial channel requirements, and finally to reserve the required spatial channels, avoiding any collision. MRS did not provide an algorithm for channel assignment; instead, the channel requirement for each connection (and so the spatial channel requirement) was assumed to be determined, and MRS is to coordinate these connections to concurrently share/split the channels.

An asynchronous medium access protocol for multi-user MIMO based uplink WLANs is proposed in [74]. It assumes that a network with multiple senders and one receiver, the access point. After receiving CTS or ACK frames, whenever a node notices there is a vacant space that accommodates more simultaneous packet receptions, it can start a new transmission with a probability although on-going transmissions still exist. Note that this requires the AP can transmit ACK to one sender through a so-called feedback channel even when it is still receiving packets from other senders; similarly, all the senders are required to be able to receive the ACK frame from feedback channel. This is a mix of the MIMO and multiple channels.
Some works studied other perspectives of MIMO ad hoc networks. An interesting study on energy efficiency for IEEE 802.11n ad hoc networks is proposed in [75]. This study shows that limited power devices are not suitable to carry WWW traffics by MIMO transmission because of large overheads of physical layer in the IEEE 802.11n High Throughput (HT) mode. However, if large file transmissions by File Transfer Protocol are considered, the energy efficiency in HT mode can be very high because of the large aggregated frame size by frame aggregation. A Receiver-Oriented Interference Suppression model (ROIS) is proposed in [76] and authors claim that link scheduling based on ROIS achieves significant higher network throughput than that based on stream control. Some research challenges and opportunities for MIMO vehicular networks were studied in [79], in which mobility is investigated. Proposing analytical model and analysis for MIMO ad hoc networks is very difficult due to many dynamics for such networks, especially for multiple hops networks. The analysis for single-hop networks are proposed in [80], [83]. Cooperative relay for high performance communications in MIMO ad hoc networks is exploited in [82]. Unlike conventionally applying for single antenna, it considered cooperative MIMO multiplexed transmission in which multiple nodes can simultaneously transmit to a receiver that has multiple antennas, i.e., forming a virtual MIMO array, and a sender with multiple antennas can also transmit multiple streams to a set of nodes. In this way, many-to-many transmissions are allowed between node pairs to better exploit multiplexing gain. Powered by multiple streams reception/transmission of spatial multiplexing, a node can obtain the relay packet without extra overheads and forward the relay packet in conjunction with normal packet transmissions.

Figure 2-10 provides a good illustration of the timeline chart of two flows under synchronized MIMO MAC protocols, the IEEE 802.11 and its variant, including IEEE 802.11n, and asynchronous MIMO MAC protocols.
Figure 2-10. Timeline of the activities of two flows under different MAC approaches [72]

There are some limitations and drawbacks of the existing proposals for MIMO ad hoc networks. First, most proposals rely on frame synchronization and use a contention period to exchange several sets of control frames for the purpose of reservation or channel estimation. However, global synchronization and scheduling for a multi-hop ad hoc network is not easy to achieve, or introduces considerable overheads. Secondly, most of the proposed schemes are proposed for single-hop ad hoc networks or simple multi-hop ad hoc networks and do not solve hidden terminal, exposed terminal, and deafness problems, which often occur in multi-hop ad hoc networks. Last but most importantly, almost all of the proposed protocols aim at splitting or sharing the multiple spatial channels powered by the MIMO to enable simultaneous
transmissions. In the simplest form, it is to find a proper antenna assignment to fulfill the following equation:

$$\sum_{i=1}^{j} n_i = N, \text{ for } n_i \in (1, 2, ..., M), j \in (1, 2, ..., M)$$

Where $n_i$ is the number of antennas used to transmit the DATA frame in the $i_{th}$ link; $j$ is the number of concurrent transmissions; $M$ is the number of antennas available at a node; and $N$ is the maximum number of spatial streams a channel can accommodate. In these protocols, only $n_i$, the number of antennas used to transmit the DATA frame in a link, and $j$, the number of concurrent transmissions, are considered; however, due to implicitly viewing the link as the target of the assignment scheme, $N$, the maximum number of spatial streams a channel can accommodate, is fixed and always limited to be equal to $M$, the number of antennas available at a node.

Nevertheless, wireless link requires bi-directional transmissions between the sender and receiver. When using different number of antennas, the transmission from one end of the link can have different impact on its neighbors depending on the number of antennas used for the transmission. Moreover, this also imposes different resource requirements necessary to receive the frame transmitted from the other end of the link. Therefore, a node will determine the available channel resource depending on not only if its neighbor is a sender or receiver, but also the role of itself as a sender or a receiver in its own transmission. For example, if we assume that the DATA frame is being transmitted with $n_i$ antennas; it will leave the neighbors of the sender $M - n_i$ streams for receiving other simultaneous transmissions. However, if the neighbors of the sender are going to transmit rather than receive, the available resource at these nodes will be $M - 1$ if the upcoming ACK frame to be received at the sender node only uses a single antenna. The asymmetry of the bi-directional transmissions can be exploited to increase the value of $N$ in a multi-hop wireless ad
hoc network. In fact, as it will be presented in this thesis, \( N = 2 \times (M - 1) \) can be achieved, which is a significant improvement than \( N = M \) applied in other works.

2.9 A categorization of the MAC protocols

MAC is one of the key contributors to a high-performance wireless ad hoc network. Figure 2-11 shows a categorization of the MAC protocols surveyed in this chapter.

For single-hop wireless ad hoc networks, the key is to improve utilization of the channel and reduce the overhead, which leads to the approaches, such as refining backoff mechanism, frame aggregation, and rate adaptation. For the multi-hop wireless ad hoc networks, the hidden terminal, exposed terminal and deafness problems significantly limit the network performance. There are many approaches for solving these problems — in the form of the controlled communication distance, leading to the transmission power control protocols; in the form of the disjointed frequencies, leading to the multi-channel protocols; in the form of the narrowed communication directions, leading to the directional antennas protocols; or in the form of utilizing the multi-path propagation, leading to the schemes employing MIMO distributed spatial multiplexing. MIMO has been widely used as a powerful technique in wireless networks to boost the raw data rate and this makes it a strong candidate and competitor for the future wireless networks. Although it has become a hot topic, the research of enhancing MAC layer efficiencies by MIMO for wireless ad hoc networks is still in its early stage and its full potential has not been explored.
Figure 2-11. A categorization of the MAC protocols for wireless ad hoc networks
Chapter 3
Overview of the HCS Framework

In this thesis, a novel Hybrid Carrier Sense – HCS – framework is proposed, mainly in the MAC layer, to exploit the power of MIMO and enhance the efficiencies of wireless ad hoc networks. An overview of the HCS Framework is provided in this chapter. More details will be given in the following two chapters.

HCS senses the channel availability jointly by the virtual carrier sense and physical carrier sense and a finite state machine is devised to model the HCS states and decision-makings. HCS does not require the synchronization among nodes; each node independently and locally makes its own decision when to start its transmission. HCS enables simultaneous medium access, which would otherwise be suppressed among neighboring nodes. Moreover, HCS not only shares the channel, but also exploits the bi-directional handshakes of the wireless transmissions and increases the number of simultaneous stream transmissions. For a network with \( M \) antennas in each node, HCS can accommodate \( 2 \times (M - 1) \) streams, a significant increase compared to \( M \) streams achieved by all other existing works. Moreover, HCS is aimed for use with multi-hop wireless ad hoc networks, in which hidden terminal, exposed terminal, and deafness problems greatly degrade network performance. The HCS framework solves all of these problems.

This chapter is organized as follows. First we will briefly review the limitations of current protocols that employ MIMO distributed spatial multiplexing. Then we will present an overview of HCS-MAC. We will discuss how this design can solve hidden terminal, exposed terminal, and deafness problems; why \( M - 1 \) antennas to transmit DATA frames and a single antenna for control frames should be chosen; and the motivation for using hybrid-carry sensing. At the end of this chapter, we will outline the functionalities that the HCS-PHY can provide for the HCS-MAC.
3.1 The limitations of existing protocols

In wireless ad hoc networks, the hidden terminal problem causes collisions; the exposed terminal problem decreases spatial reuse; and the deafness problem elevates unfairness. As being surveyed in Chapter 2, there are many approaches for solving these problems — in the form of the controlled communication distance, leading to the transmission power control protocols; in the form of the disjointed frequencies, leading to the multi-channel protocols; in the form of the narrowed communication directions, leading to the directional antennas protocols; or in the form of utilizing multi-path propagation, leading to schemes employing MIMO distributed spatial multiplexing. MIMO has been widely used as a powerful technique in wireless networks to boost the raw data rate and this makes it a strong candidate and competitor for the future wireless networks compared to other techniques. Although it has become a hot topic, the research of enhancing MAC layer efficiencies by MIMO for wireless ad hoc networks is still in its early stage and its full potential has not been explored.

MIMO turns multi-path propagation, traditionally a pitfall of wireless transmissions, into a benefit for the user. MIMO channels offer a linear increase in capacity (in the order of $\min(M_T, M_R)$, where $M_T$ and $M_R$ are the number of antennas at the transmitter and the receiver respectively) for no additional power or bandwidth expenditure [62], [63], [64]. The spatial multiplexing gain is achieved by transmitting independent streams or layers of data by all available transmit antennas simultaneously using the Vertical Bell Labs Layered Space Time (VBLAST) architecture [64], for example. MIMO spatial multiplexing can significantly improve the raw rate and the throughput of a single-hop wireless LAN as in IEEE 802.11n. Nevertheless, unresolved hidden terminal, exposed terminal, and deafness problems still downgrade the performance of a multi-hop wireless ad hoc network.
Spatial multiplexing can be extended to a multi-user scenario, in which each node is equipped with $M$ antennas, and a node can successfully receive all $K$ streams from $N$ nodes, if $N \leq K \leq M$. This distributed spatial multiplexing or multi-user detection technique can be exploited to solve the MAC inefficiencies in a multi-hop wireless ad hoc network. By using a subset of the antennas to transmit, multiple simultaneous transmissions can carry out among several contending links as long as $K \leq M$ holds at each receiving node.

Many schemes [65]—[83] have been proposed for MIMO ad hoc networks and a comprehensive survey has been provided in chapter 2.8. Most of them rely on frame synchronization and use a contention period to exchange several sets of control frames for the purpose of reservation or channel estimation, such as MIMA-MAC [65], PRP-MAC [67] and [68]. However, global synchronization and scheduling for a multi-hop ad hoc network is not easy to achieve, or introduces considerable overheads or extra hardware requirements. SCMA [70] and [71] estimates the resource availability at each node in its two-hop neighborhood, but this only works for a network with stable traffic pattern and requires spatial diversity with at least four antennas. On the other hand, an asynchronous MIMO ad hoc network can alleviate the limitations of synchronization, but will need more careful protocol design. ARAM [72] is designed for asynchronous MIMO ad hoc networks with a randomized resource allocation. However, due to the complexity of multi-hop ad hoc networks, it is difficult to configure many parameters required by the randomized resource allocation. MRS [73] is another asynchronous protocol, however, which assumes that the channel requirement for each connection has already been determined, and the aim of the protocol is to share or split the channel for these connections. Another work [74] is proposed for a single-hop wireless LAN, where multiple senders and one single receiver exist.
All the proposed protocols for MIMO ad hoc networks aim at splitting or sharing the multiple spatial channels powered by the MIMO to enable simultaneous transmissions. We have shown that in the simplest form, the design of MAC protocol for MIMO ad hoc network is to find a proper antenna assignment to fulfill the following equation:

\[ \sum_{i=1}^{j} n_i = N, \text{ for } n_j \in (1, 2, \ldots, M), j \in (1, 2, \ldots, M) \]

Where \( n_i \) is the number of antennas used to transmit the DATA frame in the \( i_{th} \) link; \( j \) is the number of concurrent transmissions; \( M \) is the number of antennas available at a node; and \( N \) is the maximum number of spatial streams a channel can accommodate.

In these protocols, only \( n_i \), the number of antennas used to transmit the DATA frame in a link, and \( j \), the number of concurrent transmissions, are considered; however, due to implicitly targeting a single link for the resource assignment, \( N \), the maximum number of spatial streams a channel can accommodate, is fixed and always limited to be equal to \( M \), the number of antennas available at a node. However, wireless link requires bi-directional transmissions between the sender and the receiver. When using different number of antennas, the transmission from one end of the link can have different impact on its neighbors depending on the number of antennas used for the transmission. Moreover, this also imposes different resource requirement necessary to receive the frame transmitted from the other end of the link. Therefore, a node will determine the available channel resource depending on not only if its neighbor is a sender or receiver, but also the role of itself as a sender or a receiver in its own transmission. The asymmetry of the bi-directional transmissions can be exploited to increase the value of \( N \).

