# ON IMPROVING THE PERFORMANCE OF MULTIHOP WIRELESS NETWORKS: CONCEPTS AND METHODOLOGIES

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# Abstract

On Improving the Performance of Multihop Wireless Networks: Concepts and Methodologies

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Recently, wireless ad hoc networks have witnessed a remarkable interest. In such networks, the medium spatial reuse has a tremendous impact on the network performance, since it determines the number of concurrent transmissions and hence the network capacity. Although increasing spatial reuse can enhance the overall network performance, it raises the total interference level on the spectrum, therefore increasing the chance of collisions and adversely impacting the throughput. In this thesis, we optimize the network capacity of IEEE 802.11 based wireless networks through balancing the tradeoff between the level of spatial reuse and collisions in the network.

We propose a dynamic spatiotemporal algorithm using the joint control of carrier sensing threshold and contention window size (both are tunable parameters) in order to enhance the spatial reuse and optimize the overall network throughput. In order to efficiently decide which protocol parameter(s) to tune, we deem it necessary to first faithfully distinguish among the causes of frame loss. We propose an effective loss differentiation mechanism to separate packet losses due to collisions from those due to interference(s) and establish accordingly appropriate reactive methods. Simulation results have demonstrated the significant throughput gains that can be achieved by the proposed scheme.

We also present decentralized, localized heuristics in order to balance the tradeoff between exposed terminals and hidden terminals, through searching for the optimal transmission power and rate assignment (two other tunable parameters). Our simulation results indicate a remarkable performance for our proposed heuristics.

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# List of Publications

Conference papers (accepted):

- Yongning Zhang, Bassel Alawieh and Chadi Assi. "A Novel Physical Carrier Sensing Scheme for Enhancing Spatial Reuse in Multihop Wireless Networks", *Proceedings of IEEE WoWMoM 2008* (acceptance rate 24%).
- Bassel Alawieh, Yongning Zhang and Chadi Assi. "A Distributed Power and Rate Control Scheme for MANET", *Proceedings of IEEE Wiopt 2008* (acceptance rate 23 %).

Journal papers (submitted):

- Yongning Zhang, Bassel Alawieh and Chadi Assi. "A Spatiotemporal Contention Resolution for Enhancing Spatial Reuse in Multihop Wireless Networks", *IEEE Transactions on Mobile Computing.*
- Bassel Alawieh, Yongning Zhang and Chadi Assi. "Improving the Performance of Multihop Wireless Networks Through Power and Rate Control", *IEEE Transactions on Mobile Computing.*
- Bassel Alawieh, Yongning Zhang and Chadi Assi. "Improving Spatial Reuse in Multihop Wireless Networks: A Survey", *IEEE Communications Surveys and Tutorials.*

# List of Acronyms

**ACK** – Acknowledgement

**AIFS** – Arbitration Interframe Space

**AIMD** – Additive Increase Multiplicative Decrease

**AODV** – Ad Hoc On Demand Distance Vector

**AP** – Access Point

**CBR** – Constant Bit Rate

**CSMA/CA** – Carrier Sense Multiple Access with Collision Avoidance

**CTS** – Clear To Send

**CW** – Contention Window

**DCF** – Distributed Coordination Function

**DIFS** – Distributed Inter Frame Space

**EIFS** – Extended Inter Frame Space

**IEEE** – Institution of Electrical and Electronics Engineers

**MAC** – Media Access Control

**MANET** – Mobile Ad Hoc Network

**MSDU** – MAC Service DATA Unit

**NAV** – Network Allocation Vector

**PCS** – Physical Carrier Sensing

**PRAS-CP** – Power and Rate Adaptive Scheme with Collision Prevention

**RTS** – Request To Send

**SIFS** – Short Inter Frame Space

**SINR** – Signal to Interference plus Noise Ratio

**VCS** – Virtual Carrier Sensing

**WLAN** – Wireless Local Area Network

# Chapter 1

# Introduction

## 1.1 Overview of Wireless Ad Hoc Networks

The rapid evolution of the wireless ad hoc network has provided incentives for building efficient multi-hop wireless networks. A wireless ad hoc network [1] is a decentralized network, wherein each node forwards data for other nodes. This is in contrast to wired networks in which routers perform the task of routing. It is also in contrast to centralized wireless networks, in which an access point (AP) manages the communication among other nodes. A typical wireless ad hoc network is shown in Figure 1.1.

The decentralized and self-organized nature of wireless ad hoc networks makes

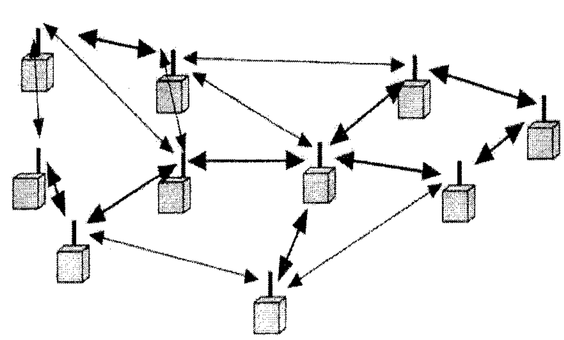


Figure 1.1: An Example Ad Hoc Network

them applicable to a variety of environments where there is no pre-existing hardware such as base stations in traditional cellular networks or any centralized mechanism managing the network. The application of wireless ad hoc wireless networks may include the monitoring of herds of animals, supporting communication in military battle-fields and civilian disaster recovery scenarios, or emergency warning system for vehicles. As opposed to those centralized networks, the scalability of wireless ad hoc networks is substantially improved, and this has been identified through both theoretical [2] and practical [3] studies of the overall capacity of such networks.

In a wireless ad hoc network, individual nodes share the channel through a distributed mechanism. Therefore, it is vital for network standards to support an efficient *Medium Access Control* layer protocol. Currently, the distributed coordination function (DCF) of the IEEE 802.11 [4] is the most widely used MAC protocol for wireless multihop ad hoc environments due to its simple implementation and distributed nature.

## 1.2 Motivations and Preliminaries

In an IEEE 802.11 based wireless ad hoc networks, one of the most dominant performance issues is *spatial reuse*. Being an important benchmark that characterizes the overall network performance, spatial reuse determines the number of concurrent transmissions available in a given area.

Although increasing the spatial reuse can improve the overall system performance by allowing multiple concurrent transmissions, it also raises the level of interference in the network. Consequently, this may cause severe increase in the rate of transmission failures, which is another important metric in determining the capacity of a multihop wireless network, resulting ultimately in throughput deterioration. Thus, the optimal system performance can only be achieved through balancing the tradeoff between the level of spatial reuse and collision probability, through controlling the level of access to the channel. However, achieving this optimal trade-off is not trivial in IEEE 802.11 DCF based multihop networks, since the amount of spatial reuse and collision probability are both severely affected by two inherent problems, known as *exposed terminals* and *hidden terminals* [5].

According to the IEEE 802.11 DCF, when a station senses a busy medium according to CSMA (Carrier Sensing Multple Access) [4], it simply blocks its own transmission to yield to other ongoing communication. However, clearly if the transmission of this station does not cause enough interference to corrupt the frame reception of the ongoing transmission, then blocking that transmission would be unnecessary. This problem has been referred to as the *exposed terminal problem* and has been shown to severely affect the spatial reuse of the spectral source and thus limit the network capacity. Now, after a node senses an idle medium, it can initiate a transmission; the signal to interference plus noise ratio (SINR) perceived at the receiver determines whether this transmission is successful or not. Namely, if the SINR is smaller than a minimum threshold ($\zeta$), the transmission cannot be correctly decoded. However, the interference contributed by concurrent transmissions outside the carrier sense range of the sender may corrupt the ongoing communication. Those potential interferes that are outside the carrier sense range of the sender are commonly known as the *hidden terminals.* To conclude, hidden terminals problem is the main source of collision while the exposed terminal problem results in low spatial reuse. Thus, in order to achieve the optimal trade-off between spatial reuse and collision probability, it is mandatory to effectively resolve the hidden and exposed terminal problems.

In order to improve the spatial reuse in wireless multihop networks, various approaches have been proposed, including tuning of the carrier sensing threshold, PHY transmission rate adaptation and transmission power control.

Transmission power control is vital for reducing the energy consumption and interference on the neighboring on-going transmissions and may enhance the overall network throughput by allowing more concurrent transmissions. However, achieving an optimal transmission power control in an IEEE 802.11 based multihop network is challenging [6]. When reducing the transmission power, the number of nodes included within the transmission range of the sender competing for wireless channel access is reduced and hence the number of collisions from contending nodes is reduced. Moreover, intuitively when using reduced transmission power, the interference level among neighboring nodes reduces. On the other hand, since the network supports more concurrent transmissions, due to the improvement in spatial reuse, the aggregate interference level in the network increases. Consequently, the overall SINR might degrade when using a lower transmission power and this may lead to an increase in collision probability. Additionally, although reducing the transmit power may indeed decrease the energy consumption for one transmission attempt, since the likelihood of packet corruptions (error or collisions) during packet reception becomes high, retransmissions of the same packet could yield to a power consumption higher than the maximum power.

The physical carrier sensing, on the other hand, is essentially used to determine whether or not a node may access the medium. Typically, a node senses the medium, before initiating any communication, and defers its transmission if the channel is sensed busy; a channel is considered to be busy if the strength of the received signal exceeds a carrier sensing threshold, denoted as $CS_{th}$. The PCS method reduces the likelihood of collision by preventing nodes in the vicinity of each other from transmitting simultaneously, while allowing nodes that are separated by a safe margin (termed as the carrier sensing range, $r_c$) to engage in concurrent transmissions. Indeed, the former is referred to as collision avoidance while the latter is known as spatial reuse. Recently, the concept of spatial separation has been proposed by [7] in order to resolve contention among contending hosts and improve the utilization of the channel. Namely, by adjusting the space occupied by each transmission, spatial backoff [7] controls how the channel usage is divided over space, and also helps to adjust the temporal channel contention around each transmitter. In order to control the space occupied by each transmission, a joint control of $CS_{th}$ and transmission rate is proposed. In addition to tuning the $CS_{th}$, one can increase the level of spatial reuse by reducing the transmit power; the authors of [8] analyzed the relation between the transmit power and the $CS_{th}$ in determining the network capacity. Here, a combination of lower transmit power and higher $CS_{th}$ leads to a large number of concurrent transmissions with each transmission sustaining a lower data rate.

In addition, the temporal approaches for contention resolution attempts to better utilize the channel along the time dimension by optimizing access parameters or improving the backoff algorithm [9],[10] of the DCF protocol. Currently, the adopted backoff strategy for IEEE 802.11 is the binary exponential backoff (BEB). Here, a node wishing to transmit senses the channel for a period of Distributed Inter Frame Space (DIFS) and then transmits only if the channel is sensed idle. Otherwise, the node waits until the channel is free and after the DIFS interval, it waits for a random contention time: it chooses a backoff $b$, an integer distributed uniformly in the window [0, $CW$] ($CW$ is the contention window size), and waits for $b$ time slots before attempting to transmit. When a node detects a failed transmission, it doubles the size of the contention window ($CW$) until it reaches a maximum value ($CW_{max}$). This kind of backoff behavior has shown to cause short term unfairness. The authors of [11] tried to resolve this aspect by first turning off the BEB and proposed a new method to dynamically tune the contention window size. In their new access method, termed as *Idle Sense*, each host measures the average number of consecutive idle slots between transmission attempts and make sure that this number is close to an optimal number (the optimal number that maximizes the throughput is derived analytically) by either increasing or reducing the contention window size in an Additive Increase Multiplicative Decrease (AIMD) manner.

In summary, we can observe that transmission power, physical carrier sensing threshold, transmission rate and contention window size all play important roles in determining the capacity of IEEE 802.11 based wireless ad hoc networks. Accordingly, one may selectively adjust one or more of those parameters to improve the network performance by enhancing the spatial reuse and/or reducing collisions.

## 1.3 Thesis Contribution

In this thesis, we propose two localized mechanisms that improve the network performance. Specifically,

- In a multihop wireless network, access to the medium can effectively be controlled by properly tuning protocol parameters, such as the contention window ($CW$) and the carrier sensing threshold ($CS_{th}$). We propose a dynamic spatiotemporal algorithm using the joint control of $CS_{th}$ and $CW$ with the objective of controlling the access to the channel in order to enhance the spatial reuse and optimize the overall network throughput. In order to efficiently decide which protocol parameter(s) to tune, we deem it necessary to first accurately distinguish among the causes of frame loss. We propose an effective loss differentiation mechanism to separate packet losses due to collisions from those due to interference(s) and establish accordingly appropriate reactive methods. Our results have shown that there is a tradeoff between spatial reuse and collisions from concurrent transmissions and the optimal performance is obtained with smaller contention windows, which effectively yields to a higher collision ratio, but that indeed comes at the expense of promoting higher spatial reuse. The proposed method has shown leading performance when compared with two recent algorithms from the literature.

- We present a novel scheme, called PRAS-CP (transmission power and rate adaptive scheme with collision prevention), which enhances network performance through balancing the tradeoff between the hidden terminals and the exposed terminals. To accomplish this, PRAS-CP integrates the Physical/MAC attributes (the carrier sensing range and the interference range) and carrier sensing mechanisms (PCS,VCS) to assign the appropriate data rate and transmission power values to successfully exchange the RTS/CTS DATA/ACK packets. Simulation results under different scenarios are used to demonstrate the significant throughput, energy gains, and fairness that can be obtained by PRAS-CP.

## 1.4 Thesis Organization

The rest of the this thesis is organized as follows. Chapter 2 introduces the system architecture of IEEE 802.11 DCF and the communication background. The related work in this area are also reviewed. In Chapter 3, we propose an effective method for differentiating among frame losses and accordingly tune the $CS_{th}$ and $CW$ to improve the network capacity. Our distributed localized power and transmission rate heuristics are presented in Chapter 4, whose performance improvements are verified through simulation. Finally, the conclusions and future work are discussed in Chapter 5.

# Chapter 2

# Background and Related Work

## 2.1 Introduction of IEEE 802.11 DCF

The IEEE 802.11 distributed coordination function relies on carrier sensing multiple access with collision avoidance (CSMA/CA) [4]. DCF employs two different channel access modes for data packet transmission; the default 2-way (basic access) and the optional four-way handshaking (RTS/CTS) access scheme [4]. Here, the optional (RTS/CTS) scheme assumes the transmission of short request-to-send (RTS) and clear-to-send (CTS) control packets prior to the data packet transmission will reduce the vulnerability duration, i.e, the time interval in which hidden nodes can interfere with data packet transmission. In the (RTS/CTS) access scheme, a node with packets to transmit first senses the medium through physical carrier sensing (PCS). Specifically, the node considers the channel to be idle if the strength of the received signal is below $CS_{th}$. If the medium is idle for at least a certain period DIFS (Distributed Interframe Space), it will immediately request the channel by sending a short control frame request to send (RTS) to the receiver node. If the receiver correctly receives the RTS, it will reply with a short control frame clear to send (CTS) after waiting a SIFS (Short Interframe Space) period. Once the sender receives the CTS, it will start sending out its DATA packet. After the successful reception of

DATA, the receiver sends an acknowledgement (ACK) packet to the sender. Here, SIFS duration is the shortest of the interframe spaces and is used after the RTS, CTS, and DATA frames to give the highest priority to CTS, DATA and ACK, respectively. Nodes implementing IEEE 802.11 maintain a NAV (Network Allocation Vector), which shows the remaining time of the on-going transmission sessions. Using the duration information in the RTS, CTS, and DATA packets, nodes adjust their NAVs whenever they receive a packet. This is shown in Figure 2.1. For the basic scheme, nodes upon sensing the DATA or ACK packet will refrain from transmitting any packet for EIFS duration.

Moreover, if the channel is sensed busy, the station has to wait until the channel is sensed idle for a DIFS time. At this point, the station generates a random backoff time interval before transmission, in order to minimize the probability of collisions with packets being transmitted by other stations. DCF adopts a binary exponential back off scheme upon packet losses. At each packet transmission, the back off time is uniformly chosen in the range $[0, CW]$. The value $CW$ is called contention window, and depends on the number of failed transmissions. At the first transmission attempt, $CW$ is set to $CW_{min}$. After each retransmission, $CW$ will be exponentially increased until the maximum $CW$ value, i.e., $min(2^{i-1} \times (CW_{min} + 1) - 1, CW_{max})$. Upon successful transmission, $CW$ will be reset to $CW_{min}$. In addition, to avoid the capture channel effect[1], the station has to back off between two new packet transmissions, even if the medium is sensed idle during the DIFS time[2].

[1]Capture channel effect is caused by the fact that a node with heavy traffic captures the channel more easily than a node with light traffic, which will cause short term unfairness.

[2]As an exception to this rule, the protocol provides a fragmentation mechanism, which allows the MAC to split an MSDU (MAC Service DATA Unit, packets delivered from the MAC layer to the physical layer), if the MSDU size exceeds the maximum MPDU payload size. The different fragments are then transmitted in sequence, with only one SIFS between them, so only the first fragment needs to contend for the channel access.

