A cross-layer payload-dropping scheme for improving CSMA/CA throughput in interference-limited co-channel cells

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**A CROSS-LAYER PAYLOAD-DROPPING
SCHEME FOR IMPROVING CSMA/CA
THROUGHPUT IN INTERFERENCE-LIMITED
CO-CHANNEL CELLS**

**RAYMOND J. JAYABAL
SCHOOL OF COMPUTER ENGINEERING
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RAYMOND J. JAYABAL

School of Computer Engineering

A thesis submitted to the Nanyang Technological University
in fulfilment of the requirement for the degree of
Doctor of Philosophy

2013

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This research work has been a marathon that has nearly completely taken the wind out of me, but I'm glad I'm finally here at this section of this thesis that I've kept for last. A lot of people have helped motivate me to complete it, and I would like to forward them words of appreciation here.

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List of Acronyms

ACK	Acknowledgement
AP	Access Point
BEB	Binary Exponential Backoff
BER	Bit Error Rate
BRAM	Broadcast Recognizing Access Method
CCA	Clear Channel Assessment
CCI	Co-Channel Interference
CID	Cell Identifier (refer Section 3.2)
CSMA	Carrier-Sense Multiple Access
CSMA/CA	CSMA with Collision Avoidance
CST	Carrier-Sensing Threshold
CTS	Clear-To-Send
DCF	Distributed Coordination Function
DIFS	DCF Interframe Spacing
DS	Data-Sending Frame
DTMC	Discrete-Time Markov Chain
ED	Energy Detection
EIFS	Extended Interframe Spacing

FAF	Floor Attenuation Factors
FHSS	Frequency Hopping Spread-Spectrum
FER	Frame Error Rate
IR	Infra-Red
MAC	Medium Access Control
LLAP	LocalTalk Link Access Protocol
LOS	Line Of Sight
NACK	Negative Acknowledgement
PAF	Partition Attenuation Factors
PCF	Point Coordination Function
PD-CSMA/CA	Payload-Dropping CSMA/CA (refer Section 1.2)
PD-DCF	Payload-Dropping DCF (refer Section 3.5.1)
PHY	Physical Layer
PMF	Probability Mass Function
RF	Radio Frequency
RR	Round Robin
RO	Random Order
RCPI	Received Channel Power Index
RSSI	Received Signal Strength Index
RTS	Request-To-Send
SIF	Short Interframe Space
SINR	Signal to Interference/Noise Ratio
STA	Station
T-R	Transmitter-Receiver
TDMA	Time Division Multiple Access

TPC	Transmit Power Control
UDP	User Datagram Protocol
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network

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Abstract

Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is still the de facto contention-based Medium Access Control (MAC) protocol in many of today's Wireless Local (WLAN) and Personal Area Network (WPAN) standards such as the IEEE 802.11a/b/g/n/ad, IEEE 802.15.3, IEEE 802.15.4, and ECMA 387. While CSMA/CA is efficient in single cell scenarios, in multi-cell scenarios it suffers a severe MAC-level co-channel interference problem which affects its spatial reusability. Known as the exposed node problem, it prevents nodes in different cells within carrier-sensing range from sharing a channel even though the cells are interference-limited.

To mitigate this problem, many schemes have been proposed, of which schemes combining carrier sensing threshold (CST) and transmit power control (TPC) stand out in terms of practicality. Unfortunately, such schemes require features that may not be available in simpler transceivers. Also, for CST to work, transceivers must use a carrier-sensing mode that can lead to poor detection rates especially for wideband signals.

In this thesis, we propose an alternative scheme to overcome this issue: the Payload-Dropping CSMA/CA (PD-CSMA/CA). This special variant of the CSMA/CA protocol incorporates a MAC/PHY cross-layer mechanism which aborts the reception of the payload portions of frames from co-channel cells in interference-limited multi-cell deployments, based on a cell identifier embedded in the frame's header. For transceivers

which do not support CST, PD-CSMA/CA adequately mitigates the exposed node problem, thereby allowing nodes to enjoy nearly the maximum throughput as provided by CSMA/CA in the single cell scenario.

To evaluate this new scheme, we incorporated it into the IEEE 802.11's CSMA/CA protocol and tested its performance in three different indoor spatial re-use scenarios using the ns-2 simulator. From the simulation results, it can be seen that in deployments where either cell spacings or partitions are used to limit the co-channel interference, better throughputs are achieved when PD-CSMA/CA is used instead of CSMA/CA. The results also show that, under exactly the same deployment scenario and propagation environment, and using exactly the same TPC and CST settings, the throughput for PD-CSMA is more than the throughput for CSMA/CA, and the increase in the throughput for PD-CSMA/CA is larger than the increase of the throughput for CSMA/CA as the fade margin (employed to combat lognormal shadowing) for both protocols is increased in equal amount.

We also developed analytical formulations for the throughput of PD-CSMA/CA in two co-channel interference-limited cells using the Markov chain modeling approach. For comparison, the throughput model for CSMA/CA in the same setup was also developed. Compared to simulations results, these models are very accurate. Although limited to the fixed frame size and fixed contention window case, these models shed light on the throughput trends of PD-CSMA/CA with respect to the contention window length, number of nodes and header to frame length ratio of transmitted frames, and demonstrates its throughput gains over normal CSMA/CA theoretically.

As a by-product of the effort to develop the analytical model for PD-CSMA/CA, we also developed formulations for the idle period distribution of single-cell CSMA/CA. This model passed the Pearson's Chi-squared test for a wide range of contention window

sizes and numbers of nodes. Although limited to fixed contention windows, we feel it is an important first step towards developing a more general expression for CSMA/CA with exponentially increasing windows.

1 Introduction

1.1 Background & Motivation

Many of today's Wireless Local (WLAN) and Personal (WPAN) Area Network radio standards such as the IEEE 802.11 [1], 802.15.3 [2] and 802.15.4 [3] rely on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [4-7] as their asynchronous Medium Access Control (MAC) method. As its name implies, CSMA/CA uses carrier-sensing to detect whether the channel is busy with transmissions from other nodes before attempting a transmission. After a successful transmission, a node with a new frame to transmit initializes a counter with a random value w which falls within a certain fixed range, $[0, W_0 - 1]$, where W_0 is known as the contention window size. The value of this counter signifies the number of idle slots it must wait, or backoff, before transmitting. The node then proceeds to sense the channel at each slot, decrementing its backoff counter for each slot in which the channel is idle. If the channel is idle throughout w slots, its counter value will have been decremented to zero, and the node will thus transmit right after the end of the last idle slot. If the channel is sensed busy at any slot within the required backoff period of w slots, the backoff process is suspended, and resumed later when the channel is sensed idle again.

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Figure 1.1: CSMA/CA Transmission Pattern for Two Nodes in a Single Cell.

A basic embodiment of this mechanism is illustrated in Fig 1.1 for two nodes in a single cell. Here, nodes A0 and A1 are assumed to be having at least one frame in their queues to be transmitted at all times. The sequence is shown starting with A1 having nearly completed a transmission, and A0 having suspended its backoff counter at the value '5' while A1's transmission was ongoing.

On completing its transmission, A1 reinitializes its counter randomly. Here, it is assumed that A1 obtains '4' as the new value for its backoff counter. Both A0 and A1 decrement their counters for every slot after the end of A1's transmission in which they sense the channel to be idle. Since A1 has a smaller counter value than A0, it transmits again after 4 idle slots. As A1 transmits, A0 suspends its counter again, this time at the value '1'. Since only A1 is transmitting at this point, the transmission is successful.

After A1 completes this second transmission, A1 randomly obtains '1' as its new backoff counter value, and starts counting it down. Meanwhile, A0 resumes its count down also at the value '1'. Since both counter values are the same, they both transmit after one idle slot, resulting in a collision.

While CSMA/CA is efficient in single cell scenarios, in multi-cell scenarios it suffers a serious MAC-level Co-Channel Interference (CCI) problem which affects its spatial reusability. Known as the exposed node problem [8], it prevents nodes in different cells within carrier-sensing range from sharing a channel even though the cells are interference-limited (i.e., path-loss separating them is enough to ensure that a singular

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transmission in one cell is received correctly in that cell even if nodes in other cells are transmitting concurrently).

To understand the exposed node problem and how it affects spatial throughput, we consider a simple scenario depicted in Fig 1.2. Here, nodes A0 and A1 are transmitting to each other in cell A; likewise, B0 and B1 in cell B. Due to proximity, frames from A0 are received by A1 at a very good power level of -37 dBm and vice versa. Likewise, B0 frames are also received at the same level by B1 and vice versa. Both pairs of nodes are also not far away from each other, so frames from A0 and A1 can also be sensed and received by B0 and B1 at the level of -68 dBm; vice versa from B0 and B1 to A0 and A1.

Now, if the minimum multi-user Signal to Interference/ Noise Ratio (SINR) needed by the Physical Layer (PHY) transceiver for successful reception of frames is 20 dB, both pairs of nodes should be allowed to freely transmit as if they are in isolation, since they would receive their partner nodes' frames with a SINR of at least 31 dB. That being the case, the resulting transmission pattern would be as shown in Fig 1.3. Unfortunately, in practice, that may not be the case as signals from the neighboring nodes can cause suspension of transmission. What we have instead is the transmission pattern shown in Fig 1.4, whereby a transmission between one pair causes the other pair to be in the

Figure 1.2: A Simple Exposed Node Scenario

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Figure 1.3: CSMA/CA Transmission Pattern for Two Isolated Pairs of Nodes.

exposed state, and thus blocked from using the channel. This exposed state is due to the latter pair of nodes suspending their backoff processes after incorrectly assessing that their cell's spatially reused channel is busy, and proceeding to receive and decode the transmitted frame in full. Since this frame is transmitted between the former pair of nodes, it is subsequently discarded by the latter pair. Channel reuse in this case can only take place when transmissions in both cells start in exactly the same backoff slot.

In Table 1.1, we compare the theoretical per-cell normalized throughputs for the two node-pairs in the isolated and exposed node condition, over a range of contention window sizes. Here, IEEE 802.11b [1] slot, preamble, header and payload timings are assumed,

Figure 1.4: CSMA/CA Transmission Pattern for Two Exposed Pairs of Nodes.

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Table 1.1: Comparison of Normalized Throughputs for Two Isolated and Exposed Node Pairs (Based on IEEE 802.11b 11Mbps Transmission Timings for 1500-Byte Payloads)

W_0	Isolated	Exposed	Loss
2	0.43	0.33	23%
4	0.64	0.45	30%
8	0.73	0.46	37%
16	0.75	0.43	43%
32	0.71	0.41	42%

and the frame payload size is fixed at 1500 bytes. Both throughputs are determined using analytical models which we will describe in Chapter 5. From this table, it can be seen that the losses in throughput due to the exposed condition are quite large (e.g., 43% for $W_0 = 16$).

To overcome this throughput degradation, two approaches stand out in terms of practicality. The first and perhaps the simplest is to use different preambles for different cells [9]. However, the number of available orthogonal patterns for a given preamble scheme may be limited, especially for short preamble patterns used in simpler radio protocols. This would limit the number of co-channel cells that can be placed within carrier-sensing distance of one another. For example, the 11-bit Barker code used in the IEEE 802.11b physical transceiver has only 2 orthogonal patterns [1].

The second is to use carrier sensing threshold (CST) control, where a threshold is applied to PHY's carrier-sensing circuitry such that any signal with a power level below it is not sensed. Coupled with transmit power control (TPC) schemes to ensure that cells are interference-limited, signals from co-channel cells could be prevented from being sensed at all [10-24]. As a result, the CSMA/CA mechanism in interference-limited cells can operate as if the cells are isolated. However, for this approach to work, the PHY transceiver must operate in a carrier-sensing mode where the power level for incoming signals measured over a fraction of the idle slot duration is used as the main criteria for

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deciding whether the channel is busy or idle. Due to measurement inaccuracies and signal power fluctuations over such a small period of time, this approach may badly affect frame missed detection and false alarm rates, especially for wideband signals [25, 26].

Considering the limitations and disadvantages of these two approaches, we propose a new approach – the Payload-Dropping CSMA/CA (PD-CSMA/CA) protocol.

1.2 PD-CSMA/CA

The PD-CSMA/CA protocol is similar to CSMA/CA in all aspects except one: in PD-CSMA/CA, nodes in one cell drop the payload portion of frames transmitted by nodes in co-channel cells if the cells are determined to be interference-limited. By dropping the payload portion of frames from the co-channel interference-limited cells, the CSMA/CA protocol is allowed to resume its contention process during the time that would have otherwise been wasted in receiving the payload of frames which would eventually be discarded anyway (since the frames originate and are destined for nodes in other cells). As a result, the length of periods when the protocol spends in the exposed state is greatly reduced.

PD-CSMA/CA also does not depend on power level of signals for carrier-sensing. Rather, it depends on just preamble detection. As such, it does not suffer the bad frame missed detection and false alarm rates that the CST-based approach can cause [25, 26]. Also, like a typical packet radio protocol, it uses only one preamble pattern and thus will not have the problem of not having enough preamble patterns to use in different cells.

Fig. 1.5 illustrates the basic concept of the operation of the PD-CSMA/CA protocol in two exposed pairs of nodes. As in Fig 1.3 and 1.4, the sequence begins with B1 having the smallest backoff counter value. As such, B1 is first to transmit. Since A0, A1 and B0 are in backoff mode performing carrier-sensing during this time, they all receive B1's

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Figure 1.5: Transmission Pattern for PD-CSMA/CA Between Two-Interference Limited Pairs of Nodes.

preamble and header transmission (annotated as just 'header' in the diagram to avoid clutter) and subsequently suspend their backoff processes. Unlike in CSMA/CA however (Fig. 1.4), at the end of the preamble and header transmission by B1, A0 and A1 resume their backoff, whereas B0 continue to receive B1's payload transmission.

Since A1 is allowed to continue its backoff process, it proceeds to transmit a frame even while B1's payload transmission is not finished. As A1 transmits, A0 suspends its backoff process while it receives this transmission in full. Meanwhile, after B1's payload transmission has ended, both B0 and B1 are able to resume their backoff process even though A1's payload transmission is ongoing, since their carrier-sensing process, which is based on preamble detection, would not detect A1's payload transmission.

To facilitate the payload-dropping decision and execution, the following five requirements must be observed:

- The PHY preamble or header of the frame must contain information which can be used to identify the co-channel cell which the transmitter of the frame belongs to.

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- There must be a means for MAC to instruct PHY to drop the payload of frames with a given cell identification information. This could be a direct command primitive from MAC to PHY to immediately abort an ongoing frame reception, or a configuration primitive to filter or admit the payload of all frames with the configured cell identification information.
- Measurements have to be carried by the nodes within each cell to determine whether the co-channel cells are indeed interference-limited, i.e., the maximum received power of the cumulative signals from neighboring cells is below the minimum received power of any singular signal in the cell by at least the minimum SINR required by PHY for successful frame reception. These measurements can be the Received Signal Strength Index (RSSI) or Received Channel Power Index (RCPI) typically performed by PHY over the preamble of frames. Alternatively the frame retransmission or failure statistics typically recorded by MAC may be used to infer this interference-limited condition.
- The access point or controlling node for the cell must convey to the other nodes in its cell a threshold or a set of threshold values for determining if a co-channel cell is interfering (i.e., maximum received preamble power for external signals, maximum retransmission limit, etc.)
- Once a node has determined that a co-channel cell is interfering or not interfering, it should transmit this information to all other nodes, so that other nodes will also enable or disable their payload dropping mechanism accordingly.

The actual way in which these conceptual requirements are designed and implemented is left to implementers' discretion, and it may vary from one CSMA/CA system to another depending on what features are available in that system (e.g., what kind of PHY

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and MAC measurements are available for the decision process, or what kind of signaling mechanisms can be used for spreading information). As an example, in Chapter 3, we describe how these requirements can be designed and implemented for the IEEE 802.11 standard [1].

1.3 Contributions

The main thrust of our research was to develop and verify the performance of our proposed PD-CSMA/CA protocol. To this end, we designed a way to incorporate it into the IEEE 802.11 standard [1]. The designs were then implemented on the ns-2 network simulation platform [27] and tested under three different indoor spatial re-use scenarios. From the simulation results, we were able to determine how much throughput improvement the proposed protocol yielded over the original CSMA/CA protocol described in that standard, when fixed transmit powers were used. The results obtained also show that PD-CSMA/CA could serve as a viable replacement to simple, open loop TPC and CST schemes. In addition, it was also shown that the addition of PD-CSMA/CA also improves the throughput for CSMA/CA with TPC and/or CST schemes, especially when such schemes incorporate a fade margin to compensate for lognormal shadowing. In all cases, the throughput improvements were obtained without significantly degrading the frame transmission retry or failure rates or the bandwidth fairness between nodes. These findings form our first contribution in this thesis.

Having determined through simulation that PD-CSMA/CA is viable, we then attempted to analytically model the performance of PD-CSMA/CA in interference-limited scenarios, with a goal to make the model applicable for any number of co-channel cells. Due to the complexity of the problem however, we could only come up with a model that only worked for two interference-limited cells. Nonetheless, the model we developed was

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very accurate when compared with simulation results. Just as Bianchi's [28, 29] and Hu et al.'s [30] analytical models allow the throughput of CSMA/CA in a single cell to be determined without simulation, we can now use our model to determine the throughput of PD-CSMA/CA in two cells, albeit for fixed contention windows. While developing and verifying this analytical model, some additional insights were also gained regarding the behavior of PD-CSMA/CA, such as how it tends to force the transmissions in the two cells to stagger and thus reduce further the likelihood of the occurrence of exposed states. For comparison, the throughput model for the original CSMA/CA in the same two-cell scenario was also developed. These models are not available in the literature, and thus form our second contribution.

Our third contribution comes from solving an analytical problem which we encountered while attempting to model PD-CSMA/CA: the mathematical expression for the idle period distribution of CSMA/CA in a single cell. This problem turned out to be as challenging (if not more) as the modeling of PD-CSMA/CA itself. Since this distribution was needed in our PD-CSMA/CA throughput model, we could not avoid studying it. Eventually, we came up with a model which was accurate enough to pass the Pearson's Chi-squared goodness-of-fit test for a wide range of contention window sizes and number of nodes. For small contention window sizes and numbers of nodes, the accuracy of our model is a distinct improvement over existing models. The model however is limited to fixed contention windows. Nonetheless, it forms the first step towards a more general expression for CSMA/CA with exponentially increasing windows.

1.4 Thesis Outline

The rest of this thesis is organized as follows. In Chapter 2, we review related works. These include:

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- Some basic information regarding the CSMA/CA protocol.
- Various schemes that have been proposed to improve the spatial reusability of CSMA/CA.
- Analytical models for CSMA/CA in single and multi-cell scenarios, and also under PHY-MAC cross-layer effects that have some similarities with the effects observed in PD-CSMA/CA.

In Chapter 3, we present our proposed method for incorporating PD-CSMA/CA into the IEEE 802.11 standard, and simulation results to demonstrate the throughput improvements it yields over the original CSMA/CA protocol.

In Chapter 4, we present our method for deriving the analytical model of CSMA/CA's idle period distribution, comparisons with simulation results and existing methods, and Chi-square test results to demonstrate its accuracy. This distribution is used subsequently in our analytical throughput model of PD-CSMA/CA.

In Chapter 5, we present our method for deriving the throughput model of PD-CSMA/CA for two interference-limited cells, and comparisons with simulation results to demonstrate its accuracy.

Finally, in Chapter 6, we conclude the thesis with a summary and suggestions for future work.

2 Literature Review

In this chapter, we review historical information and related research contributions regarding CSMA/CA and its spatial reuse, providing our own interpretation of the information and how they relate to each other.

2.1 CSMA/CA

CSMA/CA has been adopted by a wide range of wired and wireless LAN and PAN standards, the earliest of which being AppleTalk for RS-422 LAN networking [6, 7] which was released in 1985, and the latest, International Telecommunication Union's Standardization's (ITU) G.hn standard for power line communications [31] released in 2010. It belongs to a class of decentralized, random multiple-access protocols that were originally developed for packet radio networks [32-34]. In packet radio networks, nodes transmit on a shared channel using an uncoordinated or minimally coordinated contention-based technique. Each transmission is typically a short burst of data that is prefixed with a preamble to allow receivers to detect the transmission and obtain symbol synchronization. The biggest advantage of a packet radio protocol is that, unlike Time-Division Multiple-Access (TDMA) protocols where the channel time is divided among nodes, nodes do not have to wait for their turns to transmit. Because of this, packet radio protocols are able to serve a large number of nodes with small access delay when the

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traffic load is small. The biggest disadvantage it has is collisions due to simultaneous transmissions from multiple nodes, which typically results in garbled or undetected transmissions, and nodes having to retransmit frames that are not received correctly. With increasing traffic load, the probability of collisions gets higher, resulting in much worse throughput performance than TDMA protocols.

In the early days of packet radio protocols research, efforts were mainly focused on reducing collisions. Two important features of CSMA/CA which address this issue is ‘carrier sensing’ and ‘collision avoidance’.

2.1.1 Carrier Sensing

Carrier sensing was first introduced in the slotted and unslotted non-persistent and p -persistent CSMA protocols devised by Kleinrock et al. [35]. Prior to this, the two main protocols for packet radio networks were Abramson’s ALOHA [36] and slotted-ALOHA [37, 38].

Carrier-sensing differentiates CSMA from the ALOHA protocols as follows: In CSMA, nodes listen to the channel for a short period of time before attempting a transmission. By listening to the channel, nodes can determine if the channel is busy with other nodes’ transmissions, and can thus defer its transmission until the channel is idle to avoid collision with ongoing transmissions.

In pure-ALOHA, a node transmits immediately without listening to the channel when there is a frame to be transmitted. In order for the transmission to not collide, any previous transmission must already have concluded, and no new transmission should start before this transmission ends. If all transmissions are fixed for duration T , this means that no other node must transmit within a period $2T$ centered at the start of this transmission. This period of $2T$ is also known as the ‘vulnerable period’ for the protocol. The larger this

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period is, the lower the effective throughput since more transmissions will collide. Assuming a Poisson arrival process with mean rate of λ for both new transmissions and retransmissions (due to collision), Abramson showed in [36] that the normalized throughput (also known as the channel utilization rate), S , for ALOHA is,

$$S = \lambda e^{-2\lambda} \quad (2.1)$$

Based on the above equation, the peak throughput for ALOHA can be shown to be 0.184. This indicates poor channel utilization as over 80% of the channel time is wasted.

With slotted-ALOHA, transmissions are only allowed to occur in fixed time slots of the same duration as the transmission period, to which all nodes in the network are synchronized. Since any previous transmission would have concluded before the start of a new transmission in this case, the vulnerable period is reduced to T . Accordingly, the throughput for slotted-ALOHA is larger, as shown by Robertson in [37]:

$$S = \lambda e^{-\lambda} \quad (2.2)$$

Based on the above the equation, the peak throughput for slotted-ALOHA can be shown to be 0.368. While this is twice of ALOHA's throughput, it still indicates a poor utilization rate since over 50% of the channel time is wasted.

With the carrier sensing feature in CSMA, this vulnerable period is reduced tremendously to just the short time it takes to sense the state of the channel. This short time is also known as the backoff or idle slot period. If we express this slot period, σ , as a fraction of the fixed transmission duration, then the normalized throughput for the slotted non-persistent CSMA protocol is shown by Kleinrock et al. in [35] to be:

$$S = \frac{\sigma \lambda e^{-\alpha \lambda}}{(1 - e^{-\alpha \lambda}) + \sigma} \quad (2.3)$$

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Here, σ includes both the propagation delay of the channel, and the time it takes a receiving node to detect a transmission once it arrives at its antenna. Assuming $\sigma = 0.01$ (i.e. 1% of the transmission period), it can be worked out from the above equation that the peak throughput for slotted non-persistent CSMA is 0.857. This is a large improvement over slotted-ALOHA's throughput. More importantly, since the channel utilization is nearer to the ideal value of 100%, it shows that, with the aid of carrier sensing, CSMA is able to make use of the channel time quite efficiently.

In real systems, the duration of the backoff slot period, as well as the nature of how carrier sensing is performed, is PHY-specific. For example, in AppleTalk's LocalTalk Link Access Protocol (LLAP) [6, 7] which was designed for wired networking of Mac computers, the backoff slot period is 100 μ s, and carrier sensing is facilitated by flag bytes at the start and at the end of the frame, as well as by polling bit registers provided by the RS-422 chip which acts as the PHY for that standard. One of these bits is set when the chip searches for the next frame, and is cleared when it is in the process of receiving a frame. A synchronization pulse is also sent before frames, which the RS-422 hardware can detect as a 'missed clock' event and signal through another bit register. This 'missed-clock' event provides a faster way for LLAP to detect the start of a transmission.

In WLAN systems such as the IEEE 802.11 [1] and the IEEE 802.15.4 [3], carrier sensing is generally implemented in one of 5 modes [39]:

- Mode 1: In this mode, PHY indicates that the channel is busy if the received signal energy goes above a factory-configured threshold known as the Energy Detection (ED) threshold.
- Mode 2: In this mode, the preamble correlation sum is used. If it goes above a certain threshold designed for optimal missed / false detection rates, then the busy condition is signaled.

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- Mode 3: In this mode, a combination of Mode 1 and Mode 2 is used, i.e., both the preamble correlation and energy detection thresholds must be breached before the busy condition is signaled.
- Mode 4: This mode is similar to Mode 2, except that upon detecting a preamble, a guard period corresponding to the duration of the longest possible frame is applied. During this period, if PHY does not receive a valid frame or if the frame header is corrupted, the busy condition is maintained throughout the guard period.
- Mode 5: This mode is a combination of modes 1 and 4.

In all modes, PHY decodes the frame duration from the header of the frame and maintains the channel busy status for only the duration of the frame. The backoff slot period for the IEEE 802.11 ranges from $5\mu\text{s}$ for the millimeter-wave PHY [40] to $50\mu\text{s}$ for the Frequency Hopping Spread-Spectrum (FHSS) PHY [1].

2.1.2 Collision Avoidance

The second important feature of CSMA/CA is ‘collision avoidance’. According to [33], collision avoidance was initially mooted by Chlamtac et al. in [4] and Kleinrock et al. in [5]. It refers to the decentralized scheduling method in which nodes defer their subsequent transmissions or retransmissions upon sensing an ongoing transmission, or upon detecting that a collision had occurred.

This feature was added to CSMA to make it possible for certain nodes to have higher priority in accessing the channel. Since fair scheduling is desired (i.e., nodes to fairly take turns to transmit), typically, priority is accorded to the node that has been deferring its transmission for the longest time. The addition of this feature to CSMA results in two performance improvements: Firstly, the maximum access delay experienced by any node

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is reduced. Secondly, since certain nodes (e.g., the nodes that have waited the longest in the case fair scheduling) have higher priority in accessing the channel, the chances of collision occurring when the node eventually transmits, is also reduced.

These two improvements are especially useful in dealing with high collision rates and long access delays in CSMA when the traffic load is high and the number of nodes in the network is large. This is because, in CSMA, after sensing a clear channel, all nodes will attempt to transmit with equal probability (e.g., p in the case of p -persistent CSMA, or the arrival probability used to model the new and retransmitted traffic, in the case of non-persistent CSMA). Obviously, if the number of nodes is high (in the case of p -persistent CSMA) or if the traffic arrival rate is high (in the case of non-persistent CSMA, if each arrived frame is assumed to have arrived at different nodes in the network), then it can be shown mathematically that the chance of collision is high. Also, since the probability of a node transmitting a frame doesn't change despite the number of times it has deferred transmitting it, statistically, the node may find itself indefinitely not able to transmit it. Collision avoidance deals with these two issues concurrently by causing the transmit probability to increase with the length of time the node has deferred its transmission.