The HCS framework to be proposed in this thesis utilizes complete random access among the nodes. HCS explores the asymmetry of the bi-directional transmissions between a sender and a receiver and increases the value of \( N \) – the maximum number of spatial streams a channel can
accommodate – to \( N = 2 \times (M - 1) \), which is a significant improvement over \( N = M \) in other works.

3.2 HCS-MAC

3.2.1 \( M - 1 \) antennas for DATA frames, and a single antenna for control frames

HCS-MAC is based on the IEEE 802.11 four-way handshake and MIMO. We assume that all the nodes are equipped with \( M \) antennas. The MIMO distributed spatial multiplexing mode is enabled and a node is capable of successfully receiving all the \( K \) streams from \( N \) nodes, provided that \( N \leq K \leq M \). We use \( M - 1 \) antennas to transmit DATA frames whenever deemed feasible (otherwise using a single antenna to avoid collisions with another DATA frame with \( M - 1 \) streams), and a single antenna to transmit the control frames (i.e., RTS/CTS/ACK). Thus, 1) a DATA frame and any one of the control frames, 2) two control frames, or 3) two data frames as long as one is transmitted using a single stream can be received successfully by the one node. As we discussed previously, the MAC inefficiencies are often attributed to the collisions among DATA and control frames or the effort to avoid such collisions. For example, the deafness problem results from the RTS frame collisions, or the fact that the receiver does not reply with a CTS frame to avoid colliding with an ongoing transmission. The exposed terminal problem arises as a result of the effort to avoid collisions involving ACK frames. In our novel proposal, we can resolve all these problems.

3.2.2 An illustration

Take Scenarios 1 to 3 in Figure 2 as illustrations. First, for a 2I2O system, each data and control frame will be transmitted using a single antenna. With distributed spatial multiplexing, it is easy to demonstrate that all the transmissions in the three scenarios can be carried out simultaneously, each using a single antenna. Secondly, for a MIMO system with \( M > 2 \), each data stream may be transmitted using \( M - 1 \) or a single antenna(s), and control frames are
transmitted using a single antenna. With distributed spatial multiplexing, in the hidden terminal problem illustrated in Scenario 1, one link can transmit data frames using $M - 1$ antennas, while another link uses a single antenna; in the deaf terminal and exposed terminal problems illustrated in Scenarios 2 and 3 respectively, all the links can transmit the data frames using $M - 1$ antennas. In all three scenarios, the transmission of two links can be carried out simultaneously. In doing so, the spatial efficiency is significantly improved because the hidden and exposed terminals are allowed to transmit without harming an existing transmission. The deafness and unfairness problems are resolved as well. Although one antenna is sacrificed to attain this, and the data rate in a single-hop transmission is reduced accordingly, a higher aggregate throughput (especially in the deaf terminal and exposed terminal problems illustrated in Scenario 2 and Scenario 3 when $M > 2$) can be achieved. For example, considering Scenarios 2 and assuming $M = 3$. When the DATA frames are transmitted using two antennas and other control frames are transmitted with a single antenna, an aggregate throughput of $2 \times (M - 1) = 4$ streams can be achieved. But when all nodes use three antennas for transmissions, an aggregate throughput will be only three streams.

Figure 3-1. An illustration to show how HCS-MAC can solve hidden terminal, exposed terminal, and deafness problems
3.2.3 A discussion: why use $M – 1$ antennas for DATA frames

Why use $M – 1$ antennas to transmit data frames whenever deemed feasible and a single antenna to transmit other control frames? It is to maximize the data rate in a single hop and thus achieve a higher aggregate throughput, and meanwhile provide an extra degree of freedom to cope with hidden terminal, exposed terminal, and deafness problems. The goal of this design is to enable two simultaneous transmissions. If we try to schedule more simultaneous transmissions, we have to determine how many links are going to transmit so as to decide how many streams will be allocated to each transmission link. To achieve this, more control frame exchanges and a more complicated control system will be required to estimate the topology and traffic pattern. This will significantly increase the complexity and overheads. Moreover, in multi-hop wireless ad hoc networks, the dynamically and rapidly changing topology, traffic, and other network factors make such effort even less cost-effective and justifiable. Finally, using $M – 1$ antennas to transmit data frames whenever deemed feasible and using a single antenna to transmit other control frames does not only enable two simultaneous transmission, but also maximizes the data rate in a single hop; thus, a higher aggregate throughput is achieved. Scenarios 2 and 3 shown in Figure 3-1 for a MIMO system with $M > 2$ clearly illustrating this benefit of the design; an aggregate throughput of $2 \times (M – 1)$ streams is achieved. If we use the same number of antennas to transmit both DATA and control frames, a maximum of aggregate throughput of $M$ streams can be achieved, although we enable multiple simultaneous transmissions.

3.2.4 Motivation of using hybrid carrier sensing

HCS-MAC is based on the IEEE 802.11 four-way handshake and MIMO. To enable two simultaneous transmissions and avoid collisions, carrier sensing in IEEE 802.11 ought to be redesigned. The conventional PCS and VCS procedures are indeed two separate processes, and, traditionally, either one can determine whether the channel is busy. However, for the sake of HCS-MAC-enabled ad hoc networks, neither PCS nor VCS alone is sufficient. To handle two
simultaneous transmissions, HCS integrates both PCS and VCS to jointly sense the channel and determine whether the channel can accommodate a new transmission. If at most a single active transmission is determined by HCS, the channel is regarded as available.

Figure 3-2 shows the neighbors’ expected carrier sense observations (from PCS) during different stages in a four-way handshake (from VCS) in a 2I2O system. Take the period when the sender is transmitting its DATA frame to the receiver (stage SN3 at the Neighbor of the Sender and RN3 at the Neighbor of the Receiver) as an example. On the one hand, the neighbor of the sender is expected to sense one stream (the DATA frame); therefore, in stage SN3, the channel is still available even when the PCS indicates there is one transmission. However, if the PCS indicates there is more than one transmission, the channel should be regarded as unavailable. On the other hand, in stage RN3, the neighbor of the receiver should not sense this DATA frame. Thus, in stage RN3, sensing a stream signals that there is another transmission along with the current one between the sender and the receiver, which means that there are two transmissions and the channel is unavailable to access. Thus, a node needs to integrate both VCS and PCS to jointly determine the availability of the channel. VCS is used to determine within which stage a node is positioned in a neighbor’s four-way handshake, and PCS is used to determine the number of the current transmissions in the air. We call that hybrid carrier sense – HCS.
Figure 3-2. The neighbors’ expected carrier sense observation (from PCS) during different stages of a four-way handshake (from VCS)

3.2.5 Another discussion: MIMO vs. multi-channels

In theory, the idea that we have presented of HCS-MAC can also be applied over multiple channels. Indeed, the aim of the HCS-MAC is to maximize the benefit of spatial reuse and allow multiple simultaneous transmissions; both MIMO and multiple channels can be utilized for this purpose.

Why do we prefer MIMO to multiple channels? The foremost reason is that MIMO not only facilities multiple simultaneous transmissions but also offers a linear increase in capacity for no additional bandwidth expenditure. This would not be true when applying multiple channels. Simply separating the channel into sub-channels would not increase the capacity. To increase the capacity, more bandwidth/channels would be required. Thus, we prefer MIMO as a better choice.
to multi-channel for higher capacity and network throughput. Nevertheless, the possibility of being applied over multiple channels shows that HCS-MAC is generic and flexible and applying it over multiple channels can be studied in future work.

3.3 HCS Physical Carrier Sensing (HCS-PCS)

HCS-MAC requires the PHY layer to perform physical carrier sense; however, it is unnecessary for the PHY layer to determine the exact number of ongoing streams. Actually, it is sufficient for HCS-PCS to determine whether there is no transmission, one transmission, or more than one transmission because the aim of HCS-MAC is to enable two simultaneous transmissions. A cross-layer approach is devised for this purpose. HCS-PCS will be aided by the information maintained at the upper HCS-MAC sub-layer to achieve this goal. By comparing the current interference level with the carrier sense threshold or the interference level when the last control frame was successfully received, and depending on the current HCS-MAC state, HCS-PCS determines if there is no transmission, one transmission, and more than one transmission. Taking this information from HCS-PCS, HCS-MAC then determines if the channel is available for the transmission attempt.
Chapter 4
HCS-MAC

In this chapter, we will propose Hybrid Carrier Sense MAC (HCS-MAC) design. HCS-MAC is based on the IEEE 802.11 four-way handshake and MIMO and supports both 2I2O and MIMO ($M > 2$) systems. HCS-MAC uses $M - 1$ antennas to transmit DATA frames whenever deemed feasible (otherwise using one antenna to avoid collisions with another DATA frame with $M - 1$ streams), and a single antenna to transmit the control frames (i.e., RTS/CTS/ACK). The HCS-MAC utilizes complete random access among the nodes, critical for reducing network complexity and increasing flexibility. With the help of overheard control messages, each HCS-enabled node dynamically maintains its HCS-MAC state information and determines, independently of its neighbors, when to access the channel. Consequently, HCS can not only enable simultaneous medium access, but also achieve a higher aggregate throughput. This will significantly improve the network’s performance.

This chapter is organized as follows. We will first introduce the notations used in the HCS-MAC scheme and then propose the basic scheme for a 2I2O system. The basic HCS-MAC scheme will be modeled by a Finite State Machine (FSM). The scheme for general MIMO systems, where $M > 2$, will be followed with some modifications and add-on mechanisms to the basic HCS-MAC. Lastly, the design of HCS-PCS will be presented, which is aided by the information provided by the HCS-MAC sub-layer.

4.1 HCS-MAC notations

We define some terms that will be used to formally describe the HCS-MAC scheme. The terms are categorized into statuses, timers, or decisions depending on their use and functionality.
4.1.1 Statuses

The statuses indicate what control frames a node overhears. The statuses include:

*Empty*: A node does not overhear any RTS or CTS frame, and thus has no knowledge of the upcoming transmissions around it.

*RTS*: A node is the neighbor of the sender and overhears an RTS frame.

*CTS*: A node is the neighbor of the receiver and overhears a CTS frame.

*RTS/CTS*: A node is the neighbor of both the sender and the receiver and overhears RTS and CTS frames, both belonging to the same transmission.

*n(RTS/CTS)*: A node overhears RTSs and/or CTSs frames belonging to *n* different transmissions, where *n* ≥ 2.

4.1.2 Timers

The timers indicate for how long the current status holds at a node. The timers will be used in conjunction with the *RTS* status, the *CTS* status, the *RTS/CTS* status, or the *n(RTS/CTS)* status to describe a node’s HCS-MAC state. The initial value of a timer depends on the node’s current status. The four-way handshake diagram in Figure 4-1 shows the neighbors’ HCS-MAC states and the corresponding initial value of the timers at different state. The timers are:

*CTS_Du*: The timer maintained by a neighbor of the sender. Its initial value is equal to the duration following the end of the overheard RTS frame until the beginning of the upcoming DATA frame, that is, \( l_{CTS} + 2 \times l_{SIFS} \), where \( l_{CTS} \) is the transmission time for a CTS frame and \( l_{SIFS} \) is the length of a Short InterFrame Space (SIFS).

*DATA_Du*: If it is maintained by a neighbor of the sender, its initial value is equal to the transmission time of the upcoming DATA frame, \( l_{DATA} \). Otherwise, its initial value is equal to \( l_{DATA} + 2 \times l_{SIFS} \) if maintained by a neighbor of the receiver.
ACK_Du: If it is maintained by a neighbor of the sender, its initial value is equal to the duration following the end of the upcoming DATA frame until the end of the upcoming ACK frame, that is, $l_{ACK} + l_{SIFS}$. Otherwise, its initial value is equal to $l_{ACK}$ if maintained by a neighbor of the receiver.

Figure 4-1 depicts these timers. As a rule of thumb, $l_{SIFS}$ is included in the initial value of a timer if a node is expected to sense zero streams during the period when the timer is present, because there are no transmissions by either the sender or the receiver during a SIFS period.

![Four-way handshake diagram](image)

**Figure 4-1. Four-way handshake diagram that shows the initial value of the timers corresponding to different HCS-MAC states**

There are also some other timers that are not shown in Figure 4-1 but can simply be extended from it. They will be presented in the following.
**RTS/CTS_Du:** The timer maintained by a node that is a neighbor of both the sender and the receiver, and, hence, overhears both RTS and CTS frames. The duration represented here stretches from the end of the CTS reception until the end of the ACK reception, that is, \( I_{\text{DATA}} + I_{\text{ACK}} + 2 \times I_{\text{SIFS}} \). Actually, it is the sum of the DATA_Du period and the ACK_Du period at a node that holds a CTS status, as shown in the right bottom two blocks in Figure 4-1.

**Shortest_RTS/CTS_Du:** This timer is used when a node is at the \( n(\text{RTS/CTS}) \) status and represents the shortest duration required to complete a four-way handshake among the \( n \) overheard transmissions. This means that a single transmission will be completed at the end of this time duration and the total number of the ongoing transmissions is decreased by one.

