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On the In-Band Full-Duplex Gain Scalability in On-demand Spectrum Wireless Local Area Networks

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Resumo

O advento de técnicas de cancelamento de auto-interferência (*Self-Interference Cancellation*, SIC) tem possibilitado a implementação de rádios *Full-Duplex* (FD). Tais rádios são capazes de enviar e receber transmissões simultâneas dentro do mesmo canal de comunicação sem fio, o que lhes permite dobrar a capacidade teórica de um rádio *half-duplex*. Uma questão desafiadora resultante daquele advento consiste em verificar a possibilidade de escalar o ganho FD em redes locais sem fio (*Wireless Local Area Networks*, WLANs). De forma mais precisa, tal questão versa sobre como protocolos de acesso aleatório ao meio (*Medium Access Control*, MAC) podem manter o ganho FD sob uma quantidade crescente de estações. Além disso, a fim de garantir que os recursos de largura de banda sem fio correspondam às demandas de tráfego, espera-se que o projeto de protocolo MAC seja capaz de implementar alocação de espectro sob demanda (*On-Demand Spectrum Allocation*, ODSA) em conjunto com a funcionalidade FD. Neste sentido, o presente trabalho reporta uma pesquisa da literatura e identifica a ausência de uma solução MAC que integre as funcionalidades ODSA e FD. O presente trabalho identifica uma prática recorrente no projeto de protocolos MAC FD e rotula-a como "a diretriz de projeto MAC FD 1:1". Sob tal diretriz, um protocolo MAC FD 'enxerga' a largura de banda FD disponível através de uma única camada física (*PHYsical*, PHY). O protocolo emprega seu maior esforço para ocupar o canal com duas transmissões simultâneas arbitrárias. A largura de cada transmissão corresponde à largura do canal disponível. Como isso, a oferta de reuso espacial diminui dentro da WLAN, penalizando a vazão de rede. Também, as exigências de força de sinal no receptor (*Received Signal Strength Indication*, RSSI) são maiores pelo fato de toda a largura de banda ser empregada para modular um único quadro de dados. Essas desvantagens podem limitar a escalabilidade de protocolos MAC FD sob a diretriz de projeto 1:1.

Para fazer frente às limitações supracitadas, nesse trabalho é proposto a diretriz de projeto de protocolos MAC FD 1:N. Sob a diretriz 1:N, os protocolos MAC FD 'enxergam' a largura de banda FD através de N>1 camadas PHY associadas a canais estreitos ortogonais. A ortogonalidade entre os canais possibilita aumentar a oferta de reuso espacial na rede e canais mais estreitos diminuem os requisitos de RSSI. Além disso, a organização em mais de um canal facilita o desenvolvimento de políticas de ODSA na camada MAC. Visando demonstrar como um protocolo MAC FD poder funcionar sob a diretriz 1:N, são propostos dois estudos de caso. Um estudo de caso consiste no *Piece by Piece Enhanced Distributed Channel Access* (PbP-EDCA), um novo protocolo de acesso aleatório sob a diretriz 1:N. O outro estudo de caso consiste em adaptar um protocolo MAC FD existente [Jain et al., 2011] – que nomeamos como 1:1 *FD Busy Tone MAC protocol* (FDBT) – à diretriz 1:N. Por meio de estudos analíticos de desempenho, nós verificamos que os protocolos MAC FD sob a diretriz 1:N apresentaram vazão saturada superior em relação ao protocolo 1:1 FDBT, mesmo em cenários onde tal protocolo é esperado beneficiar-se ao máximo do ganho FD. Nossos resultados sugerem que o limite superior de capacidade de um protocolo FD MAC arbitrário sob a direriz 1:1 pode melhorar se o funcionamento de tal protocolo puder ser adaptado para operar sob diretriz 1:N. Para verificar a validade dessa afirmação, nós propomos um estudo analítico e um experimento de prova-de-conceito baseado em rádios definidos por *software*. Nossos resultados indicam que o ganho do limite superior de capacidade auferido pelas diretrizes 1:1 e 1:N corresponde à 2$\times$ e 2.2$\times$ o limite superior de capacidade da camada MAC de uma WLAN padrão half-duplex, respectivamente. Com esses resultados, acreditamos que nossa proposta pode inspirar uma nova geração de protocolos MAC capazes de escalar o ganho FD em WLANs.

Palavras-chave: Rádios Full-duplex, Controle de Acesso ao Meio, IEEE 802.11, CSMA/CA, Avaliação de Desempenho, Rádio Definido em Software.