It should be noted that the collision avoidance techniques proposed by Chlamtac et al. [4] and Kleinrock et al. [5] were deterministic and completely collision-free. In Chlamtac et al.'s Broadcast Recognizing Access Method (BRAM) for example, the backoff function in each node was defined as,

$$B(n, n_0) = \begin{cases} (n - n_{tx} + N) \bmod N & n \neq n_{tx} \\ N & n = n_{tx} \end{cases} \quad (2.4)$$

Here, B is the number of backoff slots following the last transmission that the node must sense idle before beginning its own transmission, n is a index assigned to the node that is unique within the network, and n_{tx} is the index of the node which last transmitted.

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It should be easy to work out from this equation that the node with the index just one larger than the index of the last transmitting node would end up being the next to transmit. If the traffic load distributed among the nodes is even, this would result in the nodes taking turns to transmit and having a bound on the maximum length of time they have to defer a transmission. Also, there is no possibility of collision since the index of each node is unique. The problem with this method however, is that there must be additional signaling to assign unique indices to nodes, and the transmitted frame must contain the index of the transmitting node.

This method is similar to the Round Robin (RR) protocol proposed in Kleinrock et al.'s paper [5]. But in that paper, Kleinrock et al. also proposed three other schemes, out of which the Random Order (RO) protocol is of special historical interest to us. In this scheme, the number of backoff slots each node must wait after a transmission is randomly generated within the range $[1, N]$, subject to the condition that the same number is not generated in any two nodes. Obviously, this uniqueness condition, while guaranteeing the system to be collision-free, poses an implementation issue since it would require the transmitting node to generate the assignments and imbed it into its transmitted frame, or the assignment to be centrally communicated or agreed upon through different means. Also, since the order is arbitrarily assigned, the priority to transmit is not accorded to the node which has deferred the longest.

Nonetheless, most real-life implementations of CSMA/CA have similar collision avoidance schemes as RO, either by derivation or coincidence. But the uniqueness requirement is discarded in favor of a totally random approach, even though the collision-free feature is sacrificed in the process. In AppleTalk's LLAP [6, 7] for example, the number of backoff slots a node must wait after the last transmission is a random value generated from the range $[0, 2^{(bg+bl)} - 1]$, where bg is the global backoff stage and bl is the

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local stage increment. bg takes a value between $[0,4]$. On startup, it takes the value 0. Subsequently it is adjusted on the fly based on the number of times the node had encountered collision or had had to defer transmission due to finding the channel busy. If within the last 8 transmission attempts, the node encountered more than 2 collisions or deferrals, then the backoff stage is increased by 1. If it is below 2, then it is decremented by 1. bl is set to 0 for each new transmission, and is incremented every subsequent retransmission.

In the IEEE 802.11 [1], IEEE 802.15.3 [2] and the ECMA-387 [41], the scheme used is similar to AppleTalk's CSMA/CA, except that the global backoff stage is fixed. Here, backoff counter value is selected randomly from the range $[0, 2^b.(CW_{min}+1) - 1]$ at the start of a new transmission, where CW_{min} is the minimum backoff window, while b is the backoff stage. CW_{min} , like all other parameters so far described, is PHY-dependent, e.g., for FHSS PHY $CW_{min} = 15$, whereas for IR PHY $CW_{min} = 63$. Like LLAP's case, the backoff stage b is incremented after each collision, up until the value of $(2^b.(CW_{min}+1) - 1)$ equals 1023. Unlike LLAP's case however, the backoff value counter is not renewed when the transmission is deferred. Rather, it is frozen or suspended until the ongoing transmission is ended, and is used for the subsequent attempt to access the channel. In this way, the priority to transmit slowly shifts towards the node that has deferred transmitting the most times. This is in keeping with the BRAM or RR protocol in making sure nodes have a bounded deferment period, although albeit in a statistical manner.

In the examples given in the last two paragraphs, the backoff stage is incremented every time a collision occurs, resulting in a doubling of the backoff window since the base number for the exponent is 2. This scheme is normally referred to the Binary Exponential Backoff (BEB) algorithm. In [42], Song et al. showed that as the number of nodes in a network under saturation throughput approaches infinity, doubling the window

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in such manner would result in a maximum collision-free transmission rate that is close to the optimal (which is achieved when the base number is $1/(1 - e^{-1})$). However, BEB is not necessarily the best scheme in all conditions. In our analytical models for the idle period of CSMA/CA and the throughput of PD-CSMA, we use a fixed backoff window scheme. When the number of nodes is small, keeping the backoff window constant regardless of the number of collisions may actually yield better performance. In [43, 44] for example, Chen et al. showed that a fixed backoff window scheme actually yields better throughput and delay characteristics than BEB, for 15 to 30 nodes under all traffic load conditions. A similar conclusion was obtained by Qiao et al. in [45].

2.1.3 Virtual Collision Detection

Virtual collision detection is an important aspect of not only CSMA/CA, but in packet radio protocols in general. This is because in some PHY subsystems, it is not possible to listen while transmitting to determine if the transmission will be received with success at its intended destination. While this is typically true for the wireless PHY, this situation may also apply to the wired PHY such as the PHY for RS-422 running in half-duplex mode used in AppleTalk LocalTalk [6]. Few common handshaking schemes for this are:

- Data frame (DATA) - Positive (ACK) or Negative (NACK) acknowledgement handshake (DATA-ACK). In this scheme, short positive or negative acknowledgement frames are sent by the receiving node to indicate successful or failed reception of the data frame, after a short receive-to-transmit turnaround period. To ensure that the transmitting frame receives this ACK/NACK frame, all nodes must wait a fixed guard time which is long enough to allow the ACK frame to be detected, before they can resume contending for the channel.

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- Request-To-Send (RTS) - Clear-To-Send (CTS) handshake before DATA (RTS-CTS-DATA). In this scheme, a short frame is first sent by the transmitting node to announce its intention to transmit a frame. On receiving this frame, its intended recipient (as indicated in the destination address field in the frame), sends a CTS frame after a receiver-to-transmitter turnaround period. When the transmitting node receives the CTS frame, it sends the DATA frame after the same short period. Meanwhile, in between the RTS-CTS and CTS-DATA exchanges, all other nodes in the network wait for guard periods which are long enough to ensure detection of these frames, before they resume contending for the channel.
- RTS-CTS followed by DATA-ACK handshake (RTS-CTS-DATA-ACK). This is a four-way handshaking scheme where RTS/CTS/DATA scheme is followed by a positive or negative ACK frame.
- RTS-CTS-DS-DATA-ACK handshake. This scheme is the same as the RTS-CTS-DATA-ACK scheme, except that before the data frame is transmitted, a short Data-Sending frame is sent by the transmitter to announce the start of the longer DATA frame transmission.

In AppleTalk LLAP [6,7], the RTS-CTS-DATA handshake mechanism is used for collision detection for unicast data. The guard time used between the RTS/CTS and CTS/DATA handshake was 200 μ s. This guard time was later modified by Karn to facilitate virtual carrier sensing in [10]. In Karn's proposal, instead of using a fixed guard time sufficient for detecting the ensuing frames, the RTS frame includes an information field indicating the full duration of the entire RTS-CTS-DATA exchange, while the CTS frame similarly indicates the duration of the CTS-DATA exchange. This allows other nodes overhearing the handshake to denote the entire period spanned by the RTS-CTS-

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DATA exchange as a busy channel period. Karn's scheme for virtual carrier sensing was further extended by Bhargavan et al. [8] into the RTS-CTS-DATA-ACK scheme, and the fourth scheme: RTS-CTS-DS-DATA-ACK. In this fourth scheme, the DS frame is added to prevent a terminal that is hidden from the recipient from resuming contention for the channel upon not hearing the CTS frame sent by the recipient. Note that this scheme was only targeted for PHY transceivers without carrier-sensing abilities.

In IEEE 802.11, two collision detection modes are specified for unicast data transmission: basic access and RTS-CTS. The basic access scheme is mandatory, and it uses the DATA-ACK handshake. The RTS-CTS scheme uses the RTS-CTS-DATA-ACK handshake. All four types of frame are separated by a Short Interframe Space (SIFS) period which ranges from 3 μ s for the millimeter-wave PHY to 28 μ s for the FHSS PHY. For broadcast data transmissions, the data frames are sent without any RTS-CTS or ACK handshake.

In our simulation of PD-CSMA/CA in Chapter 3, we limited ourselves to the use of only the DATA-ACK handshaking approach. We do this not only because we felt it was adequate to demonstrate the improvements using this basic handshake, but also on the back of research information strongly suggesting that the RTS-CTS handshake not only increases overhead, but also aggravates the exposed node problem and adds two more problems: the masked node and false blocking problem [46-49]. In our analytical model of PD-CSMA/CA, we limit ourselves to the broadcast mode, or the assumption that the ACK frame requires negligible transmission time compared to the DATA frame.

2.2 Spatial Reuse Schemes for CSMA/CA

Past works on improving the spatial reuse of CSMA/CA networks have involved one or more of the following approaches:

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- Transmit Power Control (TPC). The basic idea behind this approach is for nodes in each cell to determine and transmit using an optimal power level which is strong enough to ensure reliable reception by recipient nodes in the cell, but weak enough to not interfere with transmissions in other co-channel cells.
- Carrier Sensing Threshold (CST). In this scheme, an optimal energy detection (ED) threshold is determined and set for the nodes. As mentioned in Section 2.1.1 in this chapter, in carrier-sensing modes 1, 3 and 5 of CSMA/CA systems such as the IEEE 802.11 and 802.15.4, the busy channel condition is suppressed for signals that are below the ED threshold.
- Data rate control. Schemes in this category exploit the fact that the SINR requirement for error-free reception of frames are lower for lower transmission rates than it is for higher rates. For example, in the IEEE 802.11b PHY, the minimum SINR requirement for a bit error rate (BER) of 10^{-5} for the 1 Mbps rate is 1 dB, whereas the SINR requirement for the same BER for the 11 Mbps rate is 12 dB [50]. By using this information, it is possible to allow two or more transmissions to take place in parallel, but at a lower transmission rate.
- Interference-Aware Scheduling. In this type of scheme, nodes block, proceed with or modify their contention mechanism based on knowledge of whether or not their transmissions will interfere with the transmissions of other nodes. This knowledge is obtained through estimating the interference level either through RF measurements or MAC level statistics. The PD-CSMA/CA scheme which we propose in this thesis falls in this category.

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2.2.1 Schemes Primarily Using TPC

In terms of TPC, it should be noted that the virtual collision detection scheme proposed by Karn in [10] also featured power control to facilitate spatial reuse. Here, the received power level for the RTS frame is feedback to the transmitter in the CTS frame, so that the transmitting node can adjust its transmit power for the subsequent frames sent to each receiving node. In [11], the RTS-CTS exchange is used to exchange transmit and receive power levels. Using this information, subsequent transmit powers used by the transmitter for the RTS and DATA frames and the receiver for the CTS and ACK frames are adjusted such that the circle encompassing nodes within sensing distance of the transmitter barely envelops the circle encompassing nodes within interference range of the receiver, with their edges touching at one point. In [12], Monks et al. introduced a scheme whereby receivers indicate the level of interference they can tolerate by transmitting power-controlled pulses in a separate busy tone channel, and transmitters adjust their transmit power so as to not disrupt ongoing transmissions through exchanging transmit and receive power information via the RTS-CTS handshake. In [13], Muqattash and Krunz proposed a scheme which is similar to Monk et al.'s. Here, nodes decide their transmit powers to other nodes based on overhearing RTS/CTS exchanges and calculating tolerable interference levels, but without using a separate busy tone channel. Another similar scheme can be found in [14] using two busy tone channels. In [15], Navda et al. reported that when Access Points (APs) in each co-channel cell is allowed to control its transmit power independently of each other, throughput degradation and unfairness occurs. To overcome this problem, they proposed a slotted TPC scheme whereby in each slot, all APs in the network use the same transmit power, and limit their transmissions to nodes in their respective cells that are only within reach of this synchronized transmit power.

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2.2.2 Schemes Primarily Using CST

In terms of CST-only schemes, in [16], Vasan et al. presented an algorithm to dynamically adjust the CST for nodes in 802.11-based hotspots based on observed received signal strength levels. The adjustment is based on the same principle in [11], except that here, the CST is modified instead of the TPC to ensure that the carrier-sensing range circle for the transmitter just barely encompass the interference range circle of the receiver. In [17, 18], Zhu et al. derived carrier-sense thresholds to maximize spatial reuse for common topologies, and introduced an algorithm that dynamically adjusts it to improve spatial reuse based on the received signal strength level and frame error rate (FER). In Deng et al.'s work [19], the CST is tuned based on cost function which encourages throughput and discourages excessive retransmissions. This cost function is specified as $(N_s - cN_d)$, where N_s is the observed throughput in each cell, while N_d is the total load on the medium inclusive of retransmissions. In Park et al.'s proposal [20], a cost function is used similarly, but the trade off is between the increasing transmission rate (due to less exposed nodes) and collision rate (due to transmitting while an interfering transmission is ongoing) of a node as the CST is increased, and the method of solving the cost function is based on game theory. In [21], Fu et al. developed the concept of a safe carrier sensing range taking into consideration that the CST threshold may be breached due to a nearby transmitter-receiver (T-R) pair or a few faraway T-R pairs. According to this work, if existing single-level energy detection threshold is used, then the channel would be deemed busy even though the ongoing transmissions are between faraway T-R pairs. To overcome this problem, they proposed a mechanism in PHY which keeps track of the increments in the energy detection (ED) level profile during the CCA process. The criteria for determining if the channel is busy is then based on comparing the increments rather than the sum of the ED level against the safe carrier-sensing range.

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2.2.3 Schemes Combining TPC, CST and/or Data Rate

Some methods combine TPC with CST [22-24], while some combine TPC and/or CST with rate control [51-57]. In [22], Fuemmeler et al. worked on a joint TPC and CST to reduce collisions. Based on their analysis, nodes should keep the product of their transmit power level and carrier-sense threshold equal to a fixed constant. In [51], Kim et al. proposed a decentralized TPC and data rate control algorithm to sustain high data rates while minimising interference to neighboring transmissions. In [52-54], Yang and Vaidya suggested combined CST and data rate control schemes to limit the interference range of transmissions based on consecutive failures/successes of transmissions. In [56], Akella et al. proposed auto-fallback mechanisms for the transmit power and data rate for over-populated wireless hotspots.

2.2.4 Schemes Using Interference-Aware Scheduling

It should be noted that TPC schemes proposed in [12-15] also include elements of interference-aware scheduling, since transmissions in these schemes may be allowed or disallowed to proceed depending on whether it would affect an ongoing transmission, or in the case of [14], cause asymmetric links to surface.

In [58], Cesana et al. proposed that stations embed information on channel conditions in the RTS/CTS frames so that other nodes can use this information to determine if they can use the reserved time for their own transmissions. In [59], Benveniste proposed that all co-channel cells be synchronized to a superframe structure which include periods where all cells must be free of transmission activity. These ‘global channel release’ periods may start at different times in different cells due to the different ending periods of the last transmission preceeding that period in that cell, but they all end at the same time so as to allow the resumption of the backoff period to be synchronized. With this forced

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periodic inter-cell synchronization of the backoff period, the starvation effect seen on some cells that are straddled between two or more cells is alleviated. In [60], Li et al. proposed a scheme where APs in co-channel cells only use the RTS-CTS handshake when transmitting to nodes at the edge of cells that are in the interfering range of other nodes at the edge of other cells. The nodes in the interference range identify themselves as such to the AP if they are able to overhear significant traffic from other cells. In [61], Nadeem et al. proposed that nodes embed transmit and receiver powers, gains and transmitter and receiver location information into frame headers and determine using in-built propagation models determine if they can transmit in parallel. If they cannot, then the reception of the frame continues. If they can and they have frames to transmit, then the frame reception is stopped and the transmission is initiated. The scheme also requires a priori knowledge of the path loss model for the environment, GPS/RF localisation technology and a special PHY transceiver capable of Message-In-Message reception.

2.3 Analytical Models for CSMA/CA

In Chapters 4 and 5, we present analytical models of the idle period of CSMA/CA in one cell, and throughput of CSMA/CA and PD-CSMA/CA in two cells. In this section, we review analytical modeling works that have been done prior to ours. A large portion of the contributions in this area is based on IEEE 802.11's CSMA/CA, but the analyses are applicable to any CSMA/CA protocol with random backoff using fixed or exponentially increasing contention windows. These works can be categorized as follows.

2.3.1 Ideal Single-Cell Scenario

In this scenario, CSMA/CA in a single cell is modeled under the assumption of an ideal radio environment devoid of real-life effects such noise, path loss and propagation

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delay. Each node in the cell can sense and receive a transmission from any other node in the cells with perfect fidelity if there is no collision. If there is a collision, then all other nodes sensing the channel always detect the channel as busy, and the collided frames are always received in error. When there are no transmissions in the channel, the medium is always sensed as idle. Additionally, frames arrive at all nodes at the same instant as they are transmitted.

In terms of idealistic throughput models, perhaps the most important contribution is Bianchi's discrete-time Markov chain (DTMC) model [28, 29]. In Bianchi's work, the probability that a node suffers a collision is assumed constant and independent of its current backoff stage. Based on this constant collision probability, a Markov chain model for a 2-element state vector (b_s, b_c) of the current backoff stage and backoff count for a node is then developed. The transmission probability of the node is obtained as the sum of the steady-state probabilities for the states $(b_s, 0)$, since the node transmits when its backoff count reaches zero. Using this transmission probability, the average idle period between transmissions and the collision probabilities could be derived, from which, in turn, the throughput is derived. Prior to this method, analytical studies on the protocol were based on the p -persistent model, as contributed by Cali et al. in [62-64] and Ziouva et al. in [65]. In Cali et al.'s model, the average window size for any node is first calculated. Using this average window size, the probability of collision is calculated by considering two or more nodes picking the same slot in the average window. A similar approach can be found in Tay et al.'s work [66].

In Bianchi's model, the back-off counter is decremented right after a busy period is sensed by a node. However, in actual implementation, it is only decremented at the end of the idle slot following the busy period. In [67], Ziouva et al. tried to correct this assumption, but did not take into account that only nodes that had transmitted in the

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previous busy period could start transmitting immediately after that period. Ziouva et al. also introduced a delay model in that work, something which was absent in Bianchi's work. In [68], [69] and [30] the shortcomings in both Bianchi's and Ziouva et al.'s were addressed by Xiao, Foh et al. and Hu et al., respectively. In this thesis, we use Hu et al.'s corrected Markov model as the basis for developing our models. In Xiao's work, the finite retransmission attempt was also considered, from which the frame drop rate, throughput and delay taking it into consideration could be derived. Independently in [70, 71], Chatzimisios et al. also developed a delay model with finite retransmission attempt.

In each of the above models, the traffic load on the cell is assumed to be saturating, i.e., nodes always have their queues full and are ready to transmit the next frame upon successfully transmitting the last one. Since this unlikely to be the case in real life, unsaturated models were then proposed by Foh et al. in [72], Duffy et al. in [73, 74] and Garetto et al. in [75], mainly based on infinite queue length. Foh et al.'s proposal [72] utilized a continuous-time Markov chain single state server queue to model the unsaturated condition, where the state of the queue represents the number of active nodes. Unsaturated traffic in this case is modeled with Poisson arrival process, and delay characteristic is calculated considering that the service time for the frame at the head of the queue is the saturation delay based on Bianchi's model, with the queue length equal to the number of nodes. Duffy et al.'s model [73, 74] was derived by adding an additional row of states $(0, b_c)$ into Bianchi's Markov chain model just before the first row, to account for the case when the node has just transmitted a frame but has none waiting in its queue. From these states, when a frame enters the queue of the node, the next state transitioned to is $(0, b_c - 1)$ which one of the original first row in Bianchi's model.

Other researchers sought to provide distributions rather than just averages or bounds for the performance metrics of CSMA/CA. In [76] by T. Sakurai et al. and [77] by Li et

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al., for example, the access delay distribution is modeled, while in [78] by Bowden et al., the distribution for the idle period is modeled. This latter distribution is of particular interest to us as it plays an important role in how PD-CSMA/CA behaves in a two cell environment. In Chapter 4, we propose our own model for this distribution and compare its accuracy against Bowden et al.'s.

To this date, research on modeling this ideal single-cell scenario is still very much alive, with contributions such as Dong et al.'s in [79] on the collision probability in unsaturated condition, Felemban et al.'s in [80] on a more accurate DTMC model for the throughput and access delay in both saturated and unsaturated traffic condition, and Zhao et al.'s in [81] on the throughput and delay characteristics under unsaturated traffic condition for an arbitrary queue length.

2.3.2 Single Cell with Cross-Layer Effects

Models in the category take into consideration one or more real-life radio channel effects such as noise, path loss and propagation delay. Carrier sensing may not always detect an ongoing transmission with certainty when there is noise, and may also falsely detect the channel as being busy. A singular transmission in the cell may also be received in error due to noise, while collided transmissions may resolve in a frame received without error due to capture facilitated by differences in path loss between nodes. Path loss may also result in nodes not being able to sense each others transmission and thus result in a collision (hidden node condition), or they may sense nodes that are outside the interference range and be blocked from accessing the channel (exposed node condition).

One of the earliest works to emerge in this category is that of Ho et al.'s in [82]. Here, the probability that a node is hidden node is modeled as a constant. Instead of the effect occurring at slot boundaries however, it is assumed to occur at every frame renewal time.

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Interestingly, this model, which predates Bianchi's, also uses a two-dimensional DTMC to model the backoff counter and backoff stage, but only two backoff stages were used. In [83] and [84], the effects of hidden nodes and radio capture were modeled by Zahedi et al. and Chhaya et al. The hidden node effect on a transmission is based on geometric considerations of the positions of hidden nodes relative to the transmit-receive pair (T-R), while the capture effect is based on the geometric distribution of nodes sending frames that are collided relative to the receiving node. Zahedi et al.'s geometric considerations are simpler in that all nodes transmit to the centre of the cell whereas in Chhaya's et al.'s model, T-R pairs can be located anywhere within the cell. In Chhaya et al.'s model, the hidden node effect is more accurately modeled as it also accounts for the fact that the hidden node can transmit at any slot which an ongoing transmission is occupying, and corrupt it. Both works were however based on the p -persistent CSMA model.

In [85-90], methods for injecting frame outage due to noise into Bianchi's DTMC model were proposed. In [85, 86, 89], Hadzi-Velkov et al. and Manshaei et al. directly modified the numerator in the saturation throughput equation based on Bianchi's model to account for some of the successful frames being corrupted by noise, and some of the collided frames actually being successfully received. These two approaches however, fail to take into consideration that frame outage and capture events have an effect of increasing and decreasing the contention window size of a transmitting node. In Chatzimisios et al.'s model [87], the frame error rate (FER) is fed instead into the constant collision probability that is used to denote the state transition probabilities in the DTMC model. In such way, the effect of noise on the contention window is factored in. In [91, 92], Wang et al. used the same approach to incorporate the capture and frame outage effects in transceivers with directional antennae into the DTMC model. The capture and

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frame outage probabilities in Wang et al.'s work was computed based on the geometry of the antenna's gain pattern.

In [93-95], Chong et al. extended the left and right sides of each row of Bianchi's DTMC model with states to account for when a node falsely detects or misses the carrier while backing off. Chong et al.'s work interested us as his DTMC model took into consideration false detection and scenarios where frame transmissions do not coincide. When viewed at first sight, PD-CSMA/CA's transmission pattern (Fig. 1.5) could probably be similarly modeled, where the exposed slots may be dismissed as false detection events. Unfortunately, as promising as it seemed at first sight, we realized we could not use this approach for the following reason: In Chong's DTMC model, the false detection probability is an input into the system, whereas in our system, it is an output characteristic, dependent only on the length of the preamble, payload length and the contention window. Furthermore, a peculiar effect occurs when payload-dropping is engaged, such that the two cells never get exposed to each other at all for long periods of time, with their transmissions appearing as if in cascade of one other (see Fig. 5.2). This displacement effect which is like is the alignment of the spokes on two wheels turning on a same axle at different but very close angular speeds, could not be simply modeled as a case of false preamble detection.

In the end, our analysis evolved to something quite unique in the CSMA/CA spatial reuse research arena: to our knowledge, it is the first which breaks the analysis into preamble and payload - a dramatic departure from all existing work on CSMA/CA.

2.3.3 Multi-Cell Scenario

Models in this category take into consideration the operation of CSMA/CA in two or more co-channel cells or flows when they are at least partially within the sensing range.

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While the mechanics of the single cell CSMA/CA is now quite well illuminated thanks to the contributions described in the previous two sections, the mechanics of CSMA/CA multiple co-channel cell networks is still not clearly understood, owing to the dearth of works in this area. This scarcity of works is understandable, as the system model quickly become intractable as the number of cells increase. Such complex stochastic systems, where the slot-by-slot operations of the CSMA/CA protocol in all cells are interdependent, may well turn out to be impossible to be modeled precisely.

Of the few works that actually attempt to model the multi-cell scenario, we found in most of them that these slot-by-slot interactions such as being exposed, suffering collision, or capture, etc. are abstracted away by broad generalizations regarding how time is shared between the cells, and how reception errors are formed. While such analyses may be suitable for capacity planning, giving capacity/throughput estimates for large scale networks, they are unable to provide insights as to how the CSMA/CA protocol would behave in such conditions. They generally fail to give accurate results when we test their driving principles against smaller, tractable systems such as the 2-cell co-channel interference-limited scenario which we use in Chapter 5 to derive our analytical models of CSMA/CA and PD-CSMA/CA.

Take for example the work by Garcia et al. in [96] which makes use of Chatzimizios et al.'s cross-layer FER model [87] to account for the effects of co-channel interference in very large networks. If we assume the cells are comfortably interference-limited, this FER is negligible. If we set the FER in this model to zero however, the operation in the two cells become as if in two independent cells. This is not correct as it does not model the exposed node condition at all.

In Bonard's model [97, 98], the underlying principle is that the multi-cell area could be divided into regions which are blocked when neighboring regions are transmitting. If we

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apply this model to the two cell scenario, the conclusion we get is that two cells populated by N nodes each has half the throughput of a cell with $2N$ nodes. This is not right as both our CSMA/CA simulation and model in Chapter 5 show.

In [99], Margolis et al. extended the 3-flow problem (also known as the exposed node scenario with two neighbors), to a linear network of arbitrary length. Here a conflict graph was used, where flows are modeled as the vertices and mutually exposed flows are depicted as having an edge between the vertices representing them. Flows that can transmit independently have no edges between the vertices representing them. The state of the system is then defined as the set of independent flows in action. To determine the throughput, a key approximation is made: the system is assumed to spend all of its time in the largest-size states and that all states with smaller number of elements get zero time. As an example, in the 3-flow case, the vertices for the conflict graphs are marked as '1', '2' and '3', and the system switches between the states $\{2\}$ and $\{1, 3\}$. Based on the given approximation, the frequency of state $\{2\}$ is thus zero, while the state $\{1, 3\}$ is constantly occurring. Clearly if we were to apply this analysis to either the two flow scenario depicted in Fig 1.2 or the two cell scenario depicted in Fig. 5.1, the result is a system with two states occurring with equal probability, which translates to each cell or flow having half its isolated throughput.