It is worth pointing out that in Figure 4-1 we numbered the SIFS periods within a four-way handshake. The notations will be used later in this chapter when we present the details of the HCS-MAC. Their meanings will be outlined in the following:

- **SIFS-1:** the SIFS period that locates in the first break during the four-way handshake, i.e., between RTS and CTS frames;
- **SIFS-2:** the SIFS period that locates in the second break during the four-way handshake, i.e., between CTS and DATA frames;
- **SIFS-3:** the SIFS period that locates in the third break during the four-way handshake, i.e., between DATA and ACK frames.

### 4.2 Basic HCS-MAC for a 2I2O system

We first present the basic HCS-MAC for a 2I2O system, in which every node equips two antennas and both DATA and control frames are transmitted using a single antenna. Amendments that accommodate a MIMO system, where \( M > 2 \), will be presented later in this chapter.
HCS-MAC is devised to determine whether the channel can accommodate a new transmission. If there are currently no transmissions or only a single transmission, the channel can accommodate a new transmission; otherwise, the channel is fully occupied and a node has to defer its medium access. This mechanism will be formally modeled by a Finite State Machine (FSM). For better understanding the HCS-MAC scheme, we will present two versions of the FSM, one to show the conceptual overview of the hybrid carrier sense and the other to illustrate the detailed transitions among the FSM states.

Figure 4-2 shows a conceptual overview of the hybrid carrier sense performed by HCS-MAC. It has a layered structure. The states in the FSM reflect a node’s knowledge of its neighbors’ ongoing or upcoming transmissions, but not its own. Such knowledge, coupled with HCS physical-carrier sensing, enables HCS-MAC to determine whether the channel is able to accommodate a new transmission.
Figure 4-2. Conceptual overview of the HCS-MAC FSM

The first layer has a single state – the \textit{Empty} state – which means the node has no knowledge about the transmissions around it. The second layer consists of six states, representing the different combinations of the RTS status, the CTS status, or the RTS/CTS status with their
corresponding timers. The second layer states indicate that a node is aware of one ongoing
transmission by overhearing an RTS or/and a CTS frame(s). At each state, a caption indicates the
type of overheard control frame(s) and the period of its neighbor’s four-way handshake within
which the neighbor is expected to be positioned. For example, a node in the RTS, DATA_Du state
is expected to sense the DATA frame corresponding to the overheard RTS frame if no other
transmissions are present in the vicinity; therefore, a bracketed OS, which represents One Stream,
is put under the RTS, DATA_Du state caption. A node in the RTS, ACK_Du state is expected to
sense zero streams and a bracketed ZS, which represents Zero Stream, is put under the RTS,
ACK_Du state caption. A node that holds the Layer 1 state or one of the Layer 2 states may or
may not be able to access the channel depending on the results of physical carrier sensing and
which state it is in.

The third layer consists of one state, which represents overhearing two control frames that
belong to two ongoing transmissions; the shorter transmission will end after the
Shortest_RTS/CTS_Du period. The Layer 3 state indicates that the channel is fully occupied since
HCS-MAC is devised to enable two simultaneous transmissions. In other words, Layer 3 state
signals that the channel cannot accommodate more transmissions. The rest of the layers are
similar to the third layer, except that the overheard control frames indicate \( n \) transmissions are
present rather than two.

Figure 4-2 serves as a good conceptual overview of the hybrid carrier sense; Figure 4-3
provides more details. Figure 4-3 is made up of two components: the left component is for carrier
sensing and the right component is for decisions or, equivalently, the outcome of the carrier
sensing. The Sensed-as-Free state in the decision component indicates that a node determines the
channel as accessible after the hybrid carrier sense and will decrement its backoff counter. Note
that HCS-MAC is a slotted access scheme, similar to the IEEE 802.11. If the backoff counter
reaches zero, the node proceeds to transmit. The detailed version of the FSM, as shown in Figure 4-3, is maintained at each node at all times.

![Detailed HCS-MAC FSM](image)

**Figure 4-3. Detailed HCS-MAC FSM**

Among the HCS-MAC FSM states that have been introduced above, there are four types of transitions. They are Inter-Component Transitions (ICT), IntrA-Layer Transitions (IALT), IntEr-Layer Transitions (IELT), and Same State Transitions (SST). ICT is the most important transition. It connects the carrier sensing component and the decision component and describes the rules of hybrid carrier sensing. IALT, IELT and SST are the supporting transitions. They are
confined in the carrier sense component and maintain the HCS-MAC states evolvement in the carrier sensing component. Next, we present the details of the state transitions using Figure 4-3.

4.2.1 Inter-Component Transitions (ICT)

ICTs are the transitions between the states in the first two layers of the carrier sense component and the Sensed-as-Free state in the decision component, which indicates the channel is accessible. There are three types of inter-component, unidirectional transitions from the carrier sense component to the decision component. The FSM then returns to the state in the carrier sense component from which the transition to the Sensed-as-Free state was originated. A node may perform ICT during random backoff (before initiating a new transmission) or during a SIFS period (the SIFS-1 and SIFS-2 periods within its own RTS/CTS/DATA handshake). Note that a node does not perform carrier sensing during a SIFS-3 period (before the ACK frame) and therefore there is no ICT during this period. Whenever there is a packet in the transmission queue, a node performs ICT; otherwise, it does not.

4.2.1.1 ICT during random backoff

Figure 4-1 in the beginning of this section shows the number of streams that a node in different HCS-MAC states is expected to sense. Using this figure, we will describe the different types of ICT that may be performed before a node initiates a new transmission.

4.2.1.1.1 Zero Stream Transition (ZST)

The first type of ICT occurs if zero streams are sensed, and is called Zero-Stream Transition (ZST). ZST is only relevant to the Empty state in Layer 1 and the RTS, CTS_Du state, the RTS, ACK_Du state, and the CTS, DATA_Du state in Layer 2 of the FSM.

4.2.1.1.1.1 ZST at the Empty state
A node in the *Empty* state is required to perform ZST. When a node in the *Empty* state (which has no knowledge of other transmissions around it) senses a stream, it should regard the channel as unavailable and defer its transmission attempt; otherwise, it will lose the opportunity to learn of the upcoming transmissions by overhearing this stream. As it has been shown in Figure 4-1, if a sender’s or receiver’s neighbor is in the *Empty* state and allowed to transmit, it will not be able to overhear the current RTS or CTS frame and update its HCS-MAC state. Moreover, a node does not even know whether the stream is destined to itself. As shown in Figure 4-4, node A is transmitting an RTS frame to node B. If node B, a node which is in the *Empty* state, regards the channel as accessible despite sensing one stream (the RTS frame for itself) and starts to transmit another RTS frame to node D, the ongoing communication between nodes A and B will be interrupted. Another extreme case arises when nodes A and B have packets destined to each other; a deadlock would be evitable if without the enforcement of ZST. Thus, when a node is in the *Empty* state, ZST is required.

![Figure 4-4. A scenario illustrating ZST at the Empty and RTS, CTS_Du states](image)

### 4.2.1.1.2 ZST at the *RTS, CTS_Du* state

A node in the *RTS, CTS_Du* state is required to perform ZST. As per Figure 4-2, overhearing a single stream in the *RTS, CTS_Du* state will lead the FSM to Layer 3 if this stream is an RTS or a CTS frame belonging to a different four-way handshake, or to the *RTS/CTS, RTS/CTS_Du* state if this frame is a CTS frame belonging to the same four-way handshake. In Figure 4-4, as a result of overhearing the RTS frame from node A, both nodes C and D are in the *RTS, CTS_Du* state. If
node D senses a stream, this stream must be the CTS frame from node B (because node D is a neighbor of both nodes A and B and has no other neighbors). Because this CTS frame belongs to the same four-way handshake, node D should transit to the RTS/CTS, RTS/CTS_Du state and regard the channel as available. However, being a neighbor of the transmitter only, if node C senses a stream, it must belong to another transmission, and node C is expected to transit to the two(RTS/CTS), Shortest_RTS/CTS_Du state and regard the channel as unavailable. Therefore, to correctly transit to a state upon leaving the RTS, CTS_Du state and determine the number of the ongoing transmissions, a node in the RTS, CTS_Du state is required to perform ZST.

4.2.1.1.3 ZST at the RTS, ACK_Du state and the CTS, DATA_Du state

A node in the RTS, ACK_Du state or the CTS, DATA_Du state is required to perform ZST. As it was shown in Figure 4-1, a node in both states should sense zero streams if there are no other transmissions. In both states, and without sensing any streams, a node knows that there is an ongoing transmission between its neighbors (the transmission from the sender to the receiver). If a node in either state senses another stream, it signals that there are two ongoing transmissions (the channel is fully occupied and not accessible). Therefore, in both states, ZST is applied.

4.2.1.1.2 One Stream Transition (OST)

The second type of ICT takes place upon sensing one stream, and is called the One-Stream Transition (OST). OST is applied to the RTS, DATA_Du state, the CTS, ACK_Du state and the RTS/CTS, RTS/CTS_Du state in Layer 2.

4.2.1.1.2.1 OST at the RTS, DATA_Du state and the CTS, ACK_Du state

When a node is in the RTS, DATA_Du state or the CTS, ACK_Du state, it is expected to sense one stream – the DATA frame from the sender or the ACK frame from the receiver respectively, as it was shown in Figure 4-1. As a result, if it senses a stream when it is in one of these states, it
should belong to the same four-way handshake indicated in the overheard RTS or CTS frame (the channel is still available to accommodate another stream). Thus, in both states, OST is applied.

4.2.1.1.2.2 OST at the *RTS/CTS, RTS/CTS_Du* state

Similarly, when a node is in the *RTS/CTS, RTS/CTS_Du* state, it is expected to sense one stream at any time within the *RTS/CTS_Du* period (except during two SIFS periods pertaining to the four-way handshake). Although the sender and the receiver of a four-way handshake do not transmit during a SIFS period, it does not affect the physical carrier sense since a node has to wait for a Distributed InterFrame Space (DIFS) period before starting a backoff procedure; a DIFS period is longer than a SIFS period. Therefore, OST is applied when a node is in the *RTS/CTS, RTS/CTS_Du* state.

4.2.1.2 ICT during a SIFS and Deafness Avoidance (DA)

A node also needs to perform ICT during a SIFS period pertaining to its own four-way handshake. It requires extra care for the *Empty* state; The ICTs in other states remain same as the ones that were developed in last subsection. In this subsection, we first describe the ICTs that a node in the *Empty* state will perform during the different SIFS periods within a node’s own four-way handshake. Then, we will present the new type of deafness problem arising in HCS-enabled networks and how the proposed ICTs for the SIFS periods can facilitate the deafness avoidance.

4.2.1.2.1 Zero or One Stream Transition (ZOST) and ZST at the *Empty* state

Immediately following the reception of an RTS or a CTS frame pertaining to the node’s own four-way handshake, the node will wait for a SIFS period before transmitting a CTS or a DATA frame, and the carrier sense process is continued during the SIFS period. A node will not perform carrier sensing during the SIFS-3 period before it transmits an ACK frame, same as the IEEE 802.11.
On the one hand, during the SIFS-2 period immediately following the reception of a CTS frame, a node in the Empty state will transit to the Sensed-as-Free state when it senses either zero or one frames. Such transition is referred as Zero-or-One Stream Transition (ZOST). When the SIFS-2 period ends, a node will continue the four-way handshake by sending the DATA frame even if it sensed one stream during the SIFS-2 period. This is due to the fact that receiving a CTS frame signifies successful medium reservation via the RTS/CTS handshake for the upcoming DATA and ACK frame transmissions. The newly started transmission engaged by the sensed stream should not harm the ongoing four-way handshake. Therefore, the ZOST can protect a four-way handshake from being interrupted and thus enable multiple simultaneous transmissions, or four-way handshakes.

On the other hand, during the SIFS-1 period immediately following the reception of an RTS frame, a node in the Empty state is required to perform ZST only. In doing so, a node can overhear more RTS or CTS frames to gain the knowledge of the ongoing or upcoming transmissions in its surrounding area. This makes HCS-MAC algorithm more effective and facilitates some advanced mechanisms such as deafness avoidance, which we will present soon. Besides, the cost of not replying an RTS frame that is in the initial step of a negotiation is tolerable compared to not replying a CTS frame that is in the later stage of the four-way handshake.

4.2.1.2.2 Deafness Avoidance (DA)

In HCS-enabled networks, some new types of deafness problems arise and they must be taken care of. In this subsection, we will describe the new types of deafness problem and the DA mechanisms, including the one facilitated by the design of ZST for the SIFS-1 period.