Abstract

The advent Self-Interference Cancellation (SIC) techniques has turned in-band Full-Duplex (FD) radios into a reality. FD radios doubles the theoretical capacity of a half-duplex wireless link by enabling simultaneous transmission and reception in the same channel. A challenging question raised by that advent is whether it is possible scale the FD gain in Wireless Local Area Networks (WLANs). Precisely, the question concerns on how a random access Medium Access Control (MAC) protocol can sustain the FD gain over an increasing number of stations. Also, to ensure bandwidth resources match traffic demands, the MAC protocol design is also expected to enable On-Demand Spectrum Allocation (ODSA) policies in the presence of the FD feature. In this sense, we survey the related literature and find out a coupled FD-ODSA MAC solution lacks. Also, we identify a prevailing practice for the design of FD MAC protocols we refer to as the 1:1 FD MAC guideline. Under this guideline, an FD MAC protocol 'sees' the whole FD bandwidth through a *single* FD PHYsical (PHY) layer. The protocol attempts to occupy the entire available bandwidth with up to two arbitrary simultaneous transmissions. With this, the resulting communication range impair the spatial reuse offer which penalizes network throughput. Also, modulating each data frame across the entire wireless bandwidth demands stronger Received Signal Strength Indication (RSSI) (in comparison to narrower bandwidths). These drawbacks can prevent 1:1 FD MAC protocols to scale the FD gain.

To face these drawbacks, we propose the 1:N FD MAC design guideline. Under the 1:N guideline, FD MAC protocols 'see' the FD bandwidth through $N>1$ orthogonal narrow-channel PHY layers. Channel orthogonality increases spatial reuse offer and narrow channels relaxes RSSI requisites. Also, the multi-channel arrangement we adopt facilitates the development of ODSA policies at the MAC layer. To demonstrate how an FD MAC protocol can operate under the 1:N design guideline, we propose two case studies. A case study consists of a novel random access protocol under the 1:N design guideline called the Piece by Piece Enhanced Distributed Channel Access (PbP-EDCA). The other case study consists in adapting an existing FD Wi-Fi MAC protocol [Jain et al., 2011]) – we name as the 1:1 FD Busy Tone MAC protocol (FDBT) – to the 1:N design guideline. Through analytical performance evaluation studies, we verify the 1:N MAC protocols can outperform the 1:1 FDBT MAC protocol's saturation throughput even in scenarios where 1:1 FDBT is expected to maximize the FD gain. Our results indicate that the capacity upper-bound of an arbitrary 1:1 FD MAC protocol improves if the protocol functioning can be adapted to work under the 1:N MAC design guideline. To check whether that assertion is valid, we propose an analytical study and a proof-of-concept software-defined radio experiment. Our results show the capacity upper-bound gains of both 1:1 and 1:N design guidelines corresponds to 2× and 2.2× the capacity upper-bound achieved by a standard half-duplex WLAN at the MAC layer, respectively. With these results, we believe our proposal can inspire a new generation of MAC protocols that can scale the FD gain in WLANs.

Keywords: Full-duplex Radios, Medium Access Control, CSMA/CA, Performance Evaluation, Software-Defined Radios.