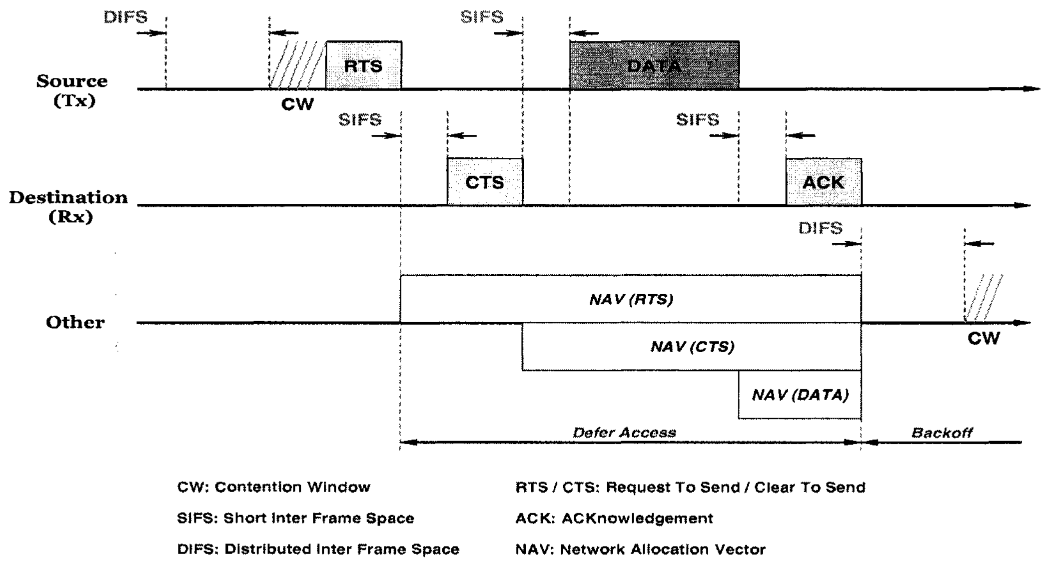



Figure 2.1: IEEE 802.11 DCF

### 2.1.1 IEEE 802.11 Model Background

Assume a sender $A$ transmits to its receiver $B$; another sender $F$ (hidden node), unaware of the transmission of $A$, may initiate a transmission to some receiver(s), as shown in Figure 2.2. Here, the two signals from $A$ and $F$ may overlap in time at the receiver $B$. Whether the signal from sender $A$ can be correctly decoded depends on the so-called capture effect, i.e., the stronger signal will capture the receiver modem, while the weaker signal will be rejected as noise. There exist in the literature various analytical models that characterize the capture effect [12], [13]. In this thesis, we present the most widely adopted model: the receiver $B$ can correctly decode the signal if the signal to interference plus noise ratio (SINR) exceeds a certain predetermined threshold denoted by $\zeta$. hence, we have the following constraint:

$$P_r \geq \zeta \times (P_n) \tag{2.1}$$

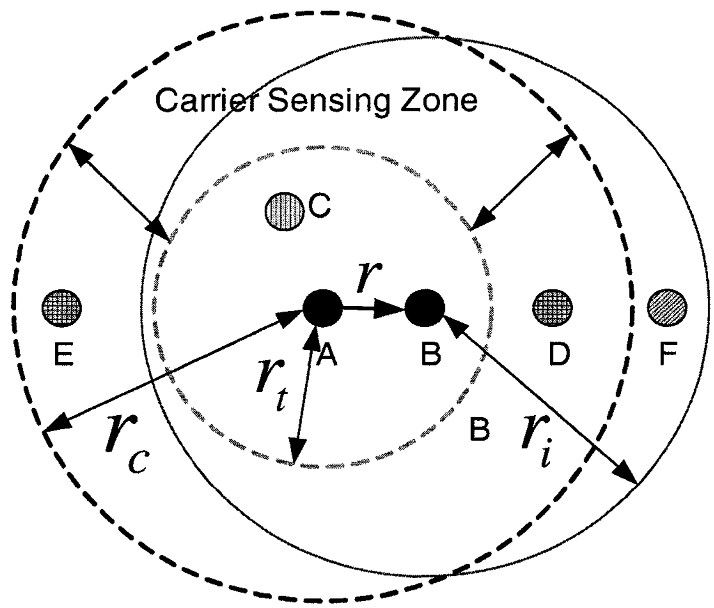



Figure 2.2: Different Ranges according to IEEE 802.11

where $P_n$ is the total allowed interference power, which consists of interference power from interfering nodes and background thermal noise. Here, the value of $\zeta$ is determined according to the rate at which a packet is received at the receiver.

Moreover, due to the path-loss constraints, a receiver $B$ is able to receive and correctly decode a packet from a transmitter ($A$) with transmission power $P_t$, if the received power, $P_r$, is higher than or equal to $\kappa$ (the receiver sensitivity). Accordingly, and adopting the two-ray model: with antenna heights and gains equal to one, the transmission range ($r_t$) is:

$$r_t = (\frac{P_t}{\kappa})^{\frac{1}{4}} \tag{2.2}$$

where $\kappa$ is dependent on the rate the packet is received at the receiver; the higher the rate, the smaller $\kappa$ is [4]. Note that, here we assume that the path loss exponent factor is 4.

Additionally, a transmitter cannot initiate any communication if it senses a signal with a power level larger than a predefined $CS_{th}$. Hence, the $CS_{th}$ specifies the signal strength above which a node determines the medium is busy and will not attempt transmission. Let the Carrier Sense set of a transmitter A (denoted as $CS_A$) be defined as the set of nodes, if any of them transmits, node A will sense the medium busy. Formally,

$$CS_A = \{A' \mid \frac{P_{A'}}{d^4} \geq CS_{th}\}$$

where $d$ is the distance between the sender A and node $A'$ (in the carrier sense set) and $P_{A'}$ is the transmission power of $A'$. If all nodes use the same transmission power, $P_t$, then the carrier sense range $d_{cs}$, defined as the maximum value of $d$ such that the above constraints hold, can be expressed as:

$$d_{cs} = (\frac{P_t}{CS_{th}})^{\frac{1}{4}} \tag{2.3}$$

Note that, however, if nodes use different power, the carrier sense region ($CS_A$) will have an arbitrary shape (not circular). Another set of interest is the silence area that results from the transmission of node A. The silence set of a transmitter A (denoted as $SL_A$), assuming fixed $CS_{th}$ for all nodes, is the set of nodes that will detect the channel to be busy if A transmits [14]. Formally:

$$SL_A = \{A' \mid \frac{P_A}{d^4} \geq CS_{th}\}$$

Clearly, $SL_A \equiv CS_A$ if all nodes use the same transmission power.

According to the above definitions, we can infer the following for Figure 2.2, assuming all nodes use the same transmit power. Nodes $B$ and $C$ can correctly receive and decode any packet that node $A$ sends since they lie in the transmission zone of node $A$. Nodes in the silence range sense the packet transmission. For instance, nodes $B$, $C$, $D$, $E$ will sense any packet transmission from node $A$ as shown in Figure 2.2. Nodes $B$ and $C$ are able to sense, and successfully receive and decode a packet transmitted from $A$ since they lie in the transmission range of the sender; nevertheless, nodes $D$ and $E$ are only able to sense the packet and not

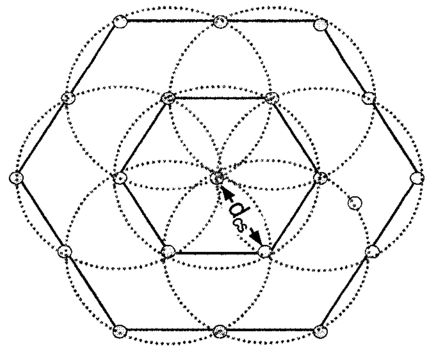


Figure 2.3: Honey Grid Model

correctly receive it and decode it. We say that nodes $D$ and $E$ lie in the silence sensing zone of node $A$.

### 2.1.2 Interference Range

We now elaborate the interference range, $r_i$ [15], from the perspective of a single interfering node receiving a packet. Consider an ongoing communication between nodes $A$ and $B$ that are $r$ units apart. If node $A$ transmits with power $P_t$, the node $B$ receives this signal with received power $P_r = \frac{P_t}{r^4}$. Moreover, if we neglect the thermal noise, $P_n$ in equation (2.1) can be expressed as $P_n = P_{cn} + P_{tn}$. Here, $P_{cn}$ is the current measured interference at node $B$ and $P_{tn}$ is the maximum remaining interference margin that node $B$ can tolerate such that it is still able to decode correctly the packet it receives from node $A$. Accordingly, and making use of equation (2.1), we can express $P_{tn}$ as follows:

$$P_{tn} \leq \frac{P_t}{r^4 \cdot \zeta} - P_{cn} \tag{2.4}$$

Now, assume an interfering node $F$, which is $d$ meters away from node $B$, initiates a communication with a power $P_i$ while node $B$ is receiving a packet from node $A$. The received power $P_{ri} = \frac{P_i}{d^4}$ at node $B$ from node $F$ should satisfy the condition that $P_{ri} \leq P_{tn}$ so that node $B$ is still able to receive and correctly decode the packet from node $A$. Accordingly, we define the interference set of a receiver B (denoted as $IN_B$) as the set of nodes whose transmissions, if overlapping with the transmission of sender ($A$), will cause collision at the receiver. Formally,

$$IN_B = \{F \mid \frac{P_i}{d^4} \geq \frac{P_t}{r^4 \cdot \zeta} - P_{cn}\} \tag{2.5}$$

With the condition of the interference set from equation (2.5), we define the interference range $r_i$ as the maximum value of $d$ such that the inequality in equation (2.5) holds:

$$r_i = \left( \frac{P_i}{\frac{P_t}{r^4 \cdot \zeta} - P_{cn}} \right)^{\frac{1}{4}} \tag{2.6}$$

Based on the above equation, we can see that both the SINR threshold $\zeta$ (whose value depends on the transmission rate) and the value of transmission power ($P_t$) of an ensuing packet determine the interference range at the receiver.

According to the definition of the interference range and the silence range, we distinguish two types of collisions for the IEEE 802.11 based multihop ad hoc networks.

- Collisions due to simultaneous transmission (i.e, during the first time slot of the packet transmission period) by one or more nodes that are located in the intersection of the interference range area of the receiver and the silence range of the transmitter

- Collisions occurring if there are one or more transmissions initiated during the vulnerable period (the duration of the packet transmission) from nodes located in the hidden area (part of the interference zone that is not covered by the silence zone). These nodes are termed as hidden terminals, since these nodes are unaware of the transmitter's transmission, so they can interfere at any time during the packet reception at the receiver. Accordingly, we define a *hidden terminal* as a node that neither senses the transmission of a transmitter node nor correctly receives the reservation packet from a corresponding receiver.

Moreover, in a multihop wireless network, frame loss may also occur due to accumulative interference resulting from nodes lying outside the silence range of the transmitter. Several accumulative interference models have been proposed in [16], [17], [18]. Specifically, the most commonly used is the honey grid model, which was first introduced in [19].

In a honey grid model, as shown in Figure 2.3, the nodes are uniformly distributed and form concentric hexagons, called rings around a transmitting node. When a node is transmitting, there are at most six nodes that can transmit concurrently with the transmitter. Thus, those six nodes form the first ring tier of interfering nodes. Based on this, the second tier is constructed and so on. Accordingly, the $j$th ring tier has $6j$ nodes. The authors of [20], based on a honey grid model, argued that the interference from the first tier (six nodes) dominates and the interference from other tier rings is negligible. Under the worst case scenario, the receiver node that is of distance $r$ away from the transmitter is so positioned such that the six first tier[3] interfering nodes are respectively $d_{cs}-r$, $d_{cs}-r$, $d_{cs}-\frac{r}{2}$, $d_{cs}$, $d_{cs}+\frac{r}{2}$ and $d_{cs}+r$ away from it, as shown in Figure 2.4. Accordingly and assuming all nodes use the same transmission power $P_t$, and adopting the two-ray model, the maximum interference $I_{max}$ can be expressed as:

$$I_{max} = \frac{2P_t}{(d_{cs}-r)^4} + \frac{P_t}{(d_{cs}-\frac{r}{2})^4} + \frac{P_t}{(d_{cs}+\frac{r}{2})^4} + \frac{P_t}{(d_{cs}+r)^4} + \frac{P_t}{(d_{cs})} \quad (2.7)$$

From the above definitions we can observe that the carrier sensing range decides the number of concurrent transmissions, i.e., level of spatial reuse. On the other hand, the interference range decides the number of potential interfering nodes, further affecting the transmission quality of a single link. Therefore, the network capacity is

[3]Recently, the authors in [21] pointed out that the number of interfering nodes at first ring is less than six.

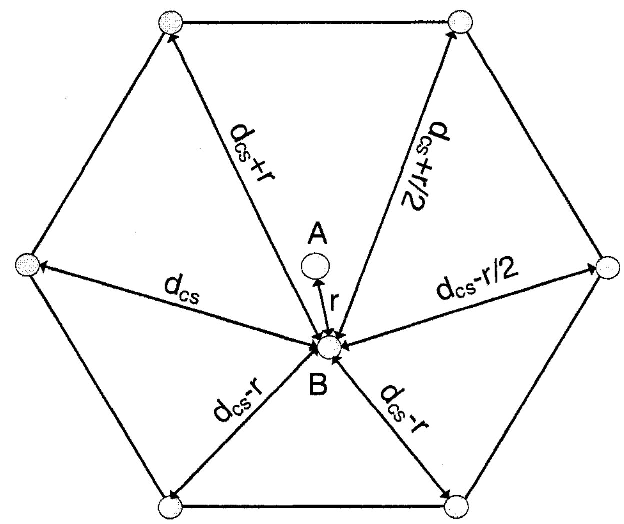



Figure 2.4: Accumulated Interference Calculation

jointly determined by the interference range and carrier sensing range (silence range). Now in order to enhance the network capacity, one can appropriately adjust the size of interference range through tuning transmission power and data rate, according to equation (2.6), or adjust the size of carrier sensing range through tuning transmission power and $CS_{th}$, according to equation(2.3).

## 2.2 Related Work

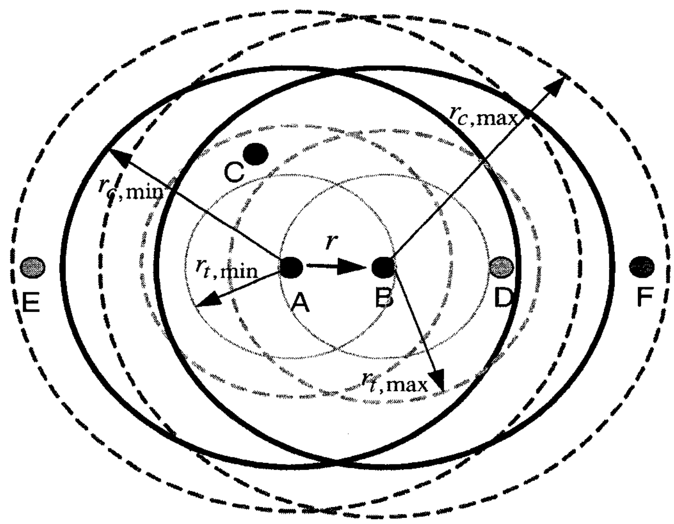
### 2.2.1 Transmission Power Control

A simple power control MAC protocol that allows nodes to vary transmission power on a per packet basis is presented in [22]; the main idea is to allow nodes to use different power levels for RTS/CTS and DATA/ACK frames. More specifically, a maximum transmission power is used for sending RTS/CTS frames and a lower power level, necessary to communicate, is used for DATA/ACK packets. This protocol is referred to as the *BASIC* protocol and the authors of [22] have pointed out its deficiencies. *BASIC* was proposed to enhance energy efficiency, nevertheless

BASIC suffers severely from high collision rate from hidden terminals due to asymmetrical link problems. This increases the energy consumption and deteriorates the throughput.

We elaborate more on the asymmetrical link problem through Figure 2.5. Nodes A and B which are of distance $r$ away from each other exchange their RTS and CTS at maximum power; nodes E and F back off for EIFS since they lie in the silence range of RTS and CTS packet transmitted at maximum power. Now nodes C and D exchange their DATA and ACK packets at minimum transmission power. Here, nodes E and F are no longer inside the silence zone of A and B respectively. Here, E and F are termed as hidden nodes. Thus, after their EIFS duration ends, they will contend for the channel if they have a packet to transmit, and if they find the channel free, they will transmit. If the duration of the DATA packet is long, node F may corrupt the DATA packet reception at node B. Similarly, node E may also corrupt the ACK packet reception. The authors in [23] further study analytically the performance of *BASIC* scheme by proposing a model to analyze the maximum throughput and the consumed energy under maximum interference achieved by the BASIC scheme. They adopted the honey grid model for accumulative interference measurement. The proposed model showed the deficiencies of *BASIC*.

In order to address this problem, the authors in [22] proposed to transmit the DATA packet periodically at maximum power. That is, the transmitter every 190 $\mu s$ raises the DATA power level to the maximum for 15 $\mu s$ so that potential interfering nodes will now be able to detect the transmission and accordingly defer their future transmissions and prevent collisions with the current transmission. The receiver, then, transmits an ACK using the minimum required power to reach the source node, similar to the BASIC scheme. The calculation of the periodic time for increasing the power is dependent on the duration of $EIFS$. Here, $EIFS = SIFS + DIFS + [(8 * ACKsize) + PreambleLength + PLCPHeader - Length]/BitRate$, where $ACKsize$




$r_{t,max}$ The Transmission range resulting from maximum power
$r_{t,min}$ The Transmission range resulting from minimum power
$r_{c,max}$ The silence range resulting from maximum power
$r_{c,min}$ The silence range resulting from minimum power

Figure 2.5: Asymmetrical Link Problem

is the length (in bytes) of an ACK frame, and *BitRate* is the physical layer's lowest mandatory rate. The *PreambleLength* is 144 bits and *PLCPHeaderLength* is 48 bits. Using a 2 Mbps channel bit rate, EIFS is equal to 212 $\mu s$. Here, the 15 $\mu s$ should be adequate for carrier sensing, 5 $\mu s$ to power up and down the power level. So the time will be 210 $\mu s$ which is less than the 212 $\mu s$. In this way, the ACK packet is well protected and the energy is assumed to be conserved. However, the spatial reuse is not improved since the RTS and CTS packets, which are sent at maximum power, may still unnecessarily silence future concurrent transmissions. Moreover, the probability for DATA packet collision still exists. The same approach to that of [22] that relies on periodic increase of transmission power to silence hidden nodes was also proposed in [24].

It was suggested in [25], as another enhancement to the BASIC scheme, that a node should be aware of the success and failure of its own transmissions. To achieve this, a node maintains a table that keeps a record of all the previous RTS-CTS-DATA-ACK transmission power levels used to communicate with each one of its neighbors. Given this information, a transmitter would be able to adjust the transmission power of his future communication adaptively according to a predefined policy. Here, the policy was that each transmitter increases/decreases its transmission power to its receiver if the last transmission to the same receiver fails/succeeds. As opposed to the BASIC scheme, a node uses the reduced power level for all its transmissions, i.e., RTS-CTS-DATA-ACK. This algorithm yields higher throughput because of the enhanced spatial reuse and lower energy consumption compared with the IEEE 802.11 MAC protocol. Here, the channel reuse is enhanced since the RTS/CTS packets are exchanged at a reduced power level, thus allowing for the occurrence of simultaneous transmissions. Nevertheless, this mechanism still suffers from hidden terminals since it does not provide an efficient protection for DATA packet; therefore, there is still a high likelihood for DATA collisions. Moreover, the asymmetric link problem is not completely addressed here.

Another enhancement to BASIC, was proposed in [26]. The authors argued that through knowing the received signal pattern, a node can foretell if the signal belongs to a transmitted CTS packet. Upon recognizing the CTS packet, the node accordingly sets its NAV so as not to interfere with the upcoming DATA packet reception.

A solution has been proposed in [27] to overcome the asymmetric link problem of the BASIC scheme by allowing nodes in the carrier sensing zone of an RTS/CTS transmission to acknowledge the transmission duration information of the up-coming DATA packet. Although these nodes are not able to correctly decode the RTS/CTS packet, they can still detect the time duration when the physical carrier is sensed or not. The physical duration of the RTS/CTS frames is increased by simply adding a few bits to them. Thus, the ALCA protocol provides a discrete set of N different

Carrier Durations (CD) for RTS/CTS frames, and each CD is is mapped to different durations for the DATA packet transmission duration. Now a node in the carrier sensing zone of RTS/CTS transmission that senses the physical carrier of RTS/CTS duration can extract the CD for the RTS/CTS frame. Correspondingly, it can acknowledge the transmission duration for the DATA packet, and set its NAV to this value, instead of setting the NAV to the standard EIFS value.