4.2.1.2.2.1 DA to the first type of deafness problem
The first type of deafness problem arises when the destination node is the sender of another ongoing transmission. In Figure 4-5, node B has sent an RTS frame to node C and the remaining of the four-way handshake between nodes B and C is underway. If node A initiates a new transmission (which is not allowed in conventional wireless ad hoc networks but takes place often in the HCS-enabled networks) to node B, node B will not be able to respond due to being engaged in an ongoing transmission.

This type of deafness problem is easier to address. Node A can discover that node B is in another ongoing transmission through overhearing the RTS frame transmitted by node B and by being aware of that, node B is unable to receive. With this information, we implement DA. A node sets up a Deafness Vector (DV) if its destination node is either the source or destination indicated in the overheard RTS or CTS frame. This node has to defer its transmission attempt until the end of the DV even if the ICT rules that it is safe to transmit now. This mechanism is similar to the DA mechanism we devised in [56], [57] and more details can be found from these references. Moreover, if First-In First-Out (FIFO) rule is not mandatory, packet reordering and multi-user diversity can be explored; a node can first send to another node that is currently not deaf, or equivalently, able to receive at the current moment.

![Figure 4-5. DA for an active transmitter](image)

4.2.1.2.2.2 DA powered by ZST to the second type of deafness problem

Another new type of deafness problem in HCS-enabled wireless networks arises when the destination node is the receiver of another ongoing transmission. The similar DA mechanism we
just developed to address the first type of deafness problem can be applied as well. Nevertheless, some extra treatments are needed, especially the ZST during the SIFS-1 period, which is immediately following the reception of an RTS frame. In Figure 4-6, node B is in the Empty state. Node C starts to transmit an RTS frame to node B when node A is doing so. If node B performs OST during the SIFS-1 period after receiving the first RTS frame transmitted by node A, it will reply with a CTS frame to node A even when node C is still in the transmission of its RTS frame to node B. Being in the transmission mode, node C is unable to overhear the CTS frame from node B. Since node C is unaware of the ongoing transmission between nodes A and B, the deafness avoidance mechanism we developed for the first deafness problem can not be applied here. To solve this problem, node B is required to perform ZST during the SIFS-1 period after it receives an RTS frame. Thus, it will not respond to the first RTS frame that is transmitted from node A, but will reply with a CTS frame to the second RTS frame that is transmitted from node C. In doing so, node A is able to overhear the CTS frame transmitted from node B and therefore being informed that node B, its destination, is engaged in another ongoing transmission. By then, the similar DA mechanism developed for the first type of deafness problem can be applied. This requires adding the source node address into an IEEE 802.11 CTS frame; the modified CTS frame is referred to as the HCS-CTS frame.

Figure 4-6. DA for an active receiver

4.2.1.3 Summary of ICT

Table 4-1 summarizes the viable ICTs. The general rule for ICT is that if a node senses one stream, it does not perform OST to be able to receive it, process it, and prevent a neighboring
node from becoming deaf, or because the newly received stream signals that there are two ongoing transmissions, which renders the channel unavailable. Otherwise, the node performs OST, because the channel can seemingly accommodate another transmission. During the SIFS-2 period immediately following the reception of a CTS frame, a node performs ZOST.

**Table 4-1. INTER-COMPONENT TRANSITIONS**

<table>
<thead>
<tr>
<th>State</th>
<th>ZST</th>
<th>OST</th>
<th>ZOST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty</td>
<td>Y</td>
<td>Y</td>
<td>Y (during SIFS-2)</td>
</tr>
<tr>
<td>RTS, CTS_Du</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RTS/CTS, RTS/CTS_Du</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RTS, DATA_Du</td>
<td></td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>RTS, ACK_Du</td>
<td></td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>CTS, DATA_Du</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTS, ACK_Du</td>
<td></td>
<td></td>
<td>Y</td>
</tr>
</tbody>
</table>

**4.2.2 IntrA-Layer Transitions (IALT)**

Intra-layer transitions take place within the second layer of the carrier sense component and between the states that have the same status. They are devised to track its neighbor’s four-way handshake, the period within which the neighbor is expected to be positioned. If a node remains in the same state until the timer held at the current state expires, the FSM will transit to the next state with the same status, as it was shown in the second layer of Figure 4-2 or in the second layer of the carrier sense component in Figure 4-3. Such transitions are straightforward when there is only one next state to which the FSM can transit. One exception is the RTS, CTS_Du state. When the CTS_Du timer expires, a node can transit to either the RTS/CTS, RTS/CTS_Du state if a CTS frame belonging to the same four-way handshake is overheard, or the RTS, DATA_Du state otherwise.
4.2.3 IntEr-Layer Transitions (IELT)

Inter-Layer transition can take place at both directions. IELT to the next layer indicates that there is one more transmission; IELT to the previous layer indicates that one transmission (four-way handshake) ends. In this subsection, we will first study these two types of IELTs, and then present another IELT devised to handle the failed four-way handshake.

4.2.3.1 IELT to the next layer

Upon overhearing a control frame that indicates a new transmission is present, an inter-layer transition takes place and the node transits to a state within the next layer. For example, if a node at the Empty state overhears an RTS frame, it will transit to the RTS, CTS_Du state; if it overhears a CTS frame instead, it will transit to the CTS, DATA_Du state. The IALT will proceed thereafter. It is noteworthy that even if a node transits to the third layer, in addition to setting up the Shortest_RTS/CTS_Du timer in the third layer, it also maintains its IALT in the second layer. In doing so, when the shortest duration in Layer 3 expires, a node can proceed to the proper state within Layer 2.

However, if every overhearing of a new control frame triggers an IELT to a higher layer, the carrier sense component will consist of $n + 1$ layers, just as shown in Figure 4-3, and will be prone to grow as a function of the number of neighbors and their traffic loads. This is not only undesired, but also unnecessary. In fact, the Layer 3 state can sufficiently represent all the states in the higher layers. As we discussed previously, the aim of HCS_MAC is to enable two simultaneous transmissions, but not more. Therefore, similar to the Layer 3 state, all higher-layer states reflect the channel’s unavailability for use by the node maintaining the FSM. In other words, all the Shortest_RTS/CTS_Du values in the higher-layer states are smaller than their counterparts in the lower-layer states, and all the higher-layer states have to transit through the Layer 3 state to reach one of the Layer 2 states. Thus, upon overhearing a new RTS or CTS
frame, a node in Layer 3 state will remain in the same state, but may update its
Shortest_RTS/CTS_Du timer in Layer 3 and the state in Layer 2 (as discussed previously, which
is not an active state, but has to be maintained to perform IALT), depending on the length of the
duration carried in the newly overheard RTS or CTS frame. The corresponding FSM, which
consists of 3 layers in the carrier sense component rather than \( n+1 \) layers is shown in Figure 4-7.

![Modified HCS-MAC FSM consisting of three layers in the CS component](image)

Figure 4-7. Modified HCS-MAC FSM consisting of three layers in the CS component

4.2.3.1.1 IELT: Layer 2 to Layer 3

Figure 4-8 shows an example of IELT from Layer 2 to Layer 3 that will be performed when a
node in the RTS, CTS_Du state overhears a new RTS frame. We first introduce four variables as
the following:
$L_2$ is the current duration maintained by the Layer 2 state, and represents the remaining time of the four-way handshake corresponding to the current transmission indicated by the Layer 2 state;

$L_3$ denotes the value of the $\text{shortest}_{\text{RTS/CTS}}_{\text{Du}}$ timer to be set up in Layer 3 after a node overhears a new control frame;

$L_{3 \_ 2}$ denotes the new Layer 2 duration to be maintained by a node in Layer 3 state;

and $L_C$ corresponds to the duration in the newly overheard control frames, i.e., RTS or CTS frames.

Due to space limitations in Figure 4-8 and the rest of the figures in this subsection, we use $\text{Shortest}_{\text{RTS/CTS}}_{\text{Du}}$ to represent the $\text{shortest}_{\text{RTS/CTS}}_{\text{Du}}$ timer. The white space between the two consecutive frames in the four-way handshake represents a SIFS period. Although a node will remain in the two(\text{RTS/CTS}), $\text{Shortest}_{\text{RTS/CTS}}_{\text{Du}}$ state until the $\text{Shortest}_{\text{RTS/CTS}}_{\text{Du}}$ timer expires, it is required to keep tracking or bookkeeping its IALT in the second layer. In this example as shown in Figure 4-8, the second layer states will evolve from the \text{RTS, CTS }_{\text{Du}} state to the \text{RTS, DATA }_{\text{Du}} state, and then to the \text{RTS, ACK }_{\text{Du}} state. When the $\text{Shortest}_{\text{RTS/CTS}}_{\text{Du}}$ timer in the third layer expires, the node will correctly transit to the \text{RTS, ACK }_{\text{Du}} state.
4.2.3.1.2 IELT: Layer 3 to Layer 3

Similarly, we devise a mechanism to manage the state updating when a node is in Layer 3 state and overhears a new control frame, as illustrated in Figure 4-9. Note that $L_3 < L_3 \_ L_2$ always holds. Among three $L_3$, $L_3 \_ L_2$, and $L_C$ values, the new $L_3 \_ L_2$ value will be updated with the largest value, and the new $L_3$ value will be updated with the second largest value. The rationale behind this state updating mechanism has been discussed; it is same as the reason why we only need a HCS-MAC FSM with three layers rather than $n + 1$ layers, which has been discussed in the beginning of this subsection. The details of the state updating mechanism are shown in Figure 4-9. It also performs IALT in the second layer, same as what has been described in Figure 4-8 example.
A node currently in layer 3 state needs to update its L2 and L3 values after overhearing a new RTS frame with duration $L_4$.

4.2.3.2 IELT to the previous layer

On the other hand, when a transmission, or equivalently a four-way handshake, indicated by a Layer 2 or Layer 3 state is completed, a node will transit to a state within the previous layer. These transitions take place when the $ACK_{Du}$ timer or the $RTS/CTS_{Du}$ timer in the second layer, or the $Shortest_{RTS/CTS}_{Du}$ timer in the third layer expires. Note that thanks to the bookkeeping for the IALT at the second layer, which has been studied in detail in Subsection 4.2.3.1, a node in the third layer state is capable of transiting to the proper state in the second layer upon the timer in the third layer expires.

4.2.3.3 IELT to handle a failed handshake

Finally, another type of IELT is devised to handle the failed four-way handshake in the vicinity of the nodes running the FSM as well as cases in which a retransmission is required. A
node in the $RTS, DATA_Du$ state, the $RTS/CTS, RTS/CTS_Du$ state, or the $CTS, ACK_Du$ state is expected to sense a single stream. If a node in either one of these states does not sense the stream after a timeout, it signals that the expected transmission is not carried out. This requires a node transitioning to the $Empty$ state and a retransmission will be rescheduled thereafter.

### 4.2.4 Same-State Transitions (SST)

The proposed carrier sense component is a backoff-slotted multi-access system. The node senses the channel at the beginning of each backoff slot. If no other transitions take place at the end of the slot, the node executes the same-state transition, thus remaining in the same state and continues to perform carrier sensing at the beginning of the next slot. Same-state transitions occur at all the states in the carrier sense component.

### 4.2.5 Flowcharts pertaining to SST, IALT and IELT

SST, IALT, and IELT are the three types of supporting transitions that take place at the carrier-sensing component of the HCS-MAC FSM. Their detailed flowcharts can be found in the appendix.
4.3 HCS-MAC for a MIMO system \((M > 2)\)

In the HCS-MAC for a MIMO system \((M > 2)\), DATA frames use \(M - 1\) streams whenever deemed feasible. Nevertheless, two DATA frames each using \(M - 1\) streams should not be present around a node at the same time; otherwise, a collision will occur because a node equipped with \(M\) antennas is not able to separate and decode \(2 \times (M - 1)\) streams. This mandates add-on mechanisms to the basic HCS-MAC scheme, which has been proposed for a 2I2O system.

4.3.1 Modifications to ICT

First, ICT needs to be modified. ICT with the transition condition “sensing 1 stream” is changed to “sensing \(M - 1\) or 1 stream(s)”, because the DATA frames are transmitted with \(M - 1\) streams, if deemed feasible, or with 1 stream otherwise. All other transitions remain the same.

4.3.2 The number of antennas to transmit a DATA frame

Secondly, a new mechanism is devised to determine the sustainable number of antennas (1 or \(M - 1\)) for a new DATA frame transmission. Rather than suppressing a link to avoid collision, the new mechanism will enable two simultaneous links: one DATA frame transmitted with \(M - 1\) streams and another DATA frame transmitted with a single stream. A node will use a single stream for its own DATA frame transmission if 1) it determines that one of its neighbors is, or will soon be, receiving a DATA frame with \(M - 1\) streams; or 2) its destination is, or will soon be, exposed to a DATA frame transmission with \(M - 1\) streams. Otherwise, it will use \(M - 1\) streams for its own DATA frame transmission.