Contents

1 Introduction **1**

1.1 Context . . . 2

1.2 Motivation . . . 4

1.3 Problem Statement . . . 4

1.4 Goals . . . 5

1.5 Thesis Outline . . . 6

2 Background **7**

2.1 Medium Access Control Protocols . . . 7

2.1.1 Channelization MAC Protocols . . . 7

2.1.2 Random Access Protocols . . . 8

2.2 The IEEE 802.11 Distributed Coordination Function . . . 9

2.2.1 Basic Access: Carrier Sensing and Exponential Back-off Algorithm . . 10

2.2.2 Virtual Carrier Sensing . . . 11

2.3 MAC Saturation Throughput and Channel Capacity . . . 11

2.3.1 Half- and Full-Duplex Capacities . . . 11

2.3.2 IEEE 802.11 MAC Saturation Throughput . . . 13

2.4 Summary of the Chapter . . . 15

3 Literature Survey **17**

3.1 On-Demand Spectrum Allocation WLANs . . . 17

3.1.1 Proposals . . . 17

3.1.2 The Standard WLAN Dynamic Bandwidth Channel Access . . . 19

3.2 Wireless FD MAC Protocols . . . 20

3.2.1 Terminology . . . 20

3.2.2 Proposals . . . 21

3.3 What Hinders the FD MAC Protocol Scalability? . . . 24

3.3.1 Self-Interference Cancellation Imperfection . . . 24

3.3.2 Networking Design Aspects . . . 25

3.4 Summary of the Chapter . . . 27

4 Proposal **28**
4.1 Project Requisites . . . 28
4.2 The 1:N FD MAC Design Guideline . . . 29
4.2.1 Description and Characteristics . . . 29
4.2.2 Key Overheads . . . 31
4.2.3 Expected Advantages and Capacity . . . 32
4.2.4 How Does this Proposal Relate to Prior Works? . . . 38
4.3 Case Study of 1:N FD MAC Protocols . . . 39
4.3.1 Case Study 1: The FD Busy Tone MAC Protocol . . . 39
4.3.2 Case Study 2: The Piece by Piece EDCA MAC Protocol . . . 40
4.3.3 Comparative Analysis of the MAC Protocols . . . 43
4.4 Assessing Throughput Scalability of 1:N FD MAC Protocols . . . 44
4.4.1 FDBT MAC Protocol Saturation Capacity . . . 45
4.4.2 Markovian Analysis of the PbP-EDCA Node . . . 46
4.5 Summary of the Chapter . . . 48

5 Results **49**
5.1 Performance of FD MAC protocols . . . 49
5.1.1 Scenarios and Methodology Review . . . 49
5.1.2 MAC Protocols Overheads . . . 52
5.1.3 Saturation Throughput Results . . . 54
5.2 Capacity Upper-Bound of FD MAC Design Guidelines . . . 56
5.2.1 Theoretical Capacity Upper-Bound . . . 56
5.2.2 Impact of Residual Self-Interference . . . 58
5.2.3 Impact of Wide Guard-bands . . . 58
5.2.4 What If N Grows? . . . 59
5.2.5 Validation . . . 60
5.3 Summary of Results . . . 66

6 Conclusion and Future Directions **69**
6.1 Summary . . . 69
6.2 Contributions . . . 70
6.3 Future Research Directions . . . 71

Bibliography **73**

A PbP-EDCA Markovian Model **83**
A.1 Probability of Accessing Secondary Channels . . . 83
A.2 Model Accuracy for Capacity Prediction of PbP-EDCA . . . 88

B Additional Results **90**
B.1 Large Data Frame Payload 90
B.2 MAC Saturation Throughput Under Ideal SIC 90

C Scripts to Calculate MAC Saturation Throughput **95**
C.1 GNU Octave Function to Calculate MAC Saturation Throughput 95
C.2 Example of Usage 109
C.3 FD Data Rate Selection 109
C.3.1 Data Rate Selection for FD Channels under RSI of 1 dB 110
C.3.2 Data Rates For Narrow FD Channels Under Negligible RSI 110

List of Figures

3.1 IEEE 802.11ac frequency band arrangement over the 5 GHz Frequency Band for the Europe, Japan and Global operating class tables. 20
3.2 FD Wi-Fi MAC protocol design classification. 27

4.1 FD MAC design guideline layering comparison over a bandwidth of B_w Hz: 1:1 (left-hand side) vs. 1:N (right-hand side). 29
4.2 Spatial reuse factor in the 1:1 (a) and 1:N (b) FD MAC design guidelines. . . . 33
4.3 Channelization and expected SNR gain ($SNR_{\mathcal{G}}$) of 1:N channels over an FD bandwidth of B_w (Hz) for $N = 2$ and $N = 4$. 34
4.4 Establishment of a symmetric dual-link by the FDBT MAC protocol. At time t_2, the AP (ST) starts sending a signal to the STA (SR) upon receiving and processing the primary transmission header (during [t_0,t_2]). In the worst-case (4.4a), it is a busy tone. In the best-case (4.4b), the signal is a data frame. . . . 41
4.5 PbP-EDCA transmission procedure (Tx) from the standard IEEE 802.11 EDCA. 42
4.6 On-demand Spectrum Allocation (ODSA) strategies in different MAC protocols *after* a node wins a CSMA/CA contention. 44

5.1 Probability of collision. 53
5.2 Saturation throughput considering the ‘best-case’ for FD MAC protocols under residual self-interference. 55
5.3 Saturation throughput considering the ‘worst-case’ for FD MAC protocols under residual self-interference. 57
5.4 Maximum theoretical capacity delivered to the MAC by each design guideline. RSI assumed negligible. 58
5.5 Impact of RSI on FD Bandwidth Capacity: RSI 25 dB, g=100KHz. 59
5.6 Impact of RSI on FD Bandwidth Capacity: RSI 30 dB, g=100KHz. 59
5.7 Impact of Guard-band on FD Bandwidth Capacity: Ideal FD, g=2MHz. 60
5.8 Impact of Guard-band on FD Bandwidth Capacity: Ideal FD, g=3.4 MHz. . . . 60
5.9 Impact of Guard-band on FD Bandwidth Capacity: RSI=1dB, g=2MHz. 61
5.10 Impact of Guard-band on FD Bandwidth Capacity: RSI 1dB, g=3.4 MHz. . . . 61
5.11 FD Bandwidth Capacity on Large N: Ideal FD, g=1MHz. 62

5.12 FD Bandwidth Capacity on Large N: Ideal FD, g=100KHz. 62
5.13 FD Bandwidth Capacity on Large N: RSI=1dB, g=1MHz. 63
5.14 FD Bandwidth Capacity on Large N: RSI=1dB, g=100KHz. 63
5.15 Software-defined radio testbed. 64
5.16 Each concurrent 5 MHz-wide channel can outperform a single 10 MHz channel about 3 dB even under the same output power. 65
5.17 Best-case throughput of each FD MAC design guideline assessed on the USRP B210 platform. 66

A.1 Markov chain model for the PbP-EDCA MAC Protocol. 85
A.2 Saturation throughput for the IEEE 802.11a basic access mode with m=3 and W=16. 88

B.1 MAC Protocols Saturation throughput: FD mode="best-case", RSI=1dB and MSDU Payload=1536 bytes. 91
B.2 Saturation throughput considering the 'worst-case' for FD MAC protocols under ideal SIC. 92
B.3 Saturation throughput considering the 'best-case' for FD MAC protocols under ideal SIC. 93

List of Tables

2.1 Largest back-off time values defined in the first and last back-off stages of EDCA. 10

4.1 Possible 1:N channel arrangements considering typical IEEE 802.11 channelizations. 30
4.2 Some IEEE 802.11a MAC timing parameters across channel widths. 31
4.3 IEEE 802.11 minimum RSSI across modulations and channel widths. 35

5.1 Common Parameter Values Set for Both IEEE 802.11 and PbP-EDCA. 50
5.2 Highest data rate supported across different bandwidths for a given RSSI. . . . 51
5.3 Summary of all variated parameters to calculate network saturation throughput. 52
5.4 Time duration (μs) of data frame collisions for each MAC protocol across different RSSI (data rates). 53
5.5 Steady-state best-case throughput of MAC design guidelines. 65
5.6 FD Gain Scalability of MAC Protocols: Summary of Results under 1 dB of RSI. 67

A.1 Common Parameter Values Set for Both (AaO) IEEE 802.11 and PbP-EDCA. . 89
A.2 PbP-EDCA vs. IEEE 802.11: Analytic and detailed steady-state simulation throughput for $m = 3$ and $W = 16$. 89

B.1 MAC Saturation Throughput Under Ideal SIC: Summary of Results. 94

Lista de Acrônimos

ACW	Adaptive Channel Width
AP	Access Point
AWGN	Additive White Gaussian Noise
AaO	All at Once
BPSK	Binary Phase-Shift Keying
BT	Busy Tone
CCA	Clear Channel Assessment
CDM	Code-Division Multiplexing
CDMA	Code-Division Multiple Access
CNB	Channel Negotiation Bit
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CTS	Clear-to-Send
CW	Contention Window
DCF	Distributed Coordination Function
DIFS	DCF Inter-Frame Space
EDCA	Enhanced Distributed Channel Access
FD	Full-Duplex
FDBT	Full Duplex Busy Tone
FDD	Frequency-Division Duplexing
FDM	Frequency-Division Multipling
FDMA	Frequency-Division Multiple Access
FER	Frame Error Rate
IBFD	In-Band Full-Duplex
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial, Scientific and Medical
MAC	Medium Access Control
MIMO	Multiple Input, Multiple Output
MPDU	MAC Protocol Data Unid
MSDU	MAC Service Data Unit
NIC	Network Interface Card
OBFD	Out-of-Band Full-Duplex

ODSA	On-Demand Spectrum Allocation
PCF	Point Coordination Function
PHY	Physical
PIFS	PCF Inter-Frame Space
PR	Primary Receiver
PT	Primary Transmitter
PT	Secondary Transmitter
PbP	Piece-by-Piece
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
RSI	Residual Self-Interference
RSSI	Received Signal Strength Indication
RTS	Request-to-Send
SDR	Software-Defined Radio
SI	Self-Interference
SIC	Self-Interference Cancellation
SIFS	Short Inter-Frame Space
SNR	Signal-to-Noise Ratio
SR	Secondary Receiver
STA	Station
TDD	Time-Division Duplexing
TDM	Time-Division Multiplexing
TDMA	Time-Division Multiple Access
USRP	Universal Software Radio Peripheral
WLAN	Wireless Local Area Network
dB	Decibel
dBm	Decibel miliwatt

Lista de Símbolos

τ	Node transmission probability
δ	Physical propagation delay
τ_0	PbP-EDCA node transmission probability in the primary channel
τ_c	PbP-EDCA node transmission probability in the secondary channel c
Δ_t	Time interval to start a secondary transmision after processing H_1.
A	Instance of an IEEE 802.11 access point
B	Channel width in the 1:N design guideline
$B_{g\to 0}$	Width limit of narrow channels in the 1:N design guideline
B_w	Widest available bandwidth for the network
C_{Bfd}	Capacity of single narrow channel in the 1:N FD MAC Design Guideline
C_{fd}	Capacity of the 1:1 FD MAC Design Guideline
C_{fdN}	Capacity of the 1:N FD MAC Design Guideline
$C_{g\to 0}$	Capacity limit of narrow channels in the 1:N design guideline
C_{hd}	Capacity of a half-duplex AWGN Channel
$DIFS$	Time duration of a DIFS
$E[L]$	Expected payload size of a packet
G	Total guard-band overhead in 1:N design guideline
H_1	PHY and MAC headers of an FD PT
H_2	PHY and MAC headers of an FD ST
L_1	Payload size of an FD PT
L_2	Payload size of an FD ST
N	Number of narrow orthogonal channels
P_c	Primary channel
P_{col}	Probability that a transmission collides in a given channel
P_{idl}	Probability that a given channel is idle
P_{suc}	Probability that a transmission succeeds in a given channel
P_{tr}	Probability that there exist at least one transmission in a given channel
S	Saturation MAC protocol throughput
$SIFS$	Time duration of a SIFS
$SLOT$	IEEE 802.11 slot time duration
STA_i	Instance of an arbitrary IEEE 802.11 station i

T_{ACK}	Time duration of an IEEE 802.11 acknowledgement control frame
T_{CTS}	Time duration of an IEEE 802.11 CTS control frame
T_H	Time duration of MAC plus PHY IEEE 802.11 headers
T_{RTS}	Time duration of an IEEE 802.11 RTS control frame
T_{col}	Time duration of a frame collision
T_{idl}	Time duration of an idle time slot of the channel
T_{suc}	Time duration of a successful frame transmission
W	Length of the minimum back-off contention window interval
$b(t)$	Stochastic process for the backoff counter value
$b_{i,k,c}$	PbP-EDCA protocol stationary distribution
c	PbP-EDCA channel number at time t
g	Guard-band overhead between a pair of channels
$h(t)$	Stochastic process for the PbP-EDCA channel value
i	CSMA/CA backoff stage at time t
k	Value of the CSMA/CA backoff counter at time t
m	Number of CSMA/CA backoff stages
n	Number of network nodes
p	Frame collision probability
$s(t)$	Stochastic process for the CSMA/CA backoff stage value
t	CSMA/CA 'channel event' time
$\mathcal{N}_{hd}$	Noise floor in a half duplex radio
$\mathcal{N}_{fd}$	Noise floor in a full duplex radio
$\Delta\mathcal{N}$	SNR gain of channels in the 1:N design guideline
$\Delta\mathcal{N}_{g\to 0}$	Minimum SNR gain of channels in the 1:N design guideline

Chapter 1

Introduction

The Wireless Local Area Networks (WLANs) have become an ubiquitous communication technology over years. According to [Negus and Petrick, 2009], this results from the fact that the WLAN technology has been adopted by users and industry as a default interface for networked devices. To assure interoperability among different brands, the Institute of Electrical and Electronic Engineers (IEEE) created a working group that has being responsible to standardize WLANs through the series of IEEE 802.11 specification documents [IEEE 802.11 Working Group, 1997]. The Wi-Fi alliance – a global industry association which certifies IEEE 802.11 compatible devices [Wi-Fi Alliance, 1999]– announced that about 9.9 billion WLAN-enabled devices such as phones, tablets and e-readers have been sold until the end of 2014 [Wi-Fi Alliance, 2015a]. The number of shipped Wi-Fi devices is expected to surpass 15 billion by the end of 2016 [Wi-Fi Alliance, 2015b]. Moreover, novel network scenarios such as the so-called “Internet of Things” are expected to bring hundreds or even thousands of new wireless devices interacting and working on the same area of IEEE 802.11 networks in the near future [Khorov et al., 2015].

In addition to the increasing popularity of WLANs, [Cheng and Shen, 2016] remark that emerging data-intensive applications such as real-time high-quality video streaming have also contributed to challenge the capacity of current WLANs. To face such a challenge, novel spectrum management techniques are expected