Medium Access Control for Full-Duplex in Wireless Local Area Networks

Deniz Marlalı

Submitted to the Graduate School of Engineering and Natural Sciences
in partial fulfillment of
the requirements for the degree of
Master of Science

Sabancı University

December, 2015

MEDIUM ACCESS CONTROL FOR FULL-DUPLEX IN WIRELESS LOCAL AREA NETWORKS

APPROVED BY:

Assoc. Prof. Dr. Özgür Gürbüz
(Thesis Supervisor)

Prof. Dr. Özgür Erçetin

Prof. Dr. Elza Erkip
(Polytechnic Institute of NYU)

DATE OF APPROVAL: 30/12/2015

Medium Access Control for Full-Duplex in Wireless Local Area Networks

Deniz Marlalı

Computer Science and Engineering, Master's Thesis, 2015

Thesis Supervisor: Assoc. Prof. Dr. Özgür Gürbüz

Abstract

Current wireless technologies strive to respond to the arising demand for the increase in mobile traffic. Recently, with the introduction of self-interference (SI) cancellation techniques, wireless full-duplex communication has become an attractive solution that doubles the spectral efficiency and enhances data rates. In this thesis, we present a medium access control (MAC) protocol, named Synchronized Contention Window Full-Duplex (S-CW FD) protocol for enabling full duplex communication in wireless local area networks (WLANs). The proposed S-CW FD protocol can not only work in ad hoc and infrastructure modes of IEEE 802.11 WLANs, but with the legacy nodes as well. In this work, saturated throughput of S-CW FD is derived based on a two dimensional Markov chain model, similar to Bianchi's, and those results are used to validate simulations in OPNET tool. Via detailed simulation experiments, the performance of S-CW FD is evaluated under different self-interference models and wireless network conditions. It is shown that when there are no hidden nodes in the network, the S-CW FD protocol can double the throughput of half-duplex IEEE 802.11, and in the presence of hidden nodes in the network, the throughput gain of full duplex over half-duplex can get as high as ten fold, even for moderate SI cancellation levels and heavy load. Comparisons with existing similar FD MAC protocols also indicate that the proposed S-CW FD protocol performs best under realistic network conditions and

residual SI. Hence, S-CW FD stands out as a promising FD MAC protocol with a high chance of application in WLANs, not only for significant performance improvements, but also for its flexibility and backwards compatibility.

Kablosuz Yerel Alan Ağlarında Tam-Çift Yönlü İletişim için Ortam Erişim Kontolü

Deniz Marlalı

Bilgisayar Bilimleri ve Mühendisliği, Yüksek Lisans, 2015

Tez Danışmanı: Doç. Dr. Özgür Gürbüz

Özet

Günümüz kablosuz teknolojileri artan ihtiyaca ve mobil trafikteki artışa yanıt vermeye çabalamaktadır. Öz-girişim engelleme tekniklerinin hayatımıza girmesi ile, kablosuz tam-çift yönlü iletişim, spektral verimliliği iki katına çıkarması ve de veri hızını yükseltmesi ile ilgi çekici bir çözüm haline gelmiştir. Bu tezde, kablosuz yerel alan ağlarında tam-çift yönlü iletişime olanak sağlamak amacı ile Synchronized-Contention Window Full-Duplex (S-CW FD) isminde bir ortam erişim kontrolü (OEK) protokolü sunuyoruz. Önerilen protokol IEEE 802.11 kablosuz yerel alan ağlarının tasarsız ve altyapı modlarının yanısıra günümüzde kullanılan istasyonlar ile birlikte de çalışabilmektedir. Bu çalışmada, S-CW FD'nin doymuş trafik başarımı Bianchi'nin modelini esas alan iki boyutlu bir Markov zinciri modeli ile elde edilmiş ve bu sonuçlar OPNET simülasyonlarını doğrulamak için kullanılmıştır. S-CW FD, farklı öz-girişim engelleme modelleri ve de kablosuz ağ durumları altında detaylıca simüle edilerek değerlendirilmiştir. S-CW FD'nin, yarı-çift yönlü IEEE 802.11'in başarımını ağda gizli terminal yokken iki katına, gizli terminal bulunan ağlarda ise orta seviye öz-girişim engellemesi ve yüksek trafikte bile on katına kadar çıkarabildiği tespit edilmiştir. Varolan benzer tam-çift yönlü OEK protokolleri ile yapılan karşılaştırmalar, S-CW FD'nin gerçekçi ağ kondisyonları ve artan öz-girişim altında en iyi çalışan protokol olduğunu göstermiştir. Bunun sonucu olarak, S-CW FD, kablosuz yerel alan ağları için sadece başarımı arttırması ile değil, esnekliği ve geri uyumluluğu ile tam-çift yönlü OEK'lar arasında dikkat çekmektedir.

to my family and significant other...

Do. Or do not. There is no try.

Acknowledgments

First and foremost, I would like to express my sincerest gratitude to my advisor Assoc. Prof. Dr. Özgür Gürbüz. This thesis and research would not have been possible without her patience, motivation, knowledge, and guidance. Her trust and confidence in me encouraged and kept me going even when I felt most unconfident about myself after being stuck in a problem for a long time.

I am thankful to my thesis jury, Prof. Dr. Özgür Erçetin and Prof. Dr. Elza Erkip, for their valuable times even in their busy schedules.

I would like to thank my fellow colleagues from Telecommunication and Networking Laboratory for the environment and friendship they provided.

I would like to express my heart-felt gratitude to my dearest Burcu Efsun Topaloğlu, she always stood by me through both good and bad times of this study, without her heartwarming support and presence this thesis would not have been possible.

None of this would have been possible without the love and patience of my family. My family has been a constant source of love, support and strength all these years. I would like to express my heart-felt gratitude to my family

Lastly, I would like to thank TÜBİTAK for partly funding this research under grant no 113E222.

Contents

List of Algorithms

List of Figures

List of Tables

1 Introduction

1.1 Motivation

With the entrance of mobile smart devices into our lives, wireless networks have become significantly more important. Every day, new smart portable devices are introduced with various capabilities are sold and used by the people. In 2014 the number of new mobile devices were reported as half a billion, it is projected that by the year 2019, mobile devices and connections will grow to 11.5 billion as depicted by Figure 1.

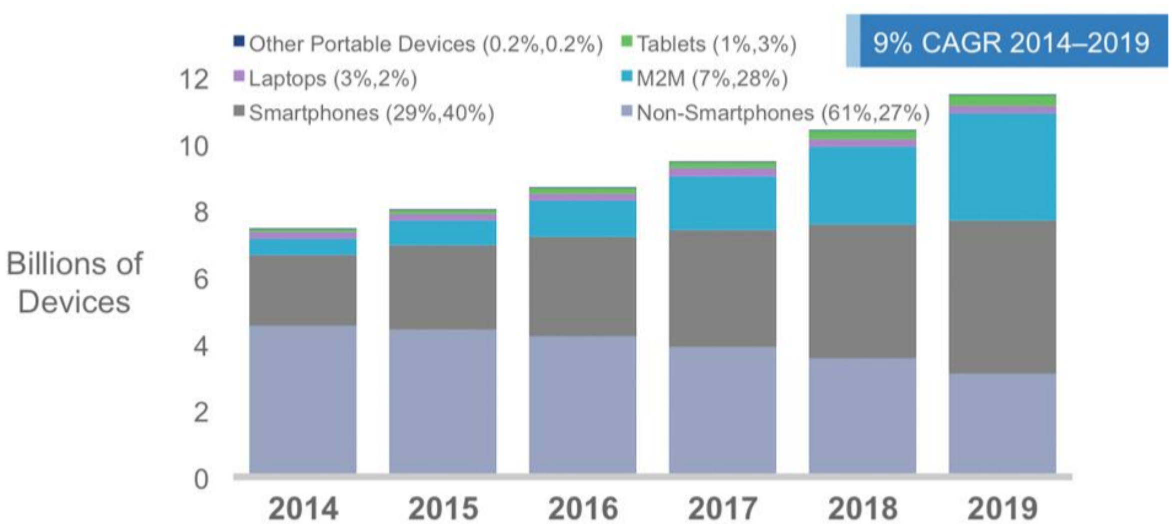

Figure 1: Growth of Mobile Devices and Connections [1]

The numbers in mobile data traffic is much more dramatic, as, in 2014 global mobile data traffic grew by 69 percent. This is because, more and more people are switching to the smart devices (Fig. 2, which generate more traffic than a non-smart device. In [1], Cisco forecasts that by 2019, the data traffic will reach 24.3 exabytes per month, which is a tenfold increase from 2014, as shown in Figures 2 and 3.

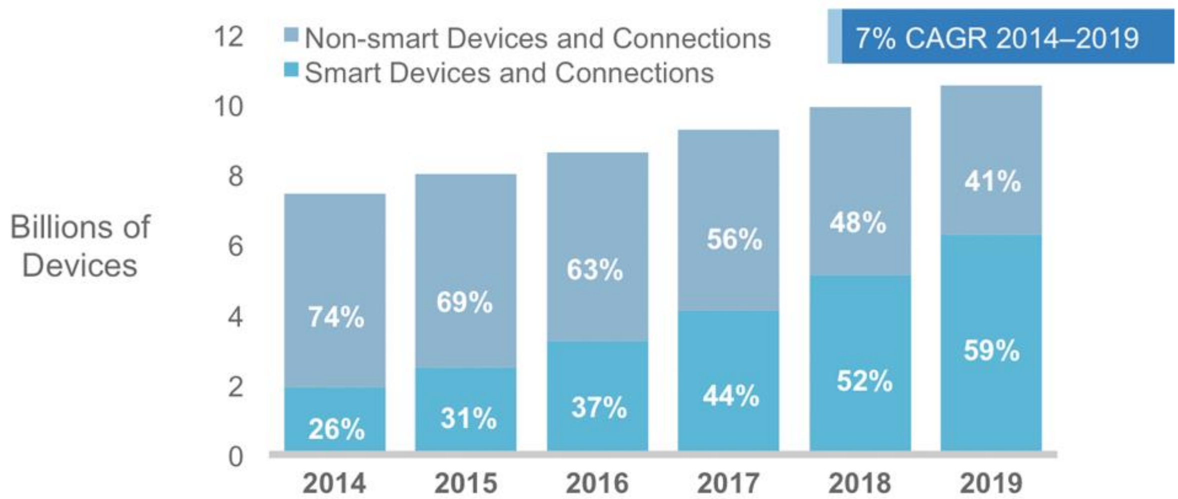

Figure 2: Projection of Percentage of Devices [1]

With such increased growth rate in wireless (data) traffic, old technologies can not keep up with the increase in demand, and the telecommunications researchers and industry are challenged to fulfill this demand. Full-Duplex is one of the evolving technologies to address this challenge, since it has the ability and potential to double the capacity of any wireless network, helping to quickly respond to the increased demand.

Enhancements in the wireless physical layer mainly aim to achieve data rates approaching channel capacity, and new medium access control (MAC) schemes provision high utilization and throughput, along with fairness or Quality of Service guarantees. However, only half of the physical bandwidth is available for one way wireless communication, since the channel needs to be partitioned for transmission and reception either in the frequency or time domain. This is because, a wireless node cannot transmit and receive over the same frequency band at the same time, in other words full-duplex (abbreviated as FD) communication is not possible.

The reason FD was not possible, in wireless systems until recently, is the significant amount of self interference: When transmitting and receiving simultaneously, a node captures the signal from its transmitter along with the signal it is attempting to receive; preventing successful reception. Recently, several radio designs (e.g., [7], [3]) with additional antennas and circuitry have been shown to cancel the self interference (SI) and enable FD communication.

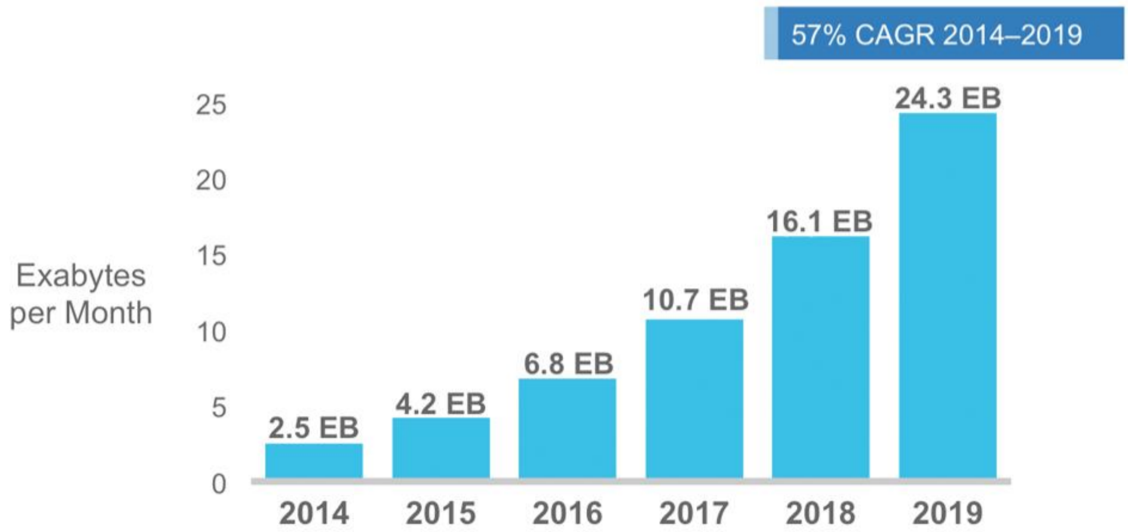

Figure 3: Forecast of Mobile Data Traffic 2014-2019 [1]

Most of the work on FD has concentrated on the physical layer, proposing and investigating techniques for SI cancellation [7], [3], [8], considering the effects of errors or residual SI after SI cancellation [9], or comparing the performance of FD systems with their half-duplex (HD) counterparts in terms of physical layer metrics, such as average achievable rates and outage capacity [10]. Recent research works include MAC design for FD wireless networks (e.g. [11], [3]), as well as FD in multi-hop wireless networks (e.g. [12], [13], [14]). In some of these works, the residual SI is considered to be zero, assuming ideal SI cancellation to quantify the upper bound of FD [10], while other works consider either a constant residual SI [15], or a constant SI cancellation factor for reducing the transmitted signal power [16]. None of these SI models are realistic, as shown by the extensive measurements on a real implementation in [17]. In [17] an empirical model is devised, showing that the power of the residual SI, i.e., SI after cancellation, is actually related to the transmitted power, along with factors representing the effects of analog and digital cancellation. This model is not only mathematically tractable, but also the most realistic one, since unlike other models, the residual SI is not underestimated and it is modeled as a function of the transmit power. For analyzing the gain of FD over HD, the level of SI cancellation and residual SI model is of critical importance, as studied in [18] and [19].

Our aim in this work is to design a simple and flexible medium access control (MAC) protocol that enables FD operation in wireless local area networks (WLANs) and to analyze its performance under realistic conditions, considering the effect of residual SI and hidden nodes. We propose Synchronized Contention Window Full Duplex (S-CW FD) protocol as a modified form of IEEE 802.11 MAC [20] with mechanisms to support the FD operation, so that the involved nodes are synchronized with minimal overhead and simultaneous transmissions can take place. Our simulations show that the network throughput can be significantly improved by S-CW FD, not only due to FD transmissions, but also due to alleviation of the hidden terminal problem.

1.2 Contributions

The contributions of this thesis can be summarized as follows:

- S-CW FD protocol is presented as a new MAC protocol, which enables full-duplex operation in WLANs, while seamlessly supporting legacy HD IEEE 802.11 nodes. S-CW FD is very easy to implement with simple modifications only in 802.11 MAC, unlike other works, which require changes at the physical layer or at the MAC-physical layer interface.

- In order to validate our simulations, we have developed two analytic models for S-CW FD, which are based on [5] and [6]. Comparison of OPNET simulations and analysis results in terms of saturation throughput shows a difference lower than 1%, in all scenarios.

- Different than existing works on FD MAC, the performance of S-CW FD is evaluated considering the effects of the wireless channel and residual SI due to FD, via simulations. Performance simulations are extended to study the effect of hidden nodes and random packet sizes, different than existing work.

- Our simulation results show that proposed S-CW FD protocol has the potential to double the throughput of HD WLANs without hidden nodes. The gain of S-CW FD is significantly increased, in the scenarios with hidden nodes, as the throughput gain of S-CW FD over HD can get as high as an order of magnitude, even for moderate SI cancellation levels and under heavy traffic load.

- Our proposed protocol S-CW FD has been compared with FD MAC protocols in [3] and [4] using the same channel model in [4]. Simulation results show that S-CW FD stands out in realistic network conditions.

- S-CW FD has low complexity, low power consumption and it is compatible with legacy nodes. Hence it can be easily applied to WLANs.

1.3 Outline

Outline of this thesis is as follows: In Section 2, we give the background work about FD radios and IEEE 802.11 protocol, as well as existing works on FD MAC. In Section 3, present S CW FD protocol in detail. In Section 4 we devise two analytical models for S-CW FD then validate them by using OPNET simulations. In Section 5, we present the results for detailed OPNET simulations considering realistic FD implementations and wireless network conditions. Finally, in Section 6 we confer our conclusions about this thesis.

2 Background Work

In this section, first we provide possible topologies for full-duplex communication, then we present a brief history and description for full-duplex radios, while explaining self-interference cancellation techniques, followed by three main residual self-interference models used in the literature. Then, we briefly explain IEEE 802.11 Basic Access, and present a summary of the FD MAC protocols proposed earlier.

2.1 Full-Duplex Communication

Before reviewing the radios or medium access control protocols, we overview the topologies for possible full-duplex operations. Both full-duplex radios and MACs should be designed to support three basic topologies, shown in Figure 4 below:

In the first topology shown in Fig. 4 (a), station S transmits a packet destined for D, R receives the packet and forwards (i.e. relays) the packet to the destination D. In half-duplex these transmission must occur in ordered fashion, such that in time slot t while S transmits the n^{th} packet,to R; and then in time slot $t+1$, R forwards the n^{th} packet to D, but in full-duplex, in time slot t, while the station S is transmitting the n^{th} packet, R can forward the $(n-1)^{th}$ packet to the D.