4.3.3 Stream Bit (SB) negotiation

A negotiation between the sender and the receiver has to be made to determine the number of the streams to be used for the upcoming DATA frame. To facilitate such negotiation, an additional bit, called the Stream Bit (SB), is added into the RTS and CTS frames to indicate
whether the upcoming DATA frame transmission will use 1 or $M - 1$ streams. This stream bit selection and negotiation mechanism is better illustrated through an example as shown in Figure 4-10, which is actually identical to the hidden terminal example we presented before.

We investigate two scenarios in Figure 4-10. In the first scenario, node A transmits an RTS frame with a SB that indicates there will be $M - 1$ streams for the upcoming DATA frame transmission. If node C has not started its transmission to node D yet, node B will reply with a CTS frame with the same SB. Then node A will transmit the DATA frame with $M - 1$ streams to node B. Being aware of its neighbors is receiving or going to receive a DATA frame consisting of $M - 1$ streams (due to overhearing node B’s CTS frame with the corresponding SB), node C will send its RTS frame with a SB to request for a single stream DATA frame transmission. Upon receiving the RTS with such SB, node D will reply with a CTS frame with the same SB, and a single stream DATA frame transmission between nodes C and D will occur simultaneously along with the DATA frame transmission with $M - 1$ streams between nodes A and B. In the second scenario, we consider another situation in which nodes C and D acquire the channel earlier than nodes A and B and have reserved a $M - 1$ stream DATA frame transmission. Node A will still transmit an RTS frame with the SB that requests the DATA frame being transmitted with $M - 1$ streams. However, being aware of its neighbors (node C) is transmitting or going to transmit an DATA frame consisting of $M - 1$ streams (due to overhearing node C’s RTS frame with the corresponding SB), node B will reply with a CTS frame with a SB that permits DATA frame transmitting with only a single antenna instead, which, in turn, forces node A to use a single stream for its upcoming DATA frame transmission to node B. Afterwards, the DATA frame transmission between nodes A and B will use a single stream simultaneously along with the DATA frame transmitted with $M - 1$ streams between nodes C and D.
4.3.4 Stream Bit Correction (SBC)

In the second scenario of SB negotiation mechanism, which was discussed in Subsection 4.3.2, the SBs in the RTS frame and the CTS frame do not match. This can be a problem because the duration of the actual DATA frame transmission (transmitted with a single stream) will be greater than the previously-advertised duration (in which DATA frame is assumed to be transmitted with $M - 1$ streams) in the RTS frame. Therefore, upon overhearing this faulty RTS frame, a node will perform IALT incorrectly, i.e., entering the $RTS, ACK_Du$ state earlier than it should, and, thus, faultily determine that the channel is inaccessible. To solve this problem arising when the SBs in the RTS and CTS frames do not match, the sender must find some means to notify its neighbors of the correct SB so that the neighbors can correct its record of the duration for the upcoming DATA frame transmission.

One solution is to add a new broadcast frame, namely the Stream Bit Correction (SBC) frame, following the RTS/CTS negotiation to correct the previously advertised SB and the corresponding duration. By taking this five-way handshake approach, the duration field in the CTS frame will need to include the time required for transmitting the newly added SBC frame. Figure 4-11 illustrates the RTS/CTS/SBC/DATA/ACK five-way handshake. The number ($M - 1$ or 1) that is labeled in the frames indicates the number of streams that will be used to transmit the upcoming DATA frame.
Figure 4-11. SBC using RTS/CST/SBC/DATA/ACK five-way handshake

4.4 HCS-PCS design

HCS-MAC requires the PHY layer to perform HCS-PCS for ICT. It is sufficient if HCS-PCS is able to determine whether there is no transmission, one transmission, or more than one transmission. The aim of HCS-MAC is to enable two simultaneous transmissions and it is unnecessary for the PHY layer to determine the exact number of ongoing streams. HCS-PCS will achieve this goal aided by the information maintained at HCS-MAC – the upper MAC sublayer. As presented before in the subsection regarding ICT, a node may perform ICT, therefore HCS-PCS, during random backoff (before initiating a new transmission) or during a SIFS period (the SIFS-1 and SIFS-2 periods within its own RTS/CTS/DATA handshake). In the rest of this subsection, we will first present the HCS-PCS for these two periods in a 2I2O system, and then discuss how it can be extended to a MIMO system, where \( M > 2 \).

4.4.1 HCS-PCS for a 2I2O system

As the HCS-PCS design is closely related to the ICT thoroughly studied in Subsection 4.2.1, we review the main results as shown in Table 4-2. The detailed ICT can be found in Table 4-1...
and the definitions of the terms of SIFS-1 and SIFS-2 can be found at the end of the Subsection 4.1.2.

Table 4-2. CONCISED ICT

<table>
<thead>
<tr>
<th>State</th>
<th>ZST</th>
<th>OST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty</td>
<td>Y (during random backoff or SIFS-1)</td>
<td>Y (during SIFS-2)</td>
</tr>
<tr>
<td>Layer 2 states</td>
<td>Y (during either random backoff or SIFS)</td>
<td>Y (during either random backoff or SIFS)</td>
</tr>
</tbody>
</table>

4.4.1.1 HCS-PCS during random backoff

We start by presenting HCS-PCS design for the period during random backoff (before initiating a new transmission). Observed from Table 4-2, there are some characteristics of HCS-MAC that loosen the requirement of the physical carrier sense and facilitate the HCS-PCS design.

4.4.1.1.1 At EMPTY state

First, before a node in the Empty state transmits an RTS frame, HCS-MAC is required to perform ZST, but not OST, as shown in Table 4-2. To sense whether the channel is idle (zero ongoing streams) is easy, similar to the conventional PCS mechanism.

4.4.1.1.2 At Layer 2 states

Secondly, in other states in Layer 2, a node may perform either ZST or OST. As discussed, it is easy for HCS-PHY to determine an idle channel. Nevertheless, it will take some effort for a node to differentiate a single ongoing stream from more than one. A simple observation reveals that a node is required to do so only when it is in one of the second layer states of the HCS-MAC FSM, which, in turn, indicates this node has the knowledge of channel through overhearing a control frame. We can leverage such information provided by HCS-MAC to enable HCS-PCS.
It can be implemented by comparing the interference level corresponding to the current transmission(s) with a reference interference level associated with the recent overheard RTS or CTS frame (the one that makes a node transit to the current HCS-MAC FSM state). This is better illustrated by an example in Figure 4-12.

Figure 4-12. An illustration scenario of HCS-PCS

In Figure 4-12, after an RTS/CTS handshake, node A is transmitting a DATA frame to node B. Nodes C and E overheard the RTS frame transmitted from node A. Interested in transmitting to node D, node C performs HCS-PCS and finds out that the current interference level that is attributed to the 3) DATA frame close to the one it recorded upon overhearing the 1) RTS frame. Note that both 1) RTS and 3) DATA frames are transmitted from the same node A and with the same transmission power. Thus, node C determines that there is only one ongoing stream. This is clearly shown in Figure 4-13. If $P_{RTS, DATA_{Du}} \approx P_{RTS}$, a node can conclude that there is one transmission, where $P_{RTS, DATA_{Du}}$ is the power level that node C is expected to sense when it is in the RTS, DATA_Du state, and $P_{RTS}$ is the power level that node C sensed when node A was transmitting the RTS frame.
After node C acquires the channel and starts transmitting to node D along with the ongoing transmission from node A to node B, node E will discover that the current interference level, which is jointly attributed to the 3) DATA and 4) RTS frames in Figure 4-12, is significantly higher compared to the previously recorded interference value, which is attributed to the 1) RTS frame in Figure 4-12, and thus can determine that there is more than one ongoing stream. In this case, at node E, there is:

\[ P_{RTS,DATA_Du} = (P_{3)\, DATA\, from\, node\, A} + P_{4)\, RTS\, from\, node\, C}) \gg P_{1)\, RTS\, from\, node\, A} \]

and this means that there are two or more transmissions.

This mechanism assumes that:

\[ P_{DATA} \approx P_{RTS}, \text{ or } P_{ACK} \approx P_{CTS} \]
where \( P_{DATA} \) denotes the receiving power level associated with the DATA frame and so do the other frames. The DATA and RTS frames (or the ACK and CTS frames) are transmitted by the same node and within the same four-way handshake. This is a reasonable assumption. Both RTS and DATA frames (or both ACK and CTS frames) are transmitted from the same node and with the same transmission power, and the channel conditions will not vary significantly during a neighbor’s four-way handshake, which is a short time interval. Moreover, the interference added by a new transmission, such as the one attributed to 4) RTS in Figure 4-12 would be much more significant than the difference (due to channel variation) between the 1) RTS and 3) DATA frames transmitted from the same neighbor (node A in Figure 4-12).

4.4.1.2 HCS-PCS during a SIFS period

In addition to the random backoff (before initiating a new transmission), a node also performs ICT, or HCS-PCS, during a SIFS period (the SIFS-1 and SIFS-2 periods within its own RTS/CTS/DATA handshake).

4.4.1.2.1 At Empty state

When a node is in the Empty state, it may perform ZOST during a SIFS-2 period (after receiving a CTS frame), or ZST only during a SIFS-1 period (after receiving an RTS frame). ZST has been handled as it was discussed in Subsection 4.4.1.1.1. The HCS-PCS for OST during a SIFS-2 period can be implemented in accordance with the algorithm we just described in Subsection 4.4.1.1.2. We still use Figure 4-12 as an example, but this time will focus on the transmissions between nodes A and B. We consider two scenarios.

4.4.1.2.1.1 Scenario 1: another tx is present before the SIFS-2 period

The first scenario is shown in Figure 4-14. After receiving the CTS frame from node B, if node A discovers that the current interference level is still above the carrier sensing threshold \( P_{CS} \), it will record this power level, which is denoted as \( P_{SIFS} \) as shown in Figure 4-14. This power level, \( P_{SIFS} \) (which is equal to \( P_{RTS \text{ from node C}} \) in this example), will be used as the reference
power level. Then the same procedure as the design of HCS-PCS during random backoff, which was presented in the Subsection 4.4.1.1.2, will follow. The reason that $P_{SIFS}$ can be used as the reference power level for a single transmission is because node A would not be able to receive the CTS frame and enter such a SIFS-2 period if there were two or more other transmissions being transmitted along with the CTS frame transmitted from node B. Thus, if the sensed power level during the SIFS-2 period is close to $P_{SIFS}$, node A can conclude that there is a single ongoing stream. Otherwise, if a new transmission is started during the SIFS-2 period, the power level sensed by node A will be much greater than $P_{SIFS}$, which, in turn, signals that two or more transmissions are present.

Scenario 1: node C starts to tx during the $L_{CTS}$ of node B

![Diagram of Scenario 1](image)

Figure 4-14. First scenario of HCS-PCS ZOST during a SIFS-2 period

4.4.1.2.1.2 Scenario 2: no tx before the SIFS-2 period

The second scenario is shown in Figure 4-15. Node A will regard the number of current transmissions as equal to one and will not perform carrier sense during the SIFS-2 period if it discovers that the current interference level is less than the carrier sensing threshold after receiving the CTS frame from node B. This is because the duration of transmitting a CTS frame,
L_{CTS}, is much longer than the duration of a SIFS period, L_{SIFS}; therefore, it is rare that there is no transmission during a L_{CTS} period. Indeed, the HCS-PCS ZOST transition during the SIFS-2 period is to protect an ongoing transmission from being interrupted as it was shown in Figure 4-14.

![Diagram of Scenario 2: node C does not tx during the L_{CTS} of node B]

**Figure 4-15. Second scenario of HCS-PCS ZOST during a SIFS-2 period**

4.4.1.2.2 At Layer 2 states

As it was shown in Table 4-2, a node at one of the Layer 2 states has the same ICTs during a SIFS period (no matter a SIFS-1 or SIFS-2 period) as those performed during backoff, and thus the same mechanism we devised in Subsection 4.4.1.1.2 can be applied.

4.4.1.3 Flowchart depicting HCS-PCS for a 2I2O system

The flowchart depicting HCS-PCS is shown in Figure 4-16.
During random backoff or SIFS-1?

At Empty state?

At Layer 2 state?

streams = 0

P_r > P_{cs}?

N

Y

streams = 1

N

P_r - P_{RTS/CTS} < \alpha \cdot P_{RTS/CTS}?

Y

streams > 1

N

|P_r - P_{RTS/CTS}| < \alpha \cdot P_{RTS/CTS}?

Y

|P_r - P_{SIFS}| < \alpha \cdot P_{SIFS}?

Y

streams > 0

N

P_r - P_{RTS} < \alpha \cdot P_{RTS}?

Y

P_r > P_{cs}?