It should be noted however that the above discussion is not meant to be a critique of the techniques proposed, but rather, just to highlight that most of the works in this category do not paint suitable pictures of how CSMA/CA protocol operates in multi-cell networks at the slot level, and were thus not suitable as starting points for the analyses we present in Chapter 5. After all, Margolis et al.'s model was intended for multi-hop adhoc networks rather than multi-cell networks. The difference in these two categories is that in the former, the exposed or hidden nodes effects are assumed to be occurring between

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individual nodes or flows, whereas in the latter, it is assumed to occur between cells. In the latter, it is typically assumed that due to careful cell planning, these effects do not occur in each cell. Nonetheless, certain concepts used in the models for multi-hop adhoc networks may be used in modeling the multi-cell environment, since each flow can be expanded to a cell. In [100] for example, Panda et al. used the ideas developed by Boorstyn et al. in [101] Garetto et al. in [102] and proposed the use of conflict graphs which are very similar to Margolis et al.'s. In Panda's conflict graphs, cells replace flows for vertices, and the edges are used to indicate cells that are exposed. An important simplifying but valid assumption in Panda's work is that any two cells are either completely exposed or completely hidden mutually, and that not one node in each cell are hidden from another. This assumption is valid because in general, the sensing range is very much larger than the reception range of transmitters. We also use this assumption in the models we develop in Chapter 5. Based on this assumption, Panda et al. then used the two staged method proposed in [102] of first determining the fraction of time each cell is idle, transmitting or exposed (as proposed in [101]), and then using the transmitting time to calculate the inter-cell collision probability, which in turn is used along with the intra-cell collision probability and exposed time fractions to calculate each cell's throughput. It should be noted that in this model, inter-cell collisions are assume to be mutually destructive. In interference-limited cells, these ought to be mutually captured. Because of this aspect, along with the simplifying assumptions on how idle/exposed/transmitting time fractions are shared between the exposed cells, we found it hard to relate to this model.

One work which we were able to relate to and did find quite useful in our modeling endeavor was in [103] by Panda et al. Here, Panda et al. used a 2-element vector state where each element represents how many slots each cell in a two-cell system needs to wait before returning to contention. We started our work on an approach very similar to

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this, but had to discard it because it could not deal with transmissions that are overlapped at more than just coincident. Despite eventually ending up with a different approach, this work gave us some ideas on how the slot-by-slot interactions in our system could be modeled.

3 Performance Evaluation of PD-CSMA/CA-Enhanced IEEE 802.11 DCF

3.1 Overview

The IEEE 802.11 [1] is the de facto standard for indoor wireless local area data networks. In that standard, two types of MAC protocols are specified: Point Coordination Function (PCF) and Distributed Coordination Function (DCF). PCF is a poll-based MAC protocol, whereas DCF is based on CSMA/CA. Most IEEE 802.11 compliant devices implement the DCF protocol as it is mandatory. In the first phase of our research, we focused on implementing and evaluating our proposed PD-CSMA/CA in the context of this latter protocol. As a result, we found a way to do this with the barest minimum of modifications to the protocol's MAC-PHY interface specification, while maintaining backward compatibility with legacy implementations. Based on this modified specifications, we then revised the IEEE 802.11 MAC module on the ns-2 platform [27] and proceeded to evaluate its performance under a few commonly occurring spatial reuse scenarios that we could think of.

The ns-2 is a popular open-source simulation platform that has been used by many researchers to validate their proposed schemes and publish their results. In general, the

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networking research community is receptive to schemes that have been validated on this platform. However, while evaluating our modifications, we found PHY-layer deficiencies that render it not very realistic when simulating the reception of concurrent transmissions in spatial reuse scenarios. To overcome these deficiencies, we also revised the PHY layer in the ns-2 platform.

In this chapter, we provide a full account of the work we did in this regard. In Section 3.2, we describe how we factored PD-CSMA/CA into the IEEE 802.11 DCF without significantly changing its specifications. In Section 3.3, we describe the revisions we made to PHY-layer in the ns-2 platform in order to support realistic simulation of the IEEE 802.11 DCF in spatial reuse scenarios. In Section 3.4, we describe the simulation scenarios used to evaluate its performance, and present the results in Section 3.5. Finally in Section 3.6, we summarize our work and findings.

3.2 Proposed Changes to IEEE 802.11 DCF

The overall approach we used in factoring PD-CSMA/CA into the IEEE 802.11 DCF basic access protocol is to embed a Cell Identifier (CID) field into the header of all transmitted frames. This CID is to be set to the identifier for the cell which the transmitter is associated with. If the cells are interference-limited, the receiver of the frame is to drop the payload of the frame if the CID field in its header is not equal to the CID assigned to the cell it is associated with. If the cells are not interference-limited, then no such action is to take place, and normal CSMA/CA operation is to take place instead.

Based on this rough idea, we then came up with the following list of implementation issues which need to be addressed by our modified IEEE 802.11 DCF:

- ***Cell Identifier Field.*** How is the CID embedded into the frame header?
- ***MAC-PHY Interface.*** How does MAC set and retrieve the CID from the frame

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header, and how does it instruct PHY to drop the payload of the frame if the CID is not that of the current cell?

- **Payload Dropping Criteria.** In what condition should a receiver drop the payload? Also, what happens if the cells are not interference-limited? How should nodes know not to engage PD-CSMA/CA in this case?
- **Backward Compatibility.** How to maintain backward compatibility with nodes not supporting PD-CSMA/CA? In order to make our proposal acceptable, it should not negatively affect the existing implementation base.

The following sections describe the minimum set of changes we came up with to handle the above issues.

3.2.1 Cell Identifier Field

Fig. 3.1 shows the header structure for 802.11b/g radio frames. As it currently stands, 3 bits still remain reserved in the SERVICE field of the header [1]. These three bits are not used in the current IEEE 802.11 protocol. It is reserved for future amendments to the specifications of the protocol. As such, this change imposes zero overhead on the payload

Figure 3.1: Proposed CID Field in the PHY Header

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capacity of the frame. As shown in the figure, we use these bits to carry the CID, with binary numbers 001 to 111 representing different co-channel cells.

In a hexagon-based cellular deployment, each cell is surrounded by 6 other co-channel cells in the first ring, 12 other co-channel cells in the 2nd ring, and so on and forth. Fig. 3.2 illustrates this deployment scheme for the case where the number of different frequencies available to be used in each reuse cluster is 3. If each cell can only detect the transmissions from the 6 cells in its first ring of neighboring co-channel cells, then only 7 (the cell itself plus the 6 cells) different cell identifiers are necessary to ensure that the nodes in each co-channel cell is able to discern whether a transmission is from its own cell or from its neighbors. To represent these 7 cells, only 3 bits are necessary. As such, the 3 bits available would be adequate for this scenario, regardless of how big the deployment is in terms of the total number of cells.

However, if the nodes in each cell can detect transmissions from as far as the nodes in the 2nd ring of neighboring co-channel cells, then the number of different cell identifiers

Figure 3.2: 1st and 2nd Ring Neighbor Co-Channel Cells in a Hexagon-Based Cellular Deployment

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required would be 19 (the cell itself, plus the 6 cells in the first ring and the 12 cells in the second ring). In this case, the minimum number of bits needed to encode the cell identifier would be 5. Since only 3 bits are available, then for this scenario, the total number of co-channel cells deployed for each frequency must be limited to at most, 7. If the number of different frequencies available to be used in each reuse cluster is 3, then the total number of cells that can be deployed at any site is limited to 21 (i.e., 7 reuse clusters, times 3 cells in each cluster). This is also true for the case where each cell is able to detect transmissions from nodes in the co-channel cells beyond the 2nd ring.

The CID of each cell can be easily configured to the node acting as the cell's Access Point (AP) by the site administrator through the wireless network's management software, based on cell planning considerations. This cell's CID is then distributed by the AP to the non-AP nodes (stations, or 'STA' in IEEE 802.11 terminology) in the cell through frames exchanged while they are associating with the AP, or through any frames (e.g. beacon frames) subsequently transmitted by the AP.

Since these bits are by default zeroes for legacy implementations, the binary value '000' is used as an indication that a node either does not support (i.e., a legacy 802.11b/g node) or unable to support (e.g., due to interference from neighboring cells) the PD-CSMA/CA mode of operation.

3.2.2 MAC-PHY Interface

In the IEEE 802.11 standard, MAC interacts with PHY through the following set of service primitives in order to perform carrier-sensing, receive and transmit frames:

- ***PHY-CCARESET.request/confirm***. Used by MAC to instruct PHY to reset and restart its clear channel assessment (CCA).
- ***PHY-CCA.indication***. Sent by PHY to MAC to indicate the channel state.

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Accompanying this primitive is a boolean parameter indicating whether the channel is 'IDLE' or 'BUSY'.

- ***PHY-TXSTART.request/confirm***. Used by MAC to initiate a frame transmission in PHY. Accompanying this primitive is a set of parameters known as the TXVECTOR, which contains information such as the type of preamble to use, the length of the frame and the modulation scheme to be used.
- ***PHY-DATA.request/confirm/indication***. Used by MAC to transfer a byte of the payload to be transmitted to PHY, or by PHY to transfer a byte of the payload received to MAC.
- ***PHY-TXEND.request/confirm***. Used by MAC to signal to PHY the completion of an ongoing frame transmission process.
- ***PHY-RXSTART.indication***. Sent by PHY to MAC right after it has completed reception of the frame's header. Accompanying this primitive is a set of parameters known as the RXVECTOR, which has the same constitution as the TXVECTOR used in the PHY-TXSTART.request primitive.
- ***PHY-RXEND.indication***. Sent by PHY to MAC to indicate the completion of an ongoing frame reception process.

In order to support PD-CSMA/CA, the only changes required to this set of primitives are as follows:

- ***PHY-TXSTART.request***. In addition to the type of preamble, length of frame and modulation scheme, a new 'CID' parameter is added to the TXVECTOR parameter list. This allows MAC to specify the value to be encoded into the CID field in the header of outgoing frames.
- ***PHY-RXSTART.indication***. Similar to PHY-TXSTART.request, a new 'CID' parameter is added to the RXVECTOR parameter list. This allows MAC to obtain

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the value of the CID field in the header of incoming frames.

- PHY-CCARESET.request.*** In addition to resetting and restarting its clear channel assessment (CCA) process, PHY will also abort any ongoing frame reception on receiving this primitive from MAC. This allows MAC to abort the reception of payloads right after receiving a PHY-RXSTART.indication where the CID value in the RXVECTOR parameter list is not the same as the current cell's identifier.

Fig. 3.3 shows the changes in the sequence with which these primitives are exchanged between MAC and PHY during the transmission and reception of a frame. On these diagrams, the changes are highlighted in red. On the transmission side (Fig 3.3(a)) the sequence is virtually unchanged: right after PHY-TXSTART.request is sent, PHY begins transmission of the preamble and header of the frame, filling up the PHY header fields

Figure 3.3: Changes to MAC-PHY Interactions During (a) Transmission and (b) Reception of a Frame

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with the information contained in the TXVECTOR parameter. When PHY is ready to receive the first byte of the payload to be transmitted, it sends PHY-TXSTART.confirm to MAC. Thereafter, MAC sends down the payload byte-by-byte via the PHY-DATA.request/confirm primitives. After the last byte of payload data has been sent and confirmed by PHY, MAC terminates the process using the PHY-TXEND.request/confirm primitives. Here, the only change is the addition of the CID field into the TXVECTOR parameter list in the PHY-TXSTART.request primitive, which PHY must now copy into the CID field in the PHY header of the outgoing frame.

On the reception side (Fig. 3.3(b)), the MAC-PHY interaction is also virtually unchanged if the payload is to be retained: it starts with MAC using the PHY-CCARESET.request/confirm primitives to restart the CCA process in PHY at the end of the last frame reception or transmission. Subsequently, if a frame is transmitted by a transmitter within carrier-sensing distance of the receiver, the Received Signal Strength Index (RSSI), which is a standard IEEE 802.11 measurement of the received signal power, will rise above a pre-calibrated threshold known as the Energy Detection (ED) threshold. When PHY's preamble correlation circuit detects the preamble part of the frame, PHY will issue PHY-CCA.indication to inform MAC the channel is busy. After the header part of the frame is received in full without errors, PHY issues PHY-RXSTART.indication to MAC with its RXVECTOR argument filled with information obtained from the frame's header. Subsequently, PHY uses the PHY-DATA.indicate primitive to send the payload byte-by-byte to MAC, and terminates the reception process with the PHY-RXEND.indication primitive. Similar to the transmission case, the only change in this case (when the payload is to be retained), is the inclusion of the CID field into the RXVECTOR parameter list in the PHY-RXSTART.indication primitive, which PHY must copy from the CID field in the frame's header.

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When the payload is to be dropped however, the sequence is altered as follows: immediately after PHY-RXSTART.indication is received, MAC uses the PHY-CCARESET.request/confirm primitives to instruct PHY to abort the ongoing payload reception, and to restart the CCA process. The criteria with which MAC decides this alternate course of action is explained in the following section.

3.2.3 Payload-Dropping Criteria

During reception, a node drops the payload portion of frames only if all the following conditions are met:

- Its cell's CID is not '000'.
- The CID in the header of the frame being received is not '000'.
- The CID in the header of the frame being received is not equal to its cell's CID value.

Note that, based on the first condition, the AP can effectively disable payload-dropping in all nodes associated with it by sending out a frame with the CID field set to '000', since, according to Section 3.2.1, all nodes will then note this value as their cell's CID. This mechanism is used by APs to turn off PD-CSMA/CA in cells which are not interference-limited.

In our scheme, the AP determines the interference-limited condition of its cell through the following transmission retry or failure rate -based interference assessment method: While its cell's CID value is not '000', each node (including the AP) keeps a running tab of either the retry or failure rate. The retry rate is the number of times an over-the-air transmission is attempted by MAC for each frame submitted by the application layer to MAC for transmission. The failure rate is the ratio of frames dropped after the maximum allowed number of retransmission attempts are made for each application layer frame

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(specified as the STA Short Retry Limit in the specification and in Table 3.1). If, within a pre-calibrated window (e.g., 100 application layer frames), the failure or retry rate is below a certain administrator-controlled margin, e.g., 10% above the expected retry rate, or 2 failed frames out of 100 application-layer frames, then the node will continue to imbed the cell's CID into the header of the frames it transmits. If the margin is exceeded, then it will override its cell's CID with '000', and use this value for the CID field of the frames it subsequently transmits.

Additionally, if any node (including the AP) receives a frame with a CID value of '000', it will also override its cell's CID to '000', and set the CID field of the frames it subsequently transmits to '000'. Since all nodes in a cell are assumed to be within reception distance of the AP, this reaction would result in the entire cell defaulting to the original CSMA/CA protocol permanently, even if only one node in the cell is experiencing transmission failures due to concurrent transmissions in a neighboring cell. This is not a desirable outcome if the interference is due to a temporary condition (e.g., an interfering edge node in a neighbor cell that is subsequently powered off or reconfigured to a different channel). As such, at some administrator-configured interval (e.g., 30 minutes), the AP will attempt to reinstate PD-CSMA/CA by resetting its cell CID value (and correspondingly the CID value it imbeds in the frames it transmit) to the original, non zero value pre-configured by the network-administrator. When this happens, all other nodes will consequently change their cell's CID value to this non-zero value, and restart the dropped-frame or retransmission-based interference assessment method.

3.2.4 Backward Compatibility

Since the value for the 3 bits occupied by the CID field in the header is set to '000' according to the original specifications (refer Section 3.2.1), then any cell which is joined

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or hosted by a legacy node will default to the original CSMA/CA operation, for the following reasons:

- If the AP hosting the cell is a legacy node, then any PD-CSMA/CA-capable node that associates with the cell will have '000' as its cell CID and will not drop any payload it receives (see Section 3.2.3 for the payload-dropping criteria).
- If a legacy node joins a cell hosted by a PD-CSMA/CA-capable AP, then upon receiving a frame from this legacy node, the AP will override its pre-configured cell CID with '000'. This new cell CID value will eventually be propagated to all PD-CSMA/CA-capable nodes associated with the cell, and cause them to discontinue their payload dropping operation.

This mechanism may seem too pessimistic, but is necessary to prevent legacy nodes from being starved of bandwidth due to PD-CSMA/CA nodes having the unfair advantage of being able to start transmissions in periods when legacy nodes are blocked (due to transmissions from interference-limited cells within carrier-sensing distance).

3.3 Ns-2 Enhancements

In addition to revising the MAC module in ns-2, we also made several modifications to the PHY module to ensure that the simulation is realistic in spatial reuse scenarios. We describe these in the following subsections. In addition to these modifications, we also describe the choice of propagation model and simulation scenarios to make our simulation as realistic as possible.

3.3.1 Physical Layer Capture Model

In the original ns-2, as long as a later frame arrives with a power level higher by some x dB than the currently received frame, regardless of how much later it arrives or how

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many overlapping transmissions there are, it is captured. From empirical results presented in [104, 105] we know this is incorrect. In fact, capture occurs only when,

$$P_i > \alpha \sum P_j, \quad |T_i - T_j| < T_{pre}, j \neq i \quad (3.1)$$

where T_{pre} is the duration of the preamble, P_n and T_n the received power and arrival time of the n th packet, and α the minimum SINR for capture to occur.

3.3.2 Bit Error Rate (BER) vs. SINR Model

There was no BER vs SINR model in the ns-2's PHY simulator. However, this data is crucial in deciding whether, having complied with Eq. (3.1), capture would indeed occur, and if frames would just be undetected or received erroneously. For this purpose we used the data from the Intersil IEEE 802.11b chipset specifications [50, 106] in our revised PHY module. To determine whether the preamble, header or payload of a frame is

Figure 3.4: BER vs SINR Curves for the Modulation Rates Used in Ns-2's IEEE 802.11b PHY Simulator

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erroneously received, we calculate the ratio of its received power versus the sum of the power of the ambient noise and background transmissions. This calculation is performed at the start of each preamble, header or payload of the frame currently locked by the PHY layer (WirelessPhy.cc), and every time another signal arrives while that particular part of the locked frame is being received by the PHY layer. The minimum of these calculated SINR values is retained at the end of the period and is used to evaluate whether that part of the frame is erroneously received or not.

To facilitate this SINR calculation, the power and duration of each and every signal that arrives at the PHY layer is recorded in an array. The size of this array is at least as big as the number of nodes in the entire system, so that it can store the maximum number of signals that can occur concurrently in the system. The power and duration of each arriving signal is retrieved from the Packet message class (packet.h) as it is passed up from the propagation layer (propagation.cc). When the signal ends, it is removed from the array.

As an example of how this is done, consider the case where the PHY layer is receiving and decoding the payload of a frame, F_1 , in the midst of two other overlapping frame transmissions, F_0 and F_2 . Assume that F_0 ends sometime after F_1 's payload transmission starts, while F_2 arrives just after F_0 's transmission ends, but not before F_1 's payload transmission ends. Also, assume that F_0 , F_1 and F_2 arrive at the node's antenna with RF powers of -80 dBm (10^{-8} mW), -50 dBm (10^{-5} mW) and -60 dBm (10^{-6} mW), respectively, while the ambient noise level, n_0 , is -100 dBm (10^{-10} mW). In this case, two calculations will be done, as follows:

- 1st calculation: This is done at the start of F_1 's payload transmission. At this point, the RF powers to be considered are that of F_0 , F_1 and the noise level. The result of this calculation is therefore:

$$\text{SINR}_1(F_1) = \text{dBm}(F_1) - \text{dBm}(\text{mW}(F_0) + \text{mW}(n_0))$$

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$$= -50 - 10\log(10^{-8} + 10^{-10})$$

$$= 29.96 \text{ dBm}$$

- 2nd calculation: This is done at the start of F_2 's transmission. At this point, F_0 has already ended so the RF powers to be considered are F_1 , F_2 and the noise level:

$$\text{SINR}_2(F_1) = \text{dBm}(F_1) - \text{dBm}(\text{mW}(F_2) + \text{mW}(n_0))$$

$$= -50 - 10\log(10^{-6} + 10^{-10})$$

$$= 10.00 \text{ dBm}$$

Since SINR_2 (=10 dBm) is the smaller of the values calculated, it is retained as the SINR for evaluating whether the payload is received correctly. Using this minimum SINR, a corresponding BER value on the BER-SINR curve (Fig. 3.4) is obtained. This BER is the probability that a bit is erroneous. The complement of this probability, (1-BER), is the probability that a bit is correctly received. If a part of the frame (e.g. preamble, header or payload) is L bits long, then we assume that all L bits must be received correctly in order for the entire part to be received correctly. The probability for this to happen is the product of the probabilities of all L bits being correctly received, i.e., $(1 - \text{BER})^L$. Consequently, in order to simulate erroneous reception of a part of the frame in the PHY layer, a uniform random number is selected between 0 and 1; if this random number is below this probability, then the part of the frame is considered successfully received. Otherwise, it is considered incorrectly received.

3.3.3 Blinded Receiver State

The “blinded receiver” state [107] is a state which the receiver enters when it receives a header in which the field indicating the duration of the remainder of the frame is corrupted. During this time, the receiver cannot receive any other frame for a fixed period of 3.5 ms. Its rate of occurrence increases with the number of parallel transmissions and

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can render any spatial reuse scheme which looks good on paper worthless in real situations. In our modified ns-2 platform, this phenomenon is accounted for by adding an extra state to the PHY's reception state machine. This state is entered when the frame header is deemed to be corrupted based on the method described in Section 3.3.2.

3.4 Simulation Scenarios

Three different scenarios and configurations were used to ascertain whether our modified DCF can provide better throughput than the original DCF when co-channel cells are packed more closely. All three scenarios are based on the indoor environment, since the IEEE 802.11 is mainly used indoors. The source code for this implementation is provided in the CD that was submitted with this thesis, along with the scripts to setup and run the different scenarios.

Table 3.1 lists the ns-2 settings that were commonly used in all three scenarios. We made no distinction in the minimum SINR required for good preamble synchronization and errorless reception of the PHY header, setting both to 2 dB by looking up the minimum SNR required for a BER of 10^{-4} or smaller on the curve given in Fig 3.3. This BER value is deduced based on the assumption that the minimum missed detection and/or header error rate is 1%, which roughly works out to 10^{-4} BER over the 120 bits ($0.01/120 = 8.3 \times 10^{-5}$). As for the 11 Mbps payload, we assume the minimum SINR for successful reception to be 12.5 dB based on a BER cut-off of 10^{-5} . This BER value corresponds to the maximum Frame Error Rate (FER) of 8% that PHY is allowed to present to MAC for a payload size of 1034 bytes ($0.08/(1034 \times 8) = 9.7 \times 10^{-6}$), as specified in the 802.11b standard.

In the following subsections, we elaborate further on the differences in the purpose, configurations used, and the results obtained for each scenario.

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Table 3.1 Common Ns-2 Settings for All Scenarios

Layer	Parameter	Value
RF	Propagation delay	2 μ s
	Ambient noise	-96 dBm
Antenna	Antenna type	Omni
	Transmit/receive gain	1
PHY	AP/STA operating frequency	2.472 GHz
	Preamble length (SYNC+SFD)	72 bits (72 μ s)
	PHY header length	48 bits (24 μ s)
	Preamble modulation scheme	Barker1 (1 Mbps)
	PHY header modulation scheme	Barker2 (2 Mbps)
	Payload modulation scheme	CCK11 (11 Mbps)
	SINR for preamble synchronization	> 2 dB
	SINR for errorless header reception	> 2 dB
	SINR for errorless payload reception	> 12.5 dB
MAC	Slot time (aSlotTime)	20 μ s
	Short Interframe Space (SIFS)	10 μ s
	DCF Interframe Space (DIFS)	50 μ s
	Extended Interframe Space (EIFS)	1005.6 μ s
	ACK frame length (at 11Mbps)	14 bytes (10.2 μ s)
	DATA frame length (at 11Mbps)	1034 bytes (752 μ s)
	ACK timeout (ACKTimeout)	120.2 μ s
	Contention Window (CWMin/Max)	32 / 1024
	STA Short Retry Limit	7
Application	Traffic model	Poisson
	Packet size	1000 bytes
	Offered load per node	>20Mbps (Saturation)

3.4.1 Scenario 1: Distance-Separated Cells with Transmit**Power Control**

The purpose of this scenario is to study the impact of the PD-CSMA/CA enhancement on the per-cell throughput gain for 2 - 3 distance-separated co-channel cells. In addition, the impact of PD-CSMA/CA on the throughput in tandem with that of a simple, open-loop transmit power control (TPC) scheme is also studied.

3.4.1.1 Path Loss Model

The lognormal path-loss with shadowing model [34] was used in this scenario:

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$$PL(d) = PL(d_0) + 10n_{sf} \log\left(\frac{d}{d_0}\right) + X_{sd} \quad (3.2)$$

where $PL(d)$ is the path loss measured in dB at a T-R distance of d meters, d_0 the close-in reference distance at which the transmitter's transmission power is measured, n_{sf} the path loss exponent value, and X is a normal random variable with standard deviation sd . Based on the empirical findings of [108], we select $n_{sf} = 4.0$ and $sd = 7.3$ dB to mimic an indoor environment.

3.4.1.2 Topology and Application Traffic

Fig 3.5 shows the topology used. It consists of 2 - 3 20 m x 20 m cells. This cell size is based on the maximum coverage possible for the path-loss index used at the highest stock transmit power level of 24.7 dBm (300 mW) known to exist in IEEE 802.11b/g client adaptor cards in the market. In each cell, 16 nodes are placed at regular intervals to ensure that all areas of the cell are represented. Despite this positioning regularity, any mechanical regularity in the interference characteristics one might expect is cancelled out

Figure 3.5: Simulation Topology for Scenario 1

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by the standard deviation in the path-loss model employed.

The offered load on each cell is 20 Mbps. Given the channel rate of 11 Mbps, this causes the throughput to be at its saturation rate. For each cell, Poisson generators of 1000-byte UDP packets were used to simulate 240 (16 x 15) single-hop mesh traffic flows between each node to all other nodes in the same cell.

3.4.1.3 TPC Schemes

Besides using a fixed transmit power of 24.7 dBm, simple open loop transmit power control (TPC) schemes were also simulated for comparison. In these TPC schemes, each node determines at the onset the minimum transmit power required to ensure that the payload portions of its frames arrive at its furthest neighbor at the BER of 10^{-5} in the presence of ambient noise. This BER value is computed based on the maximum allowed FER of 8% specified in the IEEE 802.11b specifications [1] for 1024-byte payloads. The transmit power for the node is then fixed at this minimum value for the entire duration of the simulation. The 3 settings of this TPC scheme, TPC(1σ), TPC(2σ) and TPC(3σ), correspond to the 68 / 95 / 99.7 standard deviation rule on how well the scheme compensates for the lognormal shadow fading of the signal strength at its destination. For example TPC(1σ) ensures that only 84% (68/2+50) of signals arrive at their destinations with the required BER of 10^{-5} .