The most basic and intuitive application of FD is shown in the topology in Figure 4 (b). Where two stations A and B, are transmitting data packets to each other. In HD the nodes have to wait for each other to transmit, in other words they cannot transmit and receive at the same time. In FD, thanks to the SI cancellation, stations are able transmit and receive at the same time.

The third topology shown in Fig. 4 (c), is similar to the topology in (a), with the difference of instead of relaying, an infrastructure based system is used where an access

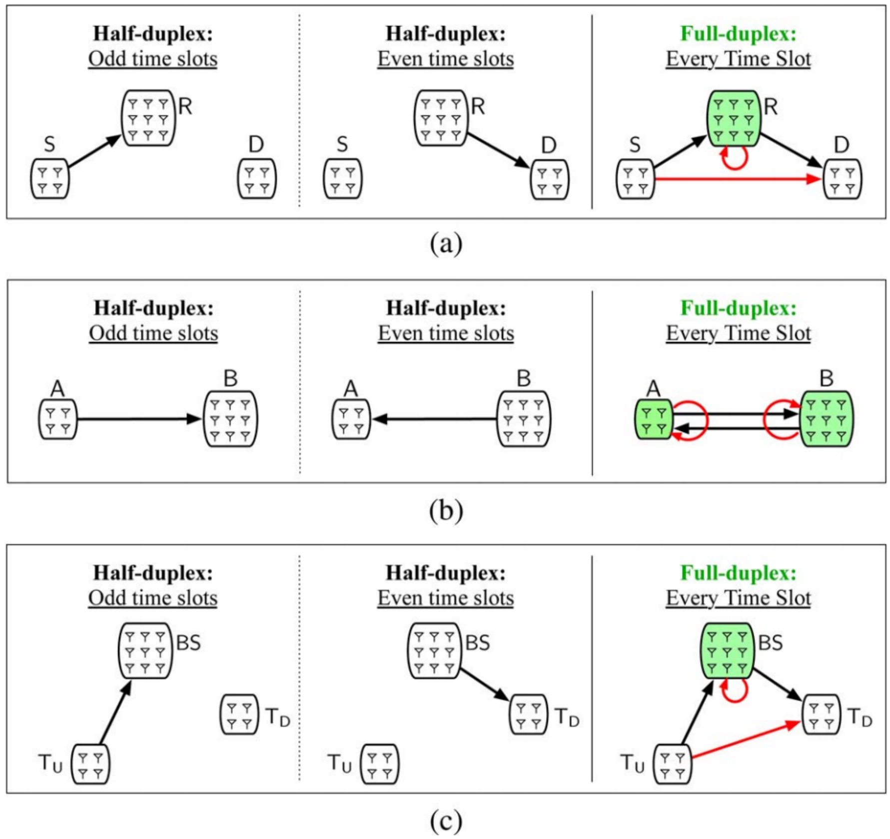

Figure 4: Three Basic Topologies for FD [2] (a)Relaying (b) Bidirectional Transmission (c) Cellular Communication

point communicates with different stations. In HD, uplink and downlink channels must take turns, but in FD version of this topology, uplink and downlink can happen at the same time.

It can be noted that, all of these topologies have the potential to double the spectral efficiency [2]. Our proposed protocol is able to work on all of these topologies, except that for the topologies shown in Fig. 4 (a) and (c), a power-control mechanism is required to prevent inter-user interference such as in [14] unless nodes S and D do not hear each other.

2.1.1 FD Radios

History of full-duplex radios go back to the radar systems of 1940s. Pulsed radar systems turn their transmitter off, while radar returns are received, thus working in half-duplex [21], whereas continuous wave radar systems use two different antennas for transmission and reception (Fig. 5(a)) or one single antenna with a circulator or a duplexer (Fig. 5(b)) to isolate the receive chain from transmit chain [2]. These designs maintain a base for today's full-duplex radios. The main challenge in FD radio design is the cancellation of the self-interference (SI).

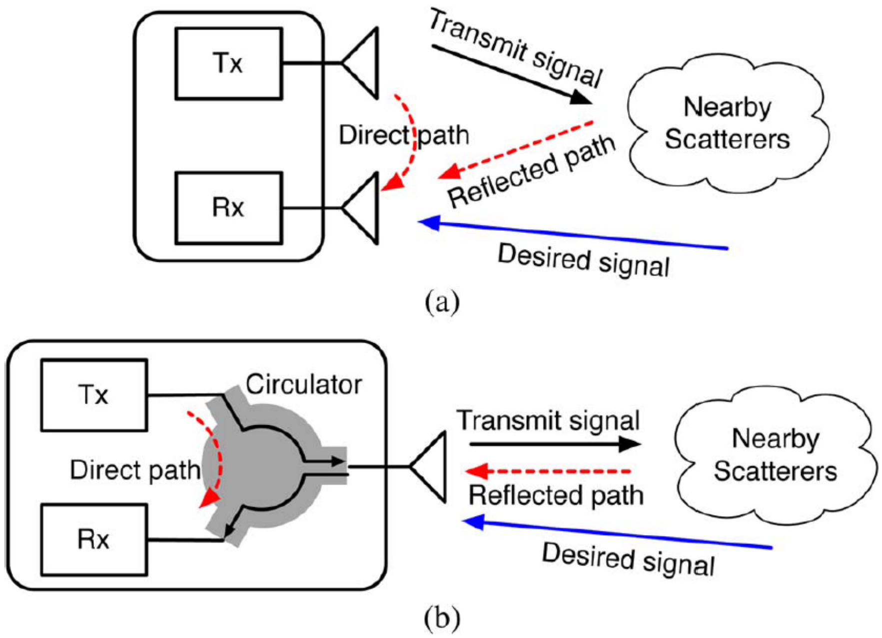

Figure 5: FD Implementations with Separate Antennas and Single Antenna [2]

Although in theory SI cancellation seems easy to accomplish, by subtracting transmitted signal from the received signal, practically it is quite challenging since digital baseband signals are not preserved, but they get distorted by the radios [22]. Furthermore full-duplex radios are subject to reflected-path self-interference as shown in Fig. 5, resulting in unpredictable signals, therefore the full-duplex radios must implement techniques to cancel both direct-path and reflected-path self-interference [2].

Generally, SI cancellation techniques are divided into two main classes. These are passive self-interference-cancellation and active self-interference-cancellation. Passive self-interference cancellation, also named propagation-domain self-interference suppression, aims to suppress the SI before it penetrates into the receive chain [2]. In systems that use separate antennas for transmission and reception, isolation can be achieved by increasing the path loss with techniques such as increasing the distance between the antennas such as in [16], [23], [3], [24], or using a material between two antennas to absorb the signals [23]. As expected, the passive self-interference cancellation techniques cannot handle reflected-path self-interference. In order to deal with both direct-path and reflected-path self-interferences active self-interference techniques must be used.

Active self-interference cancellation is divided into two classes in [2]. Analog-circuit-domain self-interference cancellation aims suppressing self-interference in the analog circuit before it goes in to the analog-to-digital converter [16], [25], [24], [7], [22]. As the last step of active self-interference cancellation, digital-domain self-interference cancellation is used which aims to cancel the self-interference after the ADC by subtracting the estimated self-interference from the received signal in the digital domain [26], [27], [28].

2.1.2 Residual Self-Interference Models

Despite the application of SI cancellation techniques, some of the SI remains at the FD radio, and hence the "residual SI" needs to be modeled, when analyzing FD. In this section, three main approaches to residual self-interference models in the literature will be summarized with examples. The first model can be named as constant residual self-interference model, where the residual self-interference after the cancellation is set to a constant value independent from transmission power and cancellation levels as in [15].

The second residual self-interference model in the literature use a constant cancellation value to reduce the transmission power

$$R_{SI} = \frac{P_t}{C_{SI}} \tag{1}$$

where R_{SI} is residual self-interference power, P_t is the transmission power and C_{SI} is the constant self-interference cancellation value as used in [4].

The last model, which is the employed in this thesis, is an experimentally characterized model proposed in [17]. This is the most accurate and realistic residual SI model in the FD literature. According to this model, the power of the residual SI signal, R_{SI}

is obtained as a function of the transmission power, P_T as;

$$R_{SI} = \frac{P_T^{(1-\lambda)}}{\beta \mu^{\lambda}}, \tag{2}$$

where β is the interference suppression factor and μ depends on the SI cancellation technique[1]. The parameter λ denotes the SI cancellation capability or level. $\lambda = \infty$ stands for the perfect SI cancellation case, resulting in zero residual SI; $\lambda = 0$ corresponds to a constant reduction in the transmission power as applied by many FD MAC papers, such as [4]; $\lambda = 1$ corresponds to the constant residual SI model, which assumes a constant power for residual SI similar to noise. Realistic values for λ lie within $0 < |\lambda| < 1$, where negative values are employed when the transmission power is below 1 W, which can be typical for WLANs. Note that, this model is general to include the earlier models.

2.2 IEEE 802.11 Basic Access

Since our proposed protocol S-CW FD MAC is based on and can work with IEEE 802.11 basic access [20], in this subsection, we provide a summary of the IEEE 802.11 Distributed Coordination Function (DCF).

A station with packets in their queue for transmission monitors the medium until it detects the medium is *idle* for a period of *DIFS* seconds. After detecting the idle channel for *DIFS* period, each station generates a random backoff slot number from the range $[0, CW]$ where CW is initially set as CW_{min}, and increased to $2^m CW_{min}$, and m is the level of backoff stage which is determined by the number of retransmission attempts [20].

The stations start their backoff timers, and they decrement their backoff counters for each slot sensed as idle. If a transmission is sensed during backoff, the counter is stopped immediately to continue again after detecting the channel idle for DIFS period. If the channel stays idle until the end of a random backoff time for a station, it means that the corresponding station has won the contention and it starts to transmit its data

[1] In this thesis, $\beta = 38$ dB and $\mu = 13$ dB as in [18].

packet [20].

After the data packet is transmitted, the receiving station waits for short interframe space (SIFS) period, and transmits an acknowledgement (ACK) packet using the lowest possible transmission speed in order to minimize packet error probabilities. If the transmitting station does not receive any ACK packet for a specified timeout period, or it detects another transmission on the chanel other than the ACK it is waiting, it reschedules the packet for a retransmission incrementing the m value by one. If an erroneous packet is received by any station, the receiving stations will monitor the channel while it is idle for extended interframe space ($EIFS^2$) period instead of $DIFS$ before the backoff period [20].

An example of IEEE 802.11 DCF Basic Access packet sequence can be seen from Figure 6.

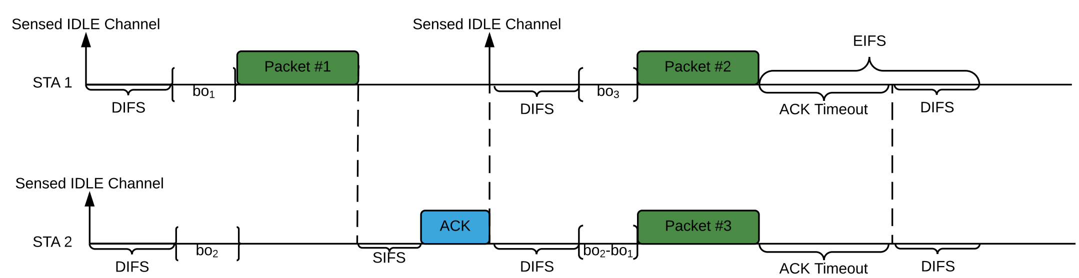

Figure 6: Example 802.11 DCF Packet Sequence

2.3 Full-Duplex MAC

In this section, we review the existing work that include MAC design for FD. We specify the differences of our protocol when necessary.

[2]EIFS = ACK transmission time in lowest mandatory PHY rate + SIFS + DIFS

In [3] a shared random backoff procedure is proposed to coordinate the nodes in FD operation. This scheme cannot succeed in a heavily loaded network, since it is highly likely that a node with a lower backoff than the shared back off can seize the channel from the FD nodes. In order to prevent this problem in our design, each FD node stores the remaining backoff slots with the other FD nodes. Even when another node obtains the medium, the backoff slots of the two FD nodes are frozen at the same level, so that they have a (high) chance of gaining access for again FD operation in the next contention period instead of purging the shared random backoff information for each node winning the medium. [29] presents an access mechanism called semi-synchronous channel access, which works as follows: Before a transmission, a transmitting node sends a preamble to the receiving node. The receiving node acts according to status of the channel (busy or idle) and whether it has packets, and FD is enabled when applicable. While this semi-synchronous channel access mechanism increases the overall throughput of the system, it does not support legacy 802.11 nodes, unlike ours.

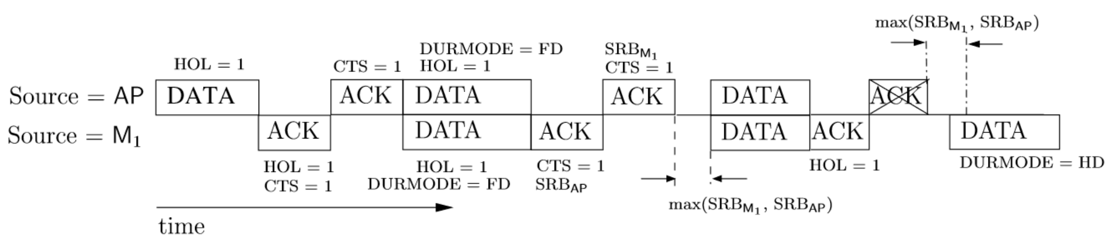

Figure 7: Packet Sequence for FD-MAC [3]

In [8] and [4] Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) based, basic IEEE 802.11-like MAC protocols are proposed, where different frame structures and protocol operations are employed for FD topologies in Figure 4, depending on which node is initiating FD operation, or whether it is a bidirectional transmission or FD relay. However, such protocol designs lack the practicality, since it is quite difficult to decode packet headers and take actions accordingly, while receiving a packet. Example packet sequences for protocol in [4] can be seen in Figure 8. This requires substantial changes in conventional MAC implementations; whereas in our protocol the packet fields for FD operation are processed after the packet is received completely.

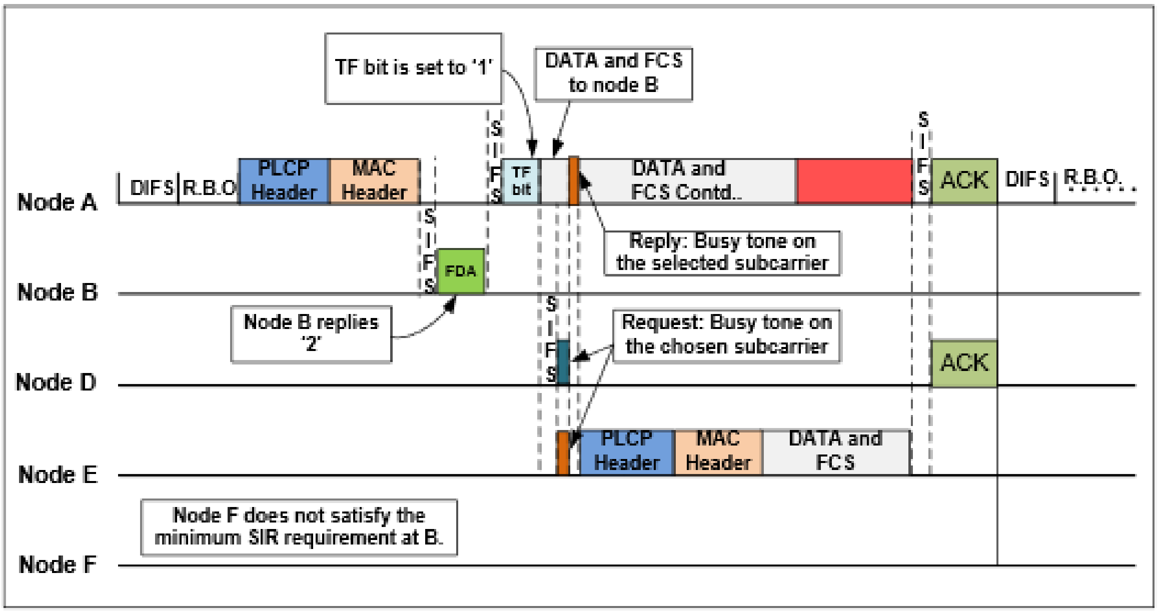

Figure 8: Packet Sequence for [4] for Topology in Fig. 4 (a)

Moreover, unlike [4] S-CW FD protocol can be applied to different FD scenarios (bidirectional or relaying) via the same access mechanism. Hence, S-CW FD is not only flexible, but also it can be easily implemented by making use of the off-the-shelf WLAN hardware and firmware, while working seamlessly with legacy 802.11 nodes.

MACs depicted in [4], [30] and [31] use busy-tone signals to prevent collisions if uplink and downlink is not utilized at the same time. If only the downlink of a node is used then that node transmits a busy-tone. In [32] authors argue that though FD enables transmission of busy tones, power consumption is increased, hence they are not practical for mobile wireless nodes.

In [33] a reservation (RTS/CTS) based approach is proposed, where the protocol uses a two way handshake mechanism use FCTS (FD clear to send) to start an FD transmission. In our proposed protocol, FD transmission is initiated with information embedded in the packet header, causing much smaller overhead than RTS/CTS exchange. Furthermore, RTS/CTS is no longer necessary for FD, since by nature FD solves the hidden terminal problem.

In [34], a reservation based approach Directional Asynchronous Full-Duplex MAC (DAFD-MAC) is proposed which is also based on reservation. This work uses directional antennas in order to prevent collision in multi-hop full-duplex and a five-way handshake protocol in order to prevent the deafness problem which is caused by directional antennas. Directional antenna based schemes require the nodes additional hardware and processing for not only supporting directional antennas, but also for determining the location information of the nodes and their surroundings by employing technologies such as angle on arrival localization and GPS, therefore they might be impractical in real scenarios.