N

streams = 0

N

Exit PCS

Channel is available

Exit PCS

4.4.2 HCS-PCS for a MIMO system \((M > 2)\)

In HCS-MAC for a MIMO system \((M > 2)\), HCS-PCS is implemented in a similar fashion to the two-antenna case. Although whenever deemed possible, the DATA frame uses \(M - 1\) streams instead of a single stream, it should have a similar interference level at the receiver side because the same transmission power is spread among \(M - 1\) antennas [64]. As a matter of fact, the goal of HCS-PCS is to sense whether there are one or more than one ongoing transmissions; whether they use 1 or \(M - 1\) streams does not matter.
Chapter 5

Performance Evaluation

In this chapter, we will conduct computer simulations and study the performance of the proposed HCS framework. HCS-MAC was implemented in the NS2 network simulator and an exhaustive performance study had been conducted.

5.1 Simulation setup

In this section, the performance of the proposed HCS-MAC is examined. We implement HCS-MAC in the Network Simulator (NS2) [84] and run extensive computer simulations. We will first study the performance of HCS-MAC in Subsections 5.2, 5.3, and 5.4 with three fundamental scenarios as shown in Figure 5-1. Scenarios 1, 2, and 3 represent the conventional hidden terminal, deafness, and exposed terminal problems respectively. We will use these three fundamental scenarios to examine and validate the design of HCS-MAC and compare its performance to Legacy IEEE 802.11 and MIMO IEEE 802.11, in which all available antennas are used to transmit. We will study the aggregate throughput and fairness for each scenario.

![Scenario 1](image1)

![Scenario 2](image2)

![Scenario 3](image3)

Figure 5-1. The fundamental HCS-MAC performance evaluation scenarios

Subsection 5.5 will summarize and compare the results drawn from the study of three individual scenarios. In Subsection 5.6, we will study another two scenarios, Scenarios 4 and 5, and investigate the effectiveness of the DA mechanism, which is proposed to solve the new problem.
deafness problem arising in HCS-enabled networks. Finally, in Subsection 5.7, we will run the simulations of the large scale wireless ad hoc networks in which a large number of wireless nodes are randomly deployed in a given topology and data traffic is randomly generated. We will compare the performances of HCS-MAC and MIMO IEEE 802.11 with respect to the aggregate throughput and Packet Delivery Ratio (PDR).

The IEEE 802.11g PHY parameters, including a 54 Mbps channel bandwidth, are used in the simulation experiments. Radio propagation is modeled using the two-ray propagation model [85]. In the computer simulations, the carrier sense range is made equal to the nominal wireless transmission range. Constant Bit Rate (CBR) traffic is generated by the application layer at the source nodes according to a Poisson process with a predetermined arrival rate of packets per second (pps). The packet length is 1k-byte. User Datagram Protocol (UDP) is used at the transport layer. Other parameters general to all the simulations are summarized in Table 5-1.

Table 5-1. HCS-MAC GENERAL SIMULATION PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel bandwidth</td>
<td>54 Mbps (per antenna)</td>
</tr>
<tr>
<td>Transceiver rate – DATA</td>
<td>54 Mbps (per antenna)</td>
</tr>
<tr>
<td>Transceiver rate – CTRL</td>
<td>24 Mbps</td>
</tr>
<tr>
<td>Radio propagation model</td>
<td>Two-ray</td>
</tr>
<tr>
<td>Traffic category</td>
<td>CBR UDP</td>
</tr>
<tr>
<td>Data frame size</td>
<td>1K bytes</td>
</tr>
<tr>
<td>CWmin</td>
<td>15</td>
</tr>
<tr>
<td>CWmax</td>
<td>1023</td>
</tr>
<tr>
<td>Backoff slot</td>
<td>9 us</td>
</tr>
<tr>
<td>SIFS</td>
<td>16 us</td>
</tr>
<tr>
<td>DIFS</td>
<td>34 us</td>
</tr>
</tbody>
</table>
The parameters for the simulations of the individual scenarios, including three fundamental scenarios and deafness scenarios, are listed in Table 5-2. They will be used throughout Subsection 5.2 to Subsection 5.6.

Table 5-2. HCS-MAC SIMULATION PARAMETERS FOR CONTROLED SCENARIOS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packet generation rate</td>
<td>Saturation</td>
</tr>
<tr>
<td>Number of antennas</td>
<td>2, 3, 4, 5, 6 (in Scenarios 1, 2, 3)</td>
</tr>
<tr>
<td></td>
<td>2 in Scenarios 4 and 5</td>
</tr>
<tr>
<td>Distance between node pairs</td>
<td>200 m</td>
</tr>
<tr>
<td>Sampling interval (for calculating the instantaneous throughput)</td>
<td>100 ms</td>
</tr>
<tr>
<td>Simulation length</td>
<td>50 s</td>
</tr>
</tbody>
</table>

The network parameters pertaining to the large scale random ad hoc networks will be listed later in Subsection 5.7.

5.2 Performance of fundamental Scenario 1

In this subsection, we study the performance of Scenario 1 as shown in Figure 5-2, which represents the hidden terminal scenario.

![Scenario 1](image)

Figure 5-2. HCS-MAC simulation Scenario 1

We first study the 2I2O systems and compare the performance of HCS-MAC to Legacy and MIMO IEEE 802.11. Then we will study the performance of MIMO systems, where $M > 2$. 

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5.2.1 2I2O system

We will study the performance of 2I2O systems in this subsection.

First, as shown in Figure 5-3, the aggregate throughput of HCS-MAC is significantly higher than the aggregate throughputs of MIMO and Legacy IEEE 802.11 although the throughput of link 2→3 with MIMO IEEE 802.11 tops all other simulated results. HCS-MAC achieves an aggregate throughput of about 36 Mbps, a 44% increase with respect to the 25 Mbps of MIMO IEEE 802.11, and an 80% increase compared to the 20 Mbps of Legacy IEEE 802.11.

Secondly, as shown in Figure 5-3, it is evident that Legacy IEEE 802.11 and MIMO IEEE 802.11 allocate the bandwidth extremely unfairly. Using Legacy IEEE 802.11 and MIMO IEEE 802.11, although link 2→3 achieves a high throughput, even higher than either link using HCS-MAC, it comes with the cost of almost completely suppressing another link 0→1, a typical result attributed to the hidden terminal problem. As shown in Figure 5-2, because it is a hidden terminal to node 0, node 2’s transmissions will corrupt the RTS frames addressed to node 1. In addition, when node 2 starts to transmit, node 1 will not be able to receive the RTS frames transmitted by node 0 and node 0 will increase its contention window after each failure of the RTS frame transmission, which, in turn, further reducing node 1’s chance of capturing the channel. On the contrary, HCS-MAC resolves the hidden terminal problem and both links achieve relatively
similar high throughput. Moreover, Figure 5-4, Figure 5-5, and Figure 5-6 show the instantaneous throughputs of three MAC schemes, and further confirm the unfairness of Legacy IEEE 802.11 and MIMO IEEE 802.11, while affirming the fairness achieved by HCS-MAC. Note that in our simulations for all the scenarios, we set the sampling interval to 100 ms for calculating the instantaneous throughput.

![Figure 5-4. Legacy 802.11 unfairness – Scenario 1 (2 antennas)](image)

![Figure 5-5. MIMO IEEE 802.11 unfairness – Scenario 1 (2 antennas)](image)
5.2.2 MIMO system

We further examine the performance of HCS-MAC with more antennas in this subsection.

First, we compare HCS-MAC to MIMO IEEE 802.11 for three antennas. As shown in Figure 5-7, HCS-MAC achieves significantly higher aggregate throughput and equally distributes the bandwidth between two competing flows.
Figure 5-8 and Figure 5-9 show the instantaneous throughput attributed to the two schemes and we can draw the same conclusion as we studied in the 2I2O systems.

![Figure 5-8. MIMO IEEE 802.11 unfairness – Scenario 1 (3 antennas)](image)

![Figure 5-9. HCS-MAC fairness – Scenario 1 (3 antennas)](image)

Then, we examine the link-layer throughput of HCS-MAC and MIMO IEEE 802.11 for MIMO systems where $M \in \{2, ..., 6\}$ as shown in Figure 5-10.
First, the more the antennas deployed, the higher the throughput can be achieved for both HCS-MAC and MIMO IEEE 802.11 schemes. For all antenna deployments, the HCS-MAC aggregate throughput is significantly higher than the MIMO IEEE 802.11 aggregate throughput although link 2→3 in MIMO IEEE 802.11 tops all other simulated results. The improvements to the aggregate throughputs are between 36.5% (or equivalently 10 Mbps) to 49.7% (or equivalently 14.8 Mbps) depending on the number of antennas being deployed.

Next, it is evident that MIMO IEEE 802.11 allocates the bandwidth unfairly. Although link 2→3 achieves a high throughput, it comes with the cost of almost completely suppressing link 0→1. On the contrary, HCS-MAC resolves the hidden terminal problem and both links achieve relatively similar high throughput. It also shows that for HCS-MAC link 2→3 achieves slightly higher throughput than link 0→1 as the number of antennas increases. This is because in Scenario 1, link 2→3 is more likely to transmit its DATA frames using $M - 1$ antennas than link 0→1 when HCS-MAC is implemented.
5.3 Performance of fundamental Scenario 2

In this subsection, we study the performance of Scenario 2, as shown in Figure 5-11, which represents the deafness scenario.

![Scenario 2 Diagram](image)

**Figure 5-11. HCS-MAC simulation Scenario 2**

We will first study the 2I2O systems and compare the performance of HCS-MAC to Legacy and MIMO IEEE 802.11. Then we will study the performance of MIMO systems, where $M > 2$.

5.3.1 2I2O system

We will start from the performance study of 2I2O systems.

First, as shown in Figure 5-12, for Scenario 2, when two antennas are used, HCS-MAC achieves at least 50 and 92% higher individual throughput for both links than MIMO IEEE 802.11 and Legacy IEEE 802.11 respectively. Therefore, HCS-MAC achieves a significant improvement on aggregate throughput than MIMO and Legacy IEEE 802.11 in Scenario 2.

![Saturation throughput comparison](image)

**Figure 5-12. Saturation throughput comparison – Scenario 2 (2 antennas)**
Notably, the link-layer throughput is almost identical for both links regardless of the MAC scheme used. It seems that all the schemes do not suffer from the unfairness problem. Nevertheless, a careful inspection of Figure 5-13 and Figure 5-14 reveals that the instantaneous link-layer throughputs of Legacy IEEE 802.11 and MIMO IEEE 802.11 fluctuate drastically (from 5Mbps to 20Mbps), a strong indication that unfairness resurfaces in Scenario 2.

**Figure 5-13. Legacy 802.11 unfairness – Scenario 2 (2 antennas)**

**Figure 5-14. MIMO IEEE 802.11 unfairness – Scenario 2 (2 antennas)**
As we pointed out previously, Scenario 2 illustrates the deafness problem. As shown in Figure 5-11, using Legacy or MIMO IEEE 802.11, if node 3 starts to transmit an RTS frame to node 2, which is overhearing or has already overheard a CTS frame from node 1, node 2 either will not be able to receive this RTS frame or cannot reply with a CTS frame (due to the overheard CTS frame from node 1). Thus, node 3 will have to double its contention window after each failed retry. This reduces the chances of link 3→2 acquiring the channel, enabling link 0→1 to repeatedly capture the channel. However, once node 3 and node 2 capture the channel, a reversed version of what we just presented will take place; a similar deafness scenario will occur for link 0→1. This is shown clearly in the drastic, instantaneous throughput fluctuation in Figure 5-13 and Figure 5-14. In the long run, however, the two links achieve similar throughput since they each rotate to transmit for a period of time.

On the contrary, for Scenario 2, the HCS-MAC instantaneous throughput is approximately equal to 19 Mbps throughout the simulation for both links, as shown in the thin upper layer in Figure 5-15. This confirms HCS-MAC’s ability to attain fairness since the transmission of another link can be carried out along with the transmission of an ongoing link.
5.3.2 MIMO system

We further examine the performance of HCS-MAC with more antennas in this subsection.

First, we compare HCS-MAC to MIMO IEEE 802.11 for three antennas. When three antennas are used, Figure 5-16, Figure 5-17, and Figure 5-18 show that HCS-MAC achieves 55% higher link-layer throughput for both links and is fairer than MIMO IEEE 802.11. The aggregate throughput improvement for three antennas is even bigger than that for two antennas. This is because in Scenario 2, both links can transmit DATA frames using $M - 1$ antennas; the bigger the $M$ is, the higher the aggregate throughput can be achieved.
Figure 5-16. Saturation throughput comparison – Scenario 2 (3 antennas)

Figure 5-17. MIMO IEEE 802.11 unfairness – Scenario 2 (3 antennas)
Then, we examine the link-layer throughput of HCS-MAC and MIMO IEEE 802.11 for MIMO systems where $M \in \{2,...,6\}$ in Scenario 2, as shown in Figure 5-19, which illustrates the average link-layer throughput of HCS-MAC and MIMO IEEE 802.11 for Scenario 2 when different numbers of antennas are used.