All the above power control schemes are not interference aware protocols. Now we discuss interference-aware protocols.

A power controlled multiple access protocol (*PCMA*) has been proposed in [28]; in *PCMA*, the receiver advertises its tolerable interference margin on an out-of-band channel and the transmitter selects the transmission power that does not disrupt any ongoing transmissions. To elaborate more, each receiver transmits busy-tone pulses over a separate channel to inform its neighbors (potential interferers) of its interference margin. A potential interfering node, upon receiving the pulse, determines its signal strength and accordingly takes a decision to bound its future transmission or not. Specifically, a potential interfering node first senses the busy-tone channel to calculate an upper bound on its transmission power on all of its control and data packets complying to the most sensitive receiver in its transmission zone. This potential interfering node, upon determining this upper bound value will transmit an RTS packet and waits for the CTS from the receiver. If the receiver is able to correctly decode the RTS packet (i.e., it lies within the RTS range of the transmitter node) and the power needed to send back the CTS packet is below the power bound at the receiver, the receiver then transmits back a CTS allowing the DATA packet transmission to begin. Implementation of PCMA shows significant throughput gain (more than twice) over the IEEE 802.11. Nevertheless, the collision resulting from contention among busy-tones is not addressed. Finally, a node may transmit many RTS packets without getting any reply, thus wasting the node's energy and the channel reuse and bandwidth. Performing TPC with the use of a separate control channel for (RTS, CTS, ACK) in conjunction with a busy-tone scheme was proposed in [29]. A transmitter sends the DATA packets and busy-tones at reduced power, while the receiver transmits its busy-tones at the maximum power. Upon receiving the busy-tone, a potential interfering node estimates the channel gain and decides to transmit if the interference value from its future transmission does not add more than a fixed interference on the ongoing reception. The protocol is shown to achieve considerable throughput enhancements. Nevertheless, the assumptions made in the design of the protocol are not realistic. Specifically, that the antenna system neglects the interfering power of a signal that is less than the power of the "desired" signal (i.e., they assume perfect capture) and that there is no requirement for any interference margin. Moreover, when addressing the energy consumption, the power utilized in transmitting busy tones is not considered. The collision from contention among busy-tones is also not addressed as well. Although these algorithms claim to achieve good throughput and less energy consumption, the implementation of dual or multi-channels in the framework of IEEE802.11 faces both technical difficulties and market resistance as such algorithms would require a complete change of the standards.

The authors in [30] extended the work of the authors in *PCMA*[28] to a single channel power controlled MAC protocol named *POWMAC*. Instead of delivering the interference margin information on a second channel, *POWMAC* exchanges the interference information and DATA packet using a same channel. To achieve this, POWMAC employs an access window (AW) to allow for a series of RTS/CTS exchanges to take place before several concurrent DATA packet transmissions can commence. Thus, during the AW, each node is aware of the interference margin of its neighboring nodes and accordingly bounds its transmission power as in *PCMA* such that DATA transmissions can proceed simultaneously as long as collisions are prevented.

A Kalman filter has been deployed in [31] to perform power control. A node measures the interference around its surroundings. Based on this measured interference, this node makes use of a Kalman filter to predict the future interference. Through predicting the future interference, a node can assign the transmission power of its CTS, DATA and ACK packets accordingly to meet a target SINR. For example, before transmitting a RTS packet, a node measures the interference in its surroundings and accordingly predicts the future interference when receiving the CTS packet. The node then encapsulates this information in the RTS message initiated towards the destination, which is sent at the maximum power. Upon receiving the RTS message, the destination makes use of the included predicted interference to assign a power value to the ensued CTS message. Before sending the CTS message, the destination node repeats the same procedure in measuring the surrounding interference and then predicting the interference in the future. This information is sent within the CTS message towards the source node and used for assigning a power value to the DATA packet. The same criterion is carried again by the source node A and used by the destination node B for assigning power value to the ACK frame.

In [18], the authors investigated the correlations that exist between the required transmission power of RTS, CTS, DATA and ACK frames to guarantee a successful 4-way handshake. Based on these correlations, they proposed *Core-PC*: a class of correlative power control schemes, and after further simulation performance verifications with other power control schemes from the literature, one of schemes was shown to achieve the best performance. The scheme argues that all the packets should be transmitted at the same power value to achieve the best throughput performance. In their scheme, they considered the accumulated interference from all interfering nodes. Moreover, they protected the CTS or the ACK packet from collisions by forcing the transmission range of the RTS or DATA packet to be equal to the interference

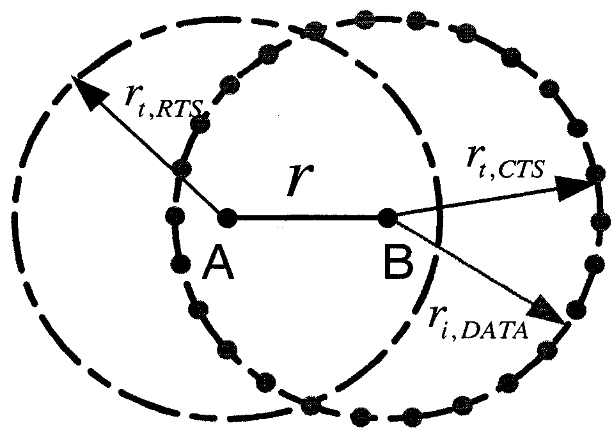



Figure 2.6: Transmission Range of CTS Protecting DATA

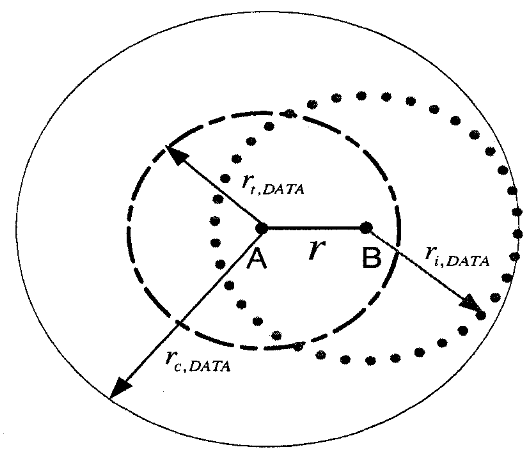



Figure 2.7: Carrier Sensing Range of DATA Protecting DATA

range of the CTS or ACK packet. Moreover, they proposed localized heuristics to determine the average power of the accumulative interference.

The authors of [32] introduced a collision avoidance power control (*CAPC*) MAC protocol to protect the transmission of DATA and ACK packets by appropriately selecting their power values; for example, a DATA packet may be protected if the interference range at its receiver as shown in Figure 2.6 (the $r_i$ equation 2.6 is set equal to $r_t$ in equation 2.2 the (transmission range of the ensuing CTS packet)). Here, the authors assumed that an interfering node always sends at maximum power to derive the interference range. Similar to *BASIC*, RTS and CTS frames are sent at maximum power and that may impact the spatial reuse in the network.

More recently, the authors of [33] extended the work in [32] and proposed an adaptive range-based power control (*ARPC*) MAC protocol for avoiding collisions and conserving energy consumption. They derived four mechanisms and studied their performances. Carrier-sensing Range Cover Mechanism (SCRC), Receivers Carrier-sensing Range Cover Mechanism (RCRC), Senders Transmission Range Cover Mechanism (STRC) and Receivers Transmission Range Cover Mechanism (RTRC) to adapt the transmission power for a node. In SCRC, the RTS and CTS packets are transmitted at maximum power and the transmission power of DATA and ACK packets are calculated such that the carrier sensing range of DATA packet covers the entire interference range of DATA packet, as shown in Figure 2.7. In RCRC, the RTS packet is also transmitted at maximum power and the DATA packet is transmitted at minimum power while the transmission power of the CTS frame is determined such that the carrier sensing range of the CTS equals the interference range of the DATA packet given that the size of DATA packet is small. Moreover, in RCRC, the ACK packet is transmitted at a maximum power. In the other two mechanisms, STRC and RTRC, RTS and CTS packets are transmitted at maximum power while DATA or ACK packets are transmitted at adapted power such that the interference range of DATA packet is protected by the transmission range of RTS or CTS packets (as shown in Figure 2.6) respectively. The authors further derived an adaptive algorithm that selects between the proposed mechanisms based on the distance between the sender and the receiver. The performance evaluation has shown that the proposed scheme has completely eliminated the hidden terminal problem and thus the DATA collision rate becomes negligible. However, in the proposed mechanisms, the interference range is always calculated under the worst case scenario, in which the potential interfering node is considered to transmit at maximum power, which does not reflect the real channel condition. However in their methods, the RTS (and most of the time CTS) frame is always transmitted at maximum power, which, as mentioned earlier, affects the channel spatial reuse.

### 2.2.2 Tuning Carrier Sensing threshold

Recently, tuning the physical carrier sensing threshold ($CS_{th}$) has been proposed as an efficient mechanism to enhance the network throughput in an IEEE 802.11-based multihop ad hoc network. The physical carrier sensing method reduces the likelihood of collision by preventing nodes in the vicinity of each other from transmitting simultaneously, while allowing nodes that are separated by a safe margin (carrier sensing range) to engage in concurrent transmission.

The authors of [34] were the first to introduce the concept of tuning the $CS_{th}$ for throughput enhancement. By setting the physical silence range, $r_c$, such that it covers the interference range (i.e., $r_c = r_i + d$), the interference impact from hidden terminals is eliminated. Accordingly, they derived the optimal $CS_{th}$ for several grid topologies to achieve maximum network throughput (via enhancing the spatial reuse) given a predetermined transmission rate and Signal to Interference plus Noise Ratio (SINR).

The *ECHOS* architecture [35] improved the network capacity in hotspot wireless networks through dynamically tuning the $CS_{th}$ to allow more flows to co-exist. Here, hot spot deployment operate in infrastructure where an Access point (AP) services connectivity to multiple clients. *ECHOS* adjusts $CS_{th}$ based on interference measured at both AP and client side. The clients report the measured interference to their APs. Then each AP estimates the maximum tolerable future interference for the clients and set its $CS_{th}$ to avoid hidden terminals.

On the contrary, the authors of [36], [37], [38], [39] studied analytically the effect of $CS_{th}$ on the performance of ad hoc networks and showed through theoretical analysis, and verified later via simulations, that the optimum $CS_{th}$ that maximizes the throughput allows hidden terminals to exist.

The authors of [20] further explored the interactions between MAC and PHY layers and studied the impact of MAC overhead on the choice of optimal carrier sense range and the aggregate throughput. They concluded that the optimal $CS_{th}$ depends on the degree of channel contention, packet size and MAC-overhead.

Besides numerical analysis, an experimental testbed in [40] has been developed to investigate the effectiveness of carrier sensing in a practical system for improving network throughput. The authors argued that in order to get the true potentials from tuning the carrier sense threshold, the carrier sense algorithm in the design should make use of the capture effect, i.e., it should make transmission deferral decisions based on the bit rates being used and the received signal strength ratios observed at all of the nearby receivers. To elaborate more on this, consider two senders, nodes A and B, that are both within transmission range of each other. The intended recipients of their transmissions, nodes A' and B' respectively, are each within range of only one transmitter. If A' can capture Bs transmissions, carrier sense should be used to defer Bs transmission to prevent it from interfering with As transmission. On the other hand, if A' can sustain a parallel transmission from B without significantly affecting As delivery rate, carrier sense should be suppressed to make efficient use of the available transmission opportunities (spatial reuse).

Based on the insights from the analytical model and testbed experiment, the authors of [39], [41] and [42] proposed heuristic algorithms for tuning the $CS_{th}$ based on the network performance. Here, a transmitter periodically measures the SINR as in [41] or FER (frame error rate) as in [39] and [42]. Then, the node compares the measured value with pre-defined thresholds (simulation parameters) and accordingly decides whether it should increase or decrease its $CS_{th}$. These proposed schemes do not completely avoid collisions from hidden terminals. This is due to the fact that a node adjusts its $CS_{th}$ only in order to improve its own performance, without considering whether such an adjustment may severely impact the transmission of neighboring nodes.

The authors of [43] argue that a fixed $CS_{th}$ can unnecessarily hinder an IEEE 802.11 receiver from responding to RTS packets (i.e., the receiver may be an exposed terminal to another ongoing communication). They observe through a simulation that if the node can receive RTS, it is able to receive the data from the same source. Accordingly, they propose 802.11 receivers use a different threshold for carrier sense prior to transmitting a CTS message.

In [44], the transmitter collects the RTS/CTS success ratio and the signal strength, and builds a mapping table between the two. This mapping table is updated after every access request. Before each transmit attempt, the sender looks up the mapping table with the current sensed signal strength to obtain the estimated success ratio. If the obtained success ratio is higher than certain threshold, the transmitter starts transmission. Otherwise, it blocks itself until it decide the channel is clear.

In [45], the authors first through analytical study claimed the $CS_{th}$ that allows a certain number of hidden terminals to exist can exploit the network capacity. Moreover, they proposed that the number of contending nodes ($n_c$) is determined by $CS_{th}$ and they derived an optimal value of $n_c$ that can maximize the throughput. Accordingly, they proposed an algorithm that adjusts $n_c$ through tuning $CS_{th}$. In this algorithm, a node first estimates $n_c$ from the measured information, such as the time that the node senses the channel as idle, busy and captured for receiving, then the node adjusts its $CS_{th}$ in order to achieve an optimal $n_c$.

### 2.2.3 Interplay among the Parameters

Different variants of access methods have been proposed to optimize the operation of DCF by helping nodes to select either optimal contention window size or optimal transmission probabilities, which may yield a decrease in collision among hosts and ultimately minimize both the collision and idle periods. The authors of [11] suggested to turn off BEB and proposed a new method to dynamically tune the contention window size. In their new access method, termed as *Idle Sense*, each host measures the average number of consecutive idle slots between transmission attempts and make sure that this number is close to an optimal number (the optimal number that maximizes the throughput is derived from analytical study) by either increasing or reducing the contention window size in an additive increase, multiplicative decrease (AIMD) manner. Furthermore, they also studied the impact of rate adaptation and noted that a node should switch to a lower transmission rate only if the throughput obtained at the lower rate is at least equal to that obtained at higher rate. Accordingly, a frame error rate threshold exists, above which it is beneficial to switch the transmission rate. For example, for IEEE 802.11b, one needs to switch from 11Mbps to 5.5Mbps when the frame error rate exceeds 50%.

An RAF (Rate Adaptive Framing) scheme was proposed in [46]. In RAF a receiver node predicts the channel condition and accordingly jointly calculates the optimal DATA rate and frame size in order to fully utilize the channel bandwidth while avoiding interference from neighboring nodes. Here, the channel condition prediction is based on the number of idle (busy) time slots during which the channel is sensed as idle (busy).

The authors of [47] addressed energy efficiency of rate adaptation and power control in 802.11-based WLAN. In [47], the authors proposed Miser, an energy efficient scheme by jointly controlling both power and rate, and that by computing offline optimal rate and power values that minimizes energy per throughput metrics.

The authors observed in [7] that the space occupied by each transmission can be adjusted by tuning some protocol parameters (e.g., $CS_{th}$ and transmission rate) and accordingly they proposed the concept of spatial backoff. More specifically, in order to allow more concurrent transmission to be initialized, $CS_{th}$ should be increased. On the other hand, in order to make sure that these transmissions can take place simultaneously without corrupting each other, one should reduce the size of interference range through lowering the transmission rate. To conclude, a lower rate and higher $CS_{th}$ result in smaller occupied space. Accordingly, they proposed an algorithm for improving the spatial reuse by dynamically adjusting the $CS_{th}$ and transmission rate. Assuming that the interference at the transmitter equals the interference at the receiver, the authors derived a set of available $CS_{th}$ associated with each transmission rate. Accordingly, the authors proposed a heuristic algorithm to adjust the transmission rate and relatively select the $CS_{th}$ from the set of $CS_{th}$ values associated with the selected rate. Initially, a node starts with the lowest transmission rate and selects the highest $CS_{th}$. If the node has a pre-determined number of consecutive successful transmissions, it increases its transmission rate to the next higher level and fixes its $CS_{th}$. On the other hand, if it encounters a pre-determined number of consecutive transmission failures, it decreases its $CS_{th}$ and fixes the transmission rate, or decreases its transmission rate and selects the most recently used $CS_{th}$ at the reduced rate. Thus, collisions from hidden terminals can be avoided. However, this proposed scheme suffers also from fairness problems as will be shown later.

Another algorithm that tunes $CS_{th}$ and transmission rate jointly was proposed in [48]. Here, all source nodes adapts their DATA rate according to the distance from their packet receivers so as to have the same interference range (equation 2.6). Furthermore, $CS_{th}$ is tuned according to the same methodology as in [39].

Moreover, the authors in [49] argued that for the CSMA protocols, the product of the transmit power and the carrier sensing threshold should be kept constant. That is, the lower the transmit power, the higher the carrier sensing threshold and hence the smaller the carrier sensing range and vice versa. Further, the authors proposed a heuristic algorithm to improve spatial reuse by incorporating this proposition.

Similarly, the authors of [50] studied the impact of spatial reuse on network capacity and derived the network capacity as a function of both transmission power and $CS_{th}$. They showed that in the case where discrete data rates are available, tuning the transmission power offers several advantages that tuning $CS_{th}$ cannot, provided there is a sufficient number of power levels available. Furthermore, the authors also pointed out that in the case the achievable channel rate follows the Shannon capacity, spatial reuse depends only on the ratio of transmission power and $CS_{th}$. This is contrary to the work of [49] where they showed that transmitters should keep the product of transmission power and $CS_{th}$ fixed at a constant. Accordingly, they proposed a heuristic algorithm that adjust the space occupied by a node through dynamic jointly tuning transmission power and rate.

Yong [14] et al. proposed an analytical model to investigate the impact of transmit power and carrier sense threshold on network throughput in the basic access mechanism; they extended both Bianchi's [51] and Kumar's [52] models to derive the single node's throughput. Through their model, the authors argue that an optimum throughput can be achieved for a specific carrier sensing threshold. Moreover, they concluded that a higher system throughput can be achieved with the use of smaller transmit power (subject to network connectivity) and carrier sense threshold.