[35] provides a nice survey of the state of the art FD wireless networks, defining its advantages and disadvantages. These advantages and disadvantages in relation to our work can be summarized as follows. It is stated that FD can double the capacity, our protocol is shown to increase the overall throughput of a single hop multiaccess wireless system even with poor SI cancellation capability. Authors also state that, FD can improve network secrecy, since it is quite challenging if not impossible to decode mixed signals from both FD stations. FD can decrease the effect of hidden terminals, this is a natural consequence of FD, and it is shown that the throughput of wireless networks can be drastically improved in hidden terminal scenarios when S-CW FD is employed. In addition to advantages, [35] also states the possible disadvantages of FD. First problem is SI and imperfect SI cancellation, unlike many other works on FD MAC, we have considered the effect of SI in analysis of our protocol. Even with high residual SI levels, S-CW FD is shown to outperform HD protocols. Another disadvantage of FD is increased inter-user interference, which power control is required to address this problem, which holds for all FD MAC protocols. The last disadvantage is increased consumed power and complexity, t is stated in [36] additional components for self-interference cancellation increases power consumption, this is a problem for all full-duplex hardware, but our protocol does not use busy-tone signals hence its power consumption is expected to be lower than the protocols that use using busy-tone signals [4], [30].

Last but not least, though the advantage of alleviating the effect of hidden nodes is mentioned in all works, their performance in the presence of hidden nodes is not evaluated. Our work is the first one that considers the effect hidden nodes in evaluating the performance of FD MAC, in addition to a realistic model of residual SI, which is a function of the transmitter power; while existing works assume ideal or constant SI cancellation.

3 S-CW FD Protocol

3.1 S-CW FD MAC Protocol

We consider an infrastructure based WLAN with an AP and a number of stations in a cell. All nodes (AP and the stations) are assumed to be FD capable, with FD radios in [17]. Our proposed protocol S-CW FD can work in both ad hoc and infrastructure modes, and also for both bidirectional and relaying FD modes.

The design of the S-CW FD protocol is based on classical IEEE 802.11 MAC with additional features, such as backoff synchronization and master-slave roles, as well as modifications to enable and maintain FD communications. Being based on IEEE 802.11 allows the S-CW FD protocol to remain compatible with the legacy nodes in HD mode, also facilitating heterogeneous scenarios involving both HD and FD nodes and transmissions.

3.1.1 Packet Format

In the S-CW FD protocol, the basic idea is to synchronize two FD nodes so that they can transmit simultaneously. This is achieved by sharing the size of the next backoff window (the number of backoff slots) between the FD nodes via a new packet structure as shown in Figure 9. In order to start FD transmission in S-CW FD, initially a successful HD transmission is required, where three new control fields are exchanged via a data packet: *FD* is a one bit field indicating that FD mode is on (which is indicated by a 1), so that the receiving node prepares itself for FD operation and obtains the other two control fields, *fd_master* and *next_bo*, which are used to achieve synchronization. The *next_bo* field carries the randomly selected number of backoff slots of the sending node for the next contention period, and *fd_master* is another one bit field informing role of the receiving node, where a 1 indicates the master and a 0 indicates the slave. These control fields are continuously exchanged via packets sent in FD mode to continue and maintain FD mode, or in HD mode to start FD with another node, or to switch to HD mode when desired. Utilizing the IEEE 802.11 frame structure, for these control bits, we propose to use two bits from the reserved bits under the subtype field of the Frame Control field in the MAC header for *FD* and *fd_master* bits. For the *next_bo* field, since we need at least 10 bits, we propose to introduce a small overhead per packet in the payload.

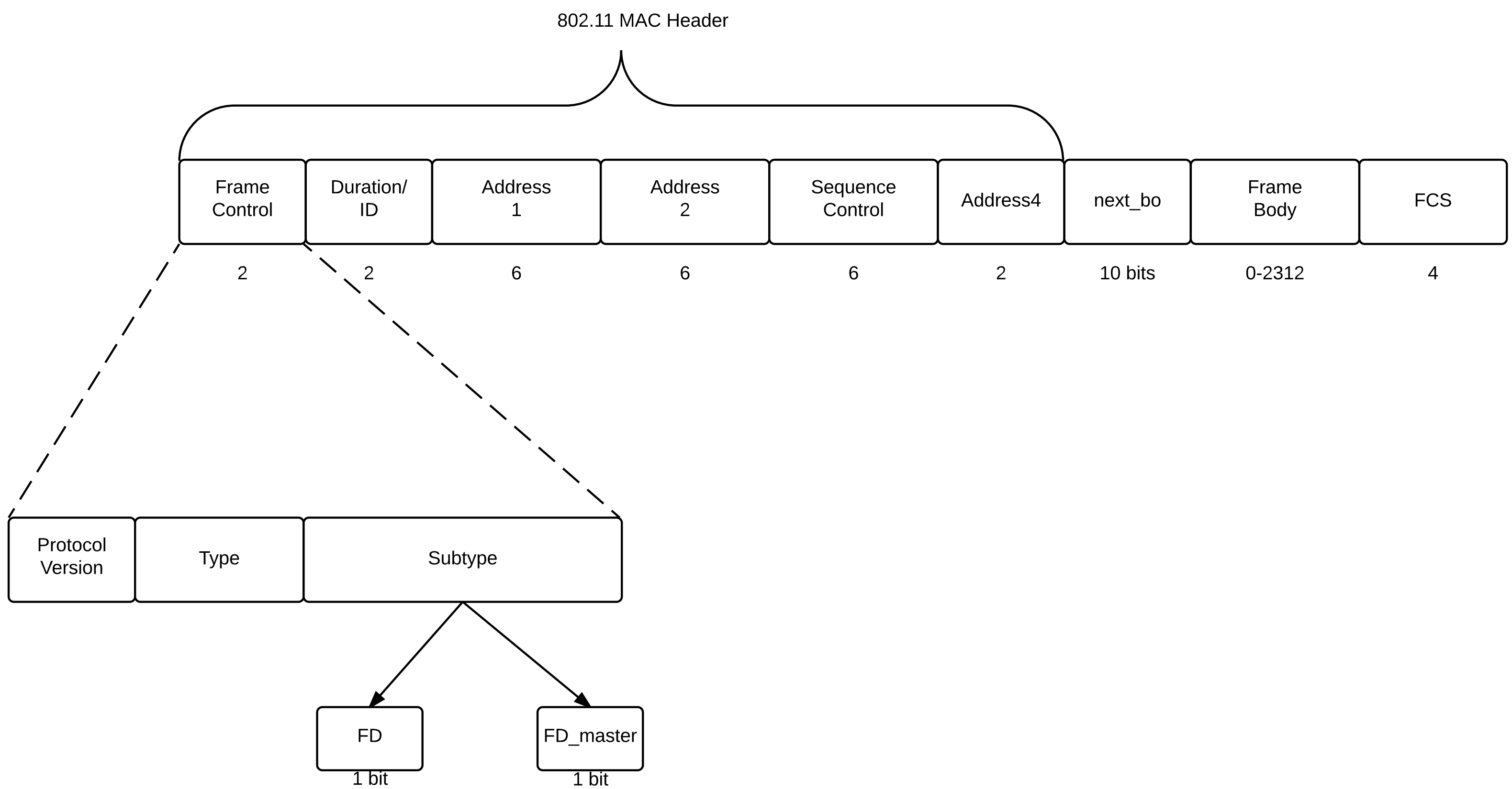

Figure 9: Packet Format for S-CW FD

3.1.2 Protocol Details

Recall that we have defined the control fields of S-CW FD in the Section 3.1.1, let us review how they can be set at the nodes: A node (station or AP) that decides to start FD operation can set the *FD* field. Also, a station sets the *next_bo* field in its packet to its single backoff window variable for transmitting to the AP, while the AP has a separate backoff window value for each station that it is communicating with. In order to coordinate its FD transmissions, the AP needs to hold a list of backoff windows for all of the nodes in its coverage. Hence, as the backoff period, the AP uses the *minimum* of the backoff windows in its list, and sets the *next_bo* field in its packet to this value, so it can start FD communication with the corresponding node, which backs off with the same amount of slots. Using this backoff slot list at the AP, even if there is a collision or another node contending for the medium at some point, we make sure that FD operation can continue without preceding HD transmissions.

The importance of backoff list is that, even if another node gets the medium after a synchronization (which is likely since backoff counter stops and continues from the same slot which is lower than the initial stop when the channel is not idle), the nodes are able to maintain synchronization with each other since a node is able to hold more than one backoff time, one for each of its pairs.

Since both AP and the stations can generate and send the *next_bo* information, a mechanism to determine which *next_bo* will be used for an FD pair is required. For this purpose, *fd_master* field is defined in order to identify the master node as the node, which dictates the backoff window. Conversely, the slave node is the node, which uses the backoff slot coming from the master. Each node is a master by default, i.e., *fd_master* field in its packet is set to 0 in order to dictate the receiving node to be the slave, and in practice, the node is able to transmit earlier becomes the master. Hence, the slave node uses the backoff window information it receives from the *next_bo* field. While one variable for defining the master-slave status is sufficient for the stations, the AP needs to keep a list for its master-slave status for its FD communication with each station similar to the backoff windows list. This is because, the AP can serve as a master for one station and a slave for another simultaneously.

Let us now observe an example packet sequence, as shown in Figure 10. Assuming it is the AP that has initiated transmission, the AP first detects the channel is idle. After ensuring it stays idle for *DIFS* seconds, the AP backs off for a random number of slots before sending the first packet (Packet #1) in HD mode. In the MAC header of this packet, *FD* field is set to 1, *fd_master* field is set to 0, and the *next_bo* field is set to a value, say bo_1, which is the new random number of slots for the next backoff. Upon receiving this packet and reading the *FD*, *next_bo* and *fd_master* fields, the destination station, say STA1 as shown in the Figure 10, discerns that it can work in FD mode, enables FD mode, marks itself as the slave and sets its next number of backoff slots to bo_1 as it transmits an ACK after the *SIFS* period. In the next contention, after deferring for *DIFS* seconds and backing off for bo_1 slots, both AP and STA1 start their transmission at the same time, sending packets #2 and #3, respectively, as shown in the Figure 10. In these packets, the S-CW FD fields are again set, so that the AP is again the master that dictates the backoff window for the next transmission, setting the *next_bo* field as bo_2. After the data packets are both received successfully, both AP and STA1 wait for the *SIFS* period and they transmit their ACKs in FD mode. After this point, we assume that another station, STA2 contends for the medium and wins it after bo_x slots, which is smaller than bo_2. Given the opportunity STA2 transmits to the AP in HD, willing to perform FD communication with its own settings for S-CW FD fields. Assuming *fd_master* field set is to 0 and *next_bo* field set to bo_3, receiving this packet, the AP updates its backoff window for STA2 as bo_3, marks itself as the slave to this station and sends the ACK to STA2. After this point, the station with the lowest backoff will seize the channel, and recalling that the earlier back off window (bo_2) has been frozen due to STA2's transmission, if $bo_2 - bo_x$ is smaller than bo_3, then the AP and STA1 will transmit to each other in FD mode, since both are already synchronized, otherwise, if bo_3 is smaller than $bo_2 - bo_x$, then the AP will perform FD transmission with STA2. Figure 10 shows the former case, where again in the FD packets the parameters for the next backoff window are being exchanged.

A flow diagram for access points can be found from Figure 11.

In a more generic way, the S-CW FD protocol works as follows

1. A station with a packet in its queue monitors the channel and ensures it stays idle for
   - DIFS period if last transmission in the medium was successful
   - EIFS period if there was a collision in the last transmission
2. The station waits for
   - a random backoff time (synchronized or not synchronized) if it is not an access point or not working in Ad Hoc mode
   - minimum random backoff time from its backoff list if it is an access point or working in Ad Hoc mode
3. Station transmits its data packet
   - If another node starts transmitting at the same time also receives the incoming packet
4. Station starts waiting for ACK packet for timeout period
   - If also received a data packet while transmitting, transmits an ACK after SIFS period
5. If station does not receive ACK packet in timeout period, it reschedules the packet

The flow diagram for stations can be seen in Figure 12.

In regular IEEE 802.11 DCF, a node waits for the EIFS period after the medium is free if it was not able to receive the last transmitted packet (the last packet is unsuccessful) or if it receives an erroneous packet. Since in FD, two nodes transmit their packets concurrently, another node which hears the medium would not be able to receive both of the packets. Here, we have modified the protocol such that, if the third node hears that both of the transmissions start at the same time, it should interpret this transmission as FD, and defer for the *DIFS* period instead of EIFS. This modification should be done on the legacy HD nodes, as well since otherwise the system would be unfair for the legacy nodes. The only time that the nodes need to use EIFS is, if there are more than two transmissions, or if the transmissions started at different times due to the exposed terminal problem.

It is worthwhile to note that, in case of a packet failure, due to collision(s) or channel errors, the nodes currently operating in FD mode will not be able to continue, since they will not be able to synchronize their backoff slots for their next transmission. In that case, both nodes will resort to HD mode, they will retransmit their packets and initiate FD mode again. Loss or difficulty of maintaining FD mode under errors is a problem for all existing FD protocols. Not being able to decode FD specific information (in preamble, specific packet fields or RTS/CTS packets), all protocols resort to HD mode.

Last but not least, S-CW FD MAC protocol operation, which has been explained here for an infrastructure scenario considering bidirectional FD between the stations and the AP, can also work for ad hoc mode bidirectional communication. In that case, the nodes need to store the master-slave and next backoff window information of all other nodes, as the AP does in the infrastructure mode. Also, S-CW FD protocol works perfectly for a three node (including relaying) scenario, where the AP is transmitting (or relaying) data to a station, while receiving from another station, as long as the two end stations do not hear each other. If these stations do hear each other, a power control scheme is necessary.

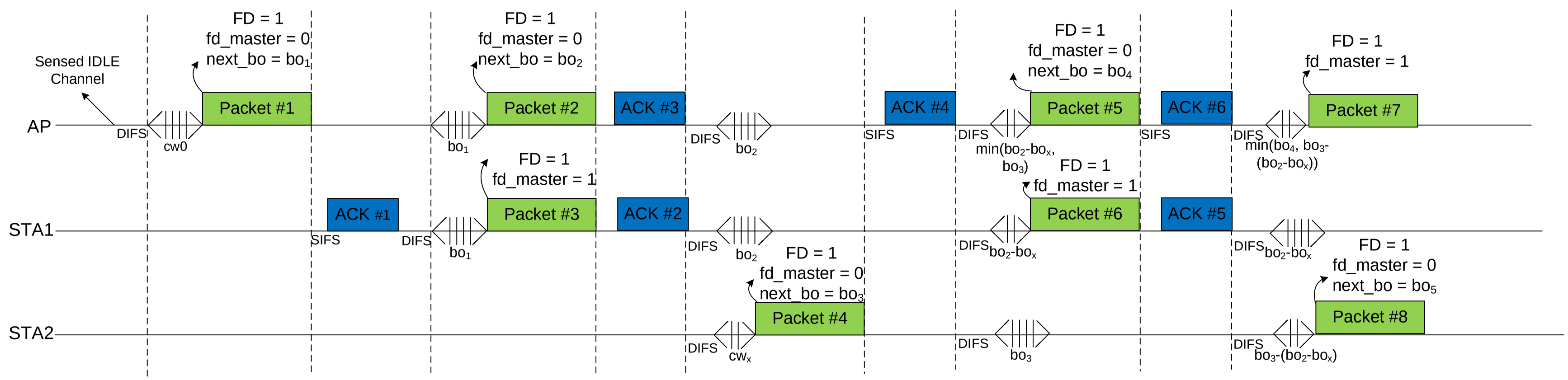

Figure 10: An example packet sequence for S-CW FD

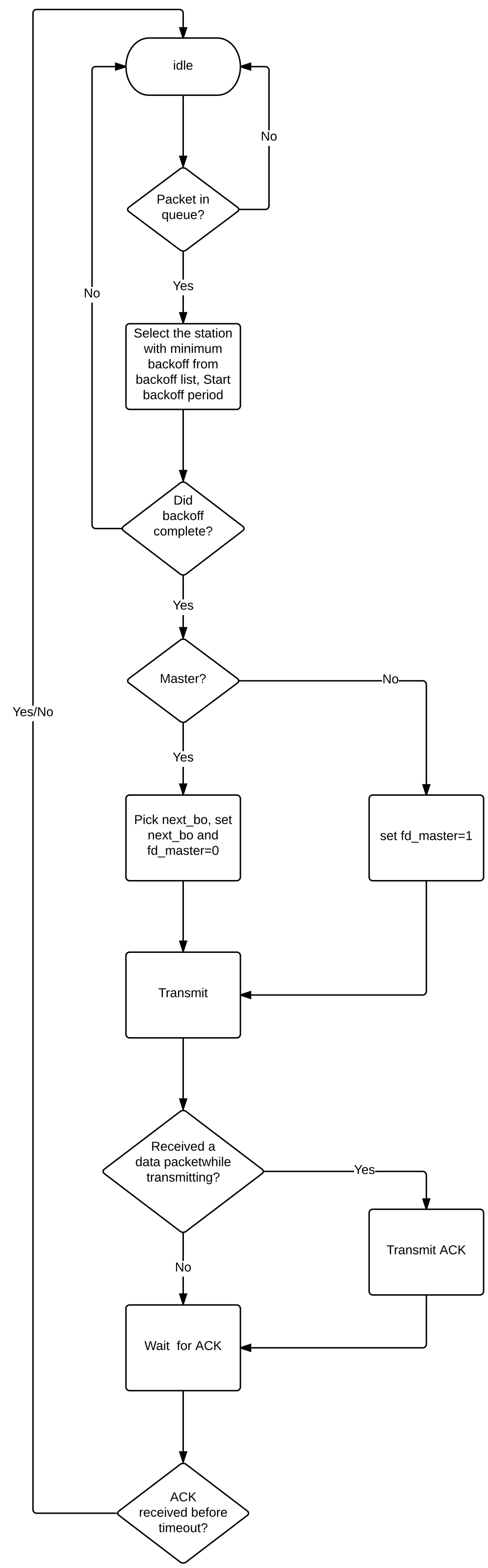

Figure 11: Flow Diagram for Access Point

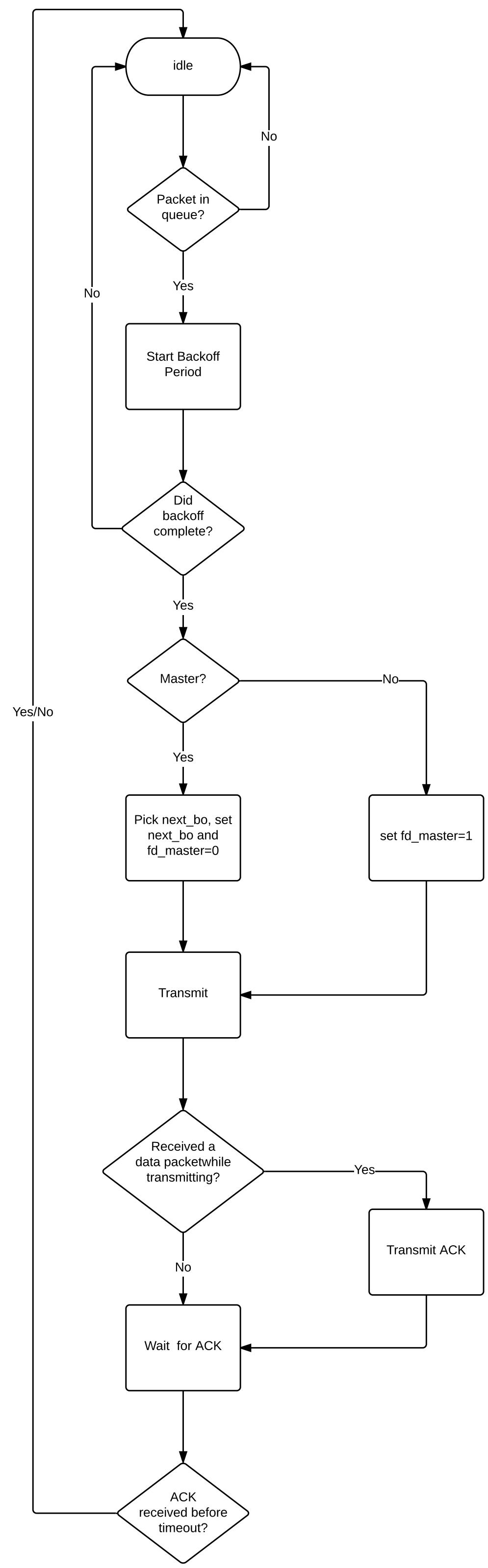

Figure 12: Flow Diagram for Stations

4 Performance Analysis of S-CW FD Protocol

In this chapter, we present the derivation of the saturation throughput for S-CW FD MAC protocol. We consider the similar works of Bianchi's [5] and Wu's [6] and adapt them for modeling S-CW FD. We present the results obtained from these analytical models, while comparing them to the result obtained from OPNET simulations.