**Figure 5-18. HCS-MAC fairness – Scenario 2 (3 antennas)**

**Figure 5-19. Saturation throughput for various antenna deployments – Scenario 2**
As the number of antennas increases, the throughput increases accordingly for both systems. Regardless of the deployed number of antennas, the HCS-MAC aggregate throughput improvement is even higher than what has been achieved in Scenario 1, ranging from 53.9% (or equivalently 13.3 Mbps) to 57.5% (or equivalently 16.8 Mbps) higher than the MIMO IEEE 802.11 aggregate throughput for 2 to 6 antennas. Next, the figure shows that the HCS-MAC throughput surpasses MIMO IEEE 802.11 (from 50% to 60%) for both links. Expectedly, HCS-MAC identically distributes the bandwidth between two links. Although the curves of two links using MIMO IEEE 802.11 bear close resemblance to each other, Figure 5-14 in Subsection 5.3.1 and Figure 5-17 in the earlier of this subsection have shown the unfairness of MIMO IEEE 802.11.

5.4 Performance of fundamental Scenario 3

In this subsection, we will study the performance of Scenario 3, as shown in Figure 5-20, which represents the exposed terminal scenario.

![Scenario 3](image)

**Figure 5-20. HCS-MAC simulation Scenario 3**

The organization of this subsection is similar to the previous two scenarios, studying the 2I2O systems first and then moving to the MIMO systems.

5.4.1 2I2O system

As before, we start by examining the performance of 2I2O systems.
As shown in Figure 5-21 which quantifies the average link-layer throughput for Scenario 3 with two antennas, following the trends observed for Scenarios 1 and 2, HCS-MAC outperforms MIMO IEEE 802.11 for 2I2O systems in Scenario 3. However, the aggregate throughput of HCS-MAC is only 12.6% (or equivalently 3.4 Mbps) higher on average than MIMO IEEE 802.11, which does not match the improvements reported for Scenarios 1 and 2. There are two reasons. First, in HCS-MAC, the aggregate throughput achieved in Scenario 3 is less than those achieved in the other two scenarios, especially Scenario 2. This is because with HCS-MAC a node in the Empty state is required to perform ZST and thus does not count down its backoff timer when a neighbor is transmitting an RTS frame. In addition, this node has to wait for another DIFS period before it resumes its backoff timer counting down. While in other two scenarios, the backoff timer counting down at one link will continue when another link is transmitting an RTS frame. The second reason is that, in Scenario 3, MIMO IEEE 802.11 achieves higher aggregate throughput than in Scenarios 1 and 2. This is attributed to the fact that in Scenario 3, the source nodes corresponding to the two competing links are exposed to each other; two source nodes compete for the channel without causing frame collisions, therefore, a higher channel utility is achieved. On the contrary, in Scenarios 1 and 2, only one transmission in the two competing links can be successful, leading to a lower channel utility. The joint effect of both reasons explains why HCS-MAC achieves less aggregate throughput improvement in Scenario 3 than in other two scenarios.
As for fairness, similar to Scenario 2, it seems that all three schemes are fair. Actually, despite illustrating considerable instantaneous throughput fluctuations, Figure 5-22 and Figure 5-23 show that Legacy and MIMO IEEE 802.11 perform relatively well in terms of fairness in Scenario 3 compared to Scenario 2. The instantaneous throughputs of Legacy IEEE 802.11 and MIMO IEEE 802.11 fluctuate between 10 Mbps and 12 Mbps, and between 12 Mbps and 15 Mbps respectively, while the corresponding numbers in Scenario 2 are both between 5 Mbps and 20 Mbps. This is as expected because the exposed terminal that contends for channel access can hear the neighbor’s transmissions and acquires the medium soon thereafter.
Figure 5-22. Legacy 802.11 unfairness – Scenario 3 (2 antennas)

Figure 5-23. MIMO 802.11 unfairness – Scenario 3 (2 antennas)

Figure 5-24 reassures that HCS-MAC outperforms MIMO IEEE 802.11 with respect to fairness.
5.4.2 MIMO system

First, we compare HCS-MAC to MIMO IEEE 802.11 for three antennas. When three antennas are used, Figure 5-16, Figure 5-17, and Figure 5-18 show that HCS-MAC achieves 30% higher link-layer throughput for both links and is fairer than MIMO IEEE 802.11.
The aggregate throughput improvement for three antennas is bigger than that for two antennas because both links can transmit DATA frames using $M - 1$ antennas in Scenario 3 and the larger the $M$ is, the higher the aggregate throughput can be achieved. However, the throughput
improvement in Scenario 3 is smaller than that in Scenario 2 for the same reason as we studied in Subsection 5.4.1 for the 2I2O case.

Figure 5-28 shows the average link-layer throughput of HCS-MAC and MIMO IEEE 802.11 for Scenario 3 for a different numbers of antennas. Following the trends observed in Figure 5-10 and Figure 5-19, HCS-MAC outperforms MIMO IEEE 802.11 for all antenna deployments. Note that although the curves of two links using MIMO IEEE 802.11 bear close resemblance to each another, they still suffer from the unfairness problem as it has been shown in Figure 5-26 and Figure 5-23.

![Figure 5-28. Saturation throughput for various antennas – Scenario 3](image)

**5.5 Summary and comparison of Scenario 1, 2 and 3**

We summarize the findings of the performance study of three fundamental scenarios in this subsection. Figure 5-29 illustrates the link-layer throughput of HCS-MAC and MIMO IEEE 802.11 for all three scenarios with $M \in \{2,...,6\}$, where $M$ is the number of deployed antennas.

Figure 5-30 illustrates the aggregate throughputs, which is the sum of the throughput of both individual links with respect to the different antenna configurations and different scenario.
Figure 5-29. Individual link saturation throughput for various antenna deployments

Figure 5-30. Aggregate saturation throughput for various antenna deployments
Some common patterns are evident in Figure 5-29 and Figure 5-30. First, the more the antennas deployed, the higher the individual and aggregate throughput for both schemes. Secondly, the aggregate throughputs of HCS-MAC are significantly higher than MIMO IEEE 802.11 in all three scenarios. Thirdly, for all three scenarios and all antennas assignments, HCS-MAC equally distributes two links and achieves a great fairness between two links.

The characteristics specific to each individual scenario will be discussed as follows.

The left part of Figure 5-29 and Figure 5-30 shows the results of Scenario 1. It is shown in Figure 5-29 that MIMO IEEE 802.11 allocates the bandwidth unfairly. Although link 2→3 using MIMO IEEE 802.11 achieves the highest throughput, it almost completely suppresses another link 0→1. On the contrary, HCS-MAC resolves the hidden terminal problem and both links achieve relatively similar high throughput. It also shows that for HCS-MAC, link 2→3 achieves slightly higher throughput than link 0→1 as the number of antennas increases. This is because in Scenario 1, link 2→3 is more likely to transmit its DATA frames using \( M - 1 \) antennas than link 0→1 when HCS-MAC is implemented.

The center of Figure 5-29 and Figure 5-30 shows the results corresponding to Scenario 2. First, as shown in Figure 5-30, the HCS-MAC aggregate throughput improvement is even higher than in Scenario 1, ranging from 53.9% to 57.5% higher than the MIMO IEEE 802.11 aggregate throughputs for 2 to 6 antennas; while the corresponding number in Scenario 1 is 36% to 50%. Next, Figure 5-29 shows that the HCS-MAC throughput surpasses MIMO IEEE 802.11 (from 50% to 60%) for both links. Lastly, although it seems that the link-layer throughput between two links using MIMO IEEE 802.11 is almost identical, as it was shown in Figure 5-29, an investigation of instantaneous link-layer throughputs of MIMO IEEE 802.11 has been done and shown that the instantaneous throughput fluctuate drastically (from 5Mbps to 20Mbps) and the unfairness resurface in MIMO IEEE 802.11 for Scenario 2. This is because two links each will rotate to capture the channel for a period of time.
The part to the right in Figure 5-29 and Figure 5-30 shows the results corresponding to Scenario 3. Figure 5-30 shows that the aggregate throughput of HCS-MAC is only 12.6% (or equivalently 3.4 Mbps) higher on average than MIMO IEEE 802.11, which is lower than the improvements reported for Scenarios 1 and 2. This is because on the one hand the aggregate throughput of HCS-MAC achieved in Scenario 3 is less than those achieved in the other two scenarios, especially than in Scenario 2, and on the other hand MIMO IEEE 802.11 achieves a higher aggregate throughput in Scenario 3 than in Scenarios 1 and 2. The effects are clearly shown in Figure 5-30 and the reasons such effects occur are studied in Subsection 5.4. Finally, although it is not shown in Figure 5-29 and Figure 5-30, the investigation to the instantaneous throughput unveils the unfairness of MIMO IEEE 802.11 (although the unfairness is less severe in Scenario 3 than in Scenario 2) and confirms the HCS-MAC’s fairness in Scenario 3.

5.6 Effect of DA

We will study the performance of the proposed deafness avoidance mechanism in this subsection.

First we will study the favorable effect of applying DA in Scenario 4 shown in Figure 5-31, in which the deafness problem arises due to transmitting to an active transmitter.

![Scenario 4](image)

**Figure 5-31. Scenario 4 – deafness due to transmitting to an active transmitter**

As shown in Figure 5-32, without penalizing the aggregate throughput, HCS-MAC with DA achieves identical throughput on both links. On the contrary, in the absence of DA, link 0→1 achieves much less throughput than link 1→2. Node 0, despite overhearing the RTS frame sent by node 1 to node 2, will continue to transmit the RTS frames to node 1 when the ICT conditions...
are satisfied. Being engaged in its transmission to node 2, node 1 will not be able to receive the RTS frame transmitted from node 0. As a result, node 0 will double its contention window after each failed RTS transmission attempt, further contributing to reduce its chances of gaining medium access. Figure 5-33 and Figure 5-34 further reassure the unfairness of HCS-MAC w/o DA and the effectiveness of the deafness avoidance mechanism.

![Figure 5-33. Saturation throughput comparison between HCS-MAC w/ DA and HCS-MAC w/o DA – Scenario 4 (2 antennas)](image)

Figure 5-32. Saturation throughput comparison between HCS-MAC w/ DA and HCS-MAC w/o DA – Scenario 4 (2 antennas)

![Figure 5-33. Unfairness of HCS-MAC w/o DA in Scenario 4 (2 antennas)](image)
Figure 5-34. Fairness of HCS-MAC w/ DA in Scenario 4 (2 antennas)

Next we will study the favorable effect of applying DA in Scenario 5 shown in Figure 5-35, in which the deafness problem arises when a node tries to transmit to a node that is the active receiver of another transmission.

Figure 5-35. Scenario 5 – deafness due to transmitting to an active receiver

As shown in Figure 5-36, Figure 5-37, and Figure 5-38, for Scenario 5, DA enabled by ZST is fairer than ZOST (w/o DA), without penalizing the throughput. The reason of the unfair instantaneous throughput as shown in Figure 5-37 is similar to what we had discussed in Subsection 5.3.1.
Figure 5-36. Saturation throughput comparison between ZST w/ DA and ZOST w/o DA – Scenario 5 (2 antennas)

Figure 5-37. Unfairness of ZOST w/o DA in Scenario 5 (2 antennas)
From Subsections 5.2 to 5.6, we thoroughly studied the performance of HCS-MAC with respect to some fundamental scenarios in wireless ad hoc networks and showed that HCS-MAC outperforms MIMO IEEE 802.11 in all these scenarios. In this subsection, we investigate the performance of HCS-MAC in large scale random ad hoc networks. In the simulation, fifty nodes are randomly placed in an area of 1000 m x 1000 m. The data sessions are created between randomly chosen sources and destination pairs. Once the transmissions begin between a source/destination pair at a time randomly chosen between 0 and 180 seconds, UDP data packets are sent at a given rate until either the simulation ends. Ad hoc On-demand Distance Vector (AODV) [86] is the routing protocol of the choice. The simulation will run for 200 seconds. The parameters used in the simulations for random ad hoc networks are summarized in Table 5-3.