Yu [53] et al. investigated the interaction between the carrier sensing threshold, contention window size CW, and discrete data rates for IEEE 802.11 DCF. To accomplish this, they adopted and extended Cali's [54] model to derive the capacity of the network mainly as a function of the carrier sensing threshold and SINR. The theoretical analysis results verified that the throughput can be maximized at various transition points of the carrier sensing threshold. Thus, the capacity is strictly not a monotonically increasing/decreasing function of the carrier sensing threshold. Moreover, the throughput can be further enhanced by tuning the contention window size. A spatial reuse optimization mechanism is considered in [55] for multihop wireless networks where the authors considered variable transmission power and different receiver sensitivities.

Investigation through analytical model for tuning carrier sensing threshold and performing power control has been presented in [56]. Moreover, the authors in [57] studied analytically the interaction between the data rate and the transmit power control and accordingly proposed a heuristic scheme that balances the tradeoff between spatial reuse and collisions.

Recently, the authors in [21] proposed an analytical model to study the impact of $CS_{th}$ on the network capacity. They claimed that the attempt probability is a function of both contention window size and $CS_{th}$. Accordingly, they showed that in order to enhance throughput, the contention windows size should remain in small values with higher $CS_{th}$.

### 2.2.4 Other Schemes

Another category of alternative collision avoidance schemes that do not consider all the above proposed techniques has been proposed in [58] and [59]. Both schemes embed extra information regarding the upcoming transmission in the PLCP (physical layer convergence procedure) header so that a larger group of potential interferers become aware of the transmission. The information can be the locations of the transmitter and receiver as in [59] or the interference range as in [58]. Upon receiving the PLCP header, a neighboring node is able to determine whether it lies inside the interference range of the receiver and accordingly, decide whether to block its own transmission or not. However, mandating extra information in the PLCP header of every control or data packet adds extra overhead.

Another enhanced carrier sensing (ECS) was proposed in [60]. Here, MAC frame type was encapsulated into the PLCP header. Upon receiving the PLCP header, neighboring nodes can distinguish the type of transmitted frame and accordingly back off for a specific duration that is assigned based on the MAC frame type information.

An Aggressive virtual carrier sense mechanism is presented in [61]. The basic idea is that a node that overhears either an RTS packet or a CTS packet but not both would not consider the media as busy and accordingly may attempt transmission.

# Chapter 3

# A Spatiotemporal Contention Resolution Algorithm for Enhancing Spatial Reuse in Multihop Wireless Networks

## 3.1 Introduction

As we already mentioned early, in wireless ad hoc networks, the physical carrier sensing (PCS) is essentially used to determine whether or not a node may access the medium. Typically, a node senses the medium, before initiating any communication, and defers its transmission if the channel is sensed busy; a channel is considered to be busy if the strength of the received signal exceeds a carrier sense threshold, $CS_{th}$. The PCS method reduces the likelihood of collision by preventing nodes in the vicinity of each other from transmitting simultaneously, while allowing nodes that are separated by a safe distance (termed as the carrier sensing range, $r_c$) to engage in concurrent transmissions. The former is referred to as collision avoidance while the latter is known as spatial reuse.

Traditional MAC protocols utilize temporal mechanisms, such as the Binary Exponential Backoff of the DCF access method, to resolve contention among simultaneous transmissions. A node wishing to transmit first senses the channel for a Distributed Inter Frame Space (DIFS) period and then transmits only if the channel is sensed idle. Otherwise, the node waits until the channel is sensed free for another DIFS interval and waits for a random contention time: it chooses a backoff $b$, an integer distributed uniformly in the window $[0, CW]$ (where $CW$ is the contention window size) and waits for $b$ idle time slots before attempting to transmit. When a node detects a failed transmission, it doubles its $CW$ until it reaches a maximum value ($CW_{max}$). By separating transmissions in time, successful transmission is achieved and several methods have been proposed to optimize the performance of these temporal mechanisms in single hop networks so that an optimal performance is obtained [9], [11].

Alternatively, to resolve contention among contending hosts and improve the utilization of the channel, recently, the concept of spatial separation has been proposed [7]. Namely, by adjusting the space occupied by each transmission, spatial backoff controls how the channel usage is divided over space such that an appropriate number of concurrent transmissions can exist while a suitable temporal contention level around each transmitter is achieved. In order to control the space occupied by each transmission, a joint control of $CS_{th}$ and transmission rate is proposed by the authors [7]. The authors have shown that substantial gain in channel utilization can be achieved as a result of the improvement in the spatial reuse. Indeed, in addition to tuning the $CS_{th}$, one can also increase the level of spatial reuse by reducing the transmit power so that multiple transmissions can co-exist without causing enough interference on one another; the authors of [8] analyzed the relation between the transmit power and the $CS_{th}$ in determining the network capacity. Here, a combination of lower transmit power and higher $CS_{th}$ leads to a large number of concurrent transmissions with each transmission sustaining a lower data rate.

Clearly, the performance of multihop wireless networks is limited both by the interference, caused by neighboring transmissions, in the network as well as the level of contention among contending hosts. In this chapter, we are interested in improving the performance of multihop wireless networks through developing methodologies to deal with the interference caused by hidden nodes as well as combatting frame collisions from simultaneous transmissions. Namely, we develop a MAC-based dynamic adaptation scheme with joint control of carrier sense threshold and contention window size.

By appropriately tuning the $CS_{th}$, one may detect strong interference and hence avoid unnecessary transmission attempts that could result in a failure (i.e., eliminate collisions from hidden terminals). Further, when selecting an appropriate carrier sense threshold, the exposed terminal problem may be reduced and the channel spatial reuse could be enhanced. When experiencing collisions due to simultaneous transmissions, adapting $CW$ helps in resolving collisions due to simultaneous transmissions. Therefore, it is critical to distinguish the causes of frame loss when deciding which protocol parameter(s) should be tuned such that a good performance is achieved. Various loss differentiation methods have recently been proposed for CSMA-based single hop networks [62], [63], [64], [65] as well as multihop networks [66]. Except the work of [65], none of the other methods can effectively differentiate the frame loss due to interference from hidden nodes or due to collisions. Hence, in this work we propose an effective method for differentiating among frame losses. Our study reveals that by jointly controlling both parameters ($CS_{th}$ and $CW$), the network performance can be substantially improved. Also, the study revealed that in a multihop network, there is a tradeoff between spatial reuse and collisions from concurrent transmissions and the optimal performance is obtained with smaller contention windows, which yields a higher collision ratio, but that indeed promotes

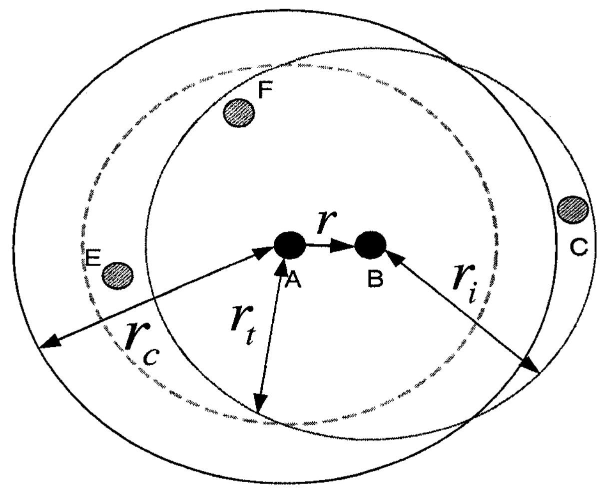



Figure 3.1: Carrier Sensing Range, Silence Range and Interference Range.

higher spatial reuse. The rest of the chapter is organized as follows. In Section 3.2 we provide the preliminaries and motivation of our work. The proposed scheme is presented in Section 3.3 and its performance evaluation, through simulations, is presented in Section 3.4. Finally, we conclude the work in Section 3.5.

## 3.2 Motivating Issues and Solutions

Although the objective of the algorithms proposed in [39], [41], [42] and [7] is to search for an optimal $CS_{th}$ that can avoid hidden terminals and improve the spatial reuse, these algorithms have some deficiencies due to their purely localized nature. In addition, none of these methods differentiate among collisions from contending nodes and those from hidden terminals, hence their adaptation method may lead to either unnecessary decease of $CS_{th}$ or increase of $CW$ (or both), which would deteriorate the system throughput rather than improving it. We explain in this section the inefficiency of these algorithms in resolving either the hidden terminal problem or contentions through three illustrative examples and provide the motivation for this chapter.

### 3.2.1 Illustrative Examples

Consider Figure 3.1 where node $A$ is transmitting a frame to node $B$ and where node $C$ is hidden from $A$ and vice versa (nodes $A$ and $C$ cannot sense each other's transmission). Moreover, consider a node ($F$) that lies in the intersection of the interference area of node $B$ and the carrier sensing range of node $A$. Below are three different scenarios in which node $A$ may encounter a transmission failure.

- **Scenario 1:** Here, node $C$ starts its transmission to its intended receiver (not shown) first. Since node $C$ is outside the carrier sensing range of $A$, $A$ senses the channel as idle (i.e., the level of energy detected is below the $CS_{th}$) and initiates a frame transmission to node $B$. Since node $B$ suffers from the interference of the on-going transmission (of node $C$), it is unable to correctly receive the packet transmitted by $A$. Hence, node $A$ faces a transmission failure. Here in our work, we refer to this kind of collision event as $\mathbf{H_1}$.

- **Scenario 2:** Here, node $A$ starts its transmission to $B$ first. Node $C$, unaware of this communication ($C$ is assumed to lie outside the silence range of $A$), initiates a transmission concurrently and thereby corrupts the transmission of node $A$. We refer to this kind of collision event as $\mathbf{H_2}$.

- **Scenario 3:** Here, nodes $A$ and $F$ initialize their transmission (suppose node $C$ is not involved in any transmission) in the same time slot. Since node $F$ lies in the interference range of $B$, it will corrupt the transmission of $A$. Accordingly, let $\mathbf{C}$ represent this kind of collision event.

Next, for each collision event ($\mathbf{H_1}$, $\mathbf{H_2}$ and $\mathbf{C}$) classified above, we propose a solution.

### 3.2.2 Solution to Scenario 1: Adaptively Adjusting $CS_{th}$ based on Network Performance

In scenario 1, a collision (of $\mathbf{H_1}$-type) can be avoided if a node adjusts its $CS_{th}$ (for instance, based on the network performance, as suggested in [39], [41] and [42]); more specifically, node $A$ can decrease its $CS_{th}$ (i.e., increase its carrier sense range) when it encounters a transmission failure such that if node $C$ transmits in the future, $A$ will be able to sense this transmission and will refrain from initiating any communication. As a result, a collision of this type ($\mathbf{H_1}$) may be avoided. However, a node may need to distinguish this type of failure from others (namely $\mathbf{H_2}$-type and $\mathbf{C}$-type) so that a corresponding reactive scheme can be developed. The method to estimate the packet error rate due to this type of failure will be presented later on.

### 3.2.3 Solution to Scenario 2: Upper-bounding $CS_{th}$

**a) Issues with existing solutions**

While the algorithms proposed in [39], [41], [42] and [7] can avoid collisions from $\mathbf{H_1}$-type transmission failure, almost none of them address the hidden terminal problem that results in $\mathbf{H_2}$-type transmission failure, as we elaborate in the following example. Suppose node $C$ initializes a transmission (after $A$'s) and corrupts the transmission of $A$. According to the schemes proposed in [39], [41] and [42], node $A$ should decrease its $CS_{th}$ due to this transmission failure. However, node $C$ does not know that its transmission had corrupted that of $A$ and accordingly $C$ fixes or increases its $CS_{th}$. As a result, if node $A$ (re)transmits, $C$ will still sense the channel status as idle and initiate a new transmission. Clearly, the transmission of node $A$ will be corrupted again. It is therefore evident that the algorithms of [39], [41] and [42] cannot avoid $\mathbf{H_2}$-type collisions. Furthermore, since the transmission from node $C$ is expected to be successful, the node will consequently increase its $CS_{th}$ for subsequent transmissions and transmit more aggressively. Therefore, the transmission from $C$ will continue corrupting that of $A$. As a result, node $A$ will keep decreasing its $CS_{th}$ until ultimately its opportunity of transmission is deprived; these methods have also been shown to deteriorate the fairness among hosts.

The algorithm proposed in [7] can avoid this kind of collision ($\mathbf{H_2}$-type) if node $A$ decreases its transmission rate (i.e., relatively decreases the SINR requirement) until node $C$ falls outside the interference range of node $B$ (the receiver of $A$'s frame). Although the mathematical analysis in [20] has demonstrated that there exists an optimal combination of transmission rate and $CS_{th}$, the value of such a combination highly relies on the network topology and the channel condition. Hence, it is not always possible for a node to adjust its transmission rate and $CS_{th}$ to achieve this optimal combination by solely depending on its transmission success/failure history. Additionally, and as pointed out in [11], it is only advantageous to transmit at a lower rate when the packet loss rate is high (usually over 50%). That is, transmitting at a lower rate does not necessarily improve the total throughput. Furthermore, neighboring nodes may unnecessarily be suppressed for a much longer time since the transmission duration becomes much longer (and hence the busy time of the channel) with lower transmission rates; consequently, the exposed terminal problem (e.g., node $E$ in Figure 3.1) is exacerbated. Another drawback of the algorithm presented in [7] is that it suffers from the fairness problem, as well, for the same reasons as stated earlier for [39], [41] and [42].

#### b) Our solution

A solution for avoiding collisions in scenario 2 is introduced; clearly, if node $C$ can, *somehow*, detect the ongoing transmission from node $A$, then it should defer its transmission to yield to that of $A$ (assuming node $C$ falls in the interference range of $A$'s receiver). However, $C$ would be able to sense a busy channel, when $A$ is transmitting, only when it falls inside the silence range of $A$ or alternatively when its carrier sense range is large enough to include $A$. Denote $CS_{max}$ (which will be derived next) as the maximum allowed carrier sensing threshold that node $C$ can use; this maximum threshold (or any value below it) guarantees that node $C$ hears $A$'s transmission and accordingly defers its own. However, evidently it is not feasible for node $C$ to determine whether its transmission may corrupt that of $A$ only based on its own transmission success/failure history. Node $C$, hence, would need some information regarding the transmission between $A$ and $B$. The key idea is to allow the receiver ($B$ in this case), through the CTS packet, to distribute necessary information to potential interfering nodes. With this information, all potential interfering nodes (node $C$ in our scenario) can adjust their $CS_{max}$ and limit their $CS_{th}$ not to exceed that value. Potential interferers will, therefore, block their own transmissions in order to allow for the current transmission to complete successfully. The detailed algorithm for determining and dynamically adjusting the $CS_{max}$ is presented later.

Note that, in the proposed solution for $\mathbf{H_2}$-type collision, the RTS/CTS handshake does not silence neighboring nodes; rather these frames only request the neighbors to bound their $CS_{th}$. That is, nodes receiving an RTS or a CTS frame will not be silenced for the whole 4-way handshake duration, as suggested in the IEEE 802.11 protocol, but rather for only an EIFS[1] (Extended Inter Frame Space) duration. Indeed, this improves the spatial reuse through avoiding unnecessary blocking of neighboring nodes that lie in the transmission range of RTS/CTS frame but outside the interference range of the receiver (for instance node $E$ in Figure 3.1). Namely, in our proposed scheme, the decision on whether to start a new transmission is totally left to the physical carrier sense mechanism, since the PCS mechanism already provides an effective way to protect DATA packets through setting an upper-bound, as discussed earlier, on the $CS_{th}$. In order to reduce the overhead induced by RTS/CTS frames, we deploy a dynamic mechanism that switches between the 2-way and 4-way

[1]This does not require any changes to the standard; rather a sender would only set the transmission duration in the ensuing frame for EIFS period.

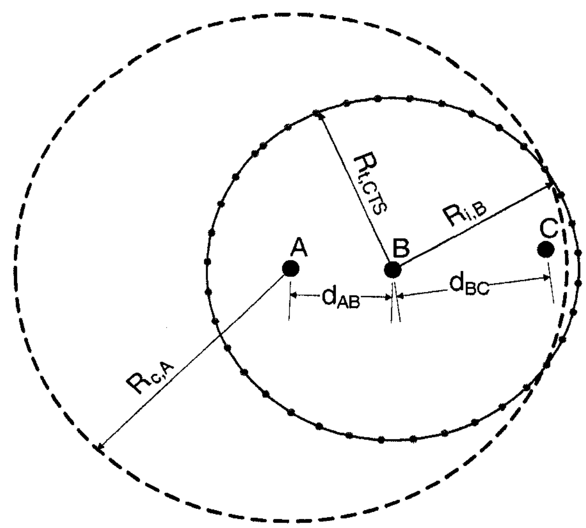



Figure 3.2: Scenario with Hidden Terminals

handshake, as will be shown later.

### c) Deriving $CS_{max}$

In this section, we present our method for deriving a suitable value for $CS_{max}$. Initially, node $A$ (Fig. 3.2) transmits an RTS frame to node $B$. After receiving the RTS packet, node $B$ is able to calculate the distance ($d_{AB}$) to $A$ as follows:

$$d_{AB} = (\frac{P}{P_{r,B}})^{1/4} \tag{3.1}$$

where, $P$ is the transmission power[2] and $P_{r,B}$ is the received power at node $B$ from $A$'s transmission. Subsequently, using equation (2.6):

$$r_i = \left( \frac{P_i}{\frac{P_t}{r^4 \cdot \zeta} - P_{cn}} \right)^{\frac{1}{4}}$$

[2]In the proposed algorithm, we assume that all the nodes use the same transmission power.

the receiver (node $B$) calculates its interference range for receiving the DATA packet(s) from node $A$ as:

$$R_{i,B} = \left(\frac{P}{\frac{P}{d_{AB}^4 \cdot \zeta_{DATA}} - CN_B}\right)^{1/4} \tag{3.2}$$

where, $\zeta_{DATA}$ is the SINR threshold for DATA packets. In the proposed scheme, we assume a fixed PHY transmission rate for DATA packets, thus the value of $\zeta_{DATA}$ is fixed. $CN_B$ represents the current noise measured at node $B$.