4.1 Analytical Model Based on Bianchi's Approach

For this analytical model same assumptions described below and Markov chain model in [5] has been used with minor modifications for S-CW FD. Network of "n" nodes is assumed to be saturated so that each node always has a packet to transmit in its queue. Each packet needs to wait for a random backoff time before transmission (after deferring DIFS seconds). In this Markov chain, the backoff slot is decreased with probability 1, and stations attempt to transmit when the slot is equal to 0. This attempt of transmission either ends with p_{HD} or p_{FD} denoting collision probability in HD and FD modes respectively, or ends with a successful transmission with probability of $1-p_{HD}$ and $1-p_{FD}$, depending on the transmission mode. A station transmits in full-duplex mode when its backoff stage is 0, which is achieved by a successful transmission. The Markov chain depicted can be seen in Figure 13.

The backoff time counter for a given station at a slot time t is represented as stochastic process *b(t)* [5]. It should be noted that slot time is specified to have a constant value σ and the time interval between two successive backoff time counter decrements.The contention window is denoted by, W set as $W = CW_{min}$ initially and $W_i = 2^i W$ denotes the contention window of $\mathrm{i^{th}}$ backoff stage with, m is "maximum

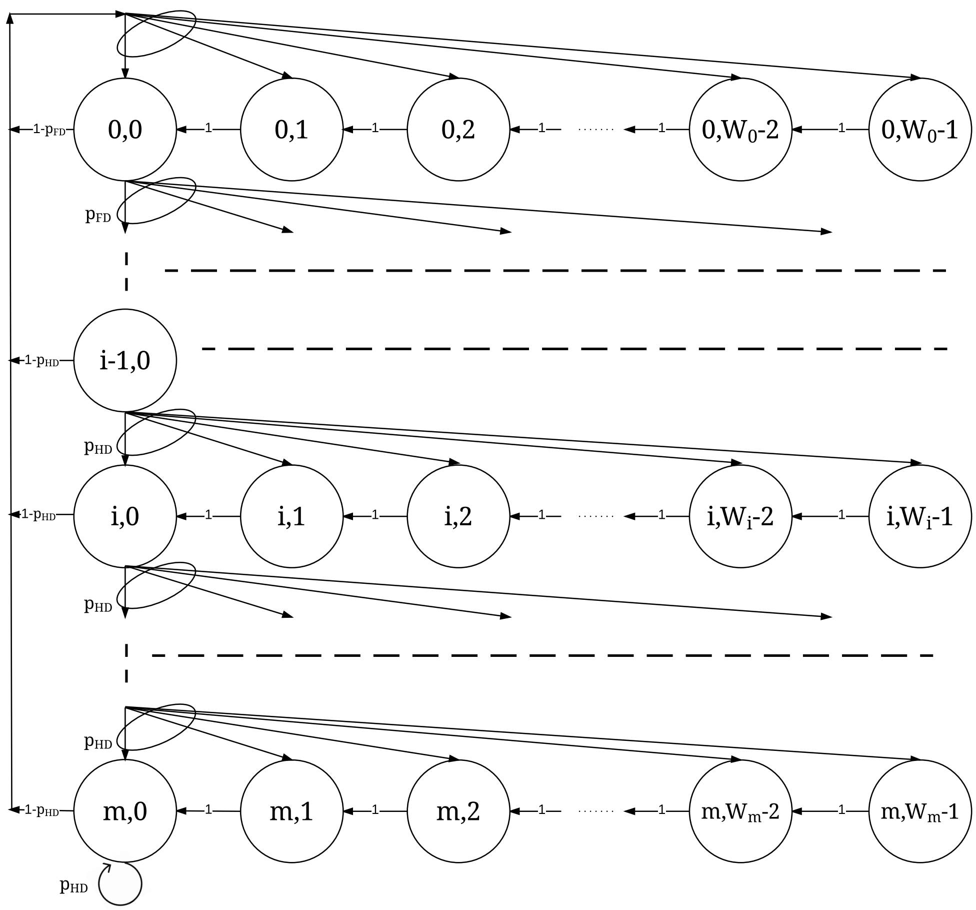

Figure 13: Markov Chain for Model of S-CW FD based on Bianchi's Model [5]

backoff" stage, $i \in (0, m)$, where $s(t)$ is defined as the stochastic process representing the backoff stage $(0, ..., m)$ of the station at time t.

The main approximation of model in [5] is that, at each transmission attempt each packet collides with constant and independent probability p. In this model instead of using single p probability, we define p_{FD} for collisions of FD transmissions that occur in state $\{0, 0\}$ and p_{HD} for else. Due to synchronization of the contention window our protocol eliminates one of the contending nodes.

In this Markov chain non-null one-step transition probabilities are

$$\begin{cases} P\{i,k \mid i,k+1\} = 1 & k \in (0, W_i - 2) \quad i \in (0,m) \\ P\{0,k \mid i,0\} = (1-p_{FD})/W_0 & k \in (0, W_0 - 1) \quad i = 0 \\ P\{0,k \mid i,0\} = (1-p_{HD})/W_0 & k \in (0, W_0 - 1) \quad i \in (1,m) \\ P\{i,k \mid i-1,0\} = p_{FD}/W_i & k \in (0, W_i - 1) \quad i = 1 \\ P\{i,k \mid i-1,0\} = p_{HD}/W_i & k \in (0, W_i - 1) \quad i \in (2,m) \\ P\{m,k \mid m,0\} = p/W_m & k \in (0, W_m - 1), \end{cases} \tag{3}$$

Where the first equation depicts the fact that, at the beginning of each slot time, the backoff time is decremented. Second and third equations account for the fact that a new packet following a successful packet transmission starts with backoff stage 0, and thus the backoff is initially uniformly chosen in the range $(0, W_0 - 1)$. Fourth and fifth equations are for modeling the system after an unsuccessful transmission. When an unsuccesful transmission occurs in stage $i-1$, the backoff stage is increased by one and it becomes i, and the new backoff value is selected randomly from the range $(0, W_i)$. Finally, the last equation models the fact that once the backoff stage reaches the value m, it is not increased for subsequent packet transmissions.

Defining $b_{i,k} = lim_{t\to\infty} P\{s(t) = i, b(t) = k\}, i \in (0,m), k \in (0, W_i - 1)$ as the steady state probability distribution of the states, the global balance equations can be written as:

$$\begin{array}{lll} b_{0,0} \cdot p_{FD} = b_{1,0} & & \\ b_{i-1,0} \cdot p_{HD} = b_{i,0} \rightarrow b_{2,0} = b_{1,0} \cdot p_{HD} & \rightarrow & b_{i,0} = b_{0,0} \cdot p_{FD} \cdot {p_{HD}}^{i-1} \quad 1 < i < m \\ b_{m-1,0} \cdot p_{HD} = (1-p_{HD}) b_{m,0} & \rightarrow & b_{m,0} = \frac{p_{FD} {p_{HD}}^{m-1}}{1-p_{HD}} b_{0,0}. \end{array} \tag{4}$$

Observing Markov chain $b_{i,k}$ can be written for any $k \in (1, W_i - 1)$ as:

$$b_{i,k} = \frac{W_i - k}{W_i} \cdot \begin{cases} (1 - p_{FD})b_{0,0} + (1 - p_{HD}) \sum_{j=1}^{m} b_{j,0} & i = 0 \\ p_{FD} \cdot b_{0,0} & i = 1 \\ p_{HD} \cdot b_{i-1,0} & 1 < i < m \\ p(b_{m-1,0} + b_{m,0}) & i = m \end{cases} \tag{5}$$

since each backoff slot is selected with probability of $\frac{1}{W_i}$, and backoff slots decrease from k to $k-1$ with probability 1.

Equation (5) can be rewritten using the Equation (4)

$$b_{i,k} = \frac{W_i - k}{W_i} b_{i,0} \quad i \in (0, m), \quad k \in (0, W_i - 1). \tag{6}$$

Then, recalling total probability theorem;

$$\begin{aligned} 1 &= \sum_{i=0}^{m} \sum_{k=0}^{W_i - 1} b_{i,k} = \sum_{i=0}^{m} b_{i,0} \sum_{k=0}^{W_i - 1} \frac{W_i - k}{W_i} = \sum_{i=0}^{m} b_{i,0} \frac{W_i + 1}{2} \\ 1 &= \frac{b_{0,0}}{2} \left[(W+1) + p_{FD} \left(2W \frac{1 - (2p_{HD})^{m-1}}{1 - (2p_{HD})} + \frac{1 - p_{HD}^{m-1}}{1 - p_{HD}} \right) + \frac{p_{HD}^{m-1}(2mW + 1)}{1 - p_{HD}} \right] \end{aligned} \tag{7}$$

By having $b_{0,0}$ alone and defining probability that a station transmits using FD mode in a randomly chosen slot time as $\tau_{FD} = b_{0,0}$ since, FD transmissions occur in state {0,0}

$$\begin{aligned} \tau_{FD} = b_{0,0} &= \frac{2(1 - 2p_{HD})(1 - p_{HD})}{a + b} \\ a &= (W+1) + 2W p_{FD}(1 - 2p_{HD})^{m-1} \\ b &= p_{FD}(1 - p_{HD}^{m-1})(1 - 2p_{HD}) + p_{HD}^{m-1}(2mW + 1)(1 - 2p_{HD}). \end{aligned} \tag{8}$$

Next, we define τ as the probability that a station transmits using FD or HD mode in a randomly chosen slot time. As any transmission occurs when the backoff time counter is equal to zero, regardsless of the backoff stage, τ is obtained as:

$$\tau = \sum_{i=0}^{m} b_{i,0} = b_{0,0} \frac{1 - p_{HD} + p_{FD}}{1 - p_{HD}}. \tag{9}$$

The probability that a station transmits using half-duplex is as follows

$$\tau_{HD} = \tau - \tau_{FD}. \tag{10}$$

At steady state, each remaining station transmits with probability τ. Notice that, during a FD transmission there are $(n-2)$ stations that can cause a collision, instead of $(n-1)$ stations in HD. We can obtain p_{FD} and p_{HD} as follows:

$$p_{FD} = 1 - (1 - \tau)^{n-2}. \tag{11}$$

$$p_{HD} = 1 - (1 - \tau)^{n-1}. \tag{12}$$

Equations (9), (11) and (12) represent a system of nonlinear equations with three unknowns τ, p_{FD} and p_{HD}, which can be solved using numerical techniques. Next we present the analysis based on Wu's [6] Markov chain model to obtain τ, p_{FD} and p_{HD} for the performance of S-CW FD which will be followed by the calculation of saturation throughput which is common for both models.

4.2 Analytical Model Based on Wu's Approach

In this chapter, we present the derivation of the saturation throughput for S-CW FD MAC protocol using a Markov model based on [6]. Again, each node always have a packet to transmit in their queue. Fixed number of n stations are considered. Again $s(t)$ and $b(t)$ denote, same as in Subsection 4.1. In [6] a single constant p value has been used for conditional collision probability whereas in our model two constant values p_{FD} and p_{HD} have been used, for collisions in FD and HD respectively.. An additional identifier "H" has been added, in order to differentiate different $s(t) = 0$ states, for synchronized ones which full-duplex transmission will be taking place we do not use

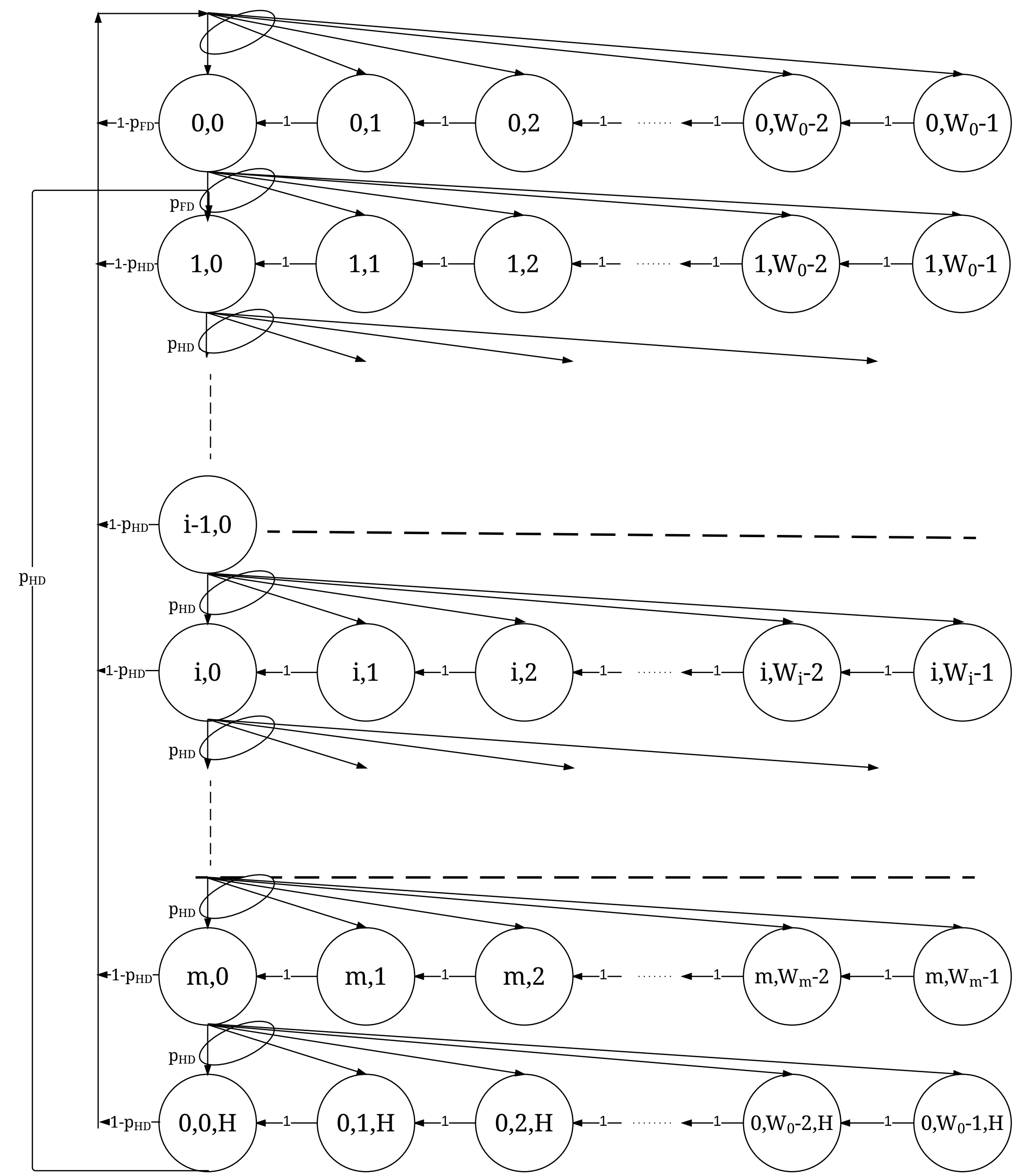

Figure 14: Markov Chain for Analytical Model based on Wu's Model [6]

any identifier and for unsynchronized one which regular half-duplex transmissions will take place we use "H" identifier. Since all packets are consecutive, each packet needs to wait for a random backoff time before transmission. Backoff slots are decreased with probability 1, in FD collision probability is p_{FD}, transmission probability is p_{HD}, in HD collision probability is p_{HD} and transmission probability is $1 - p_{HD}$. Instead of staying in the m^{th} backoff stage until a successful transmission, this model goes to 0^{th} backoff stage without synchronization if a collision occurs, which is the row denoted by H, and goes to the 0^{th} backoff stage with synchronization for FD operation if the transmission was successful. This is due to the retransmission limit [20].