These TPC schemes are similar to those proposed in [11,14]. In the Optimal Transmit Power (OTP) scheme proposed in [11], for example, the transmit power is set just high enough to ensure there are no potential hidden nodes in the cell. But while the process of determining the correct transmit power to use is determined via the RTS/CTS exchange [11], or measurements performed on a separate control channel [14], in our scheme, for convenience, we precompute the settings using the same principle prior to running the

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simulation. Additionally, by varying the scheme according to the 1σ , 2σ , and 3σ fading margins, we also take into consideration the shadow fading effect that was left out in those propositions.

3.4.1.4 Payload-Dropping Settings

As described in Section 3.2.3, PD-CSMA/CA may be engaged or disengaged based on the transmission retry and/or failure rate. In this scenario, the failure rate is used: if out of 100 application frames transmitted, the dropped frame count for any node exceeds 1, PD-CSMA/CA is disengaged. Subsequently however, no attempt is made to reinstate PD-CSMA/CA: once it is disengaged, it remains disengaged throughout the remainder of the simulation time.

3.4.1.5 Statistics Collected

The cell spacing setting is varied from 1.5 to 2.5 times the cell width (20 m) in steps of 0.25, and from 2.5 to 5.0 in steps of 0.5. For each cell spacing setting, the simulation is run for 20 minutes, repeated 10 times with the original DCF, and 10 more with the modified DCF, with each repetition using different random number generation seeds. In each simulation, the throughput, frame retry and failure rate for each node is recorded. From the recorded per-node throughputs, the throughput fairness between nodes based on Jain's index [109], and the overall per-cell throughput (normalized to the 11 Mbps channel rate) is calculated. From the retry and failure rates, the average rate and the standard deviation amongst nodes in the cell is calculated. The fairness index and standard deviation are useful for determining if throughput improvements achieved by PD-CSMA/CA are at the expense of fairness.

3.4.2 Scenario 2: Distance-Separated Cells with Power

Control and Carrier-Sensing Threshold

In the second scenario, the number of cells is increased to 4, and instead of being regularly placed, the nodes are randomly placed. In addition to TPC scheme used in the previous scenario, we also study the impact of PD-CSMA/CA in tandem with Carrier-Sensing Threshold (CST) control and combination TPC/CST schemes.

3.4.2.1 Path Loss Model

The path loss model and settings used in this scenario are the same as in the previous scenario (see Section 3.4.1.1).

3.4.2.2 Topology and Application Traffic

Fig. 3.6 shows the simulation topology. It comprises four 15 m by 15 m square cells each containing 10 randomly placed nodes. The cell size is slightly smaller than the size

Figure 3.6: Simulation Topology for Scenario 2

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used in the first scenario, and can therefore be covered using transmit power levels that are slightly lower than the stock transmit power level of 24.7 dBm (300 mW), for the path-loss index used (4.0).

All in all, Poisson generators of 1000-byte UDP packets were used to simulate 360 (4 cells x 10x9 flows per cell) single-hop mesh traffic flows between each node to all other nodes within the same cell. As in the previous scenario, the offered load on each cell is 20 Mbps so that the throughput is at its saturation rate.

3.4.2.3 TPC, CST and Combination Schemes

Besides using the stock transmit power of 24.7 dBm, open loop TPC, CST and combination schemes were included for comparison. In the TPC schemes, each node uses a fixed transmit power required to ensure that the payload portions of its frames arrive at its furthest neighbor at a BER of 10^{-5} in the presence of the ambient noise (-96 dBm). In the CST schemes, each node uses fixed sensing threshold which ensures that only signals within the same cell are sensed. In the combination scheme, each node determines its fixed transmit power and sensing threshold, in that order. For each of these 3 schemes, 3 slight variations are implemented corresponding to the 68 / 95 / 99.7 standard deviation rule on how well the scheme compensates for the lognormal shadow fading of the received signal strength. Accordingly, the name of the scheme is suffixed with “ 1σ ”, “ 2σ ” and “ 3σ ” in brackets, based on the fade margin applied. For example, TPC/CST(2σ) ensures that 97.5% ($95/2+50$) of signals are received with the minimum required BER, and 97.5% of intra-cells signals are sensed.

It should be noted that the TPC scheme used here is similar to those employed in [11,14], with some modifications to suite our simulation requirements (refer Section 3.4.1.3 for more details on the modifications). Meanwhile the CST scheme is similar to

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those proposed in [16,17]. In the AP-CST scheme described in [16] for example, the CST threshold is adjusted just barely so that each station can hear other stations from inside its own cell (i.e, to avoid hidden terminals). The scheme in [17] is also similar, i.e., threshold in each node is adjusted to a level just barely enough to detect any transmissions in the cell. In [17], the Frame Error Rate (FER) is used to indirectly deduce the CST threshold, since the key premise of that work is that real transceiver implementations are not able to provide accurate SINR measurements. In our CST scheme, the SINR is directly used to calculate the CST. In a way, our scheme may be seen as an idealistic version of [17]. But, as in the TPC case, both schemes [16,17] do not consider shadow fading, while in our scheme, we introduce variations for different fade margins. Also, as in the TPC scheme, for convenience, we ignore the signalling overhead and precompute the settings before the simulation is run.

3.4.2.4 Payload-Dropping Settings

The same settings are used as in the previous scenario (see Section 3.4.1.4). However, a slight change was made to MAC to count the header of a dropped frame as a backoff slot and decrement the backoff timer accordingly. The result of this is that slightly less time is wasted for each payload-dropping incident. Nonetheless, the effect of this saving on the overall PD-CSMA/CA throughput is negligible.

3.4.2.5 Statistics Collected

The cell spacing settings used are 1.25, 1.5, 1.75, 2.0, 2.5, 3.0, 4.0 and 6.0 times the cell width (15 m). For each cell spacing setting, 10 different randomly generated node positions were used. For each of these random node positions, the simulation was run for 10 minutes, during which individual node's throughput, transmission retry and failure rates were recorded. As in the previous scenario, these three statistics are used to compute

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the normalized per-cell throughput, Jain's index [109] for throughput fairness between nodes, the average retry and failure rate and the standard deviation amongst nodes in each cell. The average values for these statistics across the 10 random node position settings are then tabulated and/or charted. This procedure is repeated for each of the schemes used.

3.4.3 Scenario 3: Wall-Separated Cells

This scenario is slightly different from the previous two: instead of varying the distance between cells to achieve the interference-limited condition, a wall is simulated between cells. By changing the attenuation caused by this wall, we observe the per-cell throughput for the IEEE 802.11 DCF with and without our modifications, paying attention to the level of attenuation needed to achieve single-cell throughputs in the both cases.

This scenario is useful as a demonstration of PD-CSMA/CA in a building, where the spaces are usually separated by the floors and walls of the building. The consequence of this is that the signal propagation losses experienced by transmitter-receiver (T-R) pairs in the same room are likely to be smaller than those experienced by pairs in adjacent rooms or floors.

Typically, a concrete wall presents an attenuation of 8 - 20 dB [110] for 2 - 5 GHz RF signals. If the PD-CSMA/CA-enhanced DCF can achieve single-cell throughputs at these levels of attenuation, it may pave way to very dense, one-cell per room WLAN deployments in buildings.

3.4.3.1 Path Loss Model

The path loss model used in this scenario is based on the one proposed by Seidel for

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planning indoor and campus deployments [34]:

$$PL(d) = PL(d_0) + 10n_{sf} \log\left(\frac{d}{d_0}\right) + FAF + \sum PAF \quad (3.3)$$

Here, $PL(d)$ is the path loss measured in dB at a T-R distance of d meters, d_0 the close-in reference distance at which the transmitter's transmission power is measured, n_{sf} the path loss exponent value measured in the same floor with little to no clutter in the T-R line-of-sight (LOS), FAF (Floor Attenuation Factors) the cumulative losses (dB) caused by the floors of the building between the T-R pair and PAF (Partition Attenuation Factors) the loss (dB) caused by each partition crossed by straight line drawn between the T-R pair. In our simulation, we set $n_{sf} = 2.5$ and $FAF = 0$ dB since the rooms are on the same floor, and vary the PAF between 0 – 58 dB.

3.4.3.2 Topology and Application Traffic

The topology for this scenario is shown in Fig. 3.7. It consists of 2 16 m x 16 m rooms each served by an AP mounted at the centre, and separated from one other by a hard partition. Each room is divided into 4 or 16 cubicles each containing a node. The cell load is set to 20 Mbps, so that all nodes including the AP transmit in saturation mode. The

Figure 3.7: Simulation Topology for Scenario 3

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directions for the traffic follows that of infrastructure mode wireless LAN network, i.e. with STAs transmitting to the AP, and the AP randomly selecting a STA to transmit to. As a result of this, the uplink to downlink traffic ratio for each cell is $N : 1$, where N is the number of STAs in each room.

3.4.3.3 Payload-Dropping Settings

In this scenario, the following criteria is used for disabling payload dropping: if the retry rate is 10% points higher than the typical value for the original DCF in an isolated cell with the same number of nodes, then PD-CSMA/CA is disengaged. Based on our single-cell DCF simulations, the typical values for the retry rate in an isolated cell with a given number of nodes are shown in Fig. 3.8. As an example, the threshold for disabling PD-CSMA/CA for the 4 cubicle case is 30% since the number of nodes in this case is 5 (i.e., 4 STA and 1 AP), and the typical retry rate is 20%.

Figure 3.8: Average Retry Rate vs Number of Nodes for DCF in a Single Cell

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3.4.3.4 Statistics Collected

The PAF setting is varied from 0 to 58 dB in steps of 1 dB. For each PAF setting, the simulation is repeated 10 times for the original DCF and the PD-CSMA/CA-enhanced DCF. Each simulation run lasts 20 minutes, during which the average uplink and downlink throughput, frame transmission delay and retry rate for each node is measured. The frame transmission delay is the period between the time when the application layer first submits a frame to MAC for transmission, and the time when MAC successfully transmits the frame to its destination, inclusive of the time spent in transmission retries, if any. For each of these statistics, the corresponding Jain fairness index was calculated across all nodes in one cell.

3.5 Simulation Results

3.5.1 Results for Scenario 1

Figs. 3.9 - 3.12 compares the normalized per-cell throughputs for the original DCF and the PD-CSMA-enhanced DCF (labeled as 'PD-DCF' in the charts) for the simulation scenario and settings described in Section 3.4.1 as the cell spacing is increased.

In general, we see that the throughput curve of the original DCF increases monotonously as the cell spacing is increased. Its rate of increase drops as the cell spacing is increased. Apart from the increase at a cell spacing of about 2.25 times the cell width/height, the PD-DCF curve is also increasing monotonously as the cell spacing is increased. Before this point, the throughput curve of PD-DCF is nearly coincident with the throughput curve of DCF. As cell spacing is increased beyond this point, both curves increase monotonously, trending towards a common asymptote.

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Figure 3.9: Throughput vs. Cell Spacing for Scenario 1: DCF vs. PD-DCF at Stock Transmit Power of 24.7dBm

Figure 3.10: Throughput vs. Cell Spacing for Scenario 1: DCF vs. PD-DCF with TPC(1σ) Scheme

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Figure 3.11: Throughput vs. Cell Spacing for Scenario 1: DCF vs. PD-DCF with TPC(2σ) Scheme

Figure 3.12: Throughput vs. Cell Spacing for Scenario 1: DCF vs. PD-DCF with TPC(3σ) Scheme

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From these charts, it can also be seen that as the fade margin is increased, the initial boost that PD-DCF gets at the cell spacing of 2.25 times the cell width/height is increased. With this larger boost, the gap between the two curves becomes larger.

To understand the reason behind these trends, we need to consider several PHY layer and radio propagation related parameters, and how they affect the performance of PD-CSMA/CA and CSMA/CA as the cell spacing is varied. Denote the parameters as follows:

- I: the distribution of the received signal power of the interfering transmissions from neighbor cells as received by nodes in one cell,
- S: The distribution of the received signal power of the transmissions from within the cell as received by nodes in the same cell,
- R: the energy detection thresholds or receiver sensitivities of the nodes.
- $\text{SINR}_{\min}$: the SINR required for any node to receive a frame without error.

It should be noted that the widths of I and S are dependent on the relative placement of the stations and the lognormal shadowing effect in the propagation model used. R, being just a threshold in the receiver, is single valued (assuming the receivers are all designed and calibrated equally). While the probability of a frame being received without error is statistically dependent on the BER corresponding to the SINR value at which it is received (i.e., Fig. 3.4), for practical purpose we can also assume a single value for $\text{SINR}_{\min}$, taken at the point in the BER-SINR curve for the modulation scheme used in the receiver when the BER equals 10^{-5} .

For a given scheme, S and R are fixed. But I varies with the cell spacing: When the cells are coincident, I equal S, and thus the co-channel interference is at its peak. As the cells are moved further and further apart, I moves away from S towards R, and eventually goes under R when the cells are very far apart.

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Since PD-CSMA/CA is designed specifically to outdo CSMA/CA in interference-limited cells that are experiencing the exposed node problem, its performance gain is to be expected only when $(S - \text{SINR}_{\min}) > I > R$. This is because I has to be below $(S - \text{SINR}_{\min})$ in order for the interference-limited condition to be met, but above R in order for the exposed node condition to be met.

When I is above this range, i.e., $S > I > (S - \text{SINR}_{\min})$, the co-channel interference power is too high. The resulting high FER would drive PD-CSMA/CA to fallback to CSMA/CA operation. As a result, both performances of PD-CSMA/CA and CSMA/CA will be the same.

When I is within this range, PD-CSMA/CA excels the most: Just as I drops below $(S - \text{SINR}_{\min})$, the co-channel interference power is low enough to ensure a FER rate that is also low enough not to trigger PD-CSMA/CA to disengage its payload-dropping operation. As a result of this operation, PD-CSMA/CA gets a boost in its throughput since the exposed node problem is mitigated.

In the scenario at hand, this situation appears to be achieved when the cell spacing is about 2.25 times the cell width/height. Given the regularity with which nodes are placed in this scenario, we can roughly determine whether the intuition given above is reasonable for the two cell case under a fixed transmit power scheme: The maximum T-R distance in each cell in this scenario is the distance between nodes at the opposing corners of the cell. Given the cell width/height of 20 m and that the nodes near the walls of the cell are 2.5 m away from the walls, this distance equals 21.2 m ($= \sqrt{2} \times 15$). At a transmit power of 24.7 dBm, the received signal power at this distance is -68.5 dBm, according to the formula given in Eq. (3.2), ignoring the lognormal shadowing effect. This is roughly the lower end of S . With $\text{SINR} = 12.5$ dB, $(S - \text{SINR}_{\min})$ is therefore at least -81 dBm.

At the point where PD-DCF attains its throughput boost for the fixed transmit power

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case, the cell spacing is 2.0 times the cell width/height. At this cell spacing, the shortest distance between T-R pairs in different cells is 45 m (i.e., 2.0×20 for the distance between the opposing walls of the cell, plus 2×2.5 for the distance of the node to the wall). Meanwhile, the largest distance between T-R pairs in different cells is roughly 80 m (i.e., the twice the cell width/height, plus the cell spacing). At these two distances, the received signal power is -81.7 dBm and -91.7 dBm. These values, which correspond to the higher and lower ends of the values for I , clearly shows that I is within the range of $[S - \text{SINR}_{\min}, R]$, since R is fixed at -95 dBm for the given scenario.

As I shifts further below $(S - \text{SINR}_{\min})$, more and more signals within cells are arriving with higher SINR margin, resulting in lower FERs. This explains why both the throughput of the original DCF and PD-DCF gradually increase when the cell spacings increase. However, since PD-DCF already had its performance boosted at about the point when I is slightly under $(S - \text{SINR}_{\min})$, its throughput curve is always above the throughput curve of the original DCF.

As I drops under this range (i.e., $I < R$), the exposed node problem disappears and thus the performance of CSMA/CA is no longer crippled by it. As a result, both performances of PD-DCF and the original DCF will also be the same. It should be noted however that this improvement is not a sudden step since I and S are distributed across a range of values.

The information above explain how the parameters, S , I , R and $\text{SINR}_{\min}$ affect the gap between the PD-DCF and original DCF throughput curves, which starts at a certain cell spacing (e.g. about 2.25 times the cell width/height), and eventually diminishes to zero as the cells are set further and further apart. Based on this reasoning, we can also explain how a larger fade margin used in the TPC and/or CST schemes increases this gap: When a larger fade margin is used, the gap between S and R becomes larger. For example, the

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TPC(2σ) scheme will result in S values which are 7.3 dB (this being the standard deviation of the lognormal shadowing in the indoor environment used in the simulation) higher than the S values for a TPC(1σ) scheme. Since R is fixed at the receiver sensitivity level (-95 dBm) for TPC schemes, the $[S - \text{SINR}_{\min}, R]$ gap for the TPC(2σ) is larger than the same gap for the TPC(1σ) scheme by 7.3 dB.

With the gap between $(S - \text{SINR}_{\min})$ and R reduced, so reduces the range for I in $[S - \text{SINR}_{\min}, R]$ in which PD-CSMA/CA has advantage over CSMA/CA when the cells are both interference limited and exposed. Further, since both S and I are distributions that are dependent on the lognormal shadowing effect and the placement of nodes, the two conditions may be harder to achieve at the same time if the range $[S - \text{SINR}_{\min}, R]$ is small, since a higher portion of the tail-ends of I will spill over $(S - \text{SINR}_{\min})$ and under R. As a result, the percentage of interfering transmissions that are both interference-limited and exposed is reduced. Because of this, the magnitude of the boost that PD-CSMA/CA at about the cell spacings of 2.25 times the cell width/height diminishes significantly.

In Table 3.2, the numerical data for the throughput gains, and the values for the throughput fairness index, frame retry and failure rates before and after enabling the PD-CSMA/CA enhancement is shown. Here, we see that the throughput gain is quite significant (23%) in relation to the original DCF protocol using fixed transmit power level. In relation to the TPC(2σ) scheme the gain is also good (13.8%). At the same time, note that for the fixed transmit power, TPC(2σ) and TPC(3σ) schemes, the throughput fairness indices [109] are practically unchanged, whereas increases in retry and failure rates are small.

For the TPC(1σ) scheme, the gain achieved with PD-CSMA/CA is relatively small compared to the other schemes. This is because the throughput obtained with the TPC(1σ) scheme on its own merit is already quite high to begin with. However, it should be noted

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Table 3.2 PD-CSMA/CA Throughput Gains, and Before/After Values for Fairness, Retry and Failure Rates (for the 3 Cell Case of Scenario 1)

Scheme	Cell Space (m)	Throughput			Retry Rate				Fail Rate (x10 ²)			
		PD Gain (%)	Jain's Index		Avg.		Stdev.		Avg.		Stdev.	
			bef	aft	bef	aft	bef	aft	bef	aft	bef	aft
24.7 dBm	1.50	1.60	0.88	0.88	0.87	0.88	0.46	0.48	1.38	1.50	2.58	2.80
	2.25	23.0	0.92	0.88	0.75	0.82	0.35	0.44	0.72	1.09	1.41	2.22
	2.50	19.3	0.93	0.91	0.71	0.75	0.32	0.37	0.63	0.73	1.23	1.51
	3.00	13.9	0.95	0.95	0.66	0.67	0.25	0.27	0.39	0.44	0.82	0.92
TPC (1σ)	1.50	10.6	0.95	0.95	1.04	1.18	0.59	0.70	2.43	3.45	4.03	5.23
	2.25	3.7	0.97	0.96	0.80	0.82	0.42	0.42	1.04	1.03	1.89	1.85
	2.50	2.0	0.98	0.97	0.74	0.75	0.37	0.37	0.67	0.69	1.24	1.32
	3.00	0.7	0.98	0.98	0.66	0.66	0.30	0.30	0.41	0.42	0.81	0.78
TPC (2σ)	1.50	1.2	0.97	0.98	0.93	0.94	0.47	0.48	1.60	1.67	2.57	2.67
	2.25	13.8	0.98	0.98	0.76	0.80	0.33	0.37	0.70	0.86	1.29	1.41
	2.50	11.2	0.98	0.98	0.71	0.74	0.29	0.32	0.53	0.60	0.94	1.05
	3.00	6.6	0.99	0.99	0.65	0.67	0.23	0.25	0.36	0.36	0.67	0.64
TPC (3σ)	1.50	1.5	0.98	0.97	0.78	0.80	0.35	0.36	0.82	0.92	1.39	1.54
	2.25	26.7	0.98	0.97	0.73	0.78	0.29	0.36	0.55	0.79	0.96	1.40
	2.50	22.5	0.98	0.98	0.70	0.73	0.26	0.30	0.49	0.53	0.86	0.92
	3.00	18.2	0.99	0.99	0.65	0.67	0.21	0.24	0.30	0.34	0.55	0.64

that this scheme ensures only 84% of signals to be of adequate strength at their destination. So, in achieving the high throughput, it compromises FER even in the single cell scenario, as evidenced by its higher retry and failure rates in Table 3.2.

3.5.2 Results for Scenario 2

Figs. 3.13 – 3.16 show the throughputs for DCF and PD-CSMA/CA-enhanced DCF (labeled as ‘PD-DCF’) for the 4 cell scenario using a fixed transmit power of 24.7 dBm, and also the TPC, CST and combination TPC/CST schemes as described in Section 3.4.2, as the cell spacing is increased. In general, the trend of the curves are very similar to those presented in Section 3.5.1, i.e., the DCF curve monotonously increases as the cell spacing is increased, while an abrupt increase appear in the otherwise also monotonously increasing PD-DCF curve at the cell spacing of about 2.5 - 3.0 times the cell width/height.

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Figure 3.13: Throughput vs. Cell Spacing for Scenario 2: DCF vs. PD-DCF at Fixed Transmit Power of 24.7dBm

Figure 3.14: Throughput vs. Cell Spacing for Scenario 2: DCF vs. PD-DCF with TPC Schemes

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Figure 3.15: Throughput vs. Cell Spacing for Scenario 2: DCF vs. PD-DCF with CST Schemes

Figure 3.16: Throughput vs. Cell Spacing for Scenario 2: DCF vs. PD-DCF with Combination TPC/CST Schemes

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The magnitude of this abrupt throughput increase in PD-DCF increases as the fade margin employed by the TPC/CST schemes is increased. While we have explained in Section 3.5.1 why this happens for the TPC scheme, we had not done so for the CST and combination TPC/CST schemes as these schemes were not simulated in that earlier scenario. However, the same intuition applies in this case: Recall that it was mentioned in that section that since PD-CSMA/CA is designed specifically to outdo CSMA/CA in interference-limited cells that are experiencing the exposed node problem, its performance gain is to be expected only when $S - \text{SINR}_{\min} > I > R$, where the parameters S , $\text{SINR}_{\min}$, I and R are as described in Section 3.5.1. As the fade margin for the CST scheme is increased, the value for R is decreased. For example, CST(2σ) scheme would result in an R value which is 7.3 dB lower than the R value for the CST(1σ) scheme.

With the lowering of the value for R , the gap between $S - \text{SINR}_{\min}$ and R increases just the same as it does when the fade margin for the TPC scheme is increased. Thus, the reason given for the increase in the gain for PD-DCF when the fade margin employed for TPC the scheme is increased, is also valid for the CST and combination TPC/CST schemes.

Another important observation is that schemes which employ 1σ fade margins seem to taper off to lower throughput asymptotes. This limitation on the maximum throughput, which affects not only PD-DCF but also the original DCF, is caused by the low fade margin employed. The reason why a small fade margin limits the throughput thus is as follows: For the CST case, a fade margin of 1σ is based on only ensuring that 84% of signals from inside of the cell is not filtered. As a result the remaining 16% of the signals, which is heavily faded, is missed by the receiving nodes, and have to be resent by the sending nodes. For the TPC case, a fade margin of 1σ can only ensure that 84% of the signals arrive at their destinations with SINR corresponding to a BER of at least 10^{-5} . This

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causes 16% of the remaining signals to arrive at their destinations with BER below 10^{-5} , giving rise to the higher likelihood of the frame to be dropped due to bit errors, and the transmitting nodes having to resend the frame. Consequently, the limitation on the throughput persists even as the cell spacings are increased to the point where they are completely out of the carrier-sensing range and free from the exposed node problem.

In Table 3.3, numerical values for the throughput gains and other metrics of interest are shown. Here, it can be seen that the gain obtained with PD-CSMA/CA is quite large (40.2%) for the fixed transmit power scheme. For the TPC and TPC/CST schemes with standard deviation allowance above or equal 2, and the CST(3σ) scheme, the gain is also good (4.6% - 39.5%). While achieving these gains, note that the (Jain's) throughput fairness indices [109] are practically unchanged, whereas increases in retry and failure rates are not very significant. For schemes with just one standard deviation's worth of compensation, our scheme provides little or no improvement. But with such a small fade margin, even their single cell performances are adversely affected, as can be discerned from their lower throughput asymptotes and higher average retry or failure rates. As for

Table 3.3 PD-CSMA/CA Peak Throughput Gains, and Before/After Values for Retry and Failure Rates

Scheme	Cell Space	Throughput			Retry Rate				Fail Rate (units of 10^{-2})			
		Gain (%)	Jain's Index		Avg.		Std.		Avg.		Std.	
			bef	aft	bef	aft	bef	aft	bef	aft	bef	aft
24.7 dBm	3.0	40.2	0.94	0.93	0.62	0.68	0.23	0.31	0.41	0.62	0.83	1.09
TPC(1)	2.5	9.1	0.95	0.96	0.78	0.81	0.41	0.44	1.15	1.11	1.78	1.67
TPC(2)	2.5	25.6	0.97	0.97	0.70	0.80	0.28	0.36	0.68	0.91	0.95	1.31
TPC(3)	2.5	39.5	0.98	0.97	0.67	0.78	0.23	0.34	0.53	0.81	0.66	1.02
CST(1)	2.5	0.0	0.79	0.79	0.95	0.96	0.69	0.70	2.61	2.60	5.10	4.94
CST(2)	2.5	1.9	0.83	0.83	0.65	0.66	0.50	0.52	0.89	0.99	2.34	2.68
CST(3)	3.0	6.9	0.89	0.89	0.59	0.58	0.36	0.35	0.50	0.42	1.19	1.08
TPC/CST(1)	3.0	0.2	0.96	0.96	1.07	1.07	0.57	0.57	2.79	2.89	3.13	3.24
TPC/CST(2)	2.0	4.6	0.90	0.93	0.83	0.85	0.58	0.58	1.69	1.62	3.06	2.82
TPC/CST(3)	2.5	19.7	0.93	0.96	0.72	0.75	0.37	0.38	0.89	0.86	1.47	1.30

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CST schemes in general, our scheme also appears to provide very small improvements.

3.5.3 Results for Scenario 3

For the wall-separated cells scenario described in Section 3.4.3, Figs. 3.17 – 3.20 show the per-cell aggregate uplink and downlink throughput and per-node average delay and retries for the original DCF and the PD-CSMA/CA-enhanced DCF (labeled as ‘P-DCF’ in the charts) as the PAF is varied. Also shown are Jain’s fairness indices [109] for the per-node throughput, delay and retry rates computed across all nodes in one cell.

Based on these graphs, we make the following observations: Firstly, the PD-CSMA/CA-enhanced DCF starts to exhibit throughputs comparable to the DCF in cells separated by high PAFs (i.e., $\text{PAF} > 50$ dB) at a smaller ‘cut-off’ PAF value than the original DCF. For the 4 cubicle configuration, this ‘cut-off’ PAF is 10 dB for PD-CSMA/CA, whereas for the original DCF, it is 40 dB. For the 16 cubicle configuration, the cut-off PAF needed by PD-CSMA/CA is 24 dB, whereas for the original DCF it is still 40 dB.