Next, node $B$ encapsulates necessary information about the ongoing transmission from $A$ (such as $d_{AB}$ and $R_{i,B}$) in the CTS packets so that all nodes in its interference range are informed about the ongoing communication; the announced values will be used to derive an upper bound on the $CS_{th}$ to force interfering nodes to defer their transmission. Now, to make sure that all neighboring nodes in $B$'s interference range receive the CTS frame, the frame is transmitted at a rate (the transmit power is fixed) such that the transmission range, $R_{t,CTS}$, is large enough to cover the entire interference range of node $B$. Note, however, that since the transmission rate is selected from a set of discrete values, we may well have $R_{t,CTS} > R_{i,B}$; this means that some nodes may be outside the interference range of $B$ and still receive the CTS packet. Accordingly, and upon receiving the CTS packet, node $C$ calculates the distance to node $B$, $d_{BC} = (\frac{P}{P_{r,C}})^{1/4}$ where $P_{r,C}$ is the power of the received CTS frame. $C$ then checks whether it lies in the interference range of node $B$, or not, by comparing $d_{BC}$ with the value of $R_{i,B}$ carried in the received CTS packet. If $d_{BC} > R_{i,B}$, $C$ concludes that it is outside the interference range of $B$ and accordingly it does not need to limit the $CS_{th}$. Here, node $C$ discards this CTS packet and waits for EIFS period to contend for the channel again. Otherwise, node $C$ determines that it lies in the interference range of node $B$ and accordingly has to bound its $CS_{th}$, in order to make sure that $A$'s transmission completes successfully. In other words, $C$ (and other interfering nodes) upon receiving the CTS frame should adjust its $CS_{th}$ such that its carrier sense range includes $A$ and accordingly any transmission from node $A$ will be sensed by the interfering nodes (that is, the silence range of $A$ now covers the interference range of $B$). Now, in order for node $A$ to be within the carrier sensing range of $C$, we should have:

$$R_{c,C} \geq d_{AB} + d_{BC} \tag{3.3}$$

$R_{c,C}$ denotes the carrier sense range of node $C$ (Equation 3.3); the minimum carrier sense range corresponds to $R_{c,C} = d_{AB} + d_{BC}$, and that occurs when node $C$ uses the maximum allowed carrier sense threshold $CS_{max,C}$. For a $CS_{th} < CS_{max,C}$ selected by $C$, $C$'s carrier sense range is guaranteed to sense the transmission of $A$ and therefore $CS_{max,C}$ is called the upper bound. The minimum carrier sense range should be equal to the silence range of node $A$ ($R_{c,A}$, Equation 3) and is defined as follows:

$$R_{c,C} = R_{c,A} = (\frac{P}{CS_{max,C}})^{1/4} \tag{3.4}$$

Using equations (3.3) and (3.4), $CS_{max,C}$ can be derived as:

$$CS_{max,C} = \frac{P}{(d_{AB} + d_{BC})^4} \tag{3.5}$$

If the current carrier sense threshold of node $C$ is above $CS_{max,C}$, it should limit its threshold (to be lower than $CS_{max,C}$). Otherwise, it maintains the same value and records that of $CS_{max,C}$, which will be used for future adjustment (of $CS_{th}$) shortly thereafter.

Indeed, the computed value of $CS_{max,C}$ ensures that node $C$ refrains from transmitting when node $A$ transmits. However, in a multi-hop network environment, a node may be surrounded by multiple transmissions (spatially separated) from more than one node pair. Accordingly, every interfering node (e.g., $C$) maintains a table for its neighboring transmissions; every entry ($< CS^i_{max,C}, T^i_{expire} >$) in the table corresponds to a node pair $i$ currently communicating. $CS^i_{max,C}$ is the upper bound on the $CS_{th}$ a node determines for a node pair $i$ (determined, using Equation 3.5, upon receiving a CTS frame from the receiver of the node pair $i$). The maximum carrier sense node $C$ uses is then determined as $CS_{max,C} = min_i\{CS^i_{max,C}\}$. $T^i_{expire}$ is a pre-defined expiration duration for node pair $i$. If a node does not receive any CTS packet for the same node pair for a $T^i_{expire}$ (we assume $T^i_{expire} = T_{expire}$ for all $i$) duration, the corresponding entry becomes stale and is deleted from the table. This improves the spatial reuse as can be illustrated in the following example. Suppose node $A$ transmits a packet to node $B$, and node $C$ accordingly bounds its $CS_{th}$ in order not to corrupt $A$'s transmission. If node $A$ has no more packets to transmit to $B$, bounding $C$'s carrier sense threshold becomes unnecessary since that forces node $C$ to become too conservative when sensing the medium to transmit its packets, which eventually deteriorates the spatial reuse. Therefore, once node $A$ stops sending frames to $B$ for some time, node $C$ should delete the entry corresponding to this node pair and recompute the upper bound for its $CS_{th}$.

As discussed, transmitting using the 4-way handshake is an efficient solution to avoid $\mathbf{H_2}$-type collisions. However, it adds extra overhead (through the RTS/CTS exchange), which could ultimately affect the network throughput. To address this problem, we further adopt a policy that dynamically switches between the 2-way and the 4-way handshake to reduce the overhead. Initially, a node transmits using the 4-way handshake. If this transmission is successful, the next frame transmission will use the 2-way handshake; otherwise, a node continues transmitting using the 4-way handshake until the transmission is successful, and thereafter switches to the 2-way access method. Recall that when using the 4-way handshake, all potential interfering neighbors for a receiver limit their $CS_{th}$ for a pre-defined duration $T_{expire}$. If the sender has another packet to transmit (now using the 2-way access) and it wins the channel directly after it completes its prior transmission, there is a good opportunity for this initiated packet to succeed. This is due to the fact that the interfering nodes can still sense the transmission of the sender due to the larger carrier sensing range they use (for the period of $T_{expire}$). Hence, the transmission (using the 2-way handshake) is protected without any additional overhead. Finally, a node operating using the 2-way access switches back to the 4-way handshake only upon a packet loss due to $\mathbf{H_2}$.

### 3.2.4 Solution to Scenario 3: Increase $CW$

Recall that scenario 3 corresponds to packet loss from simultaneous transmissions of more than one node in the same time slot. A simple solution to recover from such frame loss is through a temporal contention resolution (e.g., increase of the contention window) that aims to separate transmissions from these contending nodes in time.

Now, for each of the above categories, which may result in a transmission failure, a corresponding solution has been proposed. However, unlike single hop WLANs networks, in a multihop network environment, when a node faces a transmission failure, it is very difficult to distinguish the exact cause ($\mathbf{H_1}$, $\mathbf{H_2}$ or $\mathbf{C}$) of that failure. Next we present our method, with some rules, for distinguishing the causes of frame loss; then, based on the determined causes of transmission failure, we present our algorithm, which adopts different solutions, in order to balance the trade-off between frame collision and spatial reuse to enhance the network capacity.

## 3.3 Proposed Algorithms

### 3.3.1 Related Loss Differentiation Methods

Various loss differentiation methods have recently been proposed for CSMA-based single hop networks [62], [63], [64], [65] as well as multihop networks [66]. The authors in [62] introduces a new NAK packet to differentiate packet collision and channel error. A receiver node transmits an NAK to the sender if it successfully receives the MAC header but fails in receiving the packet payload. Upon receiving the NAK, the sender acknowledges that this transmission failure is due to channel errors but not collisions and accordingly adapts the transmission rate. Another scheme is proposed in [64], which differentiates collisions and errors based on the transmission time information for lost packets. Moreover, the authors in [66] proposed a Collision-Aware Rate Adaptation (CARA). CARA employs RTS probing to differentiate between packet collision or packet error. To reduce RTS/CTS overhead, in CARA, the RTS/CTS exchange is switched off after a certain number of consecutive packet successes and switched on after a certain packet failures. The authors in [63] proposed two algorithms that respectively approximate the packet loss ratio due to collisions and channel errors based on MAC layer measurement. Most recently, the authors in [65] proposed an algorithm in which nodes differentiate interference according to their energy and timing relative to the desired signal, and measure packet error rate (PER) locally at the transmitter for each type of collisions. Except for the work of [65], none of the other methods can effectively differentiate the frame loss due to interference from hidden nodes or due to collisions.

### 3.3.2 Our Proposed Loss Differentiation Algorithm

In order to differentiate the possible causes of a packet loss upon a transmission, a sender ($A$) checks whether any of the following conditions (or a combination thereof) are satisfied.

- **Condition** $A_1$: The ensuing transmission is an RTS transmission.
- **Condition** $A_2$: The reference transmission is initialized at time $t$, $t \in [t_{4way}, t_{4way} + T_{expire}]$. Here, $t_{4way}$ denotes the most recent time node $A$ received the CTS packet from its receiver (node $B$ in Figure 1). At that same time also (i.e., $t_{4way}$), all potential neighboring nodes receive node $B$'s CTS packet and accordingly are informed to limit their $CS_{th}$.
- **Condition** $A_3$: When the transmission is initialized, the sender determines whether its carrier sensing range covers the interference range of the receiver; that is $r_{c,A} \geq r_{i,B} + d$, where $r_{c,A}$ is the carrier sense range of $A$, $r_{i,B}$ is the interference range of $B$ and $d$ is the distance between $A$ and $B$. In other words, the carrier sense threshold ($CS_{th,A}$) should be bounded by a "safe threshold", denoted as $CS_{safe}$, where $CS_{safe} = (\frac{P}{r_{i,B}+d})^{\frac{1}{4}}$, which is easily derived from equation (3) while the value of $r_{i,B}$ can be obtained using equation (5).

Hence, the state of any transmission can be represented by a variable $T = (a_1, a_2, a_3)$ where $a_i = 1$ if condition $A_i$ is satisfied and $a_i = 0$ otherwise. For example, $T = T_1 = (1, 1, 1)$ if all conditions are satisfied for the current transmission. Table 3.1 shows all the possible values of $T$, each corresponds to a transmission state. Now, recall that a transmission failure may be caused by either of the following events $\mathbf{H_1}$, $\mathbf{H_2}$ or $\mathbf{C}$; upon any transmission failure, the sender determines to which category (as explained above) this transmission belongs and accordingly performs some analysis to determine which event caused the failure.

For example, for those types of transmissions where $A_1$ (i.e., the ensued frame is RTS) is satisfied (e.g., $T_1$, $T_2$, $T_3$ and $T_4$), one can determine that a transmission failure is not likely caused by interference of $\mathbf{H_2}$-type (where the interfering signal comes after the reference signal and causes a frame loss) for the following reason;

indeed, when $A$ sends out its (RTS) packet, there is a vulnerable period during which if any interfering node (that is outside the silence range of $A$) attempts to transmit, the transmission from the sender to the receiver ($B$) will be unsuccessful. This vulnerable period corresponds to the transmission duration of the frame (both header and payload). With an RTS frame that is transmitted at $11Mbps$, the vulnerable period is very small, and hence the RTS collision of type $\mathbf{H_2}$ becomes negligible. Additionally, for a failed transmission where $A_2$ is satisfied, all nodes lying within the interference range of the receiver had been informed, through the CTS frame, to bound their $CS_{th}$ in order to sense the transmission of the sender and defer their own transmissions. Accordingly, these interfering (hidden) nodes could not initiate any transmission while the sender is transmitting and hence $\mathbf{H_2}$-type collisions are also unlikely. For those transmissions where $A_3$ is satisfied (e.g., $T_1$, $T_2$, $T_5$ and $T_6$), the sender would refrain from sending out its packet if at least one transmission in the vicinity of the receiver is taking place, which may in effect corrupt the sender's frame (here the sender's carrier sense range covers the interference area of the receiver). Hence, $\mathbf{H_1}$-type collision is unlikely for a transmission failure where $A_3$ is satisfied.

In the above discussion, we have precluded those unlikely causes of packet loss upon every failed transmission; a summary is shown in Table 3.1 where we present the correspondence between a transmission category and the possible cause(s) of failure. Next we present further analysis and the possible reactive schemes for every type of transmission failure.

### 3.3.3 Solutions

#### a) Type $T_1$, $T_2$ or $T_5$ transmissions

When a node encounters a failed transmission of type $T_1$, $T_2$ or $T_5$, both $\mathbf{H_1}$ and $\mathbf{H_2}$ type collisions are not likely (as per our discussion above); the more likely reason for frame loss is that of having multiple senders transmitting in the same time slot (i.e.,

Table 3.1: The Possible Causes for Packet Losses of Each Type

| Type of transmission | Possible causes of packet loss |
|---|---|
| $T_1 = (1,1,1)$ | $\mathbf{C}$ |
| $T_2 = (1,0,1)$ | $\mathbf{C}$ |
| $T_3 = (1,1,0)$ | $\mathbf{C}$, $\mathbf{H_1}$ |
| $T_4 = (1,0,0)$ | $\mathbf{C}$, $\mathbf{H_1}$ |
| $T_5 = (0,1,1)$ | $\mathbf{C}$ |
| $T_6 = (0,0,1)$ | $\mathbf{C}$, $\mathbf{H_2}$ |
| $T_7 = (0,1,0)$ | $\mathbf{C}$, $\mathbf{H_1}$ |
| $T_8 = (0,0,0)$ | $\mathbf{C}$, $\mathbf{H_1}$, $\mathbf{H_2}$ |

**C**-type collision, with no hidden nodes). Here, temporal contention resolution (i.e., BEB) is adopted while the $CS_{th}$ is kept fixed in order not to affect the spatial reuse in the network. Additionally, for $T_5$ transmission category, a node does *not* switch to the 4-way handshake (to reduce the overhead) upon a failure since already hidden nodes have limited their $CS_{th}$ (i.e., $\mathbf{H_2}$-type collisions are unlikely).

### b) Type $T_3$, $T_4$ or $T_7$ transmissions

For these three types of transmissions, a failure results from either **C**-type or $\mathbf{H_1}$-type collision (Table 3.1). Intuitively, one may decide to increase $CW$ or decrease $CS_{th}$: increasing $CW$ resolves the former type and decreasing $CS_{th}$ resolves the latter type by allowing a node to transmit more conservatively.

However, the authors of [21], using an appropriate analytical model, pointed out that in a wireless multihop network, the attempt probability is jointly determined both by $CW$ and $CS_{th}$, while the optimal attempt probability (that maximizes the network throughput) can be obtained using a smaller contention window at the expense of a higher collision ratio. This is so because a larger attempt probability promotes the spatial reuse by reducing the channel idle time (there is indeed a tradeoff between spatial reuse and collisions from concurrent transmissions). Thus, upon encountering transmission failures that may be caused by either **C** or $\mathbf{H_1}$, increasing $CW$ and decreasing $CS_{th}$ simultaneously may be too conservative and results in a lower channel utilization.

In order to decide which parameter ($CS_{th}$ or $CW$) should be tuned, we need to further determine whether the frame loss is due to $\mathbf{C}$ or $\mathbf{H_1}$. Indeed, and unlike single hop WLANs (see for example [63], [62]), it is more challenging to provide an effective loss differentiation in a multihop wireless network. For instance, the authors of [66] proposed to use the RTS/CTS frames to differentiate packet loss due to either collision ($\mathbf{C}$) or interference from hidden nodes (i.e., $\mathbf{H_1}$ and $\mathbf{H_2}$). However, their method strongly depends on the assumption that the RTS/CTS exchange completely silences hidden terminals, which indeed has been shown [15] not to always hold. In addition, this method cannot differentiate $\mathbf{H_1}$-type and $\mathbf{H_2}$-type collisions, and requires the RTS/CTS exchange to be active for all frames.

In our work, we approximate the packet error rate ($P_{ER}$) for both $\mathbf{C}$ and $\mathbf{H_1}$ through periodic measurement as follows. Among the 8 categories identified earlier, $T_1$, $T_2$ and $T_5$ transmissions can be only corrupted by $\mathbf{C}$, while $T_3$, $T_4$ and $T_7$ can be corrupted by either $\mathbf{C}$ or $\mathbf{H_1}$. Therefore, during a predetermined measurement period, the sender counts the number of frame transmissions (for each category) that have been made as well as the number of failed transmissions. We denote:

- $t_1$: the number of $T_1$, $T_2$ or $T_5$ transmissions.
- $f_1$: the number of $T_1$, $T_2$ and $T_5$ failed transmissions.
- $t_2$: the number of $T_3$, $T_4$ and $T_7$ transmissions.
- $f_2$: the number of $T_3$, $T_4$ and $T_7$ failed transmissions.

Let $P_{ER,\mathbf{C}}$ denote the collision probability from $\mathbf{C}$, and $P_{ER,\mathbf{H_1}}$ denote the collision probability from $\mathbf{H_1}$. In order to estimate $P_{ER,\mathbf{C}}$ and $P_{ER,\mathbf{H_1}}$, we first assume that the transmission failures caused by $\mathbf{C}$ and $\mathbf{H_1}$ are independent [65]. Therefore, we can write:

$$1 - \frac{f_2}{t_2} = (1 - P_{ER,\mathbf{C}})(1 - P_{ER,H_1}) \tag{3.6}$$

and with the independence assumption, $P_{ER,C}$ can be estimated as:

$$P_{ER,\mathbf{C}} = \frac{f_1}{t1} \tag{3.7}$$

Combining (3.6) and (3.7), we obtain:

$$P_{ER,\mathbf{H_1}} = 1 - \frac{1 - \frac{f2}{t2}}{1 - \frac{f_1}{t1}} \tag{3.8}$$

The values of $P_{ER,\mathbf{C}}$ and $P_{ER,\mathbf{H_1}}$ are updated through periodic measurements of $t_1$, $f_1$, $t_2$ and $f_2$. Now, according to $P_{ER,\mathbf{C}}$ and $P_{ER,\mathbf{H_1}}$, the sender decides whether it should increase $CW$ or adjust $CS_{th}$.

More specifically, a node compares the estimated $P_{ER,\mathbf{H_1}}$ value with two predefined thresholds (say $P_S$ and $P_F$). If $P_{ER,\mathbf{H_1}}$ is above $P_F$, the node gradually decreases its $CS_{th}$ (to the next lower value) to transmit more conservatively; and if $P_{ER,\mathbf{H_1}}$ is below a certain threshold $P_S$, a node gradually increases its $CS_{th}$ (to the next higher level) to encourage more concurrent transmissions. Otherwise, a node will fix its $CS_{th}$. The values of $P_S$ and $P_F$ can be obtained empirically [42]. Further, as mentioned before, in a multihop wireless network, the transmission attempt probability ($\tau$) is jointly determined by the physical carrier sense as well as the contention window ($\tau = p_1 \times p_2$, where $p_1$ is the attempt probability given that the medium is sensed idle and $p_2$ is the probability that the medium is idle given that no one transmits in the sender's carrier sensing range). Clearly, a smaller $CS_{th}$ yields a smaller $p_2$ which results in a smaller $\tau$. However, it has been shown that the optimal attempt probability should remain relatively high to improve the system throughput [21]. Accordingly, one needs to keep $p_1$ large, which corresponds to a smaller contention window. Furthermore, increasing the contention window upon a frame loss does not necessarily help in controlling the collision when the carrier sensing range does not completely cover the interference range, as has been shown in [21]. Therefore, we propose to only increase the $CW$ when $P_{ER,\mathbf{C}}$ is larger than $P_{ER,\mathbf{H_1}}$.

Finally, similar to the $T_5$ transmission, for a failed transmission of type $T_7$, a node does not switch to RTS/CTS handshake (to reduce the overhead) since the $\mathbf{H_2}$-type collisions are not likely.