In this Markov chain non-null one-step probabilities are

$$\begin{cases} P\{i,k \mid i,k+1\} = 1 & k \in (0, W_i - 2) \quad i \in (0, m) \\ P\{0,k \mid 0,0\} = (1 - p_{FD})/W_0 & k \in (0, W_0 - 1) \\ P\{0,k \mid i,0\} = (1 - p_{HD})/W_0 & k \in (0, W_0 - 1) \quad i \in (1, m) \\ P\{1,k \mid 0,0\} = p_{FD}/W_1 & \\ P\{i,k \mid i-1,0\} = p_{HD}/W_i & k \in (0, W_i - 1) \quad i \in (2, m) \\ P\{0,k \mid 0,0,H\} = (1 - p_{HD})/W_0 & \\ P\{0,k,H \mid m,0\} = p_{HD}/W_0 & k \in (0, W_0 - 1) \end{cases} \tag{13}$$

Where the first equation depicts the fact that, at the beginning of each slot time, the backoff time is decremented. Second, third and fourth equations account for the fact that a new packet following a successful packet transmission starts with backoff stage 0, and thus the backoff is initially uniformly chosen in the range $(0, W_0 - 1)$. Fifth, sixth and seventh equations are for modeling the system after an unsuccessful transmission. When an unsuccessful transmission occurs in stage $i - 1$, the backoff stage increases by one and becomes i, and a new random backoff value is selected randomly from the range $(0, W_i)$. It should be noted that, when $s(t) = m$, a successful transmission will take the system to {0,0} state, where the nodes backoff slots are synchronized for FD operation, an unsuccessful transmission will take the node to {0,0,H} state where the maximum *bt* is the same as 0,0 but the node is unsynchronized, thus a successful transmission from this state would be HD.

Since 802.11 DCF protocols use a retry limit, the assumption of staying in the maximum backoff stage until a successful transmission in [5], this is an incorrect assumption since IEEE 802.11 protocols use a retry limit. Thus in this model m is used to represent *maximum retransmission count*, and m' is used to calculate the maximum CW to be picked as in [6]. Therefore, we have

$$\begin{cases} W_i = 2^i W & i \leq m' \\ W_i = 2^{m'} W & i > m'. \end{cases} \tag{14}$$

where $W = (CW_{min} + 1)$, and $2^{m'}W = (CW_{max} + 1)$.

Let $b_{i,k} = lim_{t \to \infty} P\{s(t) = i, b(t) = k\}, i \in (0, m), k \in (0, W_i - 1)$ be the steady state probability distribution of the states. The global balance equations can be written as follows. First, note that

$$\begin{aligned}
b_{0,0} \cdot (p_{FD} + {p_{HD}}^{m+1}) &= b_{1,0} \\
b_{0,0} \cdot (p_{FD} + {p_{HD}}^{m+1}) \cdot {p_{HD}}^{i-1} &= b_{i,0} \qquad\qquad 1 \leq i \leq m \\
b_{m,0} \cdot p_{HD} &= b_{0,0,H} \rightarrow b_{0,0}\,(p_{FD} + {p_{HD}}^{m+1}) \cdot {p_{HD}}^{m} = b_{0,0,H}.
\end{aligned} \tag{15}$$

Observing the Markov chain, for each $k \in (0, W_i - 1)$, it is

$$\begin{aligned}
b_{i,k} &= \frac{W_i - k}{W_i} \cdot \begin{cases} (1 - p_{FD})b_{0,0} + (1 - p_{HD}) \sum\limits_{j=1}^{m-1} b_{j,0} + b_{0,0,H}(1 - p_{HD}) & i = 0 \\ b_{0,0}(p_{FD} + {p_{HD}}^{m+1}) & i = 1 \\ p_{HD} \cdot b_{i-1,0} & 1 < i < m. \end{cases} \\
b_{0,k,H} &= \frac{W_i - k}{W_i} \cdot p_{HD} \cdot b_{m,0}.
\end{aligned} \tag{16}$$

Equation (16) can be simplified as

$$b_{i,k} = \frac{W_i - k}{W_i} b_{i,0} \quad i \in (0, m), \quad k \in (0, W_i - 1). \tag{17}$$

Thus, by using the total probability theorem:

$$
\begin{aligned}
1 &= \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} b_{i,k} + \sum_{k=0}^{W^0-1} b_{0,k,H} \\
&= \sum_{i=0}^{m} b_{i,0} \sum_{k=0}^{W_i-1} \frac{W_i-k}{2} + b_{0,0,H} \sum_{k=0}^{W_0-1} \frac{W_0-k}{2} \\
&= \sum_{i=0}^{m} b_{i,0} \frac{W_i+1}{2} + b_{0,0,H} \frac{W_0+1}{2}.
\end{aligned} \tag{18}
$$

By having $b_{0,0}$ alone in Equation 18 and defining $\tau_{FD} = b_{0,0}$ since, FD transmissions occur in state {0,0}.

$$
\tau_{FD} = b_{0,0} = \begin{cases} \dfrac{2}{(g + a((2W+1) + 2W \cdot b + c + (2^{m'}W+1)d + p_{HD}{}^{m} \cdot g)} & m \leq m' \\ \dfrac{2}{(g + a((2W+1) + 2W \cdot e + f + p_{HD}{}^{m} \cdot g))} & m > m' \end{cases} \tag{19}
$$

where $a = p_{FD} + p_{FD}p_{HD}^{m+1}$, $b = \frac{2p_{HD}-(2p_{HD})^{m'}}{1-2p_{HD}}$, $c = \frac{p_{HD}-p_{HD}{}^{m'}}{1-p_{HD}}$, $d = \frac{p_{HD}{}^{m'}-p_{HD}{}^{m}}{1-p_{HD}}$, $e = \frac{2p_{HD}-2p_{HD}{}^{m}}{1-2p_{HD}}$, $f = \frac{p_{HD}-p_{HD}{}^{m}}{1-p_{HD}}$ and $g = W + 1$.

τ is the probability that a station transmits using full-duplex or half-duplex mode of transmissions in a randomly chosen slot time. As any transmission occurs when the backoff time counter is equal to zero, regardless of the backoff stage, it is

$$
\tau = \sum_{i=0}^{m} b_{i,0} = b_{0,0} \left(1 + (p_{FD}(1 + p_{HD}{}^{m+1})) \left(\frac{1 - p_{HD}^{m+1}}{1 - p_{HD}}\right)\right) \tag{20}
$$

Given (19) and (20), the probability that a station transmits using half-duplex is as follows

$$
\tau_{HD} = \tau - \tau_{FD}. \tag{21}
$$

Calculation of p_{FD} and p_{HD} is same as is Section 4.1. Therefore,

$$
p_{FD} = 1 - (1-\tau)^{n-2}. \tag{22}
$$

$$
p_{HD} = 1 - (1-\tau)^{n-1}. \tag{23}
$$

Equations (20), (22) and (23) represent a nonlinear system with unknowns τ, p_{FD}

and p_{HD}, which can be solved using numerical techniques.

4.3 Saturation Throughput

Since calculation of saturation throughput is same for both models, with the difference of τ_{FD}, τ_{HD}, p_{FD} and p_{HD} values which have been described in Sections 4.1 and 4.2, calculation of the saturation throughput can be explained in one section.

Let $P_{tr_{HD}}$ be the probability that there is at least one half-duplex transmission in the considered slot time.

$$P_{tr_{HD}} = 1 - (1 - \tau_{HD})^n \tag{24}$$

Since in full-duplex operation, we know that one node is synchronized with the other one due to our protocol, $P_{tr_{FD}}$, the probability that there is at least one full-duplex transmission is expressed as

$$P_{tr_{FD}} = 1 - (1 - \tau_{FD})^{n-1} \tag{25}$$

The probability Ps_{HD} that a half-duplex transmission occurring on the channel is successful is found by the probability that exactly one station transmits on the channel, conditioned on the fact that at least one station transmits is written as

$$P_{s_{HD}} = \frac{(n)\tau_{FD}(1-\tau)^{n-1}}{P_{tr_{HD}}} \tag{26}$$

The probability Ps_{FD} that a full-duplex transmission occurring on the channel is successful is as follows

$$P_{s_{FD}} = \frac{(n-1)\tau_{HD}(1-\tau)^{n-1}}{P_{tr_{FD}}} \tag{27}$$

If we define S as the normalized system throughput, S can be expressed as

$$S = \frac{E[\text{payload information transmitted in a slot time}]}{E[\text{length of a slot time}]} \tag{28}$$

Let us define $E[P]$ as the average packet payload size(we have used a single constant packet size for our analysis therefore, $E[P] = P$). Average amount of payload information successfully transmitted in a slot time is $P_{tr_{HD}} P_{s_{HD}} E[P] + P_{tr_{FD}} P_{s_{FD}} 2E[P]$. One should note that, we multiply $E[P]$ with 2, since two packets are sent at the same time in case of a full-duplex transmission.

Probability of an empty (i.e. there is no transmission from any node) slot can be defined as $(1-\tau)^n$.

Probability of collision in a slot P_c can be calculated as

$$\begin{aligned}
A &= \sum_{i=1}^{n} \sum_{j=1}^{n-i-2} \left(C(n-1, i+j) {\tau_{HD}}^{i} (1 - \tau^{n-i-1-j})\right) \\
B &= \sum_{j=2}^{n-2} C(n-1, j)(1-\tau)^{n-1} \\
C &= \sum_{i=2}^{n} C(n, i) {\tau_{HD}}^{i} (1-\tau)^{n-i} \\
P_c &= A + B + C.
\end{aligned} \tag{29}$$

which can be written in pseudo code for better understanding as in Algorithm 1.

Algorithm 1 Algorithm for Calculating Probability of collision in a slot P_c

procedure CollisionProbability$(\tau, \tau_{FD}, \tau_{HD}, n)$
    $P_c \leftarrow 0$
    for $i \leftarrow 0, n$ **do**
        for $j \leftarrow 0, n-i-1$ **do**
            if $i + j \geq 2$ **then**
                if $j = 0$ **then**
                    $P_c \leftarrow P_c + C(n, i)({\tau_{HD}}^{i})(1-\tau)^{n-i}$
                else
                    $P_c \leftarrow P_c + C(n-1, i+j)({\tau_{HD}}^{i})(\tau_{FD}^{j})(1 - \tau^{n-i-1-j})$
                end if
            end if
        end for
    end for
    return P_c
end procedure

Now two more variables must be defined, T_s and T_c, which are times for a successful transmission and a collision.

$$\begin{cases} T_s = \dfrac{H+E[P]}{\gamma} + SIFS + \delta + \dfrac{ACK}{\omega} + DIFS + \delta \\ T_c = \dfrac{H+E[P]}{\gamma} + SIFS + \dfrac{ACK}{\omega} + DIFS + \delta. \end{cases} \tag{30}$$

where H is the header of the packet, ACK is the acknowledgment packet size including its headers, δ is the propagation delay, γ is the data rate for packets and ω is the data rate for control packets in units of bits per second.

The *saturation throughput* of the system now can be defined as

$$S = \frac{P_{tr_{HD}} P_{s_{HD}} E[P] + P_{tr_{FD}} P_{s_{FD}} 2E[P]}{(1-\tau)^n \sigma + (P_{tr_{HD}} P_{s_{HD}} + P_{tr_{FD}} P_{s_{FD}}) T_s + P_c T_c}. \tag{31}$$

4.4 Model Validation

To validate our models, we have compared our results from our analytic models with the implementation and simulation results of our protocol S-CW FD in OPNET Simulator. Parameters used in both analytic model and OPNET simulations are given below.

Table 1: System Parameters for OPNET and Analytic Model

Packet Payload	1500 bytes
ACK	264
Data Rates	6, 12, 24, 36, 54 Mbps
Lowest Mandatory PHY Rate	6 Mbps
Propagation Delay	1µs
Slot Time	9µs
SIFS	16µs
DIFS	34µs
$\boldsymbol{CW_{min}}$	15
$\boldsymbol{CW_{max}}$	1023
Retry Limit	7

Using the parameters defined in Table 1, we have simulated OPNET simulations simulations with 10 random different seeds. In the figures, each "'+"' sign represents a different simulation result for these random seeds for different fixed number of nodes.

Since, some of the simulation results are very close, the symbols on figures are sometimes superposed. We have also simulated the standard half-duplex models using OPNET with same parameters and calculated the results of the original analytic models proposed in [5] and [6], in order to compare the validity of our model with the original ones.