Figure 5-38. DA fairness enabled by ZST in Scenario 5 (2 antennas)

5.7 Performance of large scale random ad hoc networks

From Subsections 5.2 to 5.6, we thoroughly studied the performance of HCS-MAC with respect to some fundamental scenarios in wireless ad hoc networks and showed that HCS-MAC outperforms MIMO IEEE 802.11 in all these scenarios. In this subsection, we investigate the performance of HCS-MAC in large scale random ad hoc networks. In the simulation, fifty nodes are randomly placed in an area of 1000 m x 1000 m. The data sessions are created between randomly chosen sources and destination pairs. Once the transmissions begin between a source/destination pair at a time randomly chosen between 0 and 180 seconds, UDP data packets are sent at a given rate until either the simulation ends. Ad hoc On-demand Distance Vector (AODV) [86] is the routing protocol of the choice. The simulation will run for 200 seconds. The parameters used in the simulations for random ad hoc networks are summarized in Table 5-3.
Table 5-3. HCS-MAC SIMULATION PARAMETERS FOR RANDOM AD HOC NETWORKS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Nodes</td>
<td>50</td>
</tr>
<tr>
<td>Topology</td>
<td>1000 m x 1000 m</td>
</tr>
<tr>
<td>Traffic sources</td>
<td>UDP with 10 CBR sources</td>
</tr>
<tr>
<td>Packet generation rate (packets/second/traffic source)</td>
<td>50, 100, 200, 400, 600, 800, 1000</td>
</tr>
<tr>
<td>Number of antennas</td>
<td>2, 3</td>
</tr>
<tr>
<td>Routing protocol</td>
<td>AODV</td>
</tr>
<tr>
<td>Simulation length</td>
<td>200 s</td>
</tr>
</tbody>
</table>

In the simulation, we will compare HCS-MAC to MIMO and Legacy IEEE 802.11 with respect to the aggregate throughput and packet delivery ratio. We will first simulate the 2I2O systems and then the MIMO systems.

First, we present the results of the 2I2O systems. Figure 5-39 and Figure 5-40 show the throughput and Packet Delivery Ratio (PDR) of HCS-MAC and MIMO IEEE 802.11 with respect to the different data session sending rates.
In a 2I2O system, HCS-MAC achieves higher throughputs than MIMO and Legacy IEEE 802.11 at every simulated data session sending rate. Moreover, HCS-MAC achieves a higher peak throughput at a higher sending rate than other two protocols and better handles the heavier traffic loads. As shown in Figure 5-39, when the network is in light traffic loads, i.e., with the sending rates lower than 100 packets per second, all the simulated protocols handle the data transmissions equally well. When the traffic loads steadily increase, i.e., with the sending rates higher than 100 packets per second, the throughput of HCS-MAC is much higher than MIMO and Legacy IEEE 802.11. When the sending rates increase, the throughputs of all the protocols start to increase and reach a peak throughput at some sending rates, and then start to decrease when the network is overloaded by the higher sending rates. HCS-MAC reaches the peak throughput of 5 Mbps at a sending rate around 400 packets per second, which is about 18% higher than the peak throughput of 4.27 Mbps achieved by MIMO IEEE 802.11 and 28% higher than the peak
throughput of 3.83 Mbps achieved by Legacy IEEE 802.11 at a sending rate around 200 packets per second.

![Graph showing Packet Delivery Ratio](image)

**Figure 5-40. Packet delivery ratio of the simulated random ad hoc network with various packets sending rates (2 antennas)**

Figure 5-40 presents the packet delivery ratio in 802.11 systems and further shows the high performance of HCS-MAC. As expected, the packet delivery ratio drops when the sending rate increases. For every sending rate, HCS-MAC achieves a higher PDR than MIMO and Legacy IEEE 802.11 except that the PDRs are almost identical when the sending rates are low at 50 and 100 packets per second. Even with a high sending rate of 1000 packets per second, HCS-MAC still achieves a good packet delivery ratio of 73%, while the percentage of the packets delivered by MIMO IEEE 802.11 is only 53% and even lower by Legacy IEEE 802.11 at merely 45%.

We conduct the simulations for the networks in which each node equips more antennas, i.e., three antennas and present the results of throughput and PDR in Figure 5-41 and Figure 5-42 respectively.
Figure 5-41 shows the throughputs for a network in which each node equips one, two, or three antennas. It follows the same trend as a 2I2O system, which was shown in Figure 5-39. In addition, when the number of antennas increases, both HCS-MAC and MIMO IEEE 802.11 achieve higher throughput and HCS-MAC with three antennas tops all the simulated protocols. Moreover, with only two antennas, HCS-MAC achieves the second highest throughput, even higher than MIMO IEEE 802.11 with three antennas. This evidently shows that HCS-MAC significantly outperforms MIMO IEEE 802.11 in terms of throughput.
Figure 5-42. Packet delivery ratio of the simulated random ad hoc network with various packets sending rates (various antennas)

Figure 5-42 shows the PDR for a network in which each node equips one, two or three antennas and further confirms the superior performance of HCS-MAC. When the number of antennas increases, both HCS-MAC and MIMO IEEE 802.11 maintain a higher packet delivery ratio. HCS-MAC with three antennas tops all the simulated protocols and HCS-MAC with two antennas is the second best. Moreover, for all the simulated sending rates, even as high as 1000 packets per second, HCS-MAC with three antennas always achieves a high PDR above 80%.
Chapter 6
Conclusion

Unlike the conventional infrastructure-based wireless networks, such as cellular network, a wireless ad hoc network is an autonomous and distributed system consisting of wireless nodes that do not rely on any fixed network infrastructure or central administration. Wireless ad hoc networks can enable anytime, anywhere communication and are expected to play an important role in the future generation of wireless networks. Wireless ad hoc networks encourage many emerging applications such as wireless sensor networks, wireless mesh networks, vehicular ad hoc networks, nano networks, smart homes/offices, cognitive networks, etc.

MAC is responsible for coordinating the channel access among multiple nodes and is the key component that determines the efficiency of wireless ad hoc networks. MAC protocol design in wireless ad hoc networks encounters significant challenges due to the lack of infrastructure support and the centralized control and coordination; the enforced bidirectional frame exchange of the DATA and ACK frames; the increased collisions resulting from the transmissions multiple hops away; the uneven channel contention and collision for nodes in different zones; and the dynamic and rapid change of topology and data traffic. This thesis studies the problems arising in wireless ad hoc networks such as the hidden terminal problems, exposed problems, and deafness problems.

Many approaches for solving these problems were surveyed — in the form of the controlled communication distance, leading to the transmission power control protocols; in the form of the disjointed frequencies, leading to the multi-channel protocols; in the form of the narrowed communication directions, leading to the directional antennas protocols; or in the form of utilizing the multi-path propagation, leading to the schemes employing MIMO distributed spatial multiplexing. MIMO as a powerful technique has been widely used in wireless networks to boost the raw data rate and this makes it a strong candidate and competitor for the future wireless
networks compared to other techniques. Although it is becoming a hot research area, the potential for enhancing MAC layer efficiencies by MIMO is still developing. In this thesis, a novel HCS framework was proposed, which utilized MIMO distributed spatial multiplexing/MUD and significantly enhanced the performance of wireless ad hoc networks.

The existing works in this area [65]—[83] allow stream sharing to enable multiple simultaneous transmissions. Most works require synchronization among multiple transmissions and split the channel but without considering the potential for expanding the channel capacity, and aim for the single-hop networks.

6.1 Summary of contributions

The novel HCS framework proposed in this thesis has significant advantages over prior solutions. It senses the channel availability jointly by the virtual carrier sense and physical carrier sense and a finite state machine is devised to model the HCS states and decision-makings. HCS does not require the synchronization among nodes; each node independently and locally makes its own decision when to start its transmission. HCS not only shares the channel, but also exploits the bi-directional handshakes of the wireless transmissions and increases the number of simultaneous stream transmissions. For a network with $M$ antennas in each node, HCS can accommodate $2 \times (M - 1)$ streams, a significant increase compared to $M$ streams seen by all other existing works. Moreover, HCS is aimed for multi-hop wireless ad hoc networks, in which the hidden terminal, exposed terminal, and deafness problems greatly degrade the network performance. These problems are thoroughly studied with a unified treatment in this thesis. The HCS framework solves all of these problems together. HCS is implemented in NS2 network simulator and the performance evaluation shows that HCS significantly outperforms MIMO-enabled IEEE 802.11 (in which MIMO is only used for enhancing the raw data rate in the physical layer), resulting in significantly higher aggregate throughput, packet delivery ratio and fairness in multi-hop wireless ad hoc networks.
The contribution of the HCS framework and this thesis is summarized as below:

i) Devised Hybrid Carrier Sensing that senses channel availability jointly by physical carrier sense and virtual carrier sense; and modeled HCS-MAC as a FSM, which defines the HCS-MAC states and decision-makings rules, including the ICTs, IELTs, IALTs, and SSTs.

ii) HCS not only enables multiple simultaneous transmissions and shares the channel among the wireless nodes, but also exploits the bi-directional handshakes of the wireless transmissions and increases the number of simultaneous stream transmissions. \( M - 1 \) antennas are used for DATA frame transmissions whenever deemed feasible, while control frames are transmitted using a single antenna. For a network with \( M \) antennas in each node, HCS can accommodate \( 2 \times (M - 1) \) streams, a significant increase compared to \( M \) streams seen by other existing works. The Stream Bit Negotiation and Correction mechanisms are devised to determine the number of antennas used to transmit the DATA frames in a MIMO system.

iii) HCS is aimed for multi-hop wireless ad hoc networks and solves the hidden terminal, exposed terminal, and deafness problems, while most existing works only solve some of the problems.

iv) New types of deafness problems arising in HCS-enabled networks and mechanisms to solve them are devised.

v) Proposed a cross-layer design of HCS-Physical Carrier Sense (HCS-PCS) that provides a practical solution to determine the number of streams currently in transmission.

vi) Implemented HCS-MAC with C++ programming language in NS2 network simulator and thoroughly studied the performance of HCS-MAC. Throughput, fairness, and
packet delivery ratio were studied on several fundamental scenarios of wireless ad hoc networks with saturated traffic load and on multiple hop large scale wireless ad hoc networks with different traffic loads. The simulation results show significant enhancements of HCS-MAC.

vii) Studied hidden terminal, exposed terminal, and deafness problems in a unified context. These problems are the major factors that degrade the performance and efficiencies of MAC protocols in multi-hop ad hoc networks.

viii) Conducted a thorough review of MAC protocols proposed for wireless ad hoc networks, including: a) BEB refinement; b) frame aggregation; c) rate adaptation; d) power control; e) multiple channels; f) directional antennas; and g) MIMO.

### 6.2 Limitations and future works

Although the HCS framework proposed for wireless ad hoc networks has shown many advantages and is anticipated to be in wide use in the future generation of wireless networks, it has some limitations, which should be further studied.

Mobility, energy conserving, QOS, and some other important aspects of MAC layer issues in wireless ad hoc networks are not considered in this thesis. These would remain as promising topics for future research.

This thesis assumes that all the nodes in the networks have $M$ antennas. The extension of the HCS framework with cooperative networks in which each node may have different number of antennas or single antenna would be interesting. The virtual MIMO arrays can be formed and the more powerful nodes which have more antennas can store and relay the packets for the less powerful nodes which have fewer antennas. Applying HCS to cognitive networks would be a good area to explore as well.
More research on PHY and routing layers and the cross layers design and optimization over all three layers – PHY, MAC, and routing – with the HCS framework is also necessary.

The HCS framework mainly exploits the benefits of MIMO spatial multiplexing. The spatial diversity is not studied. It would be good to study the impact on the spatial diversity and the trade off between spatial multiplexing and spatial diversity, in the context of the HCS frameworks.

It is very difficult to have theoretical and analytical study and modeling for wireless ad hoc networks, especially in a multiple-hop case. Most performance studies have to go through computer simulations. But it would be very beneficial if some analytic models are proposed, even with some simplified assumptions, for example, based on the fundamental scenarios proposed in the HCS simulations.

The comprehensive HCS FSM and flow-charts have been provided in this thesis and the detailed HCS-MAC protocol has been implemented with C++ in packet-level NS2 network simulator. It would be very beneficial and practical to build a HCS-enabled test-bed.

Many of the ideas – the hybrid carrier sense and the exploitation of the bi-directional handshakes that enables $2 \times (M - 1)$ streams – proposed in the HCS framework can be applied not only to MIMO, but also for many other surveyed techniques, such as multiple channels. Although the reason why the MIMO is preferred over multiple channels for the HCS framework was discussed in Section 3.2.5, applying such ideas in multiple channels would considerably improve the network performance and is worthy for further research.

We may allow a network containing both HCS framework and directional antennas MAC, for example, the DMAC-DACA proposed by author’s earlier research work, and dynamically switching between them depending on the channel’s characteristics.
Moreover, we may even integrate HCS with some of the techniques surveyed in this thesis such as BEB refinement, frame aggregation, rate adaptation, power control, or multiple channels. HCS would further enhance network performance.
References


Appendix: Flow charts for SST, IALT and IELT

Appendix 1. Flowchart depicting Process 1

Process 1:
SST: Layers 1 and 2
IELT: Layer 1 <-> Layer 2
IALT: Layer 2
Appendix 2. Flowchart depicting Process 2