**c) Type $T_6$ transmission**

When a node encounters a failed transmission of type $T_6$, it switches to the 4-way handshake for the next (re)transmission attempt and keeps its $CS_{th}$ and $CW$ unchanged, which is explained as follows. Clearly, the frame loss is not likely to be caused by $\mathbf{H_1}$-type interference (since $A_3$ is satisfied) and consequently reducing the $CS_{th}$ yields no benefits but rather unnecessarily deteriorates the spatial reuse by forcing nodes to transmit more conservatively. When collisions from **C** and **H2** exit (which is the case of $T_6$), it has been shown (both from analytical studies [56] [36] as well as simulations [42]) that the frame loss from $\mathbf{H_2}$-type interference dominates that from **C**. Hence, switching to 4-way handshake along with the solution proposed for Scenario 2, presented earlier, can effectively resolve the contention. Moreover, since $CS_{th}$ is smaller than $CS_{safe}$ (recall that $A_3$ condition is satisfied), $CW$ should not be increased in order to maintain a high transmission attempt probability and accordingly a higher channel utilization. Here, when the next re-transmission fails, the node increases its contention window to resolve the contention temporally.

**d) Type $T_8$ transmission**

When a failed transmission of type $T_8$ occurs, a node switches to 4-way handshake for the next (re)transmission and decreases its $CS_{th}$ to the next lower level. For these transmissions, hidden terminals greatly corrupt the frame reception and clearly either

Table 3.2: Transmission Rate Levels Used in Simulation

| Rate(Mbits/s) | receiver sensitivity (dBm) | SINR threshold (dB) |
|---|---|---|
| 11 | -83 | 15 |
| 5.5 | -79 | 11 |
| 2 | -75 | 9 |
| 1 | -72 | 7 |

the transmitter was too conservative estimating the hidden nodes' transmissions (resulting in $\mathbf{H_1}$-type collision) or the hidden nodes were too conservative estimating the sender's transmission (resulting in $\mathbf{H_2}$-type collision). In order to avoid these types of collisions, the $CS_{th}$ for both the sender and the interfering nodes must be tuned, as explained earlier, to ensure a safe spatial separation among concurrent transmissions. Here, we keep the same $CW$ value in order to maintain a higher attempt probability. Note that, since next the sender will retransmit using the 4-way, a retransmission failure would be resolved by appropriately tuning $CW$.

## 3.4 Performance Evaluation

In this section, we present a simulation-based study to evaluate the performance of the proposed scheme. Furthermore, we present comparisons with three other schemes: the IEEE 802.11 standard, the *dynamic CCA adaptation* scheme proposed in [39] and the *spatial backoff* scheme recently proposed in [7].

### 3.4.1 Simulation Setup

The simulation is carried out using Qualnet[67]. The 2-ray model has been adopted as the channel propagation model. The transmission power for all nodes is set to 15dBm. The final result is the average of 5 simulation runs (with different seeds). The available transmission rates and corresponding SINR and receiver sensitivity thresholds for each transmission rate are listed in Table 3.2. In the *dynamic CCA* *adaptation* scheme, IEEE 802.11 standard and basic (2-way handshake) scheme, all the packets are transmitted at 11Mbps. In the proposed scheme, the transmission rate for RTS, DATA and ACK packets is fixed to 11Mbps while the transmission rate for CTS packets varies among all available levels. The transmission rate varies in *spatial backoff* scheme. The default $CS_{th}$ for IEEE 802.11 standard is set to -84dBm. On the other hand, for other schemes that adjust the $CS_{th}$, the adaption step for $CS_{th}$ is set to 1dBm. Moreover, the $P_S$ and $P_F$ for the proposed scheme are set to 0.05 and 0.1 respectively.

In our simulation study, 100 nodes are randomly distributed over a $1000m \times 1000m$ area; we consider constant bit rate (CBR) flows randomly distributed between source-destination pairs and the packet size is assumed fixed to 512 Bytes.

We take the following measurements to evaluate simulated schemes:

- Aggregate Network Throughput, which is the sum of the bytes correctly received by the receivers per time unit (in KB/sec) in the whole network.
- Collision Probability ($P_c$), which counts the ratio of total number of transmission failures over the total number of transmission attempts that have been made.

### 3.4.2 Results and Discussions

*1) Impact of $CS_{th}$ and CW*

In this section, we try to obtain a deeper insight of the impact of $CW$ and $CS_{th}$ on the system performance through simulation study. In the experiment, the number of CBR flows is fixed to 25 and the traffic load is fixed to 400 packets/second. Figure 3.3 shows the aggregate throughput obtained for the IEEE 802.11 when varying both $CS_{th}$ and $CW$. Here, the BEB is disabled and the backoff is always selected from the the interval $[0, CW]$.

Clearly, a larger contention window (e.g., 512 and 1024) results in a serious throughput degradation regardless of the value of the carrier sense threshold. Indeed, although a very large $CW$ eliminates the (**C**)-type collisions, it results in longer idle periods, which in turn severely suppresses the spatial reuse of the wireless channel. We recall that the transmission attempt probability ($\tau$) is jointly determined both by $CS_{th}$ and $CW$ ($\tau = p_1 \times p_2$ as mentioned in section 3.3.3) and a large $CW$ leads to a small $p_1$, which in turn results in a smaller attempt probability. Consequently, the transmitter nodes become too conservative accessing the medium, causing serious throughput deterioration.

Alternatively, larger throughput is obtained when the contention window is small; more specifically, when $CW = 32$, the largest system throughput is obtained when smaller carrier sense thresholds are used (transmitting with $CW = 32$ achieves 10% to 15% of throughput improvement over $CW = 64$ and $CW = 128$). Here, a smaller contention window guarantees a higher access to the channel and a smaller carrier sense threshold guarantees a safe spatial separation among concurrent transmissions. Observe that the optimal network throughput depends on the values of both $CW$ and $CS_{th}$; for larger $CS_{th}$ (more aggressive senders), the contention windows $CW = 64$ and $CW = 128$ result in a slightly better throughput than $CW = 32$. From the results and discussions above, we can conclude that there exists a balance between the spatial reuse and the collisions due to contentions, and thus the optimal transmission probability, $\tau$, which results in optimal throughput performance is achieved by the appropriate selection of the contention window and the carrier sense threshold.

*2) Impact of network density*

We study the impact of network density on the aggregate network throughput by varying the number of CBR flows in the network. As shown in Figure 3.4, in comparison with the IEEE 802.11 standard, the proposed scheme, the *dynamic CCA adaptation* scheme and the *spatial backoff* scheme, all result in higher throughputs,

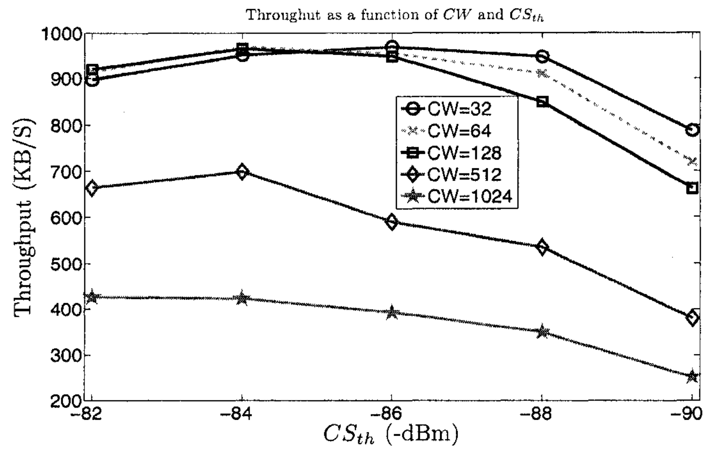



Figure 3.3: Throughput as a Function of $CS_{th}$ and $CW$

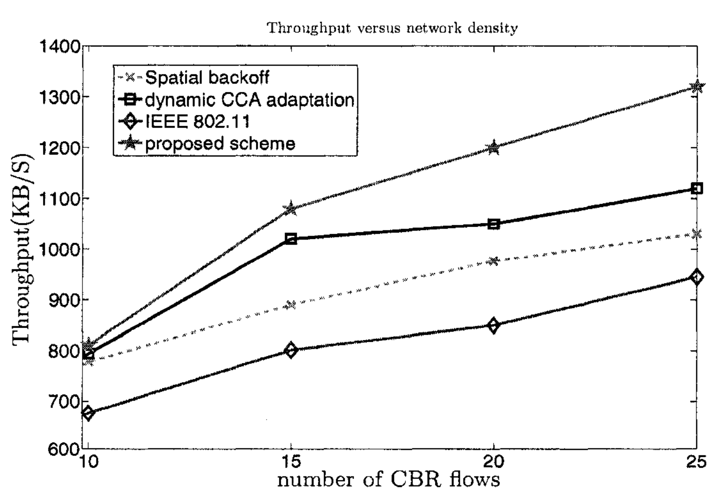



Figure 3.4: Impact of Network Density on Aggregate Throughput

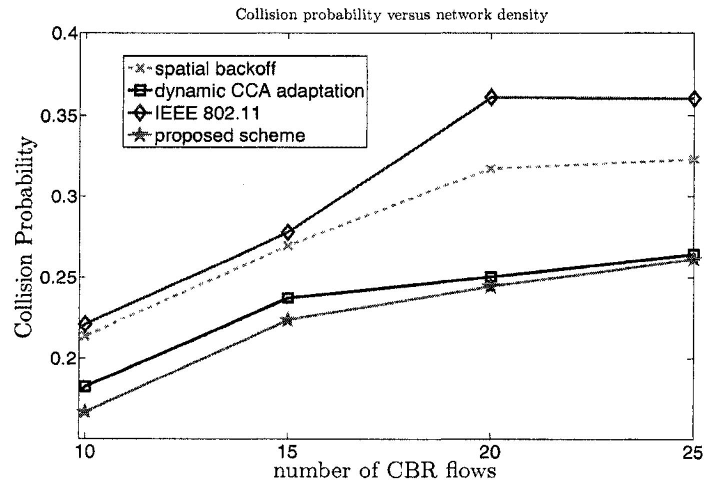



Figure 3.5: Impact of Network Density on Collision probability

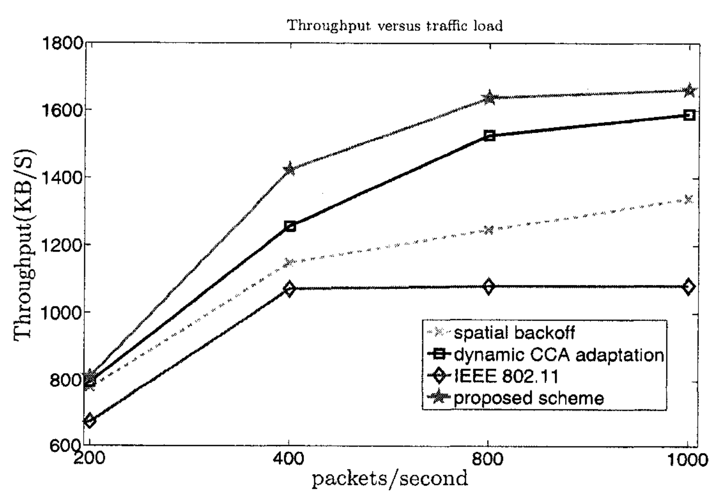



Figure 3.6: Impact of Traffic Load on Aggregate Throughput

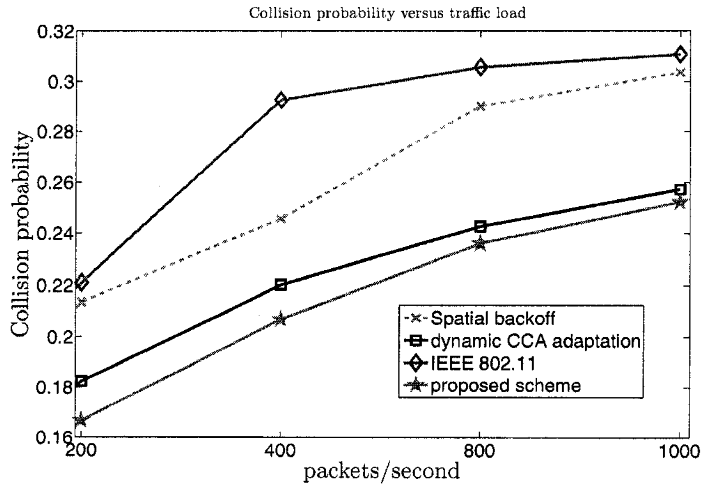



Figure 3.7: Impact of Traffic Load on Collision Probability

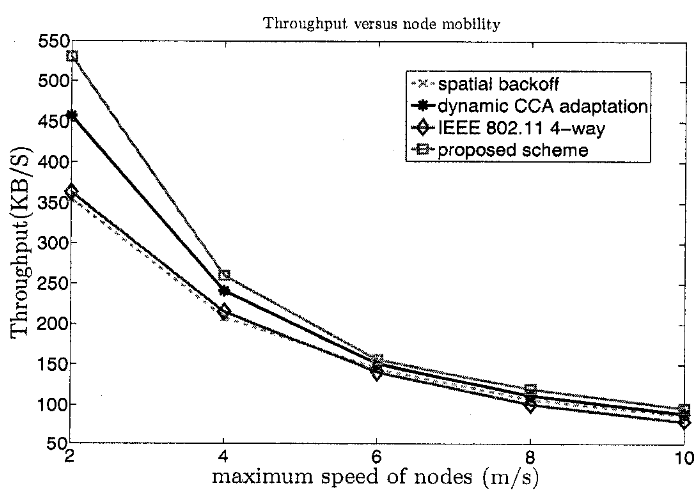



Figure 3.8: Impact of Node Mobility on Aggregate Throughput

simply because the IEEE 802.11 does not adopt any adaptation mechanism except that implemented with the binary exponential backoff in response to any packet loss.

The reason why the *dynamic CCA adaptation* scheme performs better than the *spatial backoff* scheme is due to the ineffective adaptation metrics adopted in the latter one. Namely, *spatial backoff* uses consecutive transmission successes/failures in order to estimate the network performance and performs tuning of PHY transmission rate and carrier sense threshold, while the *dynamic CCA adaptation* scheme uses periodic measurements of packet loss ratio. It is to be noted that the use of consecutive transmission successes/failures as a metric may lead to frequent fluctuations and inaccurate estimation due to its dependence on the network topology under investigation [68]. In addition, the *spatial backoff* performs premature decrease of the transmission rate even when the collision probability is low, which indeed affects the throughput since that results in longer busy periods for the wireless channel, as pointed in [11].

When facing a transmission failure, a node operating with the *dynamic CCA adaptation* scheme does not differentiate the causes of transmission failures and correspondingly reacts through decreasing $CS_{th}$ and increasing $CW$ at the same time. Consequently, this may unnecessarily oblige nodes to suppress their transmissions either by waiting for longer backoff period (effect of larger $CW$) or assuming a high level of interference before initiating a transmission (effect of lower $CS_{th}$). For example, as the network becomes more saturated, the collisions from $\mathbf{H_2}$ increase and become more dominating [21] [56]. However, when encountering $\mathbf{H_2}$-type collisions, either decreasing $CS_{th}$ or increasing $CW$ can not reduce the collision; rather, this may decrease the transmission attempt probability, and hence deteriorates the spatial reuse. In comparison, the proposed method searches for the best operating point through first effectively differentiating the type of losses and second reacting to frame loss by appropriately adapting either $CS_{th}$ or $CW$ so that a high transmission probability is achieved, encouraging more concurrent transmissions and leading to a better spatial reuse.

Another key reason for the throughput enhancement obtained by the proposed scheme is that it probes the network for the level of interference and dynamically switches between being conservative and aggressive in accessing the channel, in order to reduce the frame corruption due to $\mathbf{H_1}$-type collisions. Moreover, it efficiently eliminates the collisions from hidden terminals through limiting the $CS_{th}$ of potential interferers (i.e., eliminating $\mathbf{H_2}$-type collisions), while the *dynamic CCA adaptation* and the *spatial backoff* scheme do not completely address $\mathbf{H_2}$-type collisions. This can be observed in Figure 3.5, which shows the collision probability under different network densities. Clearly, the proposed scheme has the lowest collision probability among all the simulated methods. Indeed, it is this property (lower collisions) for our proposed method that leads to over 20% of throughput improvement compared with *dynamic CCA adaptation*, especially as the network becomes denser (e.g., more than 20 flows). We also observe that as the network becomes denser, the measured collision probability of the proposed method approaches that of the *dynamic CCA adaptation* scheme, due to its aggressive nature. However, this impact has been overcome by the high level of spatial reuse and transmission attempt probability, which is achieved by effectively jointly adjusting $CS_{th}$ and $CW$ upon differentiating among failures. Therefore, the proposed scheme continues to be more advantageous in achieving better throughput, when compared with other simulated schemes, as the network gets denser (when there are 25 flows).

*2)Impact of traffic load*

Next, we study the impact of the traffic load on the network performance by varying the packet generating rate of the CBR flows from 200 to 1000 packets/second and the results are shown in Figure 3.6; the number of CBR flows is fixed to 10. The network throughput behaves in a similar way to that of Figure 3.4. Initially, when the traffic load is light (200 packets/sec) for the network to be able to support all flows, the collision probability is small (less than 15%) and the flows are easily separated in time without the need to tune $CS_{th}$ or $CW$. Hence, all algorithms show almost the same throughput. As the traffic load increases ($\geq$ 400 packets/sec), the collisions from RTS packets increase and the IEEE 802.11 starts showing its limitations in sharing the channel. The *spatial backoff*, *dynamic CCA adaptation* both achieve better throughput than the IEEE 802.11, due to the improvement of spatial reuse achieved by tuning $CS_{th}$. However, since neither of them completely solves the hidden terminal problem, as the network load increases, the collisions from hidden terminals start to impact the throughput (Figure 3.7). In contrast, the proposed scheme is able to differentiate the transmission failures and accordingly adjust both $CS_{th}$ and $CW$ to avoid collision from hidden terminals while maintaining a high level of transmission attempt probability to yield a high channel usage. Indeed, this enables the proposed scheme to outperform *spatial backoff* and *dynamic CCA adaptation*.

*3)Impact of node mobility*

Node mobility has a great impact on the network performance. We select the Random Way-Point mobility model and vary the node's maximum speed from $2m/s$ to $10m/s$. The number of flows is 10 and the packet generating rate is 400 packets/s. Figure 3.8 illustrates the aggregate throughput of all simulated schemes under different mobility levels. It can be seen from the figure that when the speed is low (e.g., $2m/s$), the proposed scheme still posses a leading performance since the network topology does not vary rapidly. However, as the moving speed increases, it can be seen from the figure that all schemes suffer a dramatic throughput drop. This is mainly because the source and destination nodes may become outside the transmission range of each other, which results in more transmission failures. On the other hand, routing table entries may become unstable due to mobility and may require updating, which adds more congestion on the network.

## 3.5 Conclusion and Future Work

In this chapter, we presented a novel dynamic spatiotemporal scheme that balances the tradeoff between collision and spatial reuse in multi-hop wireless networks. Using this novel approach, a node dynamically adjusts its $CS_{th}$ to eliminate collisions from hidden terminal and enhances spatial reuse by diminishing the effect of the exposed terminals. At the same time, the proposed approach reduces the collisions from among contending hosts while maintaining the level of transmission attempt probability through carefully selecting the contention window. An effective loss differentiation mechanism is proposed to work in concert with the proposed methodology. Moreover, and unlike the DCF access mode, the RTS/CTS handshake does not silence neighboring nodes but rather only informs them to bound their $CS_{th}$ to yield the on-going transmissions. To reduce the overhead from the RTS/CTS handshake, and based on the network performance policy, we proposed a policy wherein a node can adaptively enable/disable the RTS/CTS exchange. Simulation results and comparisons with other recent methods showed the effectiveness of the proposed method in improving the network performance. One direction we are currently investigating is the integration of power control with the proposed scheme.

# Chapter 4

# A Distributed Power and Rate Control Scheme for Mobile Ad hoc Networks

## 4.1 Introduction

In this chapter, we present a localized, distributed power and rate control scheme through which nodes, in a multihop wireless network, dynamically adjust their transmission power and data rates to eliminate collisions from hidden terminals and enhance the spatial reuse by diminishing the effect of exposed terminals. We assume a four-way handshake access method in our work. We start from the premise that high system throughout could be achieved when the area silenced by a sender (e.g., through physical carrier sense) is reduced as much as possible while covering the interference area of its intended receiver [14]. According to the communication model introduced in Chapter 2, the area silenced by the sender depends on the transmission power and the $CS_{th}$, while the interference range depends on the distance between the sender and the receiver and the SINR threshold. It was however shown in [14] that better spatial reuse may be obtained with smaller silence area and accordingly better system throughput.

In our work, the area silenced by the sender does not need to cover the interference area around the receiver of that frame (as opposed to [14]); rather, the receiver of a frame (e.g., RTS or CTS) would adjust its transmission power (and data rate for the DATA transmission) so that the interference area of its transmission would coincide with the area silenced by the prior transmission of the sender. We adopt both physical and virtual carrier sense in our method; the former to protect the transmission of CTS and ACK frames while both mechanisms are used to protect the transmission of DATA.

The rest of this chapter is organized as follows. In Section 4.2 we present the concepts for our proposed power and rate control scheme and present different heuristics supported by sound analysis. Section 4.3 present the performance evaluation and comparisons of our methods and finally we conclude the chapter in section 4.4.

## 4.2 Distributed Power and Rate Control Scheme

### 4.2.1 Preliminaries

Clearly, the level of spatial reuse plays a key role in determining the capacity of a multihop wireless network [20]. As mentioned earlier, one can increase the level of spatial reuse either through reducing the sender transmission power or increasing the $CS_{th}$. We focus in this work on the former approach and assume a fixed $CS_{th}$. While decreasing the transmit power allows multiple concurrent transmissions to co-exist, a reduced transmission power, however, yields a lower SINR which results from either a weaker received signal or increased interference level [50]. This consequently yields a lower data rate that is sustained by each transmission, ultimately affecting the system performance. Additionally, a lower transmit power would result in a higher interference range and hence more hidden nodes that may corrupt the transmission between a sender and a receiver. Alternatively, increasing the transmit power enhances the capture effect (SINR) and thus decreases the possibility of collision from hidden terminals. Moreover, with enhanced SINR, a node can use higher rates for transmitting its packets and this would yield to a better throughput. However, larger sender transmission power adversely impacts the spatial reuse by unnecessarily suppressing concurrent communications. Hence, in order to achieve higher level of spatial reuse and thus network throughput, one needs to find a balance between the transmission power and the transmission rate. To achieve this, one can derive analytically the network capacity as a function of both the transmit power and the SINR threshold (hence the transmission rate) [14], [56] and study the interplay among these parameters so that a maximum capacity can be achieved. Instead, in this work, we propose a localized heuristic method for power control from the perspective of collision avoidance. We note first that in [14] the authors observed that a high system throughput can be achieved when the area silenced by a sender is reduced as much as possible under the premise that the interference area of its intended receiver is covered by the silence area. Next, we derive an alternative method for protecting the sender transmissions by appropriately selecting the transmission power and rate while minimizing the exposed terminals. We assume the four-way handshake mode operation of the DCF.

### 4.2.2 Methodologies

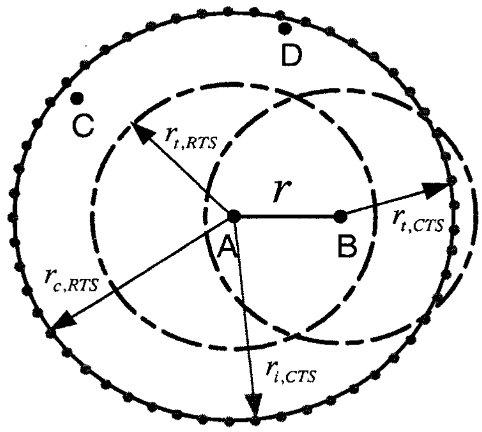
Consider a data frame transmission between two nodes $A$ and $B$. We assume an RTS frame, whose silence range is $r_{c,RTS}$, has been successfully transmitted and we consider first the protection of the CTS packet reception. Here, if the receiver ($B$) selects a transmission power for its CTS frame such that the interference range at the receiver of the CTS packet ($A$), $r_{i,CTS}$, coincides with or falls inside the silence range of the RTS, then the CTS frame will be received without corruption. We call this the physical carrier sense (PCS) approach and is shown in Figure 4.1(a). Here, although nodes $C$ and $D$ lie in the interference range of a CTS packet, they cannot initiate any communication while the CTS is being received because they already lie in the silence range of the RTS packet. Both nodes ($C$ and $D$) are silenced upon hearing the RTS for an extended inter-frame space (EIFS) [4]. Since EIFS is a sufficient duration for a CTS packet to be received at the transmitter ($A$), the reception of the CTS packet will not be corrupted. A similar approach, as shown in Figure 4.1(c), is adopted for protecting the ACK packet reception by setting $r_{c,DATA} = r_{i,ACK}$.

On the other hand, the EIFS duration is not sufficient to protect larger DATA frames since the transmission duration (or vulnerable period) may be much longer than EIFS period; accordingly, a different approach is used to protect the transmission of the DATA packet. Namely, we use virtual carrier sense (VCS) in order to protect DATA transmission from hidden nodes; this can effectively be achieved by selecting a transmission power for the DATA packet such that the resulting interference range at the receiver ($B$) is completely covered by the transmission range, $r_{t,CTS}$, of the ensuing CTS frame. Thus, all potential interfering nodes, including hidden terminals, lying within the interference range of the DATA packet (say nodes $C$ and $D$ in Figure 4.1(b)) will be silenced by the CTS packet for the whole duration of the DATA packet transmission.

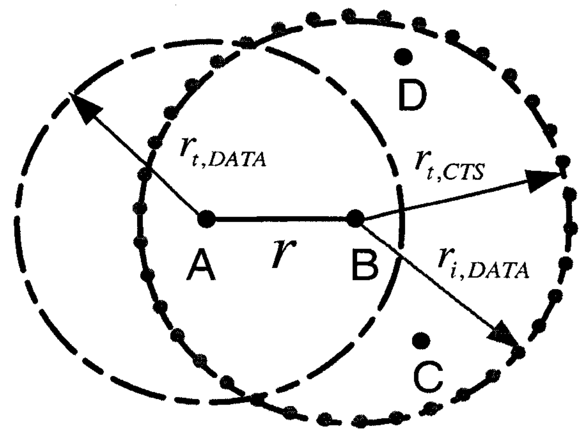
### 4.2.3 Derivation of Transmission Power and Rate

First, we analyze the minimum power requirements for delivering the CTS packet; let $P_{RTS}$ and $P_{CTS}$ be the transmission power of RTS and CTS packets respectively. The selection of $P_{RTS}$ is presented later in the section. Using equation (2.6):

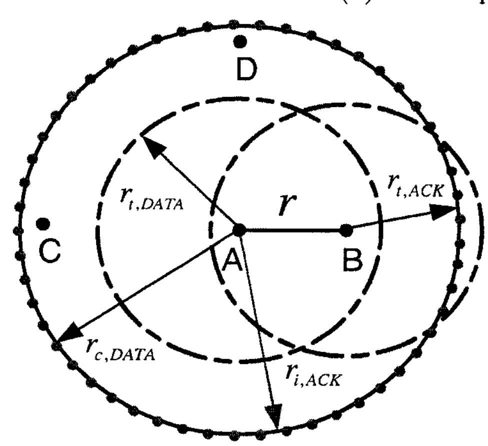
$$r_i = \left( \frac{P_i}{\frac{P_t}{r^4 \cdot \zeta} - P_{cn}} \right)^{\frac{1}{4}}$$




(a) PCS to protect CTS




(b) VCS to protect DATA




(c) PCS to protect ACK

Figure 4.1: Power Scheme Analysis

we can obtain the interference range at the receiver of the CTS packet as:

$$r_{i,CTS} = \left( \frac{P_i}{\frac{P_{CTS}}{r^4 \cdot \zeta_{R,CTS}} - P_{cn}} \right)^{\frac{1}{4}}$$

Here, $\zeta_{R,CTS}$ is the SINR threshold when receiving a CTS packet at rate $R$ and $P_i$ is the estimated transmission power of an interfering node. We will explain how to estimate $P_i$ later in the section. Furthermore, from equation (2.3):

$$d_{cs} = (\frac{P_t}{CS_{th}})^{\frac{1}{4}}$$

we can obtain $r_{c,RTS} = (\frac{P_{RTS}}{\eta})^{\frac{1}{4}}$. Since PCS is applied to control the power of the CTS packet as discussed earlier and shown in Figure 4.1(a), we choose $r_{i,CTS} \leq r_{c,RTS}$ in order to prevent collisions from hidden nodes (those in the interference range of the receiver of the CTS but outside the transmission range of the RTS frame). Thus, for equality, the lower bound on $P_{CTS}$ can be expressed as:

$$P_{CTS,low} = max(P_{min}, (\frac{\eta \cdot P_i}{P_{RTS}} + P_{cn}) \cdot \zeta_{R,CTS} \cdot r^4) \tag{4.1}$$

where $P_{cn}$ is the current noise measured at the sender node and is encapsulated in the RTS packet.

Now, in order to protect the DATA packet against interference from hidden nodes, we set the interference range of DATA equal to the transmission range of CTS (note, if the vulnerable period is smaller than EIFS, e.g., case of shorter data frames, then PCS may be used). Here, the transmission range of CTS packet can be expressed using equation (2.2):

$$r_t = (\frac{P_t}{\kappa})^{\frac{1}{4}}$$

as $r_{t,CTS} = (\frac{P_{CTS}}{\kappa_{R,CTS}})^{\frac{1}{4}}$, where $\kappa_{R,CTS}$ is the receiver sensitivity of a transmitted CTS at rate $R$. Moreover, the interference range of the DATA packet is expressed as:

$$r_{i,DATA} = (\frac{P_i}{\frac{P_{DATA}}{r^4 \cdot \zeta_{R,DATA}} - P_{cn}})^{\frac{1}{4}}$$

$P_{DATA}$ is the transmission power of the DATA packet and $\zeta_{R,DATA}$ is the SINR threshold requirement when receiving a DATA packet transmitted at rate $R_{DATA}$. Accordingly, by making $r_{t,CTS} = r_{i,DATA}$, we obtain the following system:

$$P_{DATA} = max(P_{min}, (\frac{\kappa_{R,CTS} \cdot P_i}{P_{CTS}} + P_{cn}) \cdot \zeta_{R,DATA} \cdot r^4) \quad (4.2a)$$

$$P_{max} \geq P_{CTS} \geq P_{CTS,low} \quad (4.2b)$$

where $P_{cn}$ is the current noise measured measured at the receiver upon receiving the CTS packet and $P_{DATA} \leq P_{max}$. Note that, $P_{DATA}$ is a function of $P_{CTS}$ whose value is still unknown. In addition $P_{DATA}$ is dependent on the SINR threshold, $\zeta_{R,DATA}$, whose value depends on the packet transmission rate.

The solution of the above system is a tuple ($P_{CTS}$, $\zeta_{R,DATA}$,$P_{DATA}$), and there may exist more than one feasible solution among which we need to select one that yields better performance. Recall that the values of $P_{CTS}$, $\zeta_{R,DATA}$, and $P_{DATA}$ are selected from a set of discrete power and transmission rate levels available for the node.

In this work, we consider three alternative approaches for determining $P_{DATA}$, $P_{CTS}$ and $\zeta_{R,DATA}$:

1. $PRAS - CP_1$: Here, we select $P_{CTS} = P_{CTS,low}$. This selection stems from our understanding that a large $P_{CTS}$ may unnecessarily silence more nodes and hence could severely affect the channel spatial reuse. Accordingly, a set of ($P_{DATA}$, $\zeta_{R,DATA}$) can be selected to satisfy condition 4.2(a). In our work, we select the highest possible rate such that $P_{DATA} \leq P_{max}$.

2. $PRAS - CP_2$: We set $P_{CTS} = P_{DATA}$ in equation 4.2(a), then we solve for $P_{DATA}$:

$$
\begin{aligned}
P_{DATA} =& \frac{1}{2}[P_{cn} \cdot \zeta_{R,DATA} \cdot r^4 + ((P_{cn} \cdot \zeta_{R,DATA} \cdot r^4)^2 \\
&+ 4(\kappa_{R,CTS} \cdot \zeta_{R,DATA} \cdot P_i \cdot r^4))^{\frac{1}{2}}]
\end{aligned}
\tag{4.3}
$$

after which we select the highest data rate such that the constraint $P_{CTS,low} \leq P_{DATA} = P_{CTS} \leq P_{max}$ is satisfied. In this scheme, the data rate that can be supported to transmit the DATA frame is larger than the previous scheme whereas the transmit power for DATA is lower (i.e., better spatial reuse).

3. $PRAS - CP_3$: Here, we set $P_{CTS} = P_{max}$; although a larger $P_{CTS}$ may prevent more nodes from concurrently transmitting (hence impacting the spatial reuse), a larger $P_{CTS}$ implies a smaller $P_{DATA}$ or larger supported transmission data rates. Again, we select the highest possible transmission rate such that $P_{DATA} \leq P_{max}$.

Finally, given that the DATA packet is successfully received, the ACK power value can be derived similar to the way we derived the lower bound for the power of CTS by making $r_{c,DATA} = r_{i,ACK}$ and as shown in Figure 4.1(c). The power of ACK is expressed as:

$$
P_{ACK} = max(P_{min}, (\frac{\eta \cdot P_i}{P_{DATA}} + P_{cn}) \cdot \zeta_{R,ACK} \cdot r^4) \tag{4.4}
$$

where $\zeta_{R,ACK}$ is the SIR threshold for an ACK frame received at rate $R$. $P_{cn}$ is the measured noise when receiving the CTS packet and it is encapsulated in the DATA packet.

### 4.2.4 $P_{RTS}$ tuning and $P_i$ Estimation

#### RTS Power Tuning

In PRAS, the tuning of the transmission power of an RTS frame is a key design aspect for enhancing the spatial reuse, since all the power values of other packets should be correlated with the power of RTS packet. Initially, the RTS frame is sent at a maximum power to a destination node. If $N_S$ consecutive RTS packets were sent successfully to the same destination, then the node decreases its RTS power value to the next lower possible power level that is higher than or equal to $P_{min}$ when sending to the same destination. Similarly, after $N_F$ consecutive packets reception failures, the power of RTS will be increased by one level ($P_{min} \leq P_{RTS} \leq P_{max}$). Here $N_S$ and $N_F$ are simulation parameters.

#### $P_i$ Estimation

As stated earlier, $P_i$ represents the transmission power of an interfering node $F$ ($F$ is a neighbor, say, to a receiver $B$); according to Eq. 6, determining $P_i$ is critical for determining the interference range around $B$. Furthermore, according to PRAS (equations (4.1)-(4.4)), $P_i$ is also needed to determine the power assignment of CTS/DATA/ACK frames. Therefore, a heuristic to locally determine the transmission power of a neighboring (interfering) node is needed. We note here that the value of $P_i$ differs from one node to another. For a sender($A$)-receiver($B$) pair, the receiver maintains an estimate of $P_{i,A}$ ($P_{i,B}$) where $P_{i,A}$ ($P_{i,B}$) represents the transmission power of an interfering node neighbor to $A$ ($B$). Initially, these values are assigned a value of $P_{max}$ and both values are lower bounded by $P_{min}$. When $B$ responds to an RTS received from $A$, it will use the value of $P_{i,A}$ to compute $P_{CTS}$ (Eq.4.1). Node $B$ will also use the value of $P_{i,B}$ to compute $P_{DATA}$ and the data transmission rate. For every $N_{CTS}$ CTS packets, that a node transmits, and are consecutively received successfully at the sender, $P_{i,A}$ is decreased by a factor of $\alpha \times P_{i,A}$; otherwise, if one frame is lost, $P_{i,A}$ is increased by a factor of $\alpha \times P_{i,A}$ (e.g $\alpha = 0.1$). Note, too, that $P_{i,A}$ is also updated upon the success (loss) of $N_{ACK}$ (one) ACK packets (similar procedure as before). The same methodology applies as well for updating $P_{i,B}$ with $N_{DATA}$ being the consecutive number of successful DATA packets received. Here, $N_{CTS}$, $N_{DATA}$ and $N_{ACK}$ are all simulation parameters. Note that, whether a CTS or an ACK packet was successfully received at the sender or not is indicated to the receiver through a previously transmitted RTS frame.

### 4.2.5 Network Allocation Vector Adaptation

According to the IEEE 802.11 standard[4], the NAV contained in RTS is equal to $T_{CTS} + SIFS + T_{DATA} + SIFS + T_{ACK} + SIFS$. Here $T_{CTS}$, $T_{DATA}$ and $T_{ACK}$ are time durations for transmitting CTS, DATA and ACK packets respectively and SIFS is a short inter-frame space. Recall that in our scheme, the transmission rate of DATA packet is decided at the receiver side, and accordingly the transmitter is unable to calculate $T_{DATA}$ since it does not know the transmission rate for the DATA frame when it transmits the RTS packet. To rectify this issue, in PRAS, the NAV contained in RTS is set to $T_{CTS} + 2SIFS$. This is reasonable due to the collision prevention property in PRAS. We elaborate more on this through the example shown in Figure 4.1(a). Upon transmitting the RTS frame from node A to node B, nodes in A's RTS transmission range will refrain from transmission for a $T_{CTS} + 2SIFS$ period. When node B replies with a CTS, nodes within B's CTS transmission range will update their NAV value to $T_{DATA} + SIFS + T_{ACK} + SIFS$ period. Nodes in A's RTS transmission range but outside node B's CTS transmission range will update their NAV through the information contained in node A's DATA packet.

## 4.3 Performance Evaluation

### 4.3.1 Simulation Setup

We use Qualnet [67] to evaluate by simulation the performance of PRAS-CP. Here, PRAS-CP is compared with IEEE 802.11, BASIC, and correlative (case ii,B)[18] and Adaptive [33]. In our simulation, the control channel rate is 2 Mbps and the DATA channel rate varies from 1 Mbps to 11 Mbps. The carrier sensing threshold $\eta$ is set to $-78$ dBm. The simulation time is 300 seconds. We use the transmission rate levels of the IEEE 802.11b, which are 11, 5.5, 2 and 1Mbits/s, and the receiver sensitivity ($\kappa$) for each rate is -74.37, -70.37, -68.37 and -64.37 dBm respectively. Moreover, the SINR threshold ($\zeta$) for each rate is 15, 11, 9 and 7dB respectively. The set of discrete power values used in this simulation are 1, 5, 10, 14, 18, 22, 24 dbm. Ad hoc on Demand Vector Routing (AODV) is selected as the routing protocol. $N_s = 10$, $N_F = 1$, $N_{DATA} = N_{CTS} = N_{ACK} = 10$. Other parameters such as antenna gains and heights are assumed to be fixed and equal to one, and known to all nodes. In our simulations, we take the following measurements:

- Aggregate Throughput: This counts the total number of the data bytes correctly received by the receivers per time unit
- Effective Data Delivered per Joule: This counts the total number of received data bytes divided by the entire energy consumption
- Collision Rate: This counts the total number of observed collisions that involve RTS, CTS, DATA, and ACK packets by all attempted deliveries per second.
- Fairness Index: We adopted Jain's Fairness index in order to measure the bandwidth sharing of the connections. The fairness index is given as

$$F = \frac{(\sum_{i=1}^{N} \gamma_i)^2}{N \cdot \sum_{i=1}^{N} (\gamma_i)^2}$$

Table 4.1: Performance for Chain Topology

| Algorithms | Throughput | Energy Efficiency | Collision Rate | Fairness |
|---|---|---|---|---|
| PRAS-CP1 | 320.76 | 11.51 | 0.24 | 0.81 |
| PRAS-CP2 | 436.28 | 15.69 | 0.18 | 0.87 |
| PRAS-CP3 | 179.70 | 5.91 | 0.32 | 0.75 |
| IEEE 802.11 | 168.59 | 4.76 | 0.24 | 0.73 |
| Correlative | 398.56 | 13.63 | 0.22 | 0.82 |
| BASIC | 138.76 | 2.76 | 0.4312 | 0.64 |
| Adaptive | 310.24 | 12.72 | 0.21 | 0.79 |

where N is the total number of connections and $\gamma_i$ is the number of received packets for connection $i$.

Five simulation seeds are used to calculate the average of each metric measurement.

### 4.3.2 Chain Topology

We first consider a chain topology network consisting of eight nodes. Through this topology, we can address delicately the tradeoff between spatial reuse (exposed terminal problem) and collision probability (Hidden node problem). Here, each node has a single one-hop receiver at distance 50 m for its packets throughout the simulation time, to which a CBR traffic flow with packet size 512 bytes is sent. The distance between the non-connected nodes is set to 350 m (the transmission range of RTS/CTS is $\simeq$ 353 m). Each node generates traffic at a rate of 400 packets/second.

Table 4.1 shows the network throughput in the chain topology for all protocols. As can be viewed from Table 4.1, the throughput achieved by PRAS-CP2 outperforms slightly the correlative scheme while outperforming by far the other protocols. Recall, in all proposed protocols (also PRAS-CP3) except Correlative, the RTS frames are sent at maximum power, and in most often the CTS frame. Transmitting RTS or CTS at maximum power, although it provides a good chance of eliminating the possibility of DATA collisions, nevertheless it increases the possibility of control packet collisions and highly affects the spatial reuse, which directly decreases the network throughput as can be seen from Table 4.1. In PRAS-CP1, transmitting CTS at the minimum required power leaves some hidden nodes uncovered and may corrupt the transmission of the DATA packet during the vulnerable period. Recall that $P_{DATA}$ is bounded by $P_{max}$; hence, the interference area (at the receiver of the DATA frame) resulting for the minimum selected rate may not be completely covered by the transmission range of the CTS packet. The traffic load of 400 packets/sec is considered high and thus the IEEE 802.11 starts to show its limitations in sharing the channel in the time domain. On the other hand, as stated previously, BASIC suffers from collisions from hidden nodes and low spatial reuse, which has a high effect on its final throughput. This can be verified by the overall collision probability shown in Table 4.1. Tuning the power of the RTS packet has definitely enhanced spatial reuse for PRAS-CP2 and Correlative. Furthermore, assigning the CTS power value to be equal to that of DATA and tuning the DATA rate to oblige the power constraint of the CTS and DATA packets to be less than RTS packet has caused interference suppression. This is why PRAS-CP2 achieved better throughput than Correlative.

By evaluating the energy efficiency achieved by all protocols, we an see that PRAS-CP2 achieved the best results among all protocols (this is shown in Table 4.1). In IEEE 802.11, all packets are transmitted at maximum power which results in unnecessary waste of energy. For the BASIC scheme, the collision probability dominates the network energy consumption; in other words, the higher the collision probability is, the more energy is consumed in retransmission of packets. For Adaptive, RTS and most of the times CTS is transmitted at maximum power, thus energy consumption in these schemes is due to control packet transmissions and retransmissions.

Finally, the best Fairness Index in this scenario is achieved by nodes implementing

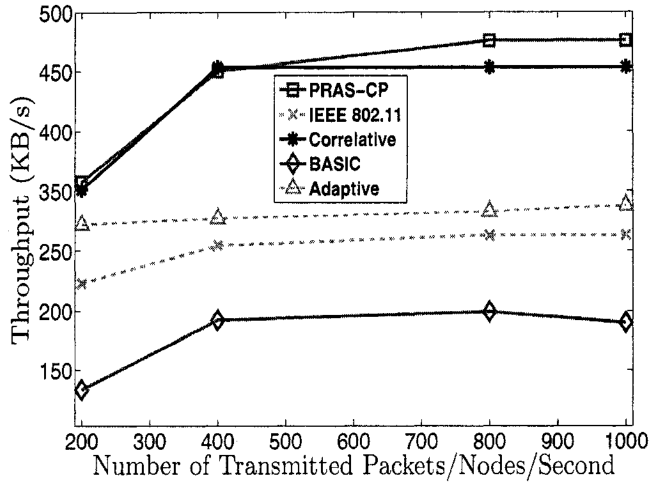



Figure 4.2: Throughput vs Packet Load

PRAS-CP2 as shown in Table 4.1. An explanation for this is that the PRAS-CP mechanism enhances spatial reuse by decreasing the number of exposed terminals. Here the exposed terminal problem is one of the main causes of unfairness in the IEEE 802.11 standard implementation. Adaptive by transmitting the RTS or CTS packets at maximum power suffers from fairness due to the exposed terminal. It was verified by simulation that at least 5 CBR flows were concurrently occurring when implementing PRAS-CP2, where in IEEE 802.11 on average there was 2 CBR flows, Correlative 4 CBR flows, Adaptive 4 CBR flows, BASIC 2 CBR Flows. Without loss of generality, we will use PRAS-CP2 in the other topology and refer to it as PRAS-CP.

### 4.3.3 Random Topology

Here, the network topology consists of 100 nodes randomly distributed into a $1000m \times 1000m$ area. Multi-hop CBR flows of packet size 1000 bytes are set between randomly chosen end-to-end source destination pairs.

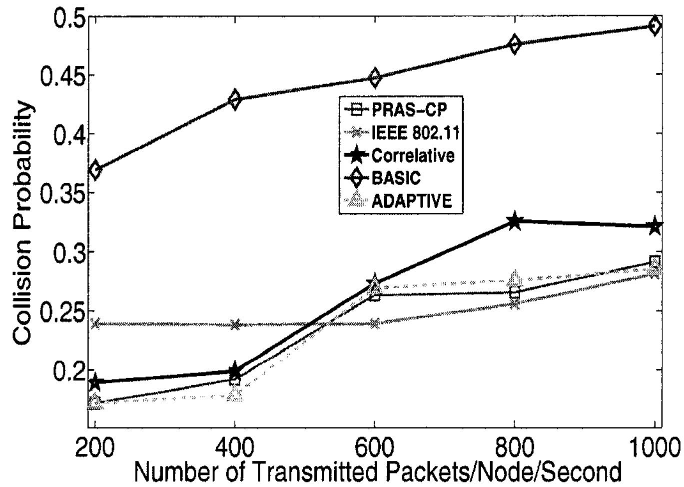



Figure 4.3: Collision Probability vs Packet Load

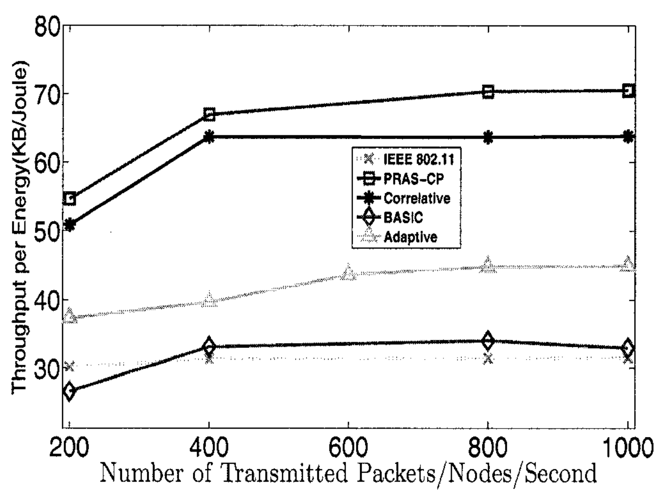



Figure 4.4: Energy Efficiency vs Packet Load

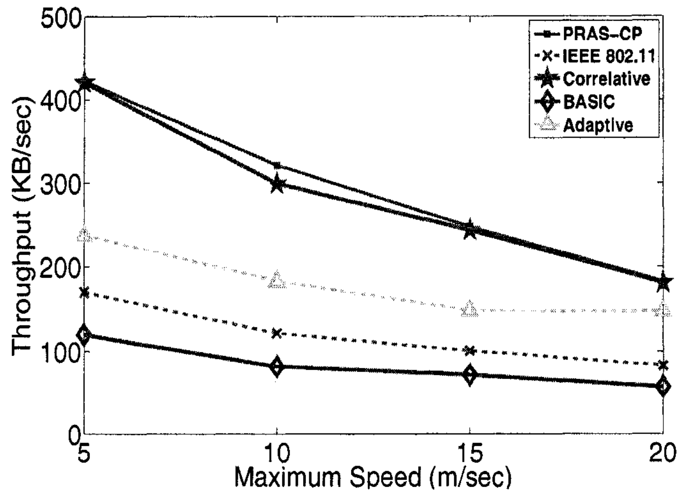



Figure 4.5: Throughput vs Mobility

### Impact of Network Load

We consider varying the packet sending rate of the CBR flows. The number of multihop CBR flows is set to 10. Here, the rate varies from 200 to 1000 packets per second. Figure 4.2 shows the network throughput obtained by all protocols for source data rates of 200, 400, 800, 1000 packets/second respectively. As can be viewed from Figure 4.2, the throughput achieved by PRAS-CP outperforms the throughput of other schemes for all traffic loads. When the traffic generation rate is low (200 and 400 packets/second) PRAS-CP and Correlative achieves similar throughput results, while the throughput achieved by PRAS-CP is better than the throughput achieved by Correlative under heavy traffic (800 and 1000 packets/second). The effectiveness of DATA rate selection gives PRAS-CP its superior performance over Correlative. IEEE 802.11 showed throughput limitations for two main reasons: high rate of RTS collision and low spatial reuse (exposed terminal problem) since all packets are sent at maximum power. When traffic load increases (400, 800, 1000 packets/second), more nodes will contend to win the channel, thus the collision rate for the RTS packet increases, which affects the overall collision rate as can be verified in Figure 4.3.

BASIC suffers severely from hidden nodes; in BASIC, DATA and ACK packets are sent at the minimum required power whereas the RTS/CTS of other communicating nodes are sent at maximum power. This increases the interference range of the DATA/ACK packet receiver and thus the probability of the DATA/ACK collision, which can be verified from Figure 4.3. Moreover, transmitting the RTS/CTS at maximum power will unnecessarily suppress neighbor communication and decrease the throughput. Adaptive shows better throughput than IEEE 802.11 and BASIC due to the fact that DATA and ACK are well protected in these schemes, nevertheless the RTS and most of the instances the CTS packet is sent at maximum power, which has reduced the spatial reuse. Moreover, the assignment of the DATA power value in Adaptive is done on the assumption that the interfering node always transmits at maximum power, which may not be true in random power-aware topology. Hence, the power value assigned to the DATA packet will be more than the sufficient power to protect its reception and thus this highly impact the spatial reuse. This is why these protocols achieve less throughput than PRAS-CP and Correlative.

Figure 4.4 depicts the energy efficiency in Kbps/Joule per traffic load. As the load increases, more packets are transmitted and accordingly the throughput increases and the energy consumption increases. Here, BASIC suffers from hidden terminals; nevertheless, the energy consumed is shown to be less than the IEEE 802.11 in this scenario due to the minimum power assigned to the DATA packet, which makes its achieved energy efficiency slightly outperform that of the IEEE 802.11 as traffic load increases. In addition to the reasons stated for energy consumption for the chain topology regarding the performance of all the mentioned protocols, it is worth while to mention that the reduction in the mutual interference in a multihop environment makes it feasible for nodes to deliver packets efficiently. As the load increases, more packets tend to be transmitted aggressively, reducing the mutual interference resulting from sending either the control or DATA packets in this case will definitely reduce energy consumption and enhance spatial reuse. Thus, PRAS-CP ought to achieve the higher energy efficiency in this scenario, since PRAS-CP reduces mutual interference through setting constraints on the packet power values.

### Impact of Node Mobility

We study the effect of node mobility on throughput in this subsection. The mobility model adopted is the Random Way Point model. The node's maximum speed is varied from 5 meters per second to 20 meters per sec. The packet rate is 400 packets per second and the number of multihop CBR flows is 10. We can see from Figure 4.5 that mobility impact the aggregate throughput. With the mobility, the source and receiver nodes may not be able to communicate with each other due to the reason that either one of them will be out of range of the other. This may trigger link failures that may occur frequently due to disconnection of adjacent nodes in a route. Routing table entries thus may get stale due to node mobility and may require updating. This will add more congestion on the network. This is the reason why for all protocols, the throughput becomes low when mobility increases.

## 4.4 Conclusion and Future Work

In this chapter, we proposed a distributed transmission power and rate adaptive control scheme with collision prevention (PRAS-CP) for mobile ad hoc networks. Both the transmitter and receiver in MANET environment make use of the PCS and VCS mechanisms to protect the transmission of control and DATA packets. PRAS-CP dynamically adapts transmission power of control and DATA packets. Moreover, PRAS-CP also dynamically adjusts transmission rate for DATA packet depending on channel condition. Thus, PRAS-CP balances spatial reuse and collision prevention. It has been shown by simulation that the proposed power control scheme is efficient in terms of throughput, energy consumption and fairness. We have compared our

PRAS-CP with the IEEE 802.11, BASIC [22], Correlative [18], and Adaptive [33]. Verification of the simulation results with real-life scenario implementation will be a target future work.

# Chapter 5

# Conclusion and Future Directions

## 5.1 Conclusion

In a wireless ad hoc network, the trade-off between spatial reuse and collision avoidance has a tremendous impact on the performance of the network. In this thesis, we have explored the benefits of adjusting several MAC/PHY parameters on the spatial reuse and collision probability in IEEE 802.11 based wireless networks. Accordingly, we proposed two localized mechanisms that enhance the network capacity.

We presented a novel scheme that balances the tradeoff between collision and spatial reuse in multi-hop wireless networks. Using this novel approach, a node dynamically adjusts its $CS_{th}$ to eliminate collisions from hidden terminals and enhances spatial reuse by diminishing the effect of the exposed terminals. At the same time, the proposed approach reduces the collisions from contentions while maintaining the level of transmission attempt probability through carefully selecting CW. Moreover, the RTS/CTS handshake does not silence neighboring nodes but rather only inform them to bound their $CS_{th}$ to yield the on-going transmission. Furthermore, to reduce the overhead from the RTS/CTS handshake, and based on the network performance policy, we proposed a policy wherein a node can adaptively enable/disable the RTS/CTS exchange. Simulation results comparing with other recent methods showed the effectiveness of the proposed method in improving the network performance.

We also proposed a distributed transmission power and rate adaptive control scheme with collision prevention (PRAS-CP) for mobile ad hoc networks. Both the transmitter and receiver in MANET environment make use of the PCS and VCS mechanisms to protect the transmission of control and DATA packets. PRAS-CP dynamically adapts transmission power of control and DATA packets. Moreover, PRAS-CP also dynamically adjusts transmission rate for DATA packet depending on channel condition. Thus, PRAS-CP balances spatial reuse and collision prevention. It has been shown by simulation that the proposed power control scheme is efficient in terms of throughput, energy consumption and fairness.

## 5.2 Future Directions

The work presented in this thesis provided considerable benefits in performance enhancement for wireless ad hoc networks. However, there are still several future directions that can provide additional benefits.

In our loss-differentiation algorithm presented in Chapter 4, we made the assumption that the transmission failures caused by collisions from contenting nodes ($\mathbf{C}$) and collisions from hidden terminals ($\mathbf{H_1}$) are independent. However, this cannot be strictly true, since when collisions from $\mathbf{H_1}$ exist, the contribution of type-$\mathbf{H_2}$ or type-$\mathbf{C}$ collisions to packet loss depends on the number of $\mathbf{H_1}$ collisions. Thus, applying mathematic analysis to further exactly characterize different types of packet loss is one possible extension.

Another future direction is to apply game theory to study the behavior of tuning protocol parameters in wireless ad hoc networks. Because nodes in a wireless ad hoc network decide their channel accesses independently in a selfish behavior, and the channel access of a node has an influence on those of its neighboring nodes, game theory naturally offers certain benefits as a tool to analyze distributed algorithms and protocols for ad hoc networks. Specifically, game theory is an effective tool to investigate the existence, uniqueness, and convergence to a steady state operating point when nodes perform independent adjusting of network parameters (e.g. power, rate and $CS_{th}$). Moreover, game theory can also provide deeper insight into cross layer optimization designs [69]. Therefore, applying game theory to distributed power control and tuning of $CS_{th}$ would be one of our future research directions.

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