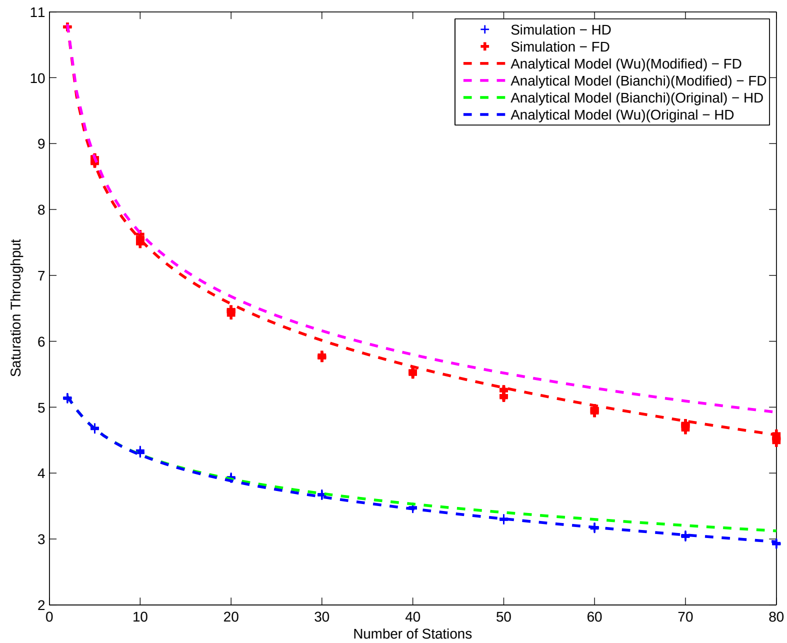

Figure 15: Simulation vs Analytic Model for 6 Mbps

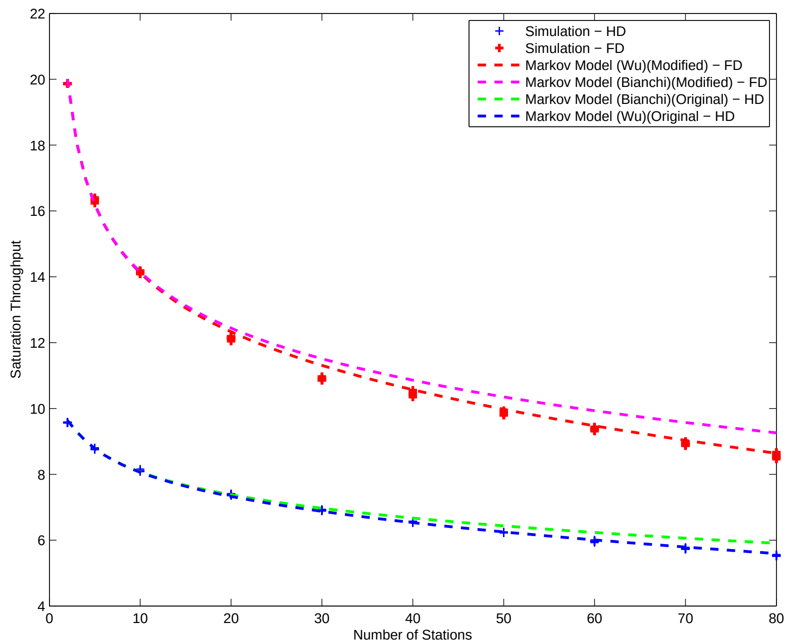

Figure 16: Simulation vs Analytic Model for 12 Mbps

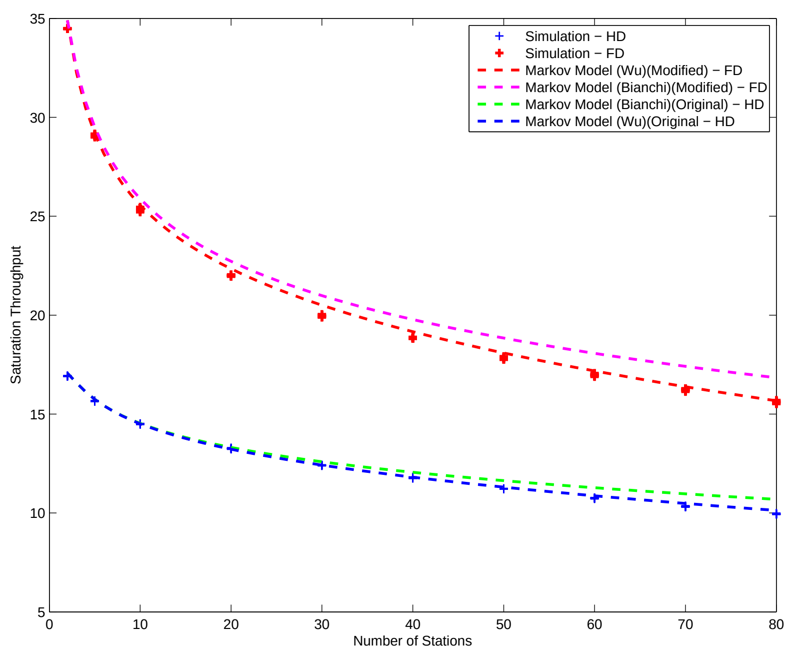

Figure 17: Simulation vs Analytic Model for 24 Mbps

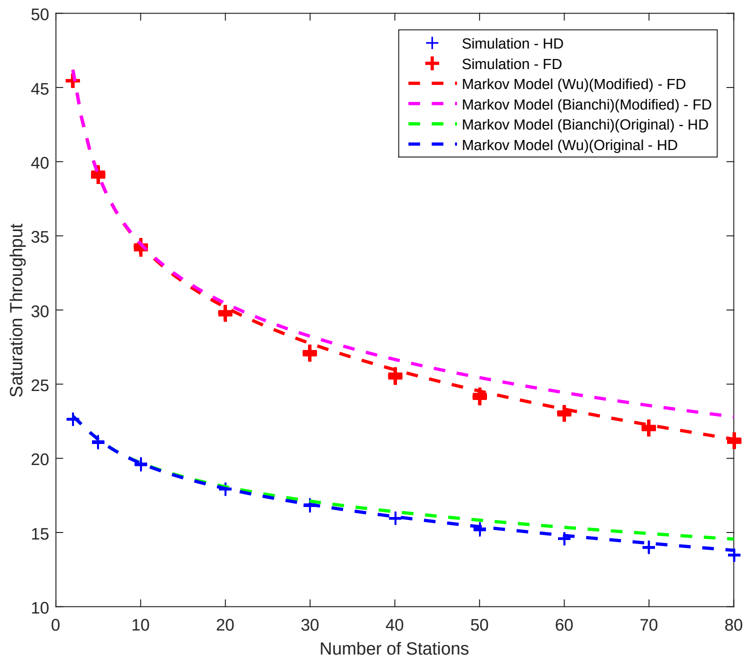

Figure 18: Simulation vs Analytic Model for 36 Mbps

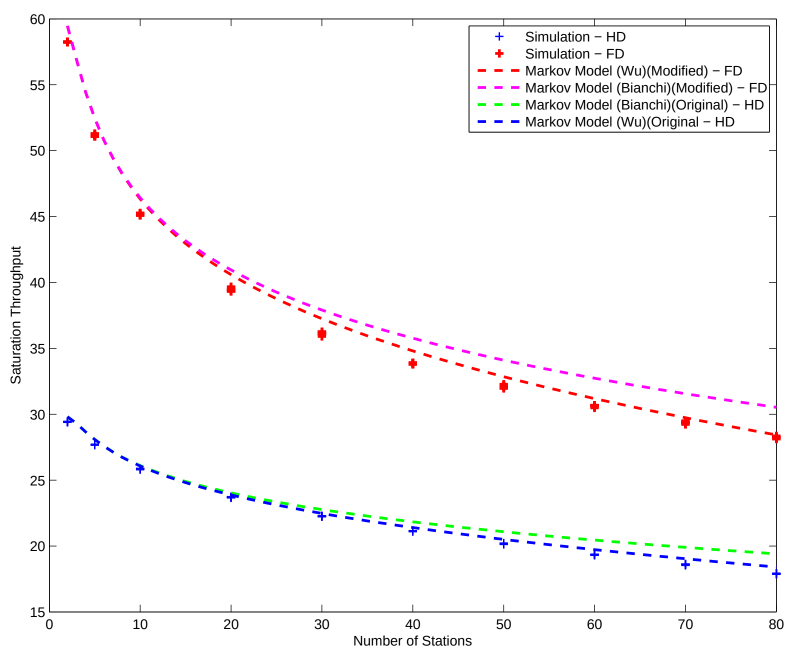

Figure 19: Simulation vs Analytic Model for 54 Mbps

As can be seen from Figures 15, 16, 18, 17 and 19, Markov model from [6] is more accurate than [5]. This accuracy is also shown on the modified full-duplex versions of both models. The reason behind this as stated in [6], the Markov model in [5] does not consider the retry limit which is defined in 802.11 protocols, thus lowering the probability of collision values. This results in overestimated throughput especially in systems with large number of stations, since a packet drop due to the retry limit is much more frequent in denser traffic.

5 Simulations

Having validated the OPNET implementation, this section provides detailed performance analysis for S-CW FD obtained via simulations that consider realistic models of FD implementations and wireless network scenarios. First performance under self-interference is presented employing the residual self-interference model explained in 2.1.2. Next, performance of S CW FD is studied in the presence of hidden nodes emphasizing full-duplex. Finally, S-CW FD MAC with similar FD MAC protocols [3], [4]. Finally, S CW FD is compared to similar FD MAC protocols , [3] and [4], from the literature. Note that, part of these results are published in [37].

5.1 System Model and Parameters

We consider an infrastructure based WLAN with an AP and a number of stations in a cell. All nodes (AP and the stations) are assumed to be FD capable, with FD radios in [17]. Our proposed protocol S-CW FD can work in both ad hoc and infrastructure modes, and also for both bidirectional and relaying FD modes; however, in order to measure and demonstrate the maximum gains of FD operation with S-CW FD, in this thesis, we consider FD for bidirectional transmissions between the stations and the AP as can be seen from Fig. 20.

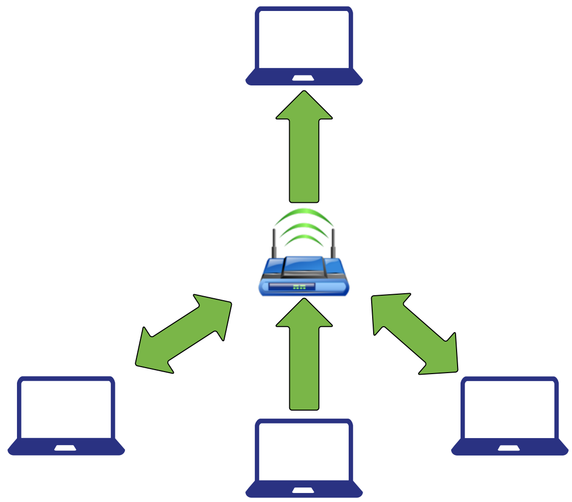

Figure 20: An example system model

We have also considered, the performance of S-CW FD with hidden terminals, the system model for hidden terminals which is described in Section 5.3 can be found in Fig. 21.

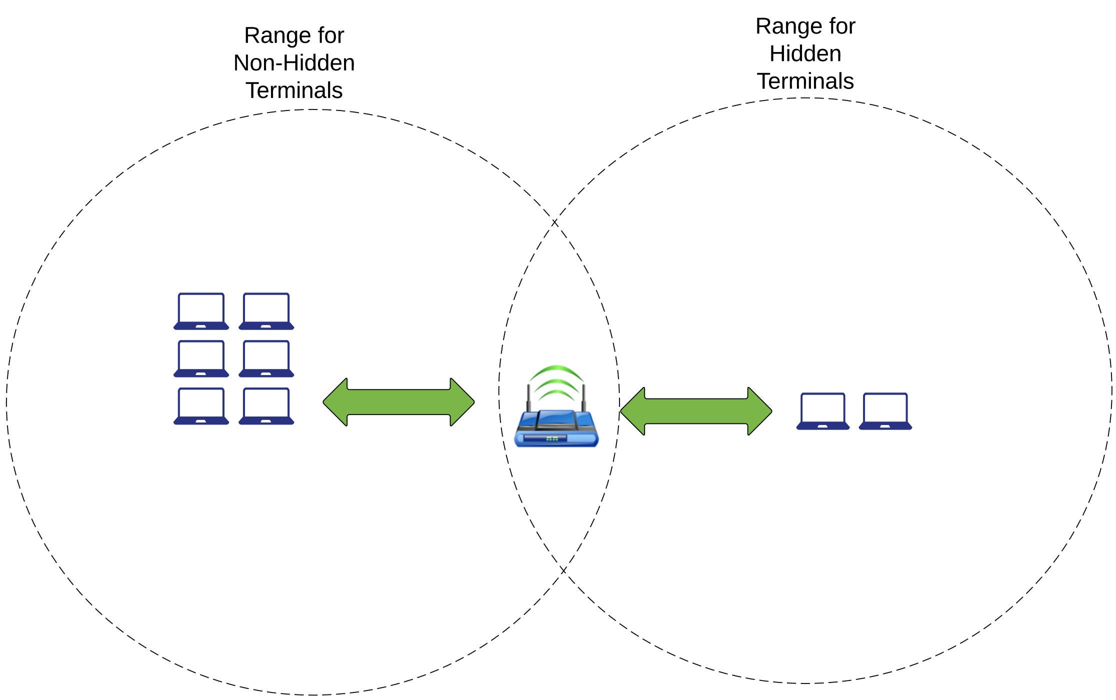

Figure 21: System Model for Hidden Terminals

OPNET and channel parameters in the following scenarios are as follows

Table 2: OPNET and Channel Parameters

Packet Payload	1500 bytes and 400(mean) bytes
Data Rates	6, 9, 12, 18, 24, 36, 48, 54 Mbps
Bandwidth	20 Mhz
Path loss exponent	3
Modulation	BPSK, QPSK, 16-QAM, 64-QAM
Channel Coding	Convolutional 1/2, 2/3, 3,4
Propagation Model	ITU-T Indoor Model and Rayleigh Fading
Minimum MAC packet error rate	10%

5.2 Performance Under Self-Interference

For modeling the wireless channel and physical layer, we followed a similar approach as in [4], where ITU-T Indoor Model is applied with Rayleigh fading. The path loss exponent is selected as 3. The stations are randomly distributed around an AP in a 100 m radius cell, and possible SINR (signal-to-noise-and-interference ratio) values are calculated for each channel between each station and the AP. Different from [4], we consider a more realistic model for the SI term in SINR calculation in FD mode, as the power of the residual SI is calculated as, $R_{SI} = \frac{P_T^{(1-\lambda)}}{\beta\mu^{\lambda}}$, obtained from [17]. For HD transmissions, only SNR is calculated, since there is no SI. Using the generated SINR (or SNR) values, the packet error rates are obtained for the IEEE 802.11g physical data rates, 6, 9, 12, 18, 24, 36, 48, 54 Mbps, corresponding to the modulation and coding schemes, BPSK, QPSK, 16-QAM, 64-QAM and convolutional codes with rates 1/2, 2/3, 3/4, as defined by the standard, and the highest physical data rate that ensures a packet error rate tolerance level, 10%, is selected. A node in OPNET makes use of this model to pick its data rate per packet for transmission. In case of FD transmissions, both nodes select the same data rate. Each simulation has a length of 50 seconds for the convergence of the results, each scenario has been simulated with different seeds for $200/n$ times (where n is the number of the nodes considered in that scenario), and the results are averaged to obtain each data point in each plot.

First, we investigate the performance of FD in a scenario where all nodes can hear each other, i.e., when there are no hidden nodes. In order to observe the saturation throughput, in the simulations the input traffic is adjusted so that both stations and the AP always have packets backlogged in their buffers. The packet size is fixed as 1500 bytes. In this experiment, we also consider the performance for Perfect Contention Window Full-duplex (P-CW FD) scheme, where the next backoff window values are known beforehand, so that perfect synchronization is always guaranteed. This scheme shows an upper bound to S-CW FD, as its ideal version, since there is no loss in synchronization at heavy load. In Figure 10, we plot the overall network throughput as a function of number of nodes for proposed S-CW FD and P-CW FD with different SI cancellation capability, i.e., λ levels, in comparison to HD IEEE 802.11 (which we refer to as HD from now on). Note that $\lambda = \infty$ denotes the perfect SI cancellation case, while $\lambda = 0.4$ and $\lambda = 0.6$ denote poor and moderate SI cancellation capability levels, respectively. As depicted by Figure 22, both FD schemes significantly outperform HD in all cases. Comparing the results for P-CW FD and S-CW FD, it can be noted that the difference between S-CW FD and P-CW FD is maximum for perfect SI cancellation, but the amount of degradation from the ideal P-CW FD gets smaller for practical residual SI levels. Considering the throughput improvement of S-CW FD over HD, S-CW FD MAC promises a gain between 1.5 and 2.1 under perfect SI cancellation. For practical moderate SI cancellation, $\lambda = 0.6$ this gain ranges between 1.4 - 1.9, and for poor SI cancellation it remains within the range 1.2 - 1.3. As the number of nodes is increased, throughput gain of S-CW FD is decreased due to increasing number of collisions, causing synchronization loss for the FD nodes, resulting in HD transmissions. Loss of synchronization, however, does not mean that FD cannot be initiated again. It is also worthwhile to note that, in practical cases, the network size is much smaller than 40 nodes in a cell, and all nodes are not simultaneously saturated. Furthermore, this situation is reversed with the presence of hidden nodes, as it will be shown in the next experiment.

Next we consider random packet sizes, specifically exponentially distributed packet sizes with mean of 400 bytes as a more realistic packet size model and we repeated the above experiments. Figure 23 shows the throughput of S-CW FD as a function of

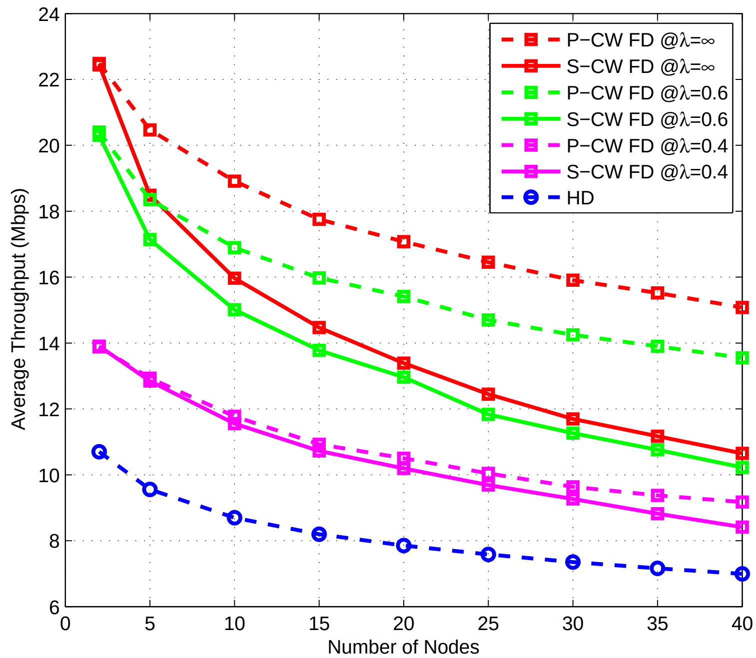

Figure 22: Comparison of HD and FD for $\lambda = \infty, 0.6, 0.4$ and using 1500 byte (constant size) packets

number of nodes, in the scenario where all nodes can hear each other. One can easily notice that, the gain of FD operation, i.e., S-CW FD, over HD 802.11 is smaller in this case due to two reasons: With smaller packet sizes, transmissions take smaller amount of time over an overall protocol sequence, lowering the throughput, hence utilization. The second reason is that due to random selection, FD nodes most likely end up in different packet sizes and one node can finish transmission earlier, but it has to wait until the other node completes transmission. Hence, FD cannot be utilized completely.

Finally, we have considered a heterogeneous scenario, where an equal number of FD and HD nodes are communicating. Figure 24 shows that the S-CW FD protocol can work in such a heterogeneous scenario and the overall system throughput is higher than a completely HD system, but lower than a completely FD system, as expected. It can be noted that as the SI cancellation become worse, the difference between hybrid system and fully FD system becomes smaller.

For the scope of this thesis we provide comparisons of S-CW FD with HD IEEE 802.11, as the benchmark scheme, since we aim to show the performance gains of our

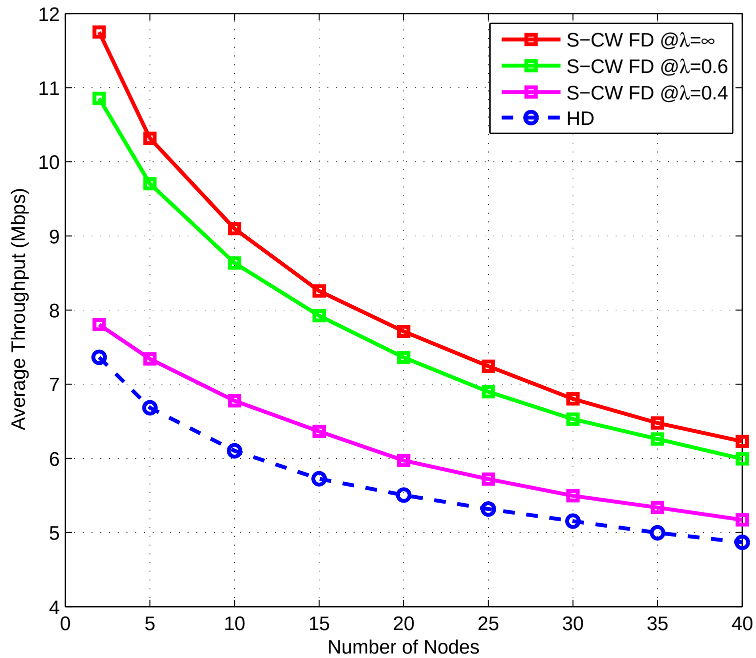

Figure 23: Comparison of HD and FD for $\lambda = \infty, 0.6, 0.4$, using exponential size packets (mean=400 bytes)

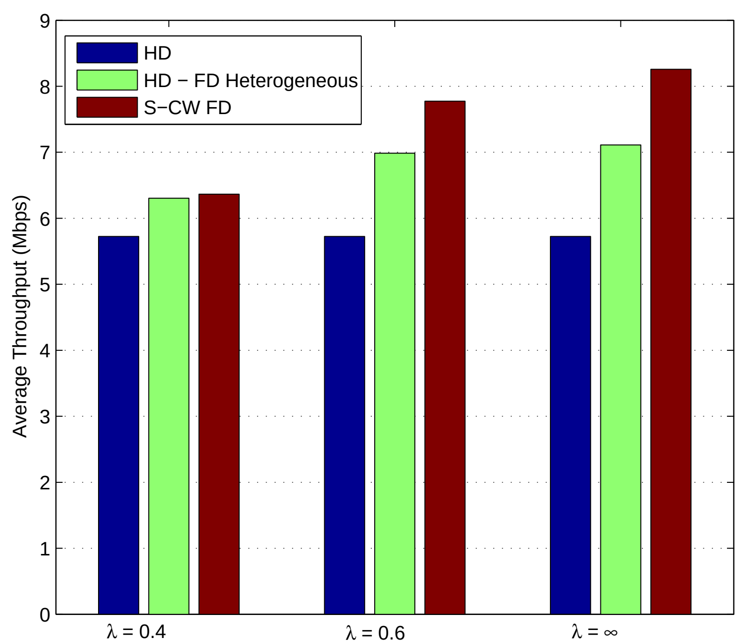

Figure 24: Performance of HD, FD and HD - FD heterogeneous system with 15 nodes

Table 3: FD Gain observed over simulations without hidden terminals

		400 bytes	1500 bytes
$\lambda = \infty$	No Hidden	1.27 - 1.59	1.56 - 2.10
$\lambda = 0.6$	No Hidden	1.27 - 1.47	1.46 - 1.90
$\lambda = 0.4$	No Hidden	1.06 - 1.04	1.20 - 1.30

$\xrightarrow{\hspace{4cm}}$

Decreasing number of nodes

FD MAC over HD, considering realistic SI models, hidden node scenarios and random packet sizes. None of these conditions were modeled for evaluation of the other proposed protocols, so the results could not be directly compared.

We have defined the metric FD gain in order to appreciate effect of FD on a HD system. FD Gain is calculated as

$$Gain_{FD} = \frac{Throughput\ of\ system\ using\ FD\ nodes}{Throughput\ of\ system\ using\ HD\ nodes}. \tag{32}$$

FD gain for various scenarios can be found in Table 3.

5.3 Performance With Hidden Terminals

Next, we introduce hidden nodes to the network and observe the performance of S-CW FD under perfect SI cancellation (i.e., $\lambda = \infty$). For these experiments, at one side of the AP we have a network of varying number of nodes, and at the other side we have hidden nodes, which cannot hear the transmissions of the nodes in the network (and vice versa).

Figures 25, 26 and 27 depicts the saturation throughput as a function of number of nodes in the network, for cases with 1, 5 and 10 hidden nodes on the other side as shown in Figure 21. As shown in the figures, the advantage of FD is actually emphasized in the presence of hidden nodes as the gain of S-CW FD over HD increases with hidden nodes, which is further improved as the hidden node situation gets worse. This is because, in the presence of hidden nodes, HD throughput decreases more drastically with increasing

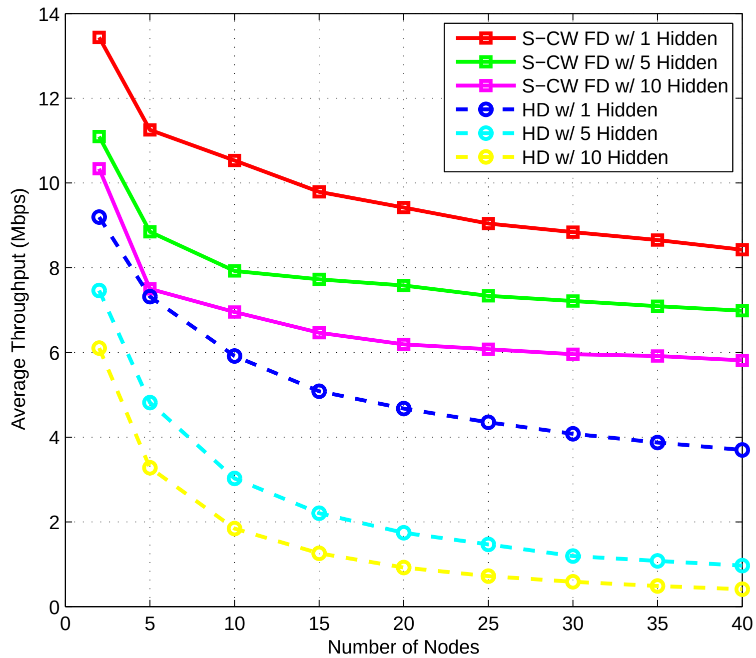

Figure 25: Comparison of HD and S-CW FD in the presence of hidden nodes for $\lambda = \infty$ and using 1500 byte (constant size) packets

number of stations, while S-CW FD conserves its throughput successfully. The same network and hidden node scenarios have been simulated for moderate and poor SI cancellation levels as well, and the minimum and maximum gain of S-CW FD over HD has been recorded in Table 4. Again, when there are no hidden nodes, the FD gain decreases with increasing number of nodes, due to unsuccessful synchronization and lower possibility of FD transmissions; whereas with hidden nodes in the network, the gain of S-CW FD is improved with increasing number of nodes, since the throughput of HD gets much lower due to hidden nodes. Therefore, the maximum gain values represent the largest number of stations in the network, which is subject to hidden nodes.

The hidden node scenarios are also simulated for exponential packet sizes (with mean of 400 bytes) and the gain of FD (FD gain) is measured as the ratio of the throughput of S-CW FD to that of HD 802.11 for all data points as summarized in Table 4. One should note that, FD gain decreases in non hidden and increases in hidden scenarios as number of nodes increase. As expected, lower gains are observed as compared to

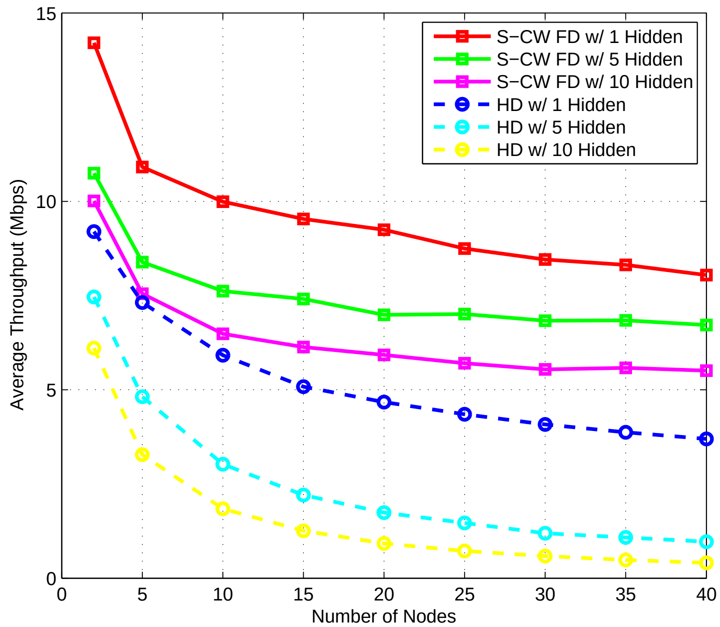

Figure 26: Comparison of HD and S-CW FD in the presence of hidden nodes for $\lambda = 0.6$ and using 1500 byte (constant size) packets

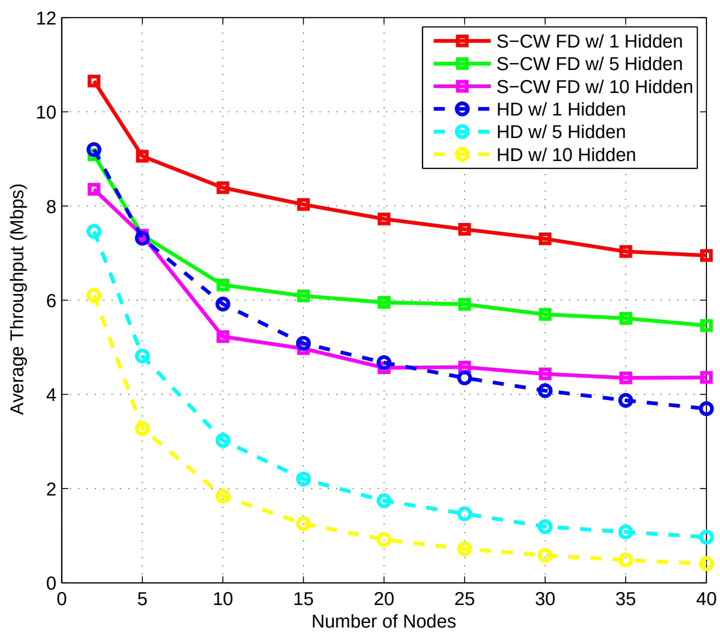

Figure 27: Comparison of HD and S-CW FD in the presence of hidden nodes for $\lambda = 0.4$ and using 1500 byte (constant size) packets

Table 4: FD Gain observed over simulations of hidden terminal scenarios

		400 bytes	1500 bytes
	1 Hidden	1.06 - 1.40	1.56 - 2.29
$\lambda = \infty$	5 Hidden	1.18 - 2.48	1.50 - 7.11
	10 Hidden	1.27 - 3.63	1.68 - 14.36
	1 Hidden	0.99 - 1.37	1.49 - 2.17
$\lambda = 0.6$	5 Hidden	1.17 - 2.40	1.44 - 6.93
	10 Hidden	1.23 - 3.37	1.64 - 13.47
	1 Hidden	0.78 - 1.15	1.15 - 1.87
$\lambda = 0.4$	5 Hidden	0.95 - 1.90	1.21 - 5.63
	10 Hidden	1.04 - 2.74	1.36 - 10.66

$\xrightarrow[\textit{Increasing number of nodes}]{}$

the case with 1500 bytes, but still with hidden nodes in the network, the FD gain is improved with increasing number of nodes, resulting in up to 2-3 fold increase in the throughput.

5.4 Two-Hop Performance

In this section, we consider the relaying and cellular scenarios, depicted in Section 2.1, in Figures 4(a) and 4(c), respectively. For this purpose, we have simulated S-CW FD for such two-hop scenarios with three nodes.

We first consider a relaying scenario, where the source and destination nodes do not hear each other. Source node sends the data packets it generated destined for Destination by using the Relay node. In FD transmissions while the Source node transmits the last packet and the next backoff slot for the next transmission, Relay node transmits the previous packet it received from Source to Destination. As depicted in Figure 28, while self-interference is minimum ($\lambda = \infty$), throughput of FD is approximately double of HD.

The next scenario, we consider three nodes, say A, B and C in a cellular setting, where B is the base station. A does not hear C, and vice versa. While A generates and transmits packet to B, B generates and transmits packet to C (i.e. both A and

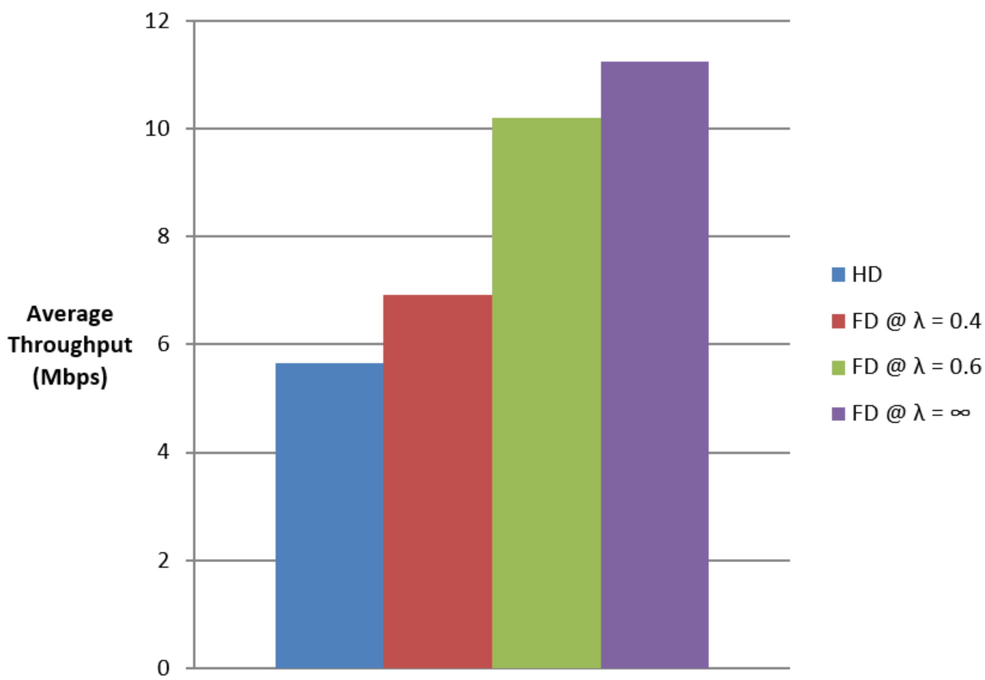

Figure 28: Throughput Results for FD Relaying with Various SI Cancellation Levels

B transmit their own packets). Because of this reason, throughput of this system is similar to the throughput of bidirectional FD scenarios. Again, as shown in Figure 29, while self-interference is minimum ($\lambda = \infty$), throughput of FD is approximately double of HD.

By these experiments, it has been verified that S-CW FD can seamlessly work in two hop scenarios, unlike [4], which proposes different packet structures for different modes. It is worthwhile to note that, neither S-CW FD nor the presented FD MAC schemes cannot work in relaying or infrastructure mode, when the end nodes hear each other, unless power control is applied. This is due to collisions induced by FD operation at the relay (base station) node. In [14] the authors have proposed an infrastructure based full-duplex MAC protocol for topologies in Figure 4 (a) and (b) using an RTS/CTS like protocol named PoCMAC, where using the power levels in RTS and CTS packets, stations contend for receiving from AP. Also, by making use of the control packets in the handshake, Source-Destination, Source-Relay and Relay-Destination channels are estimated and power levels of these transmissions are calculated via a heuristic calculation trying to maximize the end to end throughput.

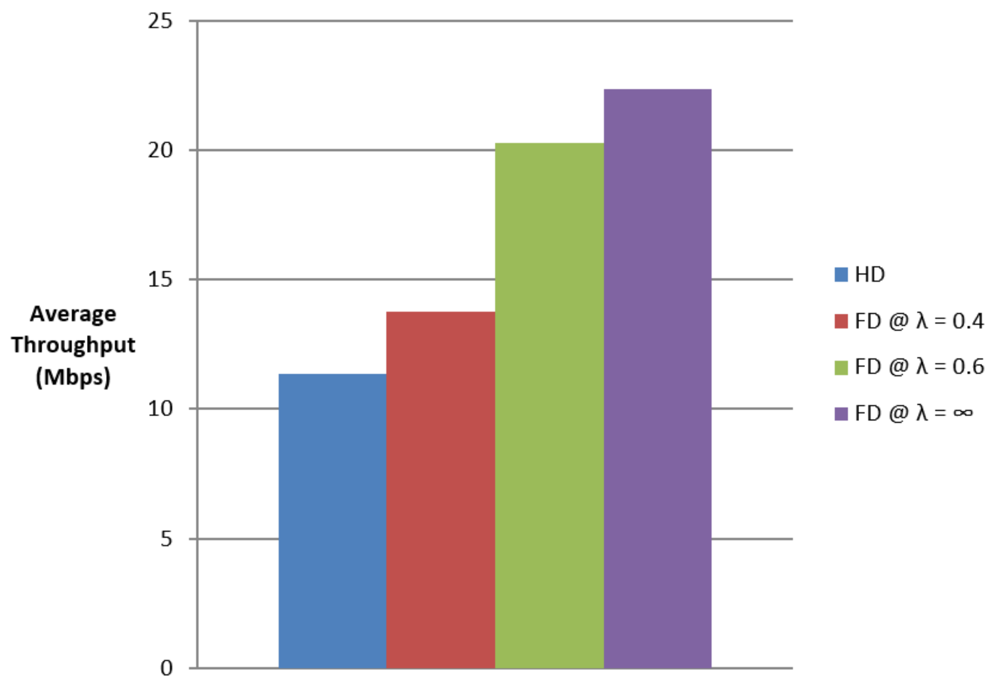

Figure 29: Throughput Results for 3-node FD with Various SI Cancellation Levels

5.5 Comparison with Other FD MAC Schemes

In this section we compare the performance of our protocol with the MAC protocol proposed in [3] and [4], since [4] is a good example of using preambles and overheads for enabling FD and [3] uses shared random backoff mechanisms as S-CW FD but instead of storing backoff value of stations in a list, AP holds a single backoff value, thus we aimed to analyze the effect of backoff list mechanism. Also in this protocol, backoffs are exchanged in ACK packets, and maximum of two backoff values which are exchanged are used. Therefore it can be said that, the main difference between S-CW FD and this protocol is the backoff list. This difference offers us a view for importance of backoff lists, the throughput drops are much more radical without the backoff list. Parameters of comparison simulations in Figures 30, 31 and 32 can be found in Table 5. Residual self-interference model in Equation 1 has been used for these simulations.

As can be seen from Figures 30, 31 and 32, due to having low overhead, S-CW FD outperforms [4] for number of stations lower than 15 - 20. As for higher number of stations, S-CW FD uses a backoff slot synchronization for leveraging full-duplex opportunities, which requires a half-duplex hand shake in case of synchronization loss due to a collision etc. as explained in Section 3.1.2, but FD-MAC uses preambles to operate in full-duplex mode, therefore does not require any half-duplex transmission. Due to this difference with overheads and synchronization for full-duplex, while S-CW FD MAC exceeds [4] for number of stations lower than 15 - 20 which is typical for WLANs, [4] has better performance for higher number of stations. Also the figures shows us that, importance of backoff lists are higher when there are higher number of nodes in the system.

Table 5: OPNET and Channel Parameters

Packet Payload	1024 bytes
Data Rates	6, 9, 12, 18, 24, 36, 48, 54 Mbps
Bandwidth	20 Mhz
Path loss exponent	3
Modulation	BPSK, QPSK, 16-QAM, 64-QAM
Channel Coding	Convolutional 1/2, 2/3, 3,4
Propagation Model	ITU-T Indoor Model and Rayleigh Fading
Minimum MAC packet error rate	10%

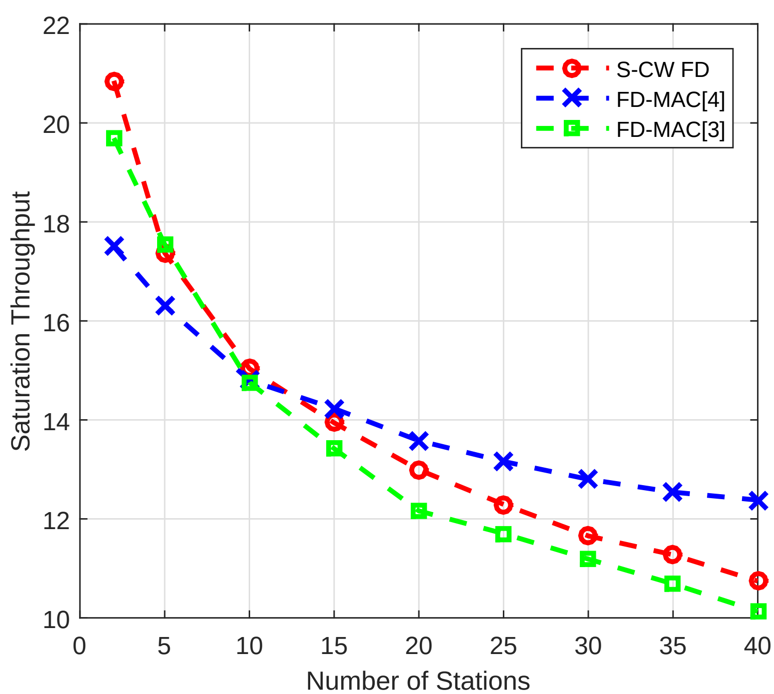

Figure 30: Comparison for S-CW FD, FD-MAC [4] and FD-MAC [3] @90dB SI Cancellation

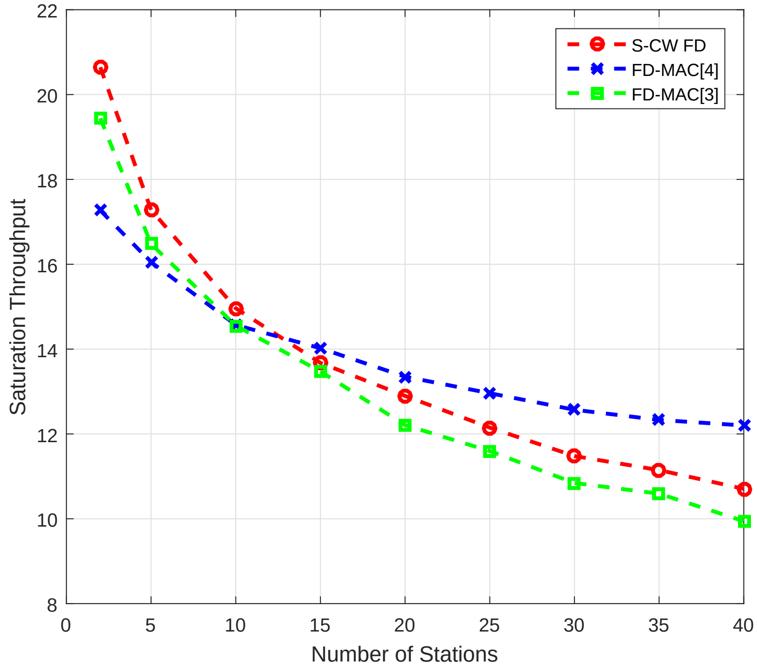

Figure 31: Comparison for S-CW FD, FD-MAC [4] and FD-MAC [3] @80dB SI Cancellation

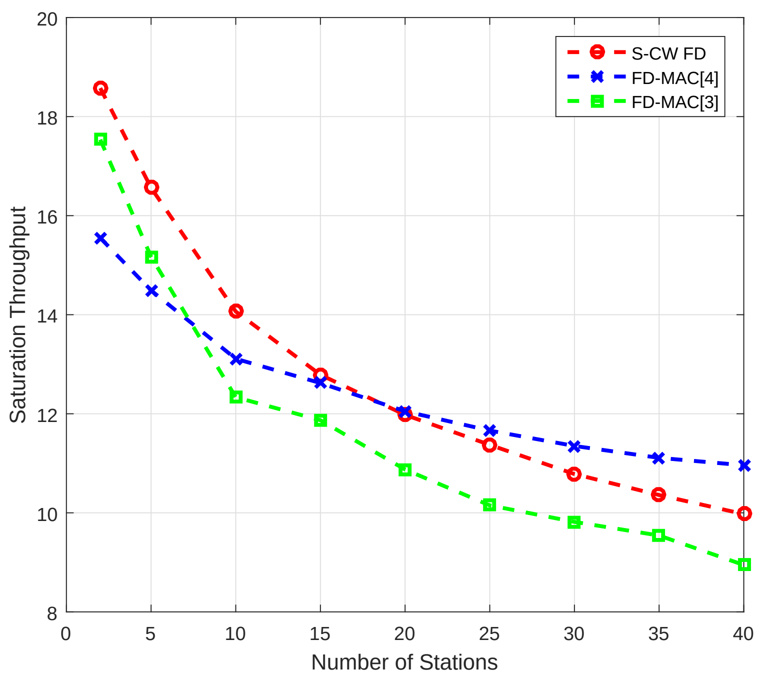

Figure 32: Comparison for S-CW FD, FD-MAC [4] and FD-MAC [3] @70dB SI Cancellation

Next, we compared S-CW FD and FD-MAC [3] without the effect of residual SI at 6 Mbps and 54 Mbps data rates. Simulation results show that, S-CW FD outperforms FD-MAC [3] in every case.

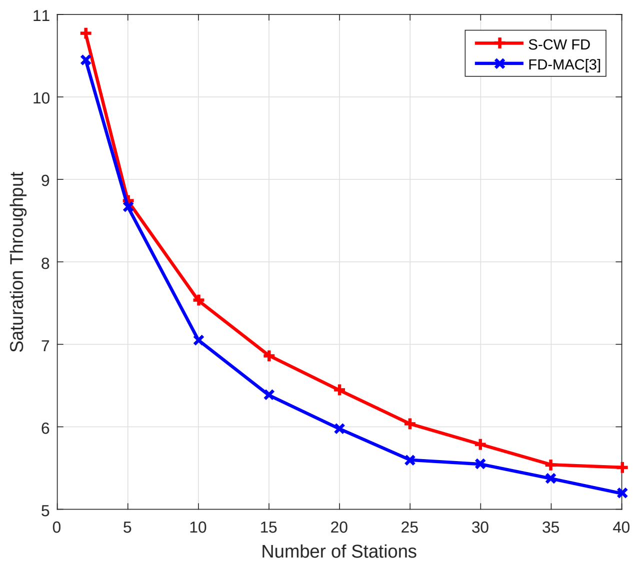

Figure 33: Comparison for S-CW FD and FD-MAC [3] with Perfect SI Cancellation @ 6 Mbps using 1500 byte packets

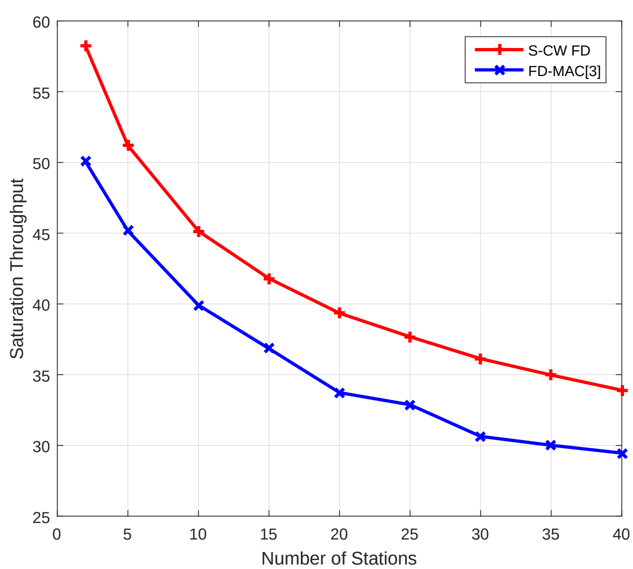

Figure 34: Comparison for S-CW FD and FD-MAC [3] with Perfect SI Cancellation @ 54 Mbps using 1500 byte packets

6 Conclusions

In this thesis firstly we have presented our design and implementation of a new full-duplex MAC protocol named Synchronized-Contention Window FD (S-CW FD). As shown by extensive OPNET simulations with settings such as different packet sizes, various SI cancellation levels, hidden terminal settings, S-CW FD is capable of doubling the IEEE 802.11's throughput in non-hidden terminal scenarios, while still supporting the legacy stations. This throughput increase can go up to 14 times when hidden terminals are introduced. Even with high residual SI, S-CW FD is able to produce throughput 8 times higher than conventional half-duplex IEEE 802.11. We have also simulated the S-CW FD in a two-hop scenario and we have shown that the protocol can seamlessly work, as long as the end nodes do not hear each other.

In order to validate our simulations, we have derived two analytic models for S-CW FD, which are based on [5] and [6]. Finally, we have compared the S-CW FD protocol with two other protocols from the literature demonstrating that S-CW FD performs best when the node numbers of nodes in the network is lower than 15-20, which is typical for a WLAN.

Our results obtained from simulations with realistic channel, residual SI and packet traffic models, prove that S CW FD is a promising MAC protocol for improving the performance of WLANs, due to its simplicity, flexibility and backwards compatibility. As future work, the protocol can be extended with power control and scheduling features.

References

[1] "Cisco visual networking index: Global mobile data traffic forecast update 2014 - 2019," Cisco, Tech. Rep., 2014.

[2] A. Sabharwal, P. Schniter, D. Guo, D. Bliss, S. Rangarajan, and R. Wichman, "In-band full-duplex wireless: Challenges and opportunities," *Selected Areas in Communications, IEEE Journal on*, vol. 32, no. 9, pp. 1637–1652, Sept 2014.

[3] A. Sahai, G. Patel, and A. Sabharwal, "Pushing the limits of full-duplex: Design and real-time implementation," *arXiv preprint arXiv:1107.0607*, 2011.

[4] S. Goyal, P. Liu, O. Gurbuz, E. Erkip, and S. Panwar, "A distributed mac protocol for full duplex radio," in *Signals, Systems and Computers, 2013 Asilomar Conference on.* IEEE, 2013, pp. 788–792.

[5] G. Bianchi, "Performance analysis of the ieee 802.11 distributed coordination function," *Selected Areas in Communications, IEEE Journal on*, vol. 18, no. 3, pp. 535–547, March 2000.

[6] H. Wu, Y. Peng, K. Long, S. Cheng, and J. Ma, "Performance of reliable transport protocol over ieee 802.11 wireless lan: analysis and enhancement," in *INFOCOM 2002. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, vol. 2, 2002, pp. 599–607 vol.2.

[7] M. Jain, J. I. Choi, T. Kim, D. Bharadia, S. Seth, K. Srinivasan, P. Levis, S. Katti, and P. Sinha, "Practical, real-time, full duplex wireless," in *Proceedings of the 17th annual international conference on Mobile computing and networking.* ACM, 2011, pp. 301–312.

[8] B. Radunovic, D. Gunawardena, P. Key, A. Proutiere, N. Singh, V. Balan, and G. Dejean, "Rethinking indoor wireless mesh design: Low power, low frequency, full-duplex," in *Wireless Mesh Networks (WIMESH 2010), 2010 Fifth IEEE Workshop on.* IEEE, 2010, pp. 1–6.

[9] D. Kim, H. Ju, S. Park, and D. Hong, "Effects of channel estimation error on full-duplex two-way networks," *Vehicular Technology, IEEE Transactions on*, vol. 62, no. 9, pp. 4666–4672, Nov 2013.

[10] S. Barghi, A. Khojastepour, K. Sundaresan, and S. Rangarajan, "Characterizing the throughput gain of single cell mimo wireless systems with full duplex radios," in *Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt), 2012 10th International Symposium on*, May 2012, pp. 68–74.

[11] J. Y. Kim, O. Mashayekhi, H. Qu, M. Kazadiieva, and P. Levis, "Janus: A novel mac protocol for full duplex radio," *CSTR*, vol. 2, no. 7, p. 23, 2013.

[12] K. Tamaki, A. Raptino, Y. Sugiyama, M. Bandai, S. Saruwatari, and T. Watanabe, "Fundamental evaluation of full-duplex communication in multi-hop networks," in *Proc. 11th International Conference on Global Research and Education (iA12)*, 2012, pp. 395–404.

[13] K. Miura and M. Bandai, "Node architecture and mac protocol for full duplex wireless and directional antennas," in *Personal Indoor and Mobile Radio Communications (PIMRC), 2012 IEEE 23rd International Symposium on*. IEEE, 2012, pp. 369–374.

[14] W. Choi, H. Lim, and A. Sabharwal, "Power-controlled medium access control protocol for full-duplex wifi networks," *Wireless Communications, IEEE Transactions on*, vol. 14, no. 7, pp. 3601–3613, July 2015.

[15] V. Aggarwal, M. Duarte, A. Sabharwal, and N. Shankaranarayanan, "Full- or half-duplex? a capacity analysis with bounded radio resources," in *Information Theory Workshop (ITW), 2012 IEEE*, Sept 2012, pp. 207–211.

[16] M. Duarte and A. Sabharwal, "Full-duplex wireless communications using off-the-shelf radios: Feasibility and first results," in *Signals, Systems and Computers (ASILOMAR), 2010 Conference Record of the Forty Fourth Asilomar Conference on*, Nov 2010, pp. 1558–1562.

[17] M. Duarte, C. Dick, and A. Sabharwal, "Experiment-driven characterization of full-duplex wireless systems," *Wireless Communications, IEEE Transactions on*, vol. 11, no. 12, pp. 4296–4307, December 2012.

[18] N. Shende, O. Gurbuz, and E. Erkip, "Half-duplex or full-duplex relaying: A capacity analysis under self-interference," in *Information Sciences and Systems (CISS), 2013 47th Annual Conference on*, March 2013, pp. 1–6.

[19] K. Akcapinar and O. Gurbuz, "Full-duplex bidirectional communication under self-interference," in *Telecommunications (ConTEL), 2015 13th International Conference on*, July 2015, pp. 1–7.

[20] "Ieee standard for information technology–telecommunications and information exchange between systems local and metropolitan area networks–specific requirements part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications," *IEEE Std 802.11-2012 (Revision of IEEE Std 802.11-2007)*, pp. 1–2793, March 2012.

[21] M. Steer, *Microwave and RF Design: A Systems Approach.* SciTech Pub., 2010. [Online]. Available: https://books.google.com.tr/books?id=FYyXPwAACAAJ

[22] D. Bharadia, E. McMilin, and S. Katti, "Full duplex radios," in *Proceedings of the ACM SIGCOMM 2013 Conference on SIGCOMM*, ser. SIGCOMM '13. New York, NY, USA: ACM, 2013, pp. 375–386. [Online]. Available: http://doi.acm.org/10.1145/2486001.2486033

[23] E. Everett, A. Sahai, and A. Sabharwal, "Passive self-interference suppression for full-duplex infrastructure nodes," *Wireless Communications, IEEE Transactions on*, vol. 13, no. 2, pp. 680–694, February 2014.

[24] M. A. Khojastepour, K. Sundaresan, S. Rangarajan, X. Zhang, and S. Barghi, "The case for antenna cancellation for scalable full-duplex wireless communications," in *Proceedings of the 10th ACM Workshop on Hot Topics in*

Networks, ser. HotNets-X. New York, NY, USA: ACM, 2011, pp. 17:1–17:6. [Online]. Available: http://doi.acm.org/10.1145/2070562.2070579

[25] J. I. Choi, M. Jain, K. Srinivasan, P. Levis, and S. Katti, "Achieving single channel, full duplex wireless communication," in *Proceedings of the Sixteenth Annual International Conference on Mobile Computing and Networking*, ser. MobiCom '10. New York, NY, USA: ACM, 2010, pp. 1–12. [Online]. Available: http://doi.acm.org/10.1145/1859995.1859997

[26] M. Duarte, A. Sabharwal, V. Aggarwal, R. Jana, K. Ramakrishnan, C. Rice, and N. Shankaranarayanan, "Design and characterization of a full-duplex multiantenna system for wifi networks," *Vehicular Technology, IEEE Transactions on*, vol. 63, no. 3, pp. 1160–1177, March 2014.

[27] D. Bliss, P. Parker, and A. Margetts, "Simultaneous transmission and reception for improved wireless network performance," in *Statistical Signal Processing, 2007. SSP '07. IEEE/SP 14th Workshop on*, Aug 2007, pp. 478–482.

[28] T. Riihonen, S. Werner, and R. Wichman, "Spatial loop interference suppression in full-duplex mimo relays," in *Signals, Systems and Computers, 2009 Conference Record of the Forty-Third Asilomar Conference on*, Nov 2009, pp. 1508–1512.

[29] X. Xie and X. Zhang, "Semi-synchronous channel access for full-duplex wireless networks," in *Network Protocols (ICNP), 2014 IEEE 22nd International Conference on*, Oct 2014, pp. 209–214.

[30] N. Singh, D. Gunawardena, A. Proutiere, B. Radunovic, H. Balan, and P. Key, "Efficient and fair mac for wireless networks with self-interference cancellation," in *Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt), 2011 International Symposium on*, May 2011, pp. 94–101.

[31] B. Radunovic, D. Gunawardena, A. Proutiere, N. Singh, V. Balan, and P. Key, "Efficiency and fairness in distributed wireless networks through self-interference

cancellation and scheduling," Tech. Rep. MSR-TR-2009-27, March 2009. [Online]. Available: http://research.microsoft.com/apps/pubs/default.aspx?id=79933

[32] S. Kim and W. Stark, "On the performance of full duplex wireless networks," in *Information Sciences and Systems (CISS), 2013 47th Annual Conference on*, March 2013, pp. 1–6.

[33] W. Cheng, X. Zhang, and H. Zhang, "Rts/fcts mechanism based full-duplex mac protocol for wireless networks," in *Globecom Workshops (GC Wkshps), 2013 IEEE*. IEEE, 2013, pp. 5017–5022.

[34] Y. Sugiyama, K. Tamaki, S. Saruwatari, and T. Watanabe, "A wireless full-duplex and multi-hop network with collision avoidance using directional antennas," in *Mobile Computing and Ubiquitous Networking (ICMU), 2014 Seventh International Conference on*, Jan 2014, pp. 38–43.

[35] D. Kim, H. Lee, and D. Hong, "A survey of in-band full-duplex transmission: From the perspective of phy and mac layers," *Communications Surveys Tutorials, IEEE*, vol. 17, no. 4, pp. 2017–2046, Fourthquarter 2015.

[36] E. Ahmed, A. Eltawil, and A. Sabharwal, "Self-interference cancellation with phase noise induced ici suppression for full-duplex systems," in *Global Communications Conference (GLOBECOM), 2013 IEEE*, Dec 2013, pp. 3384–3388.

[37] D. Marlali and O. Gurbuz, "S - cw fd: A mac protocol for full-duplex in wireless local area networks," in *2016 IEEE Wireless Communications and Networking Conference (WCNC) (Accepted for publication)*, 2016.