Secondly, beyond the cut-off PAF, PD-DCF exhibit throughput, throughput fairness, delay and delay fairness performances which are similar to that of the original DCF in cells with high PAF. And although the retry rate and retry rate fairness indices are slightly impaired, the values are still better than the corresponding values for the original DCF at its cut-off PAF.

These two observations are as expected: For PD-DCF, as the PAF is increased beyond a certain point, the concurrent transmissions facilitated by the payload-dropping operation in PD-DCF will no longer suffer high FER, due to the rooms becoming interference-limited at this point. With this low FER, the retry rate also drops below the threshold set for the scheme to fallback to the original DCF. As a result, PD-DCF remains engaged,

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Figure 3.17: Uplink Performance Metrics vs. PAF for Scenario 3 (4 STAs)

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Figure 3.18: Downlink Performance Metrics vs. PAF for Scenario 3 (4 STAs)

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Figure 3.19: Uplink Performance Metrics vs. PAF for Scenario 3 (16 STAs)

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Figure 3.20: Downlink Performance Metrics vs. PAF for Scenario 3 (16 STAs)

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and what would have been wasteful periods of being in the exposed node condition in the original DCF is now exploited by the payload-dropping operation to allow the nodes in the two rooms to transmit concurrently. At this lower cut-off PAF, the performance of PD-DCF approaches that of the original DCF in the single cell case, since effectively, the PD-DCF payload-dropping operation allows the two cells to operate as if they were in isolation.

On the other hand, without the payload-dropping operation, the original DCF will experience the exposed node problem even as the PAF is increased beyond the cut-off PAF value for PD-DCF. As a result, its performance remains stunted compared to PD-DCF at this point. It is only when the PAF is increased beyond a higher value (e.g., 40 dB in the 4 cubicle configuration) that, eventually, the performance of the original DCF in the two cell case approaches that of its performance in the single isolated cell scenario. The reason for the improvement at this higher PAF value is because the cells are no longer within the carrier-sensing range of each other, and as a result the exposed node problem is no longer in effect.

Thirdly, at around 26 – 38 dB PAF where the original DCF exhibit dips in performances, the modified DCF maintains a steady performance. A large degree of these performance dips is due to a fraction of nodes in the cell being forced to refrain from using the medium for an Extended Interframe Spacing (EIFS) duration. The EIFS duration is included in the IEEE 802.11 specs as a mechanism to recover CSMA/CA synchronization in the event of erroneous frame reception. In our simulation, the EIFS period is entered due to the reception of payloads of frames from the interfering cells, which at PAFs greater than 30 dB are mostly corrupted. In PD-DCF, this phenomenon is avoided since these payloads, whether corrupted or not, are dropped.

3.6 Chapter Summary

We have presented a method to modify the IEEE 802.11 DCF to incorporate our PD-CSMA/CA scheme, while maintaining backward compatibility with legacy devices. We have also identified a few shortcomings in the default IEEE 802.11 PHY module included in the ns-2 platform which make it unsuitable for spatial reuse scenarios, and described how we addressed them.

The modified DCF was implemented on the ns-2 platform (along with the PHY-layer enhancements) and tested under three spatial reuse scenarios. From the simulation results for the first 2 scenarios, it can be seen that the PD-CSMA/CA-enhanced DCF provides much better throughputs than the original DCF in deployments where the spacing between cells is used as the primary means to reduce the co-channel interference. The throughput improvement is especially large when fixed transmit power levels are used. For example, the gain is around 40% in the second scenario when the cells are spaced at 3 times their widths. The results also show that in tandem with TPC and/or CST schemes, the modified DCF yields slightly better throughput than the original DCF, especially when a fade margin of 2 standard deviations or more is used to compensate for lognormal shadowing typical in indoor environments. For example, in the second scenario, the improvements are 4.6% and 19.7% when a combination TPC/CST scheme with 2 and 3 standard deviation fade margin are used, respectively.

In the third spatial reuse scenario, the modified DCF was pitted against the original DCF in a situation where walls are used as the primary means to reduce co-channel interference. For this case, the simulation results show that the PD-CSMA/CA-enhanced DCF require walls with lower attenuation than the original to achieve throughputs that are nearly that of isolated cells. PD-CSMA/CA also avoids the detrimental EIFS cycles that

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occur in the normal DCF when co-channel cells are within carrier-sensing distance, but not in reception distance.

In all three scenarios, the simulation results also indicate that the throughput gains were achieved without significantly affecting other performance metrics such as the retry rates, throughput fairness and retry rate fairness.

4 Analysis on the Idle Period Distribution of CSMA/CA

4.1 Overview

CSMA/CA leaves an idle/busy signature (Fig. 4.1) in its band of operation with an idle period distribution that can be mathematically expressed as a function of its contention window size and the number of participating nodes. In the context of this thesis, this distribution is needed in the formulations for the analytical throughput of PD-CSMA/CA in two cells (Chapter 5). Knowledge of this distribution may also allow further analytical

Figure 4.1: Idle Period in (a) CSMA/CA with ACK and (b) with RTS/CTS Signaling

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modeling of CSMA/CA in scenarios that are not possible with just the knowledge currently available in the literature, especially in situations involving co-channel interference or spatial reuse.

Apart from a purely analytical perspective, this distribution may also be useful in real-life applications whereby there is a need for a device to detect CSMA/CA transmissions and the number of actively participating nodes without fully implementing the demodulation scheme for the Physical layer protocol in use. For example, the device may employ a basic energy detector with frequency and bandpass filter set to the operating band under examination, collect the idle period statistics over time and perform best-of-fit tests with the curves generated by the probability mass function (PMF) of the idle period using different values for contention window size and number of nodes. Such applications may be common in devices that have limited processing resources but are still required to perform its sensing functions across a wide range of protocols (e.g., spectrum sensing for cognitive radios, wireless sniffing, etc.).

In this chapter, we propose an accurate way to derive this distribution for CSMA/CA with a single backoff stage (i.e., with a fixed contention window size), and contrast the accuracy of our formulations with simulation results and three approximation methods – one by Bowden et al. [78] and two other which we will describe.

4.2 System Assumptions

As mentioned, our analysis is for the case when the contention window is fixed. As a result, effects such as capture or frame outage due to fading will not affect its validity. However, any node within the network must be able to sense the transmissions of other active nodes in the network, i.e., there are no hidden nodes. Otherwise, the assumption that the backoff counter is decremented when the channel is clear (as per the protocol

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definition) will not be correct. Also, active nodes are assumed to be having at least one frame in its transmission queue during the analysis period, while inactive nodes are assumed to be completely silent throughout the analysis period. Transmissions may be point-to-multipoint as in an infrastructure network, or peer-to-peer as in ad hoc network.

During the busy period, there may be gaps in the busy period (e.g., SIFS in Fig. 4.1). Such gaps are assumed to be smaller than the smallest possible idle period (e.g. DIFS), and are not considered in our analysis.

For the sake of generality and simpler mathematical representation, we denote the idle period, I , as a discrete random variable representing the number of backoff slots at the start of the CSMA/CA cycle (Fig. 4.1). The actual observable idle period, I_{actual} , can be obtained by multiplying I with the backoff slot duration, and adding in any fixed period that may precede it, e.g. $I_{\text{actual}} = I \times \text{aSlotTime} + \text{DIFS}$ as per the IEEE 802.11 standard [1]. Using this convention, for CSMA/CA with fixed contention window, the value of I will be bounded in $[0, W_0 - 1]$ since the backoff counter can only take values in this range.

4.3 Proposed Method

Denote B_n as the random variable representing the new value that a node sets its backoff counter to after a transmission, and B_f for the value at which it is frozen when it senses the channel as busy. At the end of each cycle, there will be between one to N nodes transmitting in the busy period for that cycle (resulting in a collision if more than one node is involved). Let $\Gamma[1, N]$ be the variable for this value.

Let I be the random variable representing the idle period following the busy period in any cycle. Now, in order for I to be exactly i for a particular cycle, two conditions must be met in that cycle: Firstly, the values of all backoff counters right after the busy period

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must be greater or equal to i . Secondly, having met the first condition, at least one of these backoff counter values must be equal to i .

Let us assume that $\Gamma[1, N] = t$ for that particular cycle. Then, in order for the first condition to be met for that cycle, the t transmitting nodes in that cycle must select new values from B_n that are greater or equal to i , while the $(N - t)$ non-transmitting nodes must have frozen counter values selected from B_f that are greater than or equal to i . Since B_n is uniformly flat within $[0, W_0 - 1]$ when the contention window is fixed, these two conditions are mutually exclusive. The probability for this condition to be met for that particular cycle can therefore be expressed as,

$$\Pr(\text{All counters} \geq i \mid \Gamma_{[1, N]} = t) = \Pr(B_n \geq i)^t \cdot \Pr(B_f \geq i)^{N-t} \quad (4.1)$$

The probability for the second condition to be met can be worked out by considering that the second condition is opposite of the situation where all the backoff counter values, having met the first condition, are greater than i , i.e.,

$$\begin{aligned} & \Pr(\text{At least one counter} = i \mid \text{All counters} \geq i, \Gamma_{[1, N]} = t) \\ &= 1 - \Pr(\text{All counters} > i \mid \text{All counters} \geq i, \Gamma_{[1, N]} = t) \\ &= 1 - \Pr(B_n > i \mid B_n \geq i)^t \cdot \Pr(B_f > i \mid B_f \geq i)^{N-t} \\ &= 1 - (1 - \Pr(B_n = i \mid B_n \geq i))^t \cdot (1 - \Pr(B_f = i \mid B_f \geq i))^{N-t} \end{aligned} \quad (4.2)$$

Combining Eqs. (4.1) and (4.2), we obtain,

$$\begin{aligned} \Pr(I = i \mid \Gamma_{[1, N]} = t) &= \Pr(B_n \geq i)^t \cdot \Pr(B_f \geq i)^{N-t} \times \\ & \quad \left(1 - (1 - \Pr(B_n = i \mid B_n \geq i))^t \cdot (1 - \Pr(B_f = i \mid B_f \geq i))^{N-t} \right) \end{aligned} \quad (4.3)$$

Eq. (4.3) above gives the distribution of I for the particular cycle where the number of transmitters in the cycle equals t . To get the distribution of I in any cycle, we take the sum of Eq. (4.3) for all possible values of t , weighted by the probability that the cycle has t transmitters:

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$$\Pr(I = i) = \sum_{\tau=1}^N \left[\Pr(\Gamma_{[1,N]} = \tau) \cdot \Pr(B_n \geq i)^\tau \cdot \Pr(B_f \geq i)^{N-\tau} \cdot \left(1 - (1 - \Pr(B_n = i | B_n \geq i))^\tau \cdot (1 - \Pr(B_f = i | B_f \geq i))^{N-\tau} \right) \right] \quad (4.4)$$

$i \in [0, W_0 - 1]$

Eq. (4.4) is made up of three distributions: $\Gamma_{[1,N]}$, B_n and B_f . The distribution of $\Gamma_{[1,N]}$ can be obtained through solving the Markov chain model of the number of transmitters $\Gamma \equiv \Gamma_{[0,N]}$ at the turn of each slot. The state transition probabilities for Γ are given in [30] as follows:

$$\Pr(\Gamma_{k+1} = \tau_1 | \Gamma_k = \tau_0) = \begin{cases} \binom{N}{\tau_1} \left(\frac{2}{W_0} \right)^{\tau_1} \left(\frac{W_0 - 2}{W_0} \right)^{N-\tau_1} & \tau_0 = 0, \quad \tau_1 \in [0, N] \\ \binom{\tau_0}{\tau_1} \left(\frac{1}{W_0} \right)^{\tau_1} \left(\frac{W_0 - 1}{W_0} \right)^{\tau_0 - \tau_1} & \tau_0 \in [1, N], \quad \tau_1 \in [0, \tau_0] \\ 0 & \tau_0 \in [1, N], \quad \tau_1 \in [\tau_0 + 1, N] \end{cases} \quad (4.5)$$

Its stationary distribution, $\underline{\pi}_\Gamma$ is solvable with:

$$\underline{\pi}_\Gamma = \lim_{n \rightarrow \infty} [1 \ 0 \ \dots] \cdot \underline{P}^n \quad (4.6)$$

where the i -th element of row vector $\underline{\pi}_\Gamma$ equals $\Pr(\Gamma = i)$, and the (i, j) -th element of matrix $\underline{P}$ equals $\Pr(\Gamma_{k+1} = j | \Gamma_k = i)$. $\Gamma_{[1,N]}$ is simply equal to Γ minus the case when $\Gamma = 0$, i.e.,

$$\begin{aligned} \Pr(\Gamma_{[1,N]} = \tau) &= \Pr(\Gamma = \tau | \Gamma > 0) \\ &= \frac{\Pr(\Gamma = \tau)}{1 - \Pr(\Gamma = 0)} \quad \tau \in [1, N] \end{aligned} \quad (4.7)$$

Meanwhile, the distribution for B_n by definition of the protocol is,

$$\Pr(B_n = b) = \frac{1}{W_0} \quad b \in [0, W_0 - 1] \quad (4.8)$$

This leaves us with just one more distribution to solve: B_f , the frozen counter distribution. There are two ways to derive this distribution. Both methods provide same results. To keep things simple, we start off with the easier method.

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4.3.1 Frozen Counter Distribution (Method 1)

This derivation method is based on the observation in [28, 29] and [78] that at the start of any backoff slot, the distribution of the backoff counter value for a node takes on the left-handed triangular distribution in $[0, W_0 - 1]$. We can use this observation to derive B_f . Since the counter of a node is frozen due to the transmission of *other* nodes, it is not unreasonable to assume that the distribution for B_f is also a left-handed triangular distribution, but in the range $[1, W_0 - 1]$ since at the value of zero, the node itself will transmit:

$$\Pr(B_f = b) = \Pr(B_f = W_0 - 1) + m \cdot (W_0 - 1 - b) \quad b \in [1, W_0 - 1] \quad (4.9)$$

$$\sum_{b=1}^{W_0-1} \Pr(B_f = b) = 1 \quad (4.10)$$

Eliminating gradient m from Eq. (4.9) using Eq. (4.10) we obtain:

$$\Pr(B_f = b) = \begin{cases} \frac{2(W_0 - 1 - b)}{(W_0 - 1)(W_0 - 2)} + \frac{2b - W_0}{W_0 - 2} \cdot \Pr(B_f = W_0 - 1) & W_0 > 2 \\ 1 & W_0 = 2 \end{cases} \quad (4.11)$$

where $b \in [1, W_0 - 1]$

The second clause in the above equation has the value ‘1’ because with $W_0 = 2$, B_f can only assume one value, i.e. ‘1’. Note that Eq. (4.11) has an unknown parameter in $\Pr(B_f = W_0 - 1)$. For large windows, this may be approximated to zero. But this will not hold for small windows. Having an accurate value for this point in B_f ’s distribution is the key to having an accurate formula for the idle period distribution instead of an approximation.

4.3.1.1 Probability $\Pr(B_f = W_0 - 1)$

For B_f to take the value of $(W_0 - 1)$, two events must occur consecutively following a collision: Firstly, a collided node must select $(W_0 - 1)$ as its new counter value at the end

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of a cycle in which it had transmitted. Secondly, in the following cycle, the other node (or nodes) involved in the collision transmits immediately, leaving no idle slots for the first node to decrement its counter before freezing it, resulting in B_f taking the same value as B_n . If the third cycle has no idle slots as well, then the first node will freeze its counter at $W_0 - 1$ again, and repeatedly do so as long as subsequent cycles have no idle slots.

This situation of a node having its counter frozen at its new value is not exclusive to the case when the new counter value is $W_0 - 1$: as long as the new value is within $[1, W_0 - 1]$, the above scenario can occur. In order to solve for the specific case when the new selection equals $W_0 - 1$, we must first consider this general case. By set convention, this situation can be represented as $\{B_f = b \mid B_n = b\}$. The flipside of it, i.e., the situation when the counter is not frozen at its new value, is denoted as $\{B_f \neq b \mid B_n = b\}$, or more precisely, $\{B_f < b \mid B_n = b\}$ since $B_f < B_n$. This situation is only possible for nodes that go through a cycle without transmitting in it. Denote α and β as the average times that $\{B_f = b \mid B_n = b\}$ and $\{B_f < b \mid B_n = b\}$ occur respectively, over the renewal interval comprising one cycle with an idle period followed by K ‘busy-period-only’ cycles in which the number of transmitters follow the sequence $\{\Gamma_0, \Gamma_1, \Gamma_2, \dots, \Gamma_k, \Gamma_{k+1}, \dots, \Gamma_{K-1}\}$, where Γ_k represents the number of transmitting nodes in the k -th cycle in the interval, with K in $[1, \infty]$. If α and β is found, then we would have solved $\Pr(B_f = W_0 - 1)$ since,

$$\begin{aligned} \Pr(B_f = W_0 - 1) &= \Pr(B_n = W_0 - 1 \mid B_n > 0) \cdot \frac{\alpha}{\alpha + \beta} \\ &= \frac{1}{W_0 - 1} \cdot \frac{\alpha}{\alpha + \beta} \end{aligned} \quad (4.12)$$

4.3.1.2 Average Times for $\{B_f = b \mid B_n = b\}$

Denote α_{τ_0} as the number of times $\{B_f = b \mid B_n = b\}$ occur in the interval which starts with $\Gamma_0 = \tau_0$. Obviously, with $\tau_0 = 1$, $\{B_f = b \mid B_n = b\}$ cannot happen in the subsequent

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cycle since at least 2 nodes are required to make it happen (i.e., one node to select a non-zero value and the other to select zero for their backoff counters). Hence, $\alpha_1 = 0$.

With $\tau_0 = 2$, $\{B_f = b \mid B_n = b\}$ can only occur if there is a ‘drop’ from 2 to 1 in the sequence for Γ_k . For example, sequences $\{2, 1\}$, $\{2, 1, 1\}$, $\{2, 2, 2, 1, 1\}$ all result in one node freezing its backoff counter at its initial value in each cycle after the ‘drop’. Over all possible sequences matching the general pattern $\{2\ldots, 1\ldots\}$, the average times $\{B_f = b \mid B_n = b\}$ occur can therefore be written as:

$$\begin{aligned} \alpha_2 &= \sum_{i=0}^{\infty} [\Pr(\Gamma_k = 2 \mid \Gamma_{k-1} = 2)]^i \cdot \Pr(\Gamma_k = 1 \mid \Gamma_{k-1} = 2) \cdot \sum_{i=0}^{\infty} [\Pr(\Gamma_k = 1 \mid \Gamma_{k-1} = 1)]^i \\ &= \frac{\Pr(\Gamma_k = 1 \mid \Gamma_{k-1} = 2)}{[1 - \Pr(\Gamma_k = 2 \mid \Gamma_{k-1} = 2)] \cdot [1 - \Pr(\Gamma_k = 1 \mid \Gamma_{k-1} = 1)]} \end{aligned} \quad (4.13)$$

The numerator is the probability that Γ_k transitions from 2 to 1 at some point along the sequence, while the denominator terms are the probabilities that Γ_k is stuck at 1 and 2 for all possible number of repetitions.

With $\tau_0 = 3$, three sets of ‘busy-period-only’ cycle sequences for Γ_k are possible which contains situation: $\{3\ldots, 2\ldots\}$, $\{3\ldots, 1\ldots\}$ and $\{3\ldots, 2\ldots, 1\ldots\}$. The first set will have one node repeatedly encountering this situation, while the last two sets will have 2 nodes doing so. Since the last set includes the pattern $\{2\ldots, 1\ldots\}$, α_2 can be incorporated into the formulation for α_3 as follows:

$$\begin{aligned} \alpha_3 &= \frac{\Pr(\Gamma_k = 2 \mid \Gamma_{k-1} = 3)}{[1 - \Pr(\Gamma_k = 3 \mid \Gamma_{k-1} = 3)] \cdot [1 - \Pr(\Gamma_k = 2 \mid \Gamma_{k-1} = 2)]} \\ &\quad + 2 \cdot \frac{\Pr(\Gamma_k = 1 \mid \Gamma_{k-1} = 3)}{[1 - \Pr(\Gamma_k = 3 \mid \Gamma_{k-1} = 3)] \cdot [1 - \Pr(\Gamma_k = 1 \mid \Gamma_{k-1} = 1)]} \\ &\quad + 2 \cdot \frac{\Pr(\Gamma_k = 2 \mid \Gamma_{k-1} = 3) \cdot \alpha_2}{1 - \Pr(\Gamma_k = 3 \mid \Gamma_{k-1} = 3)} \\ &= \sum_{i=1}^2 \left[(3-i) \cdot \frac{\Pr(\Gamma_k = i \mid \Gamma_{k-1} = 3)}{[1 - \Pr(\Gamma_k = 3 \mid \Gamma_{k-1} = 3)] \cdot [1 - \Pr(\Gamma_k = i \mid \Gamma_{k-1} = i)]} \right] \\ &\quad + 2 \cdot \frac{\Pr(\Gamma_k = 2 \mid \Gamma_{k-1} = 3) \cdot \alpha_2}{1 - \Pr(\Gamma_k = 3 \mid \Gamma_{k-1} = 3)} \end{aligned} \quad (4.14)$$

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With $\tau_0 = 4$, seven sets of ‘busy-period-only’ cycle sequences for Γ_k are possible: $\{4.., 3..\}$, $\{4.., 2..\}$, $\{4.., 1..\}$, $\{4.., 2.., 1..\}$, $\{4.., 3.., 2..\}$, $\{4.., 3.., 1..\}$, $\{4.., 3.., 2.., 1..\}$. The patterns for the first three sets are new. The fourth has the pattern $\{2.., 1..\}$ which is common with $\tau_0 = 2$, but instead of just 1 node having its counter repeatedly frozen, there are three nodes ($4 - 1$). The fifth, sixth and seventh are patterns that are common with $\tau_0 = 3$, but instead of just one node having its counter frozen repeatedly for the first pattern and two for the second and third patterns, we now have two ($4 - 2$) and three ($4 - 1$), respectively. Taking into account these similarities and differences, we can incorporate portions of the formulations for α_2 and α_3 into the formulation for α_4 if Eqs. (4.13) and (4.14) are modified as follows:

$$\alpha_2(\tau) = (\tau - 1) \cdot \frac{\Pr(\Gamma_k = 1 | \Gamma_{k-1} = 2)}{[1 - \Pr(\Gamma_k = 2 | \Gamma_{k-1} = 2)] \cdot [1 - \Pr(\Gamma_k = 1 | \Gamma_{k-1} = 1)]} \quad (4.15)$$

$$\begin{aligned} \alpha_3(\tau) = & \sum_{i=1}^2 \left[(\tau - i) \cdot \frac{\Pr(\Gamma_k = i | \Gamma_{k-1} = 3)}{[1 - \Pr(\Gamma_k = 3 | \Gamma_{k-1} = 3)] \cdot [1 - \Pr(\Gamma_k = i | \Gamma_{k-1} = i)]} \right] \\ & + \frac{\Pr(\Gamma_k = 2 | \Gamma_{k-1} = 3) \cdot \alpha_2(\tau)}{1 - \Pr(\Gamma_k = 3 | \Gamma_{k-1} = 3)} \end{aligned} \quad (4.16)$$

α_4 can then be expressed as follows:

$$\begin{aligned} \alpha_4 = & \sum_{i=1}^3 \left[(4 - i) \cdot \frac{\Pr(\Gamma_k = i | \Gamma_{k-1} = 4)}{[1 - \Pr(\Gamma_k = 4 | \Gamma_{k-1} = 4)] \cdot [1 - \Pr(\Gamma_k = i | \Gamma_{k-1} = i)]} \right] \\ & + \frac{\Pr(\Gamma_k = 2 | \Gamma_{k-1} = 4) \cdot \alpha_2(4)}{1 - \Pr(\Gamma_k = 4 | \Gamma_{k-1} = 4)} + \frac{\Pr(\Gamma_k = 3 | \Gamma_{k-1} = 4) \cdot \alpha_3(4)}{1 - \Pr(\Gamma_k = 4 | \Gamma_{k-1} = 4)} \\ = & \sum_{i=1}^3 \left[(4 - i) \cdot \frac{\Pr(\Gamma_k = i | \Gamma_{k-1} = 4)}{[1 - \Pr(\Gamma_k = 4 | \Gamma_{k-1} = 4)] \cdot [1 - \Pr(\Gamma_k = i | \Gamma_{k-1} = i)]} \right] \\ & + \sum_{i=2}^3 \left[\frac{\Pr(\Gamma_k = i | \Gamma_{k-1} = 4) \cdot \alpha_i(4)}{1 - \Pr(\Gamma_k = i | \Gamma_{k-1} = 4)} \right] \end{aligned} \quad (4.17)$$

Based on Eqs. (4.15), (4.16) and (4.17), it can be worked out that α_{τ_0} can be solved recursively as follows:

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$$\alpha_{\tau_0} = \frac{\sum_{i=1}^{\tau_0-1} \left[\frac{(\tau_0 - i) \cdot \Pr(\Gamma_k = i \mid \Gamma_{k-1} = \tau_0)}{1 - \Pr(\Gamma_k = i \mid \Gamma_{k-1} = i)} \right] + \sum_{i=2}^{\tau_0-1} [\Pr(\Gamma_k = i \mid \Gamma_{k-1} = \tau_0) \cdot \alpha_i(\tau_0)]}{1 - \Pr(\Gamma_k = \tau_0 \mid \Gamma_{k-1} = \tau_0)} \quad (4.18)$$

α which is the parameter we are originally interested in, is the sum of α_{τ_0} over all possible values of τ_0 , weighted by the probability that the interval starts with $\Gamma_0 = \tau_0$:

$$\alpha = \sum_{\tau_0=2}^N [\Pr(\Gamma_k = \tau_0 \mid \Gamma_{k-1} = 0) \cdot \alpha_{\tau_0}] \quad (4.19)$$

4.3.1.3 Average Times for $\{B_f < b \mid B_n = b\}$

The average times for $\{B_f < b \mid B_n = b\}$ can similarly be worked out following the recursive approach used to solve for α . Denote β_{τ_0} as the number of times $\{B_f < b \mid B_n = b\}$ is experienced by a node in the interval. Observing all possible sequences with $\tau_0 = 1$, i.e., sequences which match the pattern $\{1, 1, \dots, 1\}$, it can be worked out that:

$$\begin{aligned} \beta_1 &= \sum_{i=0}^{\infty} [\Pr(\Gamma_k = 1 \mid \Gamma_{k-1} = 1)]^i \\ &= \frac{1}{1 - \Pr(\Gamma_k = 1 \mid \Gamma_{k-1} = 1)} \end{aligned} \quad (4.20)$$

With $\tau_0 = 2$, two general patterns are possible: $\{..2..\}$ and $\{..2, 1..\}$. For this case, it can be worked out that:

$$\begin{aligned} \beta_2 &= \sum_{i=0}^{\infty} [\Pr(\Gamma_k = 2 \mid \Gamma_{k-1} = 2)]^i + \sum_{i=0}^{\infty} [\Pr(\Gamma_k = 2 \mid \Gamma_{k-1} = 2)]^i \cdot \Pr(\Gamma_k = 1 \mid \Gamma_{k-1} = 2) \cdot \beta_1 \\ &= \frac{1 + \Pr(\Gamma_k = 1 \mid \Gamma_{k-1} = 2) \cdot \beta_1}{1 - \Pr(\Gamma_k = 2 \mid \Gamma_{k-1} = 2)} \end{aligned} \quad (4.21)$$

Continuing along this route of increasing values for τ_0 , it can be worked out that β_{τ_0} can be solved recursively with,

$$\beta_{\tau_0} = \frac{1 + \sum_{i=1}^{\tau_0-1} [\Pr(\Gamma_k = i \mid \Gamma_{k-1} = \tau_0) \cdot \beta_i]}{1 - \Pr(\Gamma_k = \tau_0 \mid \Gamma_{k-1} = \tau_0)} \quad (4.22)$$

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β which is the parameter we are primarily interested in, is the sum of β_{τ_0} over all values of τ_0 for which $\{B_f < b \mid B_n = b\}$ is possible (i.e., τ_0 in $[1, N - 1]$), weighted by the probability that the interval starts with $\Gamma_0 = \tau_0$ and the number of nodes not transmitting in the interval:

$$\beta = \begin{cases} \sum_{\tau_0=1}^N [\Pr(\Gamma_k = \tau_0 \mid \Gamma_{k-1} = 0) \cdot (N - \tau_0) \cdot \beta_{\tau_0}] & W_0 > 2 \\ 0 & W_0 = 2 \end{cases} \quad (4.23)$$

The second clause in the above equation equals ‘0’, since $\{B_f < b \mid B_n = b\}$ is not possible when $W_0 = 2$. With this equation, the frozen counter distribution, B_f , is solved: α and β obtained via Eq. (4.19) and Eq. (4.23) can be substituted into Eq. (4.12) to obtain $\Pr(B_f = W_0 - 1)$, which in turn can be substituted into Eq. (4.11) to obtain the frozen counter distribution, $\Pr(B_f = b)$:

$$\begin{aligned} \Pr(B_f = b) &= \begin{cases} \frac{2(W_0 - 1 - b)}{(W_0 - 1)(W_0 - 2)} + \frac{2b - W_0}{(W_0 - 1)(W_0 - 2)} \cdot \frac{\alpha}{\alpha + \beta} & W_0 > 2 \\ 1 & W_0 = 2 \end{cases} \\ &= \begin{cases} \frac{\frac{1}{W_0 - 1} \cdot \alpha + \frac{2(W_0 - 1 - b)}{(W_0 - 1)(W_0 - 2)} \cdot \beta}{\alpha + \beta} & W_0 > 2 \\ 1 & W_0 = 2 \end{cases} \quad (4.24) \\ &\quad b \in [1, W_0 - 1] \end{aligned}$$

This, and the new counter distribution $\Pr(B_n = b)$ given in Eq. (4.8), can be substituted into Eq. (4.4) to get the idle period distribution.

4.3.2 Frozen Counter Distribution (Method 2)

The first method is based on previous researchers’ observation that the backoff counter value at the start of a backoff slot takes on a left-handed triangular distribution, and then inferring that B_f is also a left-handed triangular distribution. Without knowledge of the

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former distribution, the frozen counter distribution can still be derived by working out how it is related to the average times for the events $\{B_f = b \mid B_n = b\}$ and $\{B_f < b \mid B_n = b\}$.

From the results obtained in Sections 4.3.1.2 and 4.3.1.3, we have:

$$\sum_{b=1}^{W_0-1} \Pr(B_f = b \mid B_n = b) = \frac{\alpha}{\alpha + \beta} \quad (4.25)$$

$$\sum_{b=2}^{W_0-1} \Pr(B_f < b \mid B_n = b) = \frac{\beta}{\alpha + \beta} \quad (4.26)$$

Eqs. (4.25) and (4.26) simply state that the probability the counter is frozen at or below its new value is proportionate to α and β , respectively. Since B_n is flat within $[1, W_0 - 1]$, we get from Eq. (4.25) that:

$$\Pr(B_f = b \mid B_n = b) = \frac{1}{W_0 - 1} \cdot \frac{\alpha}{\alpha + \beta} \quad (4.27)$$

Eq. (4.26) can also be interpreted as follows:

$$\begin{aligned} \sum_{b=2}^{W_0-1} \Pr(B_f < b \mid B_n = b) &= \sum_{b_n=2}^{W_0-1} \sum_{b_f=1}^{b_n-1} \Pr(B_f = b_f \mid B_n = b_n) \\ &= \sum_{b_f=1}^{W_0-2} \sum_{b_n=b_f+1}^{W_0-1} \Pr(B_f = b_f \mid B_n = b_n) \\ &= \sum_{b=1}^{W_0-2} \Pr(B_f = b \mid B_n > b) \end{aligned} \quad (4.28)$$

The term inside the double sum on the right-hand side of the second line in Eq. (4.28) must equal some fixed value, since in the case of $\{B_f < b \mid B_n = b\}$, the event of a node having its counter frozen is independent of what value it had selected as its new counter value. Taking this into consideration, we get the following relation from Eq. (4.28):

$$\begin{aligned} \sum_{b=1}^{W_0-2} \Pr(B_f = b \mid B_n > b) &= \sum_{b_f=1}^{W_0-2} \left[\Pr(B_f = b_f \mid B_n = b_f + 1) \right. \\ &\quad \left. + \Pr(B_f = b_f \mid B_n = b_f + 2) + \dots \right. \\ &\quad \left. + \Pr(B_f = b_f \mid B_n = W_0 - 1) \right] \\ &= \sum_{b_f=1}^{W_0-2} [(W - 1 - b_f) \cdot \Pr(B_f = b_f \mid B_n = b_n, b_n > b_f)] \\ \Pr(B_f = b \mid B_n > b) &= (W - 1 - b_f) \cdot \Pr(B_f = b_f \mid B_n = b_n, b_n > b_f) \end{aligned} \quad (4.29)$$

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where the fixed value is conventionally represented as $\Pr(B_f = b_f | B_n = b_n, b_n > b_f)$. Eqs.

(4.26) and (4.28) also give us the following relation:

$$\begin{aligned}
 \frac{\beta}{\alpha + \beta} &= \sum_{b=1}^{W_0-2} \Pr(B_f = b | B_n > b) \\
 &= \sum_{b_f=1}^{W_0-2} [(W-1-b_f) \cdot \Pr(B_f = b_f | B_n = b_n, b_n > b_f)] \\
 &= [(W-2) + (W-3) + \dots + 1] \cdot \Pr(B_f = b_f | B_n = b_n, b_n > b_f) \\
 &= \frac{(W_0-1) \cdot (W_0-2)}{2} \cdot \Pr(B_f = b_f | B_n = b_n, b_n > b_f) \quad (4.30)
 \end{aligned}$$

Eliminating the fixed value $\Pr(B_f = b_f | B_n = b_n, b_n > b_f)$ from Eqs. (4.29) and (4.30) we obtain:

$$\Pr(B_f = b | B_n > b) = \frac{2 \cdot (W-1-b)}{(W_0-1) \cdot (W_0-2)} \cdot \frac{\beta}{\alpha + \beta} \quad (4.31)$$

Eqs. (4.27) and (4.31) provide us the frozen counter distribution:

$$\begin{aligned}
 \Pr(B_f = b) &= \Pr(B_f = b | B_n = b) + \Pr(B_f = b | B_n > b) \\
 &= \begin{cases} \frac{\frac{1}{W_0-1} \cdot \alpha + \frac{2(W_0-1-b)}{(W_0-1)(W_0-2)} \cdot \beta}{\alpha + \beta} & W_0 > 2 \\ 1 & W_0 = 2 \end{cases} \quad (4.32) \\
 &\quad b \in [1, W_0 - 1]
 \end{aligned}$$

which is the same as Eq. (4.24).

4.4 Bowden et al.'s Approximation

Although the analysis and verification in [78] was for the average idle period, Bowden et al. did provide an approximation for the full distribution as an intermediary step. To the best of our knowledge, prior to the analysis given by us in the previous section, Bowden et al.'s is the only one available in the literature touching this subject.

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Bowden et al.'s analysis is based on approximating the discrete backoff counter distribution as a continuous one, and further making two simplifying assumptions: Firstly, it is assumed the new backoff counter value is randomly polled from $[1, W_0]$. Although it was conceded in [78] that the actual range is in $[0, W_0 - 1]$, it was indicated that using this range would not alter the analysis, and that the changes to the results would be minor and can be easily accounted for. Based on this assumption, the continuous cumulative density function approximating the new and running backoff counter distribution was given respectively as:

$$B_{n_{cum}}(b) = 1 - \frac{W_0 - b}{W_0} \quad 0 \leq b \leq W_0 \quad (4.33)$$

$$B_{f_{cum}}(b) = 1 - \left(\frac{W_0 - b}{W_0} \right)^2 \quad 0 \leq b \leq W_0 \quad (4.34)$$

Secondly, it was assumed that in any CSMA/CA cycle, the busy period involves only one transmitter. As such, the probability of the idle period being less than i was given as the product of $(N - 1)$ stations having less than i for their frozen counter values and one station having less than i for its new counter value:

$$\begin{aligned} I_{cum}(i) &= 1 - \left(1 - B_{f_{cum}}(i) \right)^{N-1} \left(1 - B_{n_{cum}}(i) \right) \\ &= 1 - \left(\frac{W_0 - i}{W_0} \right)^{2N-1} \quad 0 \leq i \leq W_0 \end{aligned} \quad (4.35)$$

The discrete idle period distribution was then given as:

$$\Pr(I = i) = I_{cum}(i) - I_{cum}(i - 1) \quad i \in [1, W_0] \quad (4.36)$$

It should be obvious that the two simplifying assumptions as well as the method of modelling discrete probability density functions with continuous counterparts, may render this formula not very accurate especially for cases where the contention window is small

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and/or the number of nodes is large. But seeing as this method precedes our own, by custom we are obligated to compare its accuracy against ours. However, in order to make a fair ‘apples-to-apples’ comparison, at the very least we must reconcile this formula to the fact that the new backoff counter falls within $[0, W_0 - 1]$, the frozen counter within $[1, W_0 - 1]$, and the idle period within $[0, W_0 - 1]$ rather than all falling within $[1, W_0]$. To do this, we modify the analysis by shifting the continuous distributions B_{ncum} and B_{fcum} accordingly:

$$B'_{ncum}(b) = 1 - \frac{W_0 - 1 - b}{W_0} \quad -1 \leq b \leq W_0 - 1 \quad (4.37)$$

$$B'_{fcum}(b) = 1 - \left(\frac{W_0 - 1 - b}{W_0 - 1} \right)^2 \quad 0 \leq b \leq W_0 - 1 \quad (4.38)$$

This modification leads to the following corrected pair of equations for the idle period distribution:

$$I'_{cum}(i) = \begin{cases} 1 - \frac{(W_0 - 1 - i)^{2N-1}}{W_0(W_0 - 1)^{2N-2}} & 0 \leq i \leq W_0 - 1 \\ 1 - \frac{W_0 - 1 - i}{W_0} & -1 \leq i \leq 0 \end{cases} \quad (4.39)$$

$$\Pr(I = i) = I'_{cum}(i) - I'_{cum}(i - 1) \quad i \in [0, W_0 - 1] \quad (4.40)$$

4.4.1 Bowden et al.’s Frozen Counter Distribution

Although Bowden et al. did not explain this in [78], Eq. (4.36) suggests how the discrete frozen counter distribution may also be obtained through the continuous version given in their analysis, albeit after our range corrections (Eq. (4.38)):

$$\Pr(B_f = b) = B'_{fcum}(b) - B'_{fcum}(b - 1) \quad b \in [1, W_0 - 1] \quad (4.41)$$

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4.5 Markov Chain Approximation

Intuitively, the idle period distribution can also be approximated using Eqs. (4.5) and (4.6). Here, we assume that each variate i of the idle distribution has the occurrence probability of a sequence of consecutive idle states of length $(i - 1)$ following a busy period. E.g., to evaluate the probability for $\Pr(I = 3)$, we work out the chain probability for the sequence $\Gamma = \{\tau_k, 0, 0, 0, \tau_{k+4}\}$, where τ_k and τ_{k+4} are non-zeroes. Based on this logic, the idle period distribution following a busy period involving τ transmitters can be expressed as:

$$\Pr(I = i | \Gamma = \tau) = \begin{cases} \Pr(\Gamma_k > 0 | \Gamma_{k-1} = \tau) & i = 0 \\ \frac{\left[\Pr(\Gamma_k = 0 | \Gamma_{k-1} = \tau) \cdot \Pr(\Gamma_k = 0 | \Gamma_{k-1} = 0)^{(i-1)} \right] \cdot \Pr(\Gamma_k > 0 | \Gamma_{k-1} = 0)}{\Pr(\Gamma_k > 0 | \Gamma_{k-1} = 0) \cdot \sum_{\lambda=1}^{W_0-1} \Pr(\Gamma_k = 0 | \Gamma_{k-1} = 0)^{(\lambda-1)}} & i \in [1, W_0 - 1] \end{cases} \quad (4.42)$$

The denominator term in the second clause is just for normalizing the cumulative probability for the above equation to 1. It accounts for the fact that in the Markov chain model, the idle period can be infinitely long, whereas in the actual case its upper bound is $(W_0 - 1)$. Over busy periods involving all number of transmitters, the idle period distribution is therefore:

$$\Pr(I = i) = \frac{\sum_{\tau=1}^N \Pr(\Gamma = \tau) \cdot \Pr(I = i | \Gamma = \tau)}{1 - \Pr(\Gamma = 0)} \quad (4.43)$$

Note however that since this method ignores that the string length is bounded to $(W_0 - 1)$, it may not be very accurate when N is small.

4.6 Simplification of the Proposed Method

From Section 4.3.1.1, it can be surmised that in order for B_f to take the value of $(W_0 - 1)$, there must be a collision. Further, a node involved in the collision must select $(W_0 - 1)$ as its new counter value, while one or more of the other nodes select zero as their new counter values. On the other hand, for B_f to take any value within the range $[1, W_0 - 2]$, the node's counter just need to be at that value when another node transmits. This suggests that the occurrence probability for the former is two or more orders less than the latter, more so if collisions are infrequent, or if collisions involving higher number of nodes are infrequent. Therefore, we can approximate it to zero, resulting in a revision of Eqs. (4.9) and (4.11) to:

$$\Pr(B_f = b) = m \cdot (W_0 - 1 - b) \quad b \in [1, W_0 - 1] \quad (4.44)$$

$$\Pr(B_f = b) = \begin{cases} \frac{2(W_0 - 1 - b)}{(W_0 - 1)(W_0 - 2)} & W_0 > 2 \\ 1 & W_0 = 2 \end{cases} \quad b \in [1, W_0 - 1] \quad (4.45)$$

This simpler formula for B_f allows us to forgo the lengthy derivation for $\Pr(B_f = W_0 - 1)$. As before, substituting this distribution and the new counter distribution into Eq. (4.4) gives us the idle period distribution.

4.7 Simulation Results

To obtain the statistics of the idle period distribution as well as that of the frozen backoff counter for checking out the accuracy of our formulations, simulations were initially carried out using the ns-2 [27] program. Nodes were placed arbitrarily well within carrier-sensing distance in a 10 m by 10 m area with frame sizes set to a constant value (512 bytes), and fed with saturation loads. Changes were made to the IEEE 802.11

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source code to ensure that the contention window is fixed, and to prevent radio capture from occurring (since the focus of our analysis is purely on the CSMA/CA protocol). The source files for this modified ns-2 program is contained in the CD that was submitted along with this thesis.

In order to get a good sample of the statistics, the ns-2 software had to be run repeatedly for a long period of simulated time, and the results tabulated for each setting of W_0 and N . This turned out to be both extremely unwieldy and time consuming in real time. Due to this problem, we ended up writing a CSMA/CA protocol simulator of our own using C programming. This program is contained in the C file, *emp.c*, in the *idistro* software package included in the CD that was submitted along with this thesis. The correctness of our small CSMA/CA protocol implementation has been verified by crosschecking the idle period, frozen backoff and number of transmitter per slot statistics it produces against the same statistics produced by ns-2, under several combinations of W_0 and N .

Like the ns-2, this program can be used to simulate a number of nodes transmitting fixed length frames using a fixed contention window. Unlike the ns-2, for the same configuration and simulated duration, our program could complete the simulation in under a minute, whereas the ns-2 program required hours. The reason for this huge difference in performance because the ns-2 simulator involves a large degree of interaction between different C/C++ and Tcl/Tk modules imitating various layers of the communication channel (e.g., traffic generation, routing, UDP, MAC, PHY, channel, propagation, etc.) using callbacks or virtual functions, with a queue-based scheduler running at the granularity of a floating-point time variable. On the other hand, our C program just simulates the MAC protocol looping at the granularity of the integer slot. Furthermore, in the ns-2 program, transmit power, fading and attenuation due to

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propagation, noise-floor, receiver SINR and radio-capture are all accounted for in determining if a node received a frame successfully or not. Whereas in our program, the ‘channel’ is just a variable which keeps track of the number of concurrent transmissions in each slot, since our assumption is that ideally, all nodes are within sensing range and will detect any transmission with certainty, and any two or more concurrent transmissions always result in a collision.

With this C program, we ran the simulation 30 times for each combination of W_0 and N , with each run starting with a different seed value for the random value generator. In each run, the relative frequencies of 100,000 samples for the frozen backoff counter values and idle periods were recorded and normalized to obtain the probability distribution. With 30 sets of these distributions (one from each run), the 95% confidence intervals (also known as the ± 1.96 standard deviation intervals) of each point in the distribution per combination of W_0 and N were computed.

To compute the analytical formulations for the idle period distribution, we wrote another program. This program, (contained in the file *hyp.c*, in the *idistro* software package included in the CD submitted with this thesis) computes the proposed, Bowden et al.’s, Markov chain and the simplification of the proposed formulas.

In the following subsections, we present comparisons of the results obtained via these analytical methods versus those obtained through simulation.

4.7.1 Results for Frozen Counter Distribution

Since this distribution is a key component towards formulating the idle period distribution, we include it here for comparison. Of the four methods in deriving the idle period, only the proposed, its simplification and Bowden et al.’s methods will be contrasted here. The formulations based on the proposed method are given by Eqs. (4.19),

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(4.23) and (4.32) in Section 4.3, whereas for the simplified version of the proposed method by Eqs. (4.19) and (4.23) in Section 4.3, and Eq. (4.45) in Section 4.6. Formulations according to Bowden et al.'s method, albeit after we have corrected its range, are given by Eqs. (4.38) and (4.41) in Section 4.4. The Markov chain approximation method is ignored in this section since it does not make use of this distribution at all.

Figs. 4.2 – 4.5 show the frozen counter distributions for W_0 equals 4, 8, 16 and 32 based on the average of the 30 simulation results, and values obtained from the three analyses. As explained qualitatively and quantitatively in Sections 4.3.1 and 4.3.2, the frozen counter has a left-handed triangular distribution. Hence it should come as no surprise that all the charts are basically straight lines with a negative gradient. For the first two charts ($W_0 = 4$ and $W_0 = 8$) we superimpose two curves for the simulation results and the proposed formulation, one for $N = 2$ and the other for $N = 10$. For $W_0 = 16$ and $W_0 = 32$, only the curve for $N = 10$ is shown since the curve for $N = 2$ is virtually coincident at the graphing resolution. For Bowden et al.'s formulation and the simplified version of the proposed, we show only one curve per chart since the formulas are independent of N .

Based on these charts, we can surmise the following: First and foremost, the values provided by our proposed method are almost equal to the average simulation values. Although not particularly discernable, points on the curve for the proposed method fall within the 95% confidence interval error bars (computed based on the 30 runs) on the simulation curves, suggesting that our proposed method is very accurate. Meanwhile, Bowden et al.'s and our simplified method are off by a discernable margin, especially for small W_0 s (e.g., for $W_0 = 4$ and $W_0 = 8$). For even smaller W_0 s (e.g., for $W_0 = 4$), it can also be observed that our simplified method is not as good as Bowden et al.'s, especially when N is large ($N = 10$). However, starting with $W_0 = 8$, our simplified formula tends to

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Figure 4.2: Frozen Counter Distribution for $W_0 = 4$, and $N = \{2, 10\}$: Analysis vs. Simulation

Figure 4.3: Frozen Counter Distribution for $W_0 = 8$, and $N = \{2, 10\}$: Analysis vs. Simulation

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Figure 4.4: Frozen Counter Distribution for $W_0 = 16$, and $N = 10$: Analysis vs. Simulation

Figure 4.5: Frozen Counter Distribution for $W_0 = 32$, and $N = 10$: Analysis vs. Simulation

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become more accurate than Bowden et al.'s with increasing W_0 .

For a finer demonstration on the relative accuracies of the methods, we present a comparison in numerical form in Tables 4.1 and 4.2. Since differences are more telling at smaller W_0 s, we show only the results for $W_0 = 4$ and $W_0 = 7$ for $N = \{2, 4, 6, 8, 10\}$. Here, each point in the distribution, plus the expectation and variance of the distribution computed using the three methods are compared against the 30-sample 95% confidence intervals for the simulation values.

In these two tables, it can be seen that all the values computed using the proposed method fall within the 95% confidence intervals of the simulation values. In contrast, *none* of the values computed by either Bowden et al.'s method or our simplified method are within these confidence intervals. This clearly distinguishes the accuracy of the proposed method. As for the approximation methods, with $W_0 = 4$, the inadequacy of assuming $\Pr(B_f = W_0 - 1)$ is nearly zero for the simplified method is exposed severely, and as such it loses out significantly to Bowden et al.'s method in terms of accuracy. But with $W_0 = 7$, this assumption becomes acceptable, resulting in the simplified method's accuracy being slightly better than Bowden et al.'s. As evidenced by the charts, this trend in the relative accuracies of the two methods continues beyond $W_0 > 7$.

In Table 4.3, we present a set of results for large W_0 s, i.e., $W_0 = \{64, 128, 256, 512, 1024\}$. Here, since there are many points in the distribution, we show a comparison on just the expectation and variance for the distribution. At this range, the range of N in $[2, 10]$ makes little difference to the distributions, so we only tabulate data for $N = 10$.

As in all the previous results, the values for the proposed method still fall within the 95% confidence intervals of the simulation values. Meanwhile, values for the simplified method have almost converged to that for the proposed method and thus also fall in the middle of the confidence interval. However, values for the Bowden et al.'s

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Table 4.1 Frozen Counter Distribution, Expectation and Variation for $W_0 = 4$ and $N = \{2, 4, 6, 8, 10\}$: Analysis vs. Simulation

N	$Method$	$Pr(B_f =$			$E[B_f]$	$Var[B_f]$
		1)	2)	3)		
2	Simulation	0.6083	0.3282	0.0530	1.4370	0.3522
		0.6169	0.3363	0.0574	1.4482	0.3619
	Proposed	0.6111	0.3333	0.0556	1.4444	0.3580
4	Simulation	0.5927	0.3314	0.0698	1.4733	0.3890
		0.5971	0.3354	0.0735	1.4803	0.3966
	Proposed	0.5950	0.3333	0.0717	1.4767	0.3928
6	Simulation	0.5808	0.3325	0.0824	1.4987	0.4147
		0.5841	0.3354	0.0850	1.5038	0.4199
	Proposed	0.5831	0.3333	0.0836	1.5005	0.4172
8	Simulation	0.5737	0.3317	0.0910	1.5149	0.4318
		0.5764	0.3340	0.0932	1.5192	0.4360
	Proposed	0.5747	0.3333	0.0920	1.5173	0.4337
10	Simulation	0.5682	0.3315	0.0964	1.5253	0.4421
		0.5713	0.3340	0.0986	1.5301	0.4464
	Proposed	0.5687	0.3333	0.0980	1.5292	0.4450
*	Prop. Simp.	0.6667	0.3333	0.0000	1.3333	0.2222
	Bowden	0.5556	0.3333	0.1111	1.5556	0.4691

Table 4.2 Frozen Counter Distribution, Expectation and Variation for $W_0 = 7$ and $N = \{2, 4, 6, 8, 10\}$: Analysis vs. Simulation

N	$Method$	$Pr(B_f =$						$E[B_f]$	$Var[B_f]$
		1)	2)	3)	4)	5)	6)		
2	Simul.	0.3216	0.2577	0.1940	0.1311	0.0687	0.0069	2.3764	1.6606
		0.3295	0.2663	0.2024	0.1388	0.0742	0.0088	2.4000	1.7020
	Prop.	0.3254	0.2619	0.1984	0.1349	0.0714	0.0079	2.3889	1.6821
4	Simul.	0.3217	0.2585	0.1959	0.1338	0.0711	0.0091	2.3936	1.6961
		0.3259	0.2626	0.2001	0.1371	0.0736	0.0106	2.4095	1.7263
	Prop.	0.3235	0.2608	0.1980	0.1353	0.0725	0.0098	2.4019	1.7108
6	Simul.	0.3199	0.2580	0.1960	0.1344	0.0724	0.0111	2.4079	1.7284
		0.3234	0.2614	0.1991	0.1370	0.0751	0.0122	2.4222	1.7508
	Prop.	0.3217	0.2597	0.1977	0.1357	0.0736	0.0116	2.4148	1.7389
8	Simul.	0.3184	0.2575	0.1964	0.1350	0.0738	0.0129	2.4217	1.7564
		0.3212	0.2598	0.1985	0.1369	0.0756	0.0138	2.4328	1.7739
	Prop.	0.3200	0.2586	0.1973	0.1360	0.0747	0.0134	2.4270	1.7653
10	Simul.	0.3167	0.2569	0.1960	0.1352	0.0748	0.0146	2.4318	1.7815
		0.3200	0.2589	0.1978	0.1374	0.0763	0.0154	2.4437	1.7957
	Prop.	0.3184	0.2577	0.1970	0.1363	0.0757	0.0150	2.4382	1.7892
*	Prop. S.	0.3333	0.2667	0.2000	0.1333	0.0667	0.0000	2.3333	1.5556
	Bowden	0.3056	0.2500	0.1944	0.1389	0.0833	0.0278	2.5278	1.9715

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Table 4.3 Expectation and Variance for the Frozen Counter Distribution for $W_0 = \{64, 128, 256, 512, 1024\}$ and $N = 10$: Analysis vs. Simulation

<i>Par</i>	<i>Method</i>	W_0				
		64	128	256	512	1024
$E[B_f]$	Simul.	21.32	42.64	85.21	170.44	340.95
		21.36	42.71	85.44	170.87	341.69
	Prop.	21.34	42.67	85.33	170.67	341.33
	Prop. S.	21.33	42.67	85.33	170.67	341.33
	Bowden	21.50	42.83	85.50	170.83	341.50
$Var[B_f]$	Simul.	216.66	887.52	3591.32	14443.86	57954.21
		217.41	890.46	3605.88	14506.08	58177.74
	Prop.	217.02	889.01	3598.34	14478.34	58083.67
	Prop. S.	216.89	888.89	3598.22	14478.22	58083.56
	Bowden	220.47	896.03	3612.47	14506.69	58140.47

method still remain outside for $W_0 = \{64, 128, 256\}$, although eventually entering the interval for $W_0 = \{512, 1024\}$.

Seeing as the proposed method always seem to yield values within the 95% confidence intervals of the simulation values, we proceeded to run Pearson's chi-squared goodness-of-fit test [111] against a total of 11160 sets of simulation results from 20 runs of each combination of W_0 in $[3, 64]$ and N in $[2, 10]$. In each run, a total of 100000 frozen counter samples were collected. The program we wrote for this task is contained in the C file, chi.c, in the idistro software package included in the CD that was submitted along with this thesis. Table 4.4 shows the distribution of the p-values obtained for each method.

Table 4.4 Results of Pearson's Chi-Square Goodness of Fit Tests on the Hypothesized Frozen Counter Distributions for $W_0 \in [3, 64]$ and $N \in [2, 10]$.

<i>Method</i>	<i>p-value</i>				
	> 0.100	$(0.10, 0.05)$	$(0.05, 0.025)$	$(0.025, 0.01)$	< 0.01
Proposed	0.9336	0.0336	0.0159	0.0088	0.0082
Prop. Simp.	0.0816	0.0020	0.0005	0.0009	0.9150
Bowden	0.0025	0.0018	0.0034	0.0076	0.9847

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From this table, it can be seen that 96.7% (based on $p\text{-value} > 0.05$) of the simulation data exhibit acceptable deviations from the distribution hypothesized via the proposed method, compared to less than 8.3% for the two approximation methods.

4.7.2 Results for Idle Period Distribution

In this section, the accuracies of the four methods for deriving the idle period distribution will be pitted against the simulation results and each other. Formulas for the proposed method are given in Eqs. (4.4), (4.19), (4.23) and (4.32). For its simplified counterpart, the formulas are given in Eqs. (4.4) and (4.45). Bowden's formulas are expressed by Eqs. (4.39) and (4.40), while the Markov Chain approximation is given by Eqs. (4.42) and (4.43).

Figs. 4.6 – 4.9 show the idle period distributions for when W_0 equals 4, 8, 16 and 32 based on the average of the 30 simulation results, and values obtained from the four different techniques. In general the curve starts with a non-zero value at ($I = 0$), abruptly peaks at ($I = 1$) and then tapers off slowly towards the right end of the distribution. As N increases, the peak becomes narrower, but remains located ($I = 1$). The reason why the curve is shaped as such is largely due to the left-handed triangular shape of the frozen counter distribution which peaks at ($B_f = 1$). Although this latter distribution tapers off linearly to the right, the probability distribution for at least one node having a certain frozen counter value in a group of N nodes would also end up with a peak at ($B_f = 1$), but with a concaved taper that slopes off at a sharper angle as N increases.

Note that in all four charts, the proposed method yields a curve that is practically coincident on the simulation curve. Meanwhile, the curve for the simplified method is very nearly coincident but for when both the values for N and W_0 are very small (e.g., when $W_0 = 4$ and $N = 2$). In this case, its deviation from the simulation curve, though

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Figure 4.6: Idle Period Distribution for $W_0 = 4$, and $N = \{2, 10\}$: Analysis vs. Simulation

Figure 4.7: Idle Period Distribution for $W_0 = 8$, and $N = \{2, 10\}$: Analysis vs. Simulation

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Figure 4.8: Idle Period Distribution for $W_0 = 16$, and $N = \{2, 10\}$: Analysis vs. Simulation

Figure 4.9: Idle Period Distribution for $W_0 = 32$, and $N = \{2, 10\}$: Analysis vs. Simulation

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obvious, is not as bad as the other two approximation methods. The Markov chain approximation and Bowden et al.s' method seem to yield the same degrees of deviation as the simplified method when both values for N and W_0 are very small (e.g., $W_0 = 4$ and $N = 2$). However, as N gets larger while keeping to small values for W_0 , the deviation for Bowden et al.'s method is aggravated immensely, whereas the accuracy for the Markov chain method improves to the point of nearly matching the simulation curve. This trend continues in their curves for $W_0 = 8$. However, with increasing W_0 s, the accuracy of Bowden et. al's method improves to the point of matching that of the proposed method and its simplification when $W_0 = 32$, whereas the Markov chain method continues to exhibit deviations which may either not improve or improve very slowly beyond $W_0 = 32$.

Table 4.5 quantitatively confirms our initial observations regarding the relative accuracies of the methods for small W_0 s. Besides points in the distribution, we also include the expectation, variance, and the Pearson's chi-squared (χ^2) test measure and passing rates (at p-value > 0.05) for comparison. Here, it can be seen that results for the

Table 4.5 Analysis vs. Simulation: Idle Period Distribution, Expectation, Variance, Chi-Square Test Measure and Pass Rates for $W_0 = 4$ and $N = \{2, 10\}$

N	<i>Method</i>	$Pr(I =$				$E[I]$	$Var[I]$	$Avg. \chi^2$	% <i>Pass</i>
		$0)$	$1)$	$2)$	$3)$				
2	Simulation	0.295	0.492	0.181	0.026	0.935	0.578	-	-
	(95% CI)	0.299	0.496	0.184	0.027	0.942	0.585	-	-
	Proposed	0.297	0.495	0.182	0.026	0.937	0.579	2.2	100.0
	Prop. Simp.	0.297	0.516	0.172	0.016	0.906	0.522	914.7	0.0
	Bowden	0.250	0.528	0.194	0.028	1.000	0.556	1175.4	0.0
10	Markov	0.300	0.533	0.133	0.033	0.900	0.557	2226.1	0.0
	Simulation	0.524	0.472	0.000	0.000	0.473	0.250	-	-
	(95% CI)	0.528	0.475	0.001	0.000	0.476	0.251	-	-
	Proposed	0.526	0.473	0.000	0.000	0.474	0.250	4.12	66.7
	Prop. Simp.	0.526	0.474	0.000	0.000	0.474	0.250	167.47	0.0
	Bowden	0.250	0.750	0.000	0.000	0.750	0.188	40650.77	0.0
	Markov	0.526	0.473	0.000	0.000	0.474	0.250	1.03	100.0

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proposed method fall within the 95% confidence interval of the simulation results, for both $N = 2$ and $N = 10$, whereas for the results for the simplified and Markov Chain method, this occurs only for $N = 10$. At $N = 2$, the proposed method passes the chi-squared test for all 30 simulation runs. For $N = 10$ however, its pass rate drops to 67%, even though the per-test average χ^2 measure remains relatively low. At this setting, it is surpassed by the Markov Chain method by both the χ^2 measure and passing rates. Meanwhile, the simplified method shows more accuracy than Bowden et al.'s method, based on the χ^2 measure. At $N = 10$ the inadequacy of the latter method is exposed by its relatively large χ^2 value.

As indicated by the graph for $W_0 = 32$, with the exception of the Markov Chain method, results for the methods fall or converge on the simulation results for larger W_0 's. This is demonstrated numerically in Table 4.6 which shows the results for the methods falling within the 95% confidence band of the simulation results and having low χ^2 scores. In addition to this, the three methods also pass the chi-squared test for $N = 2$. For $N = 10$,

Table 4.6 Analysis vs. Simulation: Idle Period Expectation, Variance, Chi-Square Test Measure and Pass Rates for $W_0 = 64$ and $N = \{2, 10\}$

N	Method	$E[I]$	$Var[I]$	Avg. χ^2	% Pass
2	Simulation (95% CI)	15.945 16.049	149.170 151.805	-	-
	Proposed	15.996	150.560	56.4	100.0
	Prop. Simp.	15.994	150.510	56.5	100.0
	Bowden	16.000	150.534	56.6	100.0
	Markov	14.835	173.358	4893.0	0.0
10	Simulation (95% CI)	3.599 3.621	8.866 9.081	-	-
	Proposed	3.610	8.987	25.4	96.7
	Prop. Simp.	3.610	8.982	25.4	96.7
	Bowden	3.618	8.971	57.3	0.0
	Markov	3.610	9.899	2226.1	0.0

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despite having results within the confidence interval, Bowden et. al.'s method fails the test in all 30 runs. Meanwhile, the numbers for the Markov Chain method suggest that this method may not be suitable for large W_0 s.

To conclude our analysis of the results, in Table 4.7 we rank the methods based on their per-test average χ^2 scores and passing rates (at p-value > 0.05) for chi-squared tests done for 30 simulation runs for each combination of $W_0 = \{4, 8, 16, 32, 64\}$ and $N = \{2, 4, 6, 8, 10\}$ (for a total of 750 tests).

Table 4.7 Results of Pearson's Chi-Square Goodness of Fit Tests on the Hypothesized Idle Period Distributions for all combinations of $W_0 = \{4, 8, 16, 32, 64\}$ and $N = \{2, 4, 6, 8, 10\}$.

<i>Method</i>	<i>Avg. χ^2</i>	<i>% Pass</i>
Proposed	15.6	88.4
Prop. Simp.	138.8	54.8
Bowden	5480.4	16.7
Markov	1187.4	7.9

4.8 Chapter Summary

We have presented a detailed analytical formulation for the idle period distribution in CSMA/CA with a single backoff stage. Against simulation results, this formulation appears to be very accurate, judging from the results of the Pearson's Chi-squared goodness-of-fit tests under a wide range of settings for contention window size and number of nodes. This finding could be a useful addition to the knowledge base in the literature concerning CSMA/CA from a purely analytical perspective, and may act as a starting point for arriving at the exact expression for the idle period for CSMA/CA with multiple backoff stages. It may also be useful in spectrum sensing or wireless sniffing applications where there is a need to detect CSMA/CA transmissions without the full physical transceiver implementation.

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In addition to this precise method, we have also provided a simpler method which is much more accurate than existing methods. Though not as accurate as the detailed method at very small values for contention windows and number of nodes, its computation is a lot simpler and will probably suffice for our intended application, which is the derivation of PD-CSMA/CA's throughput in two interference-limited cells – the subject which we deal with in the following chapter.

It should be noted however that the proposed method (and its simplification) are derived based on making several simplifying assumptions of the operation of CSMA/CA in a single-cell. Because the existing methods are also derived based on these same set of assumptions, we are able to make an apples-to-apples comparison and show that the proposed method has the best accuracy. However, in real world scenarios, these simplifying assumptions may not hold. As such, none of the methods described in this chapter can be expected to be accurate.

5 Analytical Model of PD-CSMA/CA in Two Interference-Limited Cells

5.1 Overview

In Chapter 3, the performance of PD-CSMA/CA was evaluated under a simulation program, complete with radio propagation effects such as lognormal fading and partition attenuation, and physical transceivers that took into account cumulative interference and BER-SINR curves in deciding whether a frame's preamble was detected or missed, or if its physical layer header or payload was received correctly or erroneously. Up to 4 cells were simulated at varying spacing, and besides the exposed node syndrome, almost all other known effects such as hidden nodes, radio capture, frame outages and missed detections were accounted for. Out of those simulation efforts we obtained sufficient proof that the concept could work in real systems, and that it indeed improves the throughput for co-channel interference limited cells, even for transceivers capable of perfectly filtering out interfering signals via energy detection threshold control.

In this chapter, we propose a different way to evaluate the performance improvement of PD-CSMA/CA over normal CSMA/CA – one based purely on mathematical analysis. To do this, we developed an analytically-tractable two-cell interference-limited system

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model in which ideal radio conditions and basic CSMA/CA operations are assumed. Based on this system model, we develop a Markov chain model of PD-CSMA/CA and subsequently derive its throughput in relation to the number of participating nodes, the contention window size, frame header and payload durations. To contrast its performance, we also develop the formulations for CSMA/CA's throughput in the same system. Finally, we assess the accuracy of both formulations with simulation results.

5.2 System Assumptions

5.2.1 Network Topology

Figure 5.1: Topology under Consideration: Two Cells with N Nodes Each, Separated by at Least the Co-Channel Interference-Limiting Distance, but Still within the Preamble Detection Range.

For the analysis, we adopt the two-cell topology depicted in Fig. 5.1. In between these two cells, there may be other cells, but they operate in different channels with negligible crosstalk and are thus ignored in our analysis. Each cell serves a small but equal N number of nodes ranging between 2 to 10, and are sized and spaced above an interference-limiting distance, d_i , such that even if all nodes in one cell were to transmit concurrently, the power of the cumulative interference would not be enough to corrupt a singular transmission occurring at the same time between any two nodes in the other cell.

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To be certain that this condition is met regardless of how nodes are placed within the cells, we take the worst case scenario when all the interfering signals are originating from B0, while the singular transmission is from A1 to A0. Given the desired cell diameter ($2R$), the reference close-in transmit power (P_t) and the minimum SINR required for correct payload reception ($SINR_{pavl}$), this singular signal, after traversing a distance of $2R$, must arrive with $SINR_{pavl}$ strength above the cumulative interference which has traveled a distance of d_i , i.e.:

$$SINR_{pavl} = (P_t - 10n \log(2R)) - (P_t - 10n \log(d_i) + 10 \log N)$$

$$d_i = 2R \cdot \left(N \cdot 10^{\frac{SINR_{pavl}}{10}} \right)^{\frac{1}{n}} \quad (5.1)$$

At the same time, the cells must also be spaced below a preamble sensing/detection distance (d_s) such that each node is able to reliably detect the preamble transmission by any other node in either cell when it is sensing the channel during the contention process. In other words, there can be no hidden nodes in the system. This distance can be determined by considering that the singular preamble transmission from B1 has to be detectable at A1, i.e., the signal must arrive at a level above the receiver sensitivity threshold (for preambles), R_s , after traversing a distance of $(4R + d_s)$:

$$R_s = P_t - 10n \log(4R + d_s)$$

$$d_s = 10^{\frac{P_t - R_s}{10n}} - 4R \quad (5.2)$$

To get a feel of what these distances are like, or to dispel the doubt that cell placements based on these restrictions are unlikely to be both interference-limited and have no hidden nodes in real situations, consider an indoor system ($n = 4$) with two 10 m cells each comprising 10 IEEE 802.11b/g nodes, with each node having the following nominal values for their transceiver parameters: $P_t = 20$ dBm, $SINR_{pavl} = 20$ dBm [50] and $R_s = -76$

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dBm [1]. For this system, $d_i = 56$ m and $d_s = 231$ m. Based on these figures, scenarios meeting these two conditions are more than just plausible, since one could easily fit four interference-limited cells in a row based on these distances and still have the furthest nodes within sensing range of one another.

Based on the cell spacings expressed in Eqs. (5.1) and (5.2), a singular transmission in one cell will ideally be received error-free regardless of the number of concurrent transmissions in the other cells, due to radio capture. Capture may also occur within cells, but for simplicity sake, we assume that this does not happen (same as in [28-30, 93-95, 103]).

5.2.2 Application Traffic

There are no traffic flows between cells. Within each cell, the flows are assumed to be single-hop peer to peer as in ad hoc networks, but is also applicable to point to multi-point as in infrastructure networks.

On a side note, the minimum cell separation needed for interference-limited condition for the infrastructure type of traffic flow is theoretically half that of the ad hoc type. This is because the maximum distance a signal needs to travel in infrastructure-based networks is the distance between centre of the cell to its edge, since the AP is normally assumed to be at the centre of the cell. This distance is equivalent to the cell's radius, R . In contrast, the maximum distance a signal needs to travel in the peer-to-peer scenario, as described in Section 5.2.1, is the distance between one edge of the cell to the opposing edge, or $2R$. Taking this difference into consideration, the factor of $2R$ in Equation 5.1 ought to be revised to just R to better reflect the minimum cell separation required.

As in [28-30], each node operates at saturation load, i.e., there is always at least one frame queued up for transmission at any instance. This assumption is necessary to ensure

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that the Markov chain is not complicated further with extra states to account for nodes that are not in the contention process at the end of a busy state, or worse still, for nodes that receive frames from upper layers in between the idle to idle state transitions during the contention process.

5.2.3 CSMA/CA Protocol

The contention window, W_0 is fixed. Each frame has a duration L and comprises a header and payload part with durations H and P that are both rounded up to and expressed as multiples of the idle slot duration, σ . P is assumed to be greater than W_0 . We also simplify matters by assuming a broadcast mode of transmission, i.e., there are no ACK frames, and hence, nodes do not wait an interframe period after a busy period (e.g. DIFS in IEEE 802.11) before rejoining the contention process. Consequently, the duration of the collided transmission state T_c and the successful transmission state T_s are both equal to L . The throughput equation for CSMA/CA in a single isolated cell given in [28-30] can thus be simplified to:

$$\eta_{iso} = \frac{P \cdot \Pr(\Gamma_N = 1)}{\Pr(\Gamma_N = 0) + L \cdot (1 - \Pr(\Gamma_N = 0))} \quad (5.3)$$

This constant busy state duration assumption makes our model more suitable for representing the baseline, single payload frame transmissions as per the classical ALOHA, CSMA or CSMA/CA analyses done in [4, 5, 93-95], where it is assumed the acknowledgement mechanism is conveyed in another channel, or where its transmission time is negligible compared to the transmission time for the payload frame.

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5.2.4 PHY Preamble & Header Reception

We assume that the information obtained while receiving the preamble and header of the frame required in the decision to drop or retain the payload survives collisions. This assumption is reasonable if we consider the following points:

- **Signal strength measurement based payload dropping.** As mentioned in Section 1.2, the criteria for dropping the payload can be based purely on comparing the received signal power measurement of the preamble against a threshold. While this thresholding scheme is outside the scope of this analytical model, it is possible since, as indicated in Section 5.2.1, in an interference-limited system, the signals transmitted from outside a cell will always be weaker than the signals that are transmitted from within the cell by at least the minimum SINR required for correct reception of the payload for transmissions from within the cell, even if all nodes outside of the cell transmit concurrently. Since only the aggregate energy measurement is needed for this purpose, it can be obtained by a node regardless of how many collided signals are arriving at its antenna.
- **Low collision probability in real-life scenarios.** In practical systems, the CSMA/CA window is normally configured to minimize collisions. Take for example, the IEEE 802.11, where the minimum contention window size, W , is 32, and the maximum is 1024. Based on our simulations, Table 5.1 shows the probability distribution for the number of concurrent transmissions for 10 nodes with $W = [4, 8, 16, 32]$, based on the sampling of 5000 busy periods involving one or more concurrent transmissions. Based on this statistics, for a real-life system such as the IEEE 802.11, we see that about 95% of the time ($0.747 + 0.205$), there is no collision or collisions involving only 2 transmissions, even while it is

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Table 5.1: Probability of Concurrent Transmissions in CSMA/CA Cell according to Contention Window Size.

W	Probability of t concurrent transmissions									
	$t=1$	$t=2$	$t=3$	$t=4$	$t=5$	$t=6$	$t=7$	$t=8$	$t=9$	$t=10$
32	0.747	0.205	0.041	0.004	0.000	0.000	0.000	0.000	0.000	0.000
16	0.562	0.291	0.114	0.013	0.028	0.000	0.000	0.000	0.000	0.000
8	0.372	0.247	0.209	0.113	0.045	0.011	0.003	0.000	0.000	0.000
4	0.334	0.161	0.114	0.113	0.104	0.094	0.057	0.019	0.004	0.000

operating at the minimum contention window size of 32. Meanwhile for $W = 8$ and $W = 16$, collisions involving 5 or more transmission occur only about 5% of the time. It is only when we reduce the window size to an unreasonably small value ($W = 4$) that we see a higher percentage of collisions involving more than 5 transmissions. Even then, there is either no collision or collisions involving 5 or less transmissions 80% of the time.

- **Spreading Gain in Header, and the Effect of Delay and/or Power Capture.** It is possible to design the modulation and coding scheme for radio frame headers such as to make them resilient to collisions, especially when the number of transmissions involved in the collision is small. This seems to be the case especially for spread-spectrum based coding scheme, according to the results of analyses dealing with frame capture probability in multiple collision scenarios [112,113]. In [113] for example, it is shown that even with 20 160-bit frames arriving in the same timeslot in a spread-spectrum based S-ALOHA system under light fading, the probability of capture is still slightly above 80%. This high rate of capture is due to the processing gain provided by a spreading factor of 256 chips per symbol of information, and the very slight differences in the received power and time of arrivals of the frames.

For PD-CSMA/CA, we only need a few bits of information to represent the cell identifier. In the simulation done in Chapter 3, we used only 3 bits to

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represent this cell identity. These 3 bits, along with information typically encoded in the PHY header such as the length of the PHY payload will need not more than 30 bits (i.e., 16 bits for the payload length, 5 bits for its modulation and coding scheme, and the 3-bit cell identifier). Since the probability of failure for k stretch of bits for a given BER is $1 - (1 - \text{BER})^k$, this smaller number of bits should result in a better capture probability than what is reported in [113], where the number of bits is about 5 times as many. For this reason, and also since, as indicated in the earlier point, the likelihood of collisions involving more than 5 transmissions is small, we may also not need such a high spreading factor.

- **Theoretical Upper Bound.** Finally, we may limit the applicability of the model to just the determination the theoretical upper bound of PD-CSMA/CA throughput. If the information needed to drop the payload is corrupted, the result would be that the payload would not be dropped (since PD-CSMA/CA can only drop the payload if it is determined that the frame is from another cell). In this case, PD-CSMA/CA falls back to normal CSMA/CA operation. As a result the throughput will tend towards that of normal CSMA/CA.

5.3 CSMA/CA in Two Cells

For comparison, we formulate the throughput for CSMA/CA in the two cells. Since all nodes are in frame detection range, nodes in one cell suspend their contention process when nodes in the other cell transmit. This behavior is no different than that of nodes in a single isolated cell. Therefore, the two cells can be considered as one large cell with $2N$ nodes. Denote Γ_{2N} as the discrete-time state variable representing the number of nodes transmitting concurrently at the turn of each idle slot or busy period. In [30], it has been

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shown that Γ_{2N} can be modeled as a Markov process with the following transition probabilities if the contention window is fixed:

$$\Pr(\Gamma_{2N,k+1} = \tau_1 \mid \Gamma_{2N,k} = \tau_0) = \begin{cases} \left(\binom{2N}{\tau_1} \left(\frac{2}{W_0} \right)^{\tau_1} \left(\frac{W_0 - 2}{W_0} \right)^{2N - \tau_1} \right) & \tau_0 = 0, \quad \tau_1 \in [0, 2N] \\ \left(\binom{\tau_0}{\tau_1} \left(\frac{1}{W_0} \right)^{\tau_1} \left(\frac{W_0 - 1}{W_0} \right)^{\tau_0 - \tau_1} \right) & \tau_0 \in [1, 2N], \quad \tau_1 \in [0, \tau_0] \\ 0 & \text{otherwise} \end{cases} \quad (5.4)$$

The stationary distribution of Γ_{2N} is solvable with,

$$\underline{\pi}_{\Gamma_{2N}} = \lim_{n \rightarrow \infty} [1 \ 0 \ \dots] \cdot \underline{P}^n \quad (5.5)$$

where the i -th element of row vector $\underline{\pi}_{\Gamma_{2N}}$ equals $\Pr(\Gamma_{2N} = i)$, and the (i,j) -th element of matrix $\underline{P}$ equals $\Pr(\Gamma_{2N,k+1} = j \mid \Gamma_{2N,k} = i)$. Barring any other considerations, the throughput for the double-sized cell would then be given by:

$$\eta'_{csma/ca} = \frac{P \cdot \Pr(\Gamma_{2N} = 1)}{\Pr(\Gamma_{2N} = 0) + L \cdot (1 - \Pr(\Gamma_{2N} = 0))} \quad (5.6)$$

The above equation is based on the assumption that two or more concurrent transmissions in the two cells result in a collision and therefore do not contribute to the throughput. Due to the interference-limiting condition for this two-cell system, this is not true: Whenever a cell has only one transmitting node, despite the number of transmitting nodes in the other cell, the frame survives the collision. This effect can be accounted for through the introduction of the coefficient $p_{suc}(\tau)$, which represents the probability that the number of transmitters in an observed/tagged cell (Γ_N) equals one (successful transmission) when the total number of transmitters in the two cells combined (Γ_{2N}) equals τ :

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$$\begin{aligned}
p_{suc}(\tau) &\equiv \Pr(\Gamma_N = 1 \mid \Gamma_{2N} = \tau) \\
&= \begin{cases} \frac{\binom{\tau}{1} \cdot N \cdot N(N-1) \cdots (N-\tau+1)}{(2N)(2N-1) \cdots (2N-\tau+1)} & \tau \in [1, N+1] \\ 0 & \text{otherwise} \end{cases} \\
&= \begin{cases} \tau \cdot \frac{(2N-\tau)!}{(2N)!} \cdot N \cdot \frac{N!}{(N-\tau+1)!} & \tau \in [1, N+1] \\ 0 & \text{otherwise} \end{cases}
\end{aligned} \tag{5.7}$$

The first clause, which applies when $\tau \in [1, N+1]$, is derived by dividing the number of ways of selecting a sequence of τ nodes from the two cells with exactly one from the observed cell, by the total number of ways of selecting the nodes. The second clause states that the condition cannot be true if there is no transmission at all ($\tau = 0$), or if $(N+2)$ or more transmissions occurred. The latter case would result in at least 2 transmissions in the observed cell.

Factoring this coefficient into Eq. (5.7), we obtain the normalized per-cell throughput for CSMA/CA in the two-cell system:

$$\begin{aligned}
\eta_{csma/ca} &= \frac{P \cdot \sum_{\tau=1}^{N+1} [p_{suc}(\tau) \cdot \Pr(\Gamma_{2N} = \tau)]}{\Pr(\Gamma_{2N} = 0) + L \cdot (1 - \Pr(\Gamma_{2N} = 0))} \\
&= \frac{P \cdot \sum_{\tau=1}^{N+1} \left[\tau \cdot \frac{(2N-\tau)!}{(2N)!} \cdot N \cdot \frac{N!}{(N-\tau+1)!} \cdot \Pr(\Gamma_{2N} = \tau) \right]}{\Pr(\Gamma_{2N} = 0) + L \cdot (1 - \Pr(\Gamma_{2N} = 0))}
\end{aligned} \tag{5.8}$$

5.4 PD-CSMA/CA in Two Cells

In the case of PD-CSMA/CA, the idle and busy periods in the two cells are almost always not in alignment. As seen in Fig. 5.2, in long runs, the periods often appear staggered in pairs, with the periods in one cell leading the other cell in alternating fashion. Also, the start of the exposed periods in one cell need not necessarily be aligned to the

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Figure 5.2: PD-CSMA/CA Transmission Pattern for $H = 3$ and $P = 8$ in Two Interference-Limited Cells, Annotated with Corresponding Analytical System States.

start of the busy period in the other cell, although its ending is always aligned to the end of a header period, since the exposed period ends when the payload is dropped.

Due to this lack of synchronism, there is no longer a common transmission state that can be modeled with a Markov chain. A new definition is required for the system's states and state change boundaries.

5.4.1 System States

On inspecting this staggered transmission pattern, two characteristics that suggest how the system's state could be defined are revealed: Firstly, the degree of overlap of the t -th and $(t + 1)$ -th staggered transmissions is largely dependent on the degree of overlap of the $(t - 1)$ -th and t -th staggered pair and the length of idle period following the t -th transmission. For example, in the sequence of three staggered transmissions when the

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header, payload and average idle durations are 1, 9 and 4 slots respectively, if the first and second transmissions overlap by 2 slots, then the overlap of the second and third transmissions would be $(9 + 1) - (2 + 4) = 4$ slots on average - i.e., the total length of the frame minus the sum of the previous overlap and the average idle period, assuming that the idle period distribution is unperturbed by the stagger effects.

Secondly, if the exposed states in the transmission pattern of one cell were to be removed, the resulting pattern would be exactly that of a cell in isolation. From this we can surmise that the exposed states just add to the delay between transmissions in a cell. If we know its rate of occurrence, we can easily account for it by adding extra idle states into the single cell throughput formula. More importantly, the distribution of the cell's channel state (excluding the exposed state) remains exactly the same as that of the isolated cell.

Based on these two observations, intuitively, we take the system state as comprising a staggered pair of transmissions and the exposed slots preceding it (as delineated in Fig. 5.2). We represent these states symbolically as $S = [o \ e]$, where $o \in [1, L]$ is the overlap of the staggered transmission pair measured in slots, while $e \in [0, H]$ is the duration of the preceding exposed slots. Both o and e are counted in integral multiples of the idle slot duration, σ .

Let $\Pr(I = i)$ where $i \in [0, W_0]$ denote the distribution of the idle period following a busy period in the single cell scenario. If, neglecting the extra exposed slots, the idle period distribution in the payload dropping mode stays the same from one system state to another, we can model the system state as a Markov chain, since by definition, the next system state would depend only on the overlap width of the current system state's busy period and the subsequent idle period. Unfortunately, the statistics of the idle periods preceding two or more consecutive transmissions in a cell, or those preceding the

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staggered transmissions in the two cells, are unlikely to follow $\Pr(I = i)$, since the stagger patterns would temporarily straddle them to some fixed combinations of lengths. However, we shall make this simplifying assumption in order to approximate the system state as a Markov chain.

5.4.2 System State Transition Probabilities

The space for the system state is very large based on the definition we use. Fortunately, they fall into 4 main categories as shown in Fig. 5.3. A study of these four ranges of overlap and the permutations of the durations of the idle periods following them allows us to completely define the transition probabilities for the Markov chain approximation of the system state. We adopt the naming conventions in Fig. 5.3 for this study.

5.4.2.1 Case $o = L$

As shown in Fig. 5.3(a), this is the state where the busy periods in the two cells, $b_A(t)$ and $b_B(t)$ are exactly coincident. If following this, the next idle periods $i_A(t+1)$ and $i_B(t+1)$

Figure 5.3: General system state categories for PD-CSMA/CA in two cells.

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1) are also of equal duration, the following state will also have coincident busy periods. Since these new busy periods are coincident, neither cell will suffer exposed slots. The probability for this to occur is:

$$\Pr(S_{k+1} = [L \ 0], S_k = [L \ 0]) = \sum_{i=0}^{W_0-1} \Pr(I = i)^2 \quad (5.9)$$

If the durations of $i_A(t + 1)$ and $i_B(t + 1)$ differ by x , the subsequent busy periods will overlap by $(P - x)$ slots. Since one cell will be sensing while the other starts its busy period, H exposed slots will be encountered by the cell with the longer idle period. The transition probabilities to this new system states are:

$$\Pr(S_{k+1} = [P - x \ H], S_k = [L \ 0]) = 2 \cdot \sum_{i=x}^{W_0-1} \Pr(I = i) \cdot \Pr(I = i - x) \quad (5.10)$$

$$x \in [1, W_0 - 1]$$

A factor of two is included in the expression since the symmetrical condition allows for the next busy periods to be staggered either left or right.

5.4.2.2 Case $o \in [1, H - 1]$

These are the cases where the overlap width of the busy periods is shorter than the header period (Fig. 5.3(b)). If subsequently, cell A's idle period $i_A(t + 1)$ equals 0, the next system state will be that of cell A's $(t + 1)$ -th busy period $b_A(t + 1)$ overlapping $b_B(t)$ by $(L - o)$ slots. Because $b_A(t + 1)$ immediately follows $b_A(t)$, cell A will not have exposed slots in these new states:

$$\Pr(S_{k+1} = [L - o \ 0], S_k = [o \ e]) = \Pr(I = 0) \quad o \in [1, H - 1], \ e \in [0, H] \quad (5.11)$$

Let x be the duration of $i_A(t + 1)$. If x is not zero, then cell A will be exposed for the remainder of the header transmission period in cell B. Subsequently, the next system state will have $b_A(t + 1)$ overlapped with $b_B(t)$ by $(P - x)$. The probabilities for this set of

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transitions are:

$$\Pr(S_{k+1} = [P - x \ H - o], S_k = [o \ e]) = \Pr(I = x) \quad (5.12)$$

$$o \in [1, H - 1], \ e \in [0, H], \ x \in [1, W_0 - 1]$$

5.4.2.3 Case $o \in [H, L - W_0]$

In these system states, $b_A(t)$ fully overlaps the header period in $b_B(t)$, so that it is not possible for the next busy state in cell A to be preceded by exposed slots (Fig. 5.3(c)). Also, since the remainder part of $b_B(t)$ that is not overlapped with $b_A(t)$ is longer than maximum idle period ($W_0 - 1$), the next state will be that of $b_A(t + 1)$ overlapping with $b_B(t)$ by $(L - o - x)$, where x is the duration of $i_A(t + 1)$:

$$\Pr(S_{k+1} = [L - o - x \ 0], S_k = [o \ e]) = \Pr(I = x) \quad (5.13)$$

$$o \in [H, L - W_0], \ e \in [0, H], \ x \in [1, W_0 - 1]$$

5.4.2.4 Case $o \in [L - (W_0 - 1), L - 1]$

In these system states, $b_A(t)$ and $b_B(t)$ are overlapped such that the following idle period in cell A, $i_A(t + 1)$, have a chance to extend beyond $b_B(t)$ (Fig. 5.3(d)). If $i_A(t + 1)$ does not extend beyond $b_B(t)$, i.e., its duration x is within $[0, L - o - 1]$, then the next system states will have $b_A(t + 1)$ and $b_B(t)$ overlapped by $(L - o - x)$ with the following probabilities:

$$\Pr(S_{k+1} = [L - o - x \ 0], S_k = [o \ e]) = \Pr(I = x) \quad (5.14)$$

$$o \in [L - (W_0 - 1), L - 1], \ e \in [0, H], \ x \in [0, L - o - 1]$$

If however $i_A(t + 1)$ ends with or goes beyond $b_B(t)$, i.e., $i_A(t + 1) \in [L - o, W_0 - 1]$, a coincident busy period would occur next if $i_B(t + 1)$ and the part of $i_A(t + 1)$ extending beyond $b_B(t)$ are equal in duration, i.e., $i_B(t + 1) = i_A(t + 1) - (L - o)$:

$$\Pr(S_{k+1} = [L \ 0], S_k = [o \ e]) = \sum_{i=L-o}^{W_0-1} \Pr(I = i) \cdot \Pr(I = i - (L - o)) \quad (5.15)$$

$$o \in [L - (W_0 - 1), L - 1], \ e \in [0, H]$$

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If $i_B(t+1)$ is longer than the part of $i_A(t+1)$ extending beyond $b_B(t)$ by x , i.e., $i_B(t+1) = i_A(t+1) - (L - o) + x$, the next system state will have $b_A(t+1)$ staggered left of $b_B(t+1)$ with an overlap of $(P - x)$. Conversely, if the part of $i_A(t+1)$ extending beyond $b_B(t)$ is longer by $i_B(t+1)$ by the same amount of x , i.e., $i_A(t+1) - (L - o) = i_B(t+1) + x$, then the following system state will have its busy periods staggered to the right but with the same overlap of $(P - x)$. Since we do not make a distinction between a left stagger and a right stagger in our system state definition, the two transition probabilities are combined as follows:

$$\Pr(S_{k+1} = [P-x \ H], S_k = [o \ e]) = \begin{cases} \sum_{i=L-o}^{W_0-1-(L-o)-x} \Pr(I=i) \cdot \Pr(I=i-(L-o)+x) + \sum_{i=L-o+x}^{W_0-1} \Pr(I=i) \cdot \Pr(I=i-(L-o)-x) & x \in [1, W_0-1-(L-o)] \\ \sum_{i=L-o}^{W_0-1-(L-o)-x} \Pr(I=i) \cdot \Pr(I=i-(L-o)+x) & x \in [W_0-(L-o), W_0-1], \\ & o \in [L-(W_0-1), L-1], \ e \in [0, H] \end{cases} \quad (5.16)$$

As per Markov chain analysis, the stationary distribution for the system state is solvable with,

$$\underline{\pi}_S = \lim_{n \rightarrow \infty} [1 \ 0 \ \dots] \cdot \underline{P}_S^n \quad (5.17)$$

where the elements of row vector $\underline{\pi}_S$ equal $\Pr(S = [o \ e])$ for each valid combination of $o \in [1, L]$ and $e \in [0, H]$ based on the system state transition constraints expressed by Eqs. (5.9) - (5.17), while the elements of matrix $\underline{P}$ correspondingly equal to $\Pr(S_{k+1} = [o_{k+1} \ e_{k+1}] | S_k = [o_k \ e_k])$.

5.4.3 PD-CSMA/CA Throughput

In the single isolated cell scenario, $\Pr(\Gamma_N = 0)$ represents the rate of occurrence of an idle slot, $\Pr(\Gamma_N = 1)$ a busy period with successful transmission and $\Pr(\Gamma_N = \tau)$ where $\tau \in$

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$[2, N]$ a busy period with collided transmissions. In the payload dropping case, a new channel state is introduced - the exposed state, which has the same duration as the idle/sensing slot. Denote ε as the occurrence rate of this exposed slot compared to the occurrence rate of a busy period, i.e.,

$$\varepsilon \equiv \frac{\Pr[\text{exposed slot}]}{\sum_{\tau=1}^N \Pr(\Gamma_N = \tau)} \quad (5.18)$$

From the PD-CSMA/CA system state probabilities, we can determine the value of this exposed slot factor in one of the cells as follows:

$$\varepsilon = \frac{\frac{1}{2} \cdot \sum_{e=1}^H \sum_{o=1}^{L-1} e \cdot \Pr(S = [o \ e])}{\Pr(S = [L \ 0]) + \sum_{o=P-1}^{L-1} \Pr(S = [o \ e]) + \frac{1}{2} \cdot \sum_{e=0}^H \sum_{o=1}^{L-1} \Pr(S = [o \ e])} \quad (5.19)$$

The numerator in the equation above gives the expectation for the number of exposed slots per system state. A factor of half is applied to it since the exposed slots given by the system state is for two cells. The denominator yields the expectation of the number of busy periods per system state. The factor of half applied to the last term in the denominator is to account for the fact that in a system state $[o \ e]$ with $e \in [0, H - 1]$ and $o \in [1, L - 1]$, the lagging busy period is in fact the leading busy period for the previous system state. In this case, each new system state just adds one more busy period to the total count of busy periods encountered in the two cells, or half if only one cell is considered (as is the case at hand).

With this exposed slot factor, we can now modify the single isolated cell throughput formula given in Eq. (5.3) to yield the throughput of one cell in the payload dropping scenario as follows:

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$$\begin{aligned}
\eta_{pd-csma/ca} &= \frac{P \cdot \Pr(\Gamma_N = 1)}{\Pr(\Gamma_N = 0) + \varepsilon \cdot \sum_{\tau=1}^N \Pr(\Gamma_N = \tau) + L \cdot \sum_{\tau=1}^N \Pr(\Gamma_N = \tau)} \\
&= \frac{P \cdot \Pr(\Gamma_N = 1)}{\Pr(\Gamma_N = 0) + (\varepsilon + L)(1 - \Pr(\Gamma_N = 0))}
\end{aligned} \tag{5.20}$$

Note that added term in the denominator represents the loss of channel time due to the exposed slots.

5.5 Simulation Results

For checking on the validity our throughput formulations, we initially used the modified ns-2 program described in Chapter 3. Table 5.2 lists key radio and topological settings that are necessary to ensure that the simulated 2-cell system is interference-limited. Additionally, several more modifications were made to ensure the simulation conformed to our system assumptions: The mac-802_11.cc source file was modified to run CSMA/CA in broadcast mode. This is done by bypassing the SIF, ACK and DIFS MAC states and entering the backoff state directly after a frame transmission or reception. Header and payload durations are ensured to be integral of the idle period by use of constants (as a result, the length of the payload given by the UDP traffic generator is

Table 5.2: ns-2 Radio/Topological Settings

<i>Parameter</i>	<i>Value</i>
Propagation index (n)	4
Reference signal level at 1m (Pt)	20 dBm
Carrier sensing threshold (CSThresh)	-95 dBm
Reception threshold (RXThresh)	-50 dBm
Capture threshold (α)	20 dBm
Cell diameter (2R)	10 m
Cell distance (D)	100 m

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ignored). To simulate payload dropping, the frame reception in `mac-802_11.cc` is aborted at the end of the preamble reception state and the CCA idle signal issued if the received power of the incoming signal is below `RXThresh_`. To disable capture within cells, in `wireless-phy.cc` the received frame is signaled to `mac-802_11.cc` as erroneous if the aggregate signal's receive power is above `RXThresh_` when multiple concurrent transmissions are being received.

As in the previous chapter, the `ns-2` simulator is eventually replaced with our own MAC-level simulator written in C to speed up as well as broaden our test coverage. This C program simulates independent nodes running the CSMA/CA protocol in two cells in the isolated and interference-limited case, and PD-CSMA/CA in the interference-limited case based on the assumptions specified in Section 5.2. It also implements automatic logging and comparison (against analytical results) of additional statistics other than just throughput. The average throughput results provided by this C program for 30 runs have been verified under combinations of $W_0 = \{4, 32\}$ and $N = \{2, 10\}$ to be within ± 1.96 standard deviations of the results produced by `ns-2` in 3 runs lasting the same number of busy periods.

To obtain the analytical results, a separate program was developed to compute the CSMA/CA and PD-CSMA/CA throughputs according to Eqs. (5.7 – 5.8) and Eqs. (5.19 – 5.20), respectively. The source codes for both the MAC-level simulator and the program to calculate results based on the analytical equations can be found in the CD that is included in the submission of this thesis.

5.5.1 Throughput Results

In Figs. 5.4 – 5.7, the analytical and simulation results for the throughput of PD-CSMA/CA and CSMA/CA in the two-cell system for $W_0 = \{4, 8, 16, 32\}$ as the number

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of nodes is increased from 1 to 10, for fixed header to frame ratios (H/L) of 0.2, 0.5 and 0.8 is shown. The frame length is fixed to 160 idle slots, or 5 times the maximum W_0 (32) being considered. Also included in the charts as reference are the throughput curves for CSMA/CA in the isolated cell. In all four charts, the analytical and simulation curves are coincident, suggesting that our throughput formulations are very accurate. A few observations regarding these charts are worth noting. In general, PD-CSMA/CA throughput curves show trends that are common with CSMA/CA be it in the single cell or the 2 cell system under analysis: All three curves gradually fall as the number of nodes increase. With $W_0 = 4$, this fall is much steeper at the onset, but eventually tapers off as the number of nodes get larger. This is due to the relatively larger increase in collisions for small contention windows. With $W_0 = \{16, 32\}$, the fall is more gradual even at the onset, and there is also the situation where the throughput is lower for $N = 1$ compared to larger N because the length of contention window contributes more to the channel time being wasted in idle periods rather than collisions.

From a performance perspective, PD-CSMA/CA curves tend to be incident on the single-cell CSMA/CA curves at $H/L = 0.2$, and very close to it at $H/L = 0.5$. It is only at $H/L = 0.8$ that the performance of PD-CSMA/CA degrades to the level of CSMA/CA in the two-cell system. At this H/L ratio, it can be observed that the PD-CSMA/CA curves actually dip below the CSMA/CA curves at some point depending on the contention window length (e.g., at $N = 4$ when $W_0 = 4$, at $N = 6$ when $W_0 = 16$, and $N = 10$ when $W_0 = 32$). This characteristic is present in both simulation and analytical curves, so it cannot be due to some programming or analysis error. Intuitively, this seems to not be possible with a frame that is fully composed of header information only (i.e. $H/L = 1.0$), as in this case PD-CSMA/CA should behave like CSMA/CA in the sense that one cell gets blocked as the other cell transmits.

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Figure 5.4: Throughput vs. Number of Nodes for $W_0 = 4$, $L = 160$ and $H/L = \{0.2, 0.5, 0.8\}$: Analysis vs. Simulation

Figure 5.5: Throughput vs. Number of Nodes for $W_0 = 8$, $L = 160$ and $H/L = \{0.2, 0.5, 0.8\}$: Analysis vs. Simulation

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Figure 5.6: Throughput vs. Number of Nodes for $W_0=16$, $L=160$ and $H/L = \{0.2, 0.5, 0.8\}$: Analysis vs. Simulation

Figure 5.7: Throughput vs. Number of Nodes for $W_0=32$, $L=160$ and $H/L = \{0.2, 0.5, 0.8\}$: Analysis vs. Simulation

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We studied this effect in depth, but were unable to devise the appropriate testing methods to fully confirm the mechanism of interactions leading to this behavior. At this point we can only provide the following clues as to the cause of this anomaly: in CSMA/CA the chances of coincident transmissions across both cell is high when the number of nodes is large, since both cells remain in synchronization. The reason for this synchronization is that all nodes wait until the end of the busy period before resuming their contention process. As a result, the contention windows in both cells start at the same time, leading to a good chance of simultaneous transmissions from the two cells. With coincident transmissions, there is a good chance for a busy period to be followed immediately with a busy period without any idle slots. In PD-CSMA/CA however, there is the tendency for one cell to put off transmission until the header portion of the transmission in the other cell ends. As a result, the contention windows in the two cells are staggered. If the frame is largely made up of header portion only, then the chances for one cell to be exposed to the ending parts of the header portions of transmissions from the other cell is increased. As a result, nodes in one cell would more frequently wait an extra idle slot before resuming their contention process compared to the CSMA/CA case. The time wasted in this extra idle slot thus contributes to the dip in the throughput curves for PD-CSMA/CA under the CSMA/CA curves at this very high H/L ratio, for large N_s .

Figs. 5.8 – 5.11 present another view of the throughput results, showing their trends as the H/L ratio is gradually increased from 0.2 to 0.8. Here, the CSMA/CA throughput curves for the single cell and the two cell system are linear because a linear increase in the H/L ratio affects a linear decrease in P , which in turn affects a linear decrease to the throughput according to Eq. (5.8). The throughputs of CSMA/CA and PD-CSMA/CA are smaller at smaller W_0 s since more collisions occur at this range. In terms of the accuracy of the analysis, it can be seen that the analytical and simulation curves are coincident in

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Figure 5.8: Throughput vs. Header/Frame Ratio for $W_0 = 4$, $L = 160$ and $N = \{2,4,6,8,10\}$: Analysis vs. Simulation

Figure 5.9: Throughput vs. Header/Frame Ratio for $W_0 = 8$, $L = 160$ and $N = \{2,4,6,8,10\}$: Analysis vs. Simulation

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Figure 5.10: Throughput vs. Header/Frame Ratio for $W_0 = 16$, $L = 160$ and $N = \{2,4,6,8,10\}$: Analysis vs. Simulation

Figure 5.11: Throughput vs. Header/Frame Ratio for $W_0 = 32$, $L = 160$ and $N = \{2,4,6,8,10\}$: Analysis vs. Simulation

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all four charts. In terms of characteristics specific to PD-CSMA/CA, it can be seen clearly that the PD-CSMA/CA throughput drops noticeably from the single-cell CSMA/CA throughput at $H/L = 0.5$. At $H/L = 0.6$ the PD-CSMA/CA throughput is roughly midway between CSMA/CA's throughput in the single-cell and in the two-cell system. This observation can be explained using an intuitive understanding of how payload-dropping operates in the two cells: Since the transmission from one cell is deferred until the transmission of the header portion in the other cell completes, it follows that, if the header length is equal or close to payload length, the chances for the cell with the leading transmission to pick up on the header transmission in the lagging cell becomes significantly larger than when the header is shorter than the payload. This explanation is best understood with the aid of Fig. 5.3(c). In that figure, the header is depicted as being shorter than the payload. But had the header been equal or larger, the chance for nodes in cell A to be exposed to the remainder of the header transmission in cell B would have been significantly higher.

As further evidence of the accuracy of our throughput formulations, we present in numerical form a sampling of the results of the comparison in Tables 5.3 and 5.4. With the exception of the single result (highlighted in red), all the analytical values fall within the 95% confidence interval (± 1.96 standard deviations) of the values from 30 runs of the simulation at each setting of W_0 , N and H/L ratio.

5.6 Chapter Summary

An analytical formulation for the throughput of PD-CSMA/CA in two co-channel interference-limited cells within frame detection range was presented, and its accuracy compared to simulation results. For contrast, the throughput analysis for CSMA/CA in the same system was also presented. Both analyses are not available in the literature (to the

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Table 5.3: CSMA/CA Throughput for Selected Combinations of W_0 , N and H/L Ratios ($L = 160$): Analysis vs. Simulation

W_0	N	<i>Method</i>	<i>H/L</i>			
			<i>0.2</i>	<i>0.4</i>	<i>0.6</i>	<i>0.8</i>
4	2	Simulation	0.4005	0.3024	0.2012	0.1012
		(± 1.96 SD)	0.4166	0.3120	0.2085	0.1043
		Analysis	0.4098	0.3073	0.2049	0.1024
	10	Simulation	0.2110	0.1566	0.1043	0.0527
		(± 1.96 SD)	0.2227	0.1689	0.1127	0.0558
		Analysis	0.2172	0.1629	0.1086	0.0543
32	2	Simulation	0.3980	0.2981	0.1982	0.0995
		(± 1.96 SD)	0.4039	0.3042	0.2022	0.1012
		Analysis	0.4010	0.3008	0.2005	0.1003
	10	Simulation	0.3769	0.2828	0.1890	0.0946
		(± 1.96 SD)	0.3906	0.2919	0.1950	0.0975
		Analysis	0.3835	0.2876	0.1917	0.0959

Table 5.4: PD-CSMA/CA Throughput for Selected Combinations of W_0 , N and H/L Ratios ($L = 160$): Analysis vs. Simulation

W_0	N	<i>Method</i>	<i>H/L</i>			
			<i>0.2</i>	<i>0.4</i>	<i>0.6</i>	<i>0.8</i>
4	2	Simulation	0.5641	0.4215	0.2469	0.1043
		(± 1.96 SD)	0.5770	0.4315	0.2512	0.1069
		Analysis	0.5718	0.4269	0.2499	0.1061
	10	Simulation	0.2585	0.1943	0.1183	0.0528
		(± 1.96 SD)	0.2735	0.2027	0.1243	0.0546
		Analysis	0.2664	0.1994	0.1230	0.0554
32	2	Simulation	0.7346	0.5492	0.2998	0.1161
		(± 1.96 SD)	0.7400	0.5529	0.3022	0.1171
		Analysis	0.7369	0.5493	0.3013	0.1167
	10	Simulation	0.5838	0.4378	0.2439	0.0937
		(± 1.96 SD)	0.5944	0.4461	0.2490	0.0955
		Analysis	0.5889	0.4416	0.2465	0.0947

best of our knowledge). Although limited to the fixed frame size and fixed window case, these analytical models shed light to the throughput trends of PD-CSMA/CA with respect to the contention window length, number of nodes and header to frame length ratio of transmitted frames, and demonstrates its gains over normal CSMA/CA quantitatively.

6 Conclusion & Future Work

6.1 Conclusion

In this thesis, we have proposed a new scheme for improving the spatial reuse of CSMA/CA. This scheme involves transmitting nodes imbedding the identifier of the cell they are associated with into the header of frames, and receiving nodes discarding the payload portion of frames if they are not in the cell indicated in the header. This scheme is only engaged when it is known that the co-channel cells are all interference-limited.

In Chapter 3, we show how this scheme can be readily incorporated into the IEEE 802.11 standard without significant change to the PHY-MAC interface or additional signaling. Using the ns-2 platform, we tested this modified IEEE802.11 protocol under three spatial reuse scenarios involving two to four cells. In all three scenarios, we find that, after a certain distance or partition attenuation threshold, PDCF achieve a higher throughput than CSMA/CA at the same cell distance or partition attenuation, or conversely, the same throughput is achieved at a smaller cell distance or partition attenuation.

Under ideal interference-limited condition, PD-CSMA/CA exhibits a peculiar transmission pattern in a two cell system, whereby the busy periods in the cells alternately stagger one after another in succession, as if the cells were in isolation. In order to analyze

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the throughput for this kind of transmission pattern, we developed a Markov model for it in a two-cell scenario, assuming fixed contention window size and fixed frame size. The formulations for this model are presented in Chapter 5. For the purpose of comparison, we also develop a model for the throughput of CSMA/CA under the same two-cell interference-limited system. Both models yield throughput values that are accurate within two standard deviations of the throughput results obtained via 30 simulation trials, for all tested combinations of contention window size, number of nodes, header and frame lengths.

From comparing the throughput trends for the two schemes under different header to frame ratios, we see that the PD-CSMA/CA throughput is nearly that of the isolated cell when the header to frame ratio is at or below 0.4, and gradually reaches the exposed CSMA/CA throughput when it is at or above 0.8.

In the process of developing the analytical model for PD-CSMA/CA in two cells, we also came up with an analytical model for the idle period distribution of CSMA/CA in a single cell when the contention window is fixed. This model, which we presented in Chapter 4, is very accurate compared to existing models. Under a wide range of contention window sizes and numbers of nodes, it also passes the Pearson's chi-squared goodness-of-fit test.

6.2 Future Work

Both simulation and analysis results for PD-CSMA indicate that this new protocol performs better than CSMA/CA, at least for the case when the number of co-channel cells are less than or equal to 4, and when the number of nodes are less than or equal to 10. In typical real-life office or home deployment scenarios where the number of nodes and co-channel cells are also not very large, this new scheme should be useful.

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As such, the next step for evolving PD-CSMA/CA is to develop a real-life demonstrator. To do this however, a platform is needed where the transmission primitives follow the MAC-PHY interactions as standardized by IEEE in [1, 3]. Such deep-level interactions with the PHY layer may be possible in some wireless communication hardware platform developed for research, such as CalRadio [114] or GNU Radio [115]. This endeavor however will require much time and money.

Prior to this big step, several other aspects of the protocol may be investigated through simulation. One of these is its impact on legacy nodes. In this case, it may be necessary to evaluate how long it would take an entire cell running in PD-CSMA/CA mode to fall back to CSMA/CA when legacy nodes enter the cell, and improve the protocol in this regard if necessary. Another aspect that can be further explored is the performance of PD-CSMA/CA in propagation environments other than the office or home deployment scenarios. With the advent of Super-WiFi, and also the use of CSMA/CA in MANETs for military and first-responder communications, it may be useful to simulate PD-CSMA/CA in propagation environments such as those used to model masted APs in urban areas (e.g. Okumura-Hatta) and near ground peer-to-peer communications on irregular (e.g., Longley-Rice) or forested terrains (e.g., Plain-Earth with Early ITU or Fitted ITU-R).

On the analytical front, one area which we would have liked to have more time to work on is the exact expression for the idle period distribution for CSMA/CA with multiple, exponentially increasing backoff stages. We must concede that the task will be very difficult due to the complexity involved, but there may be approximate models that would yield decently accurate results.

As for the analytical 2-cell throughput model of PD-CSMA/CA, other possible future works include expanding the model to account for varying lengths of data frames, or to separately consider the ACK frame transmission. The anomaly uncovered, whereby the

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throughput of PD-CSMA/CA actually dips under the throughput of CSMA/CA when the header to frame length ratio is above 80%, may also be worth further analytical exploration. However, we feel that a real-life demonstrator would be a far better validation of the scheme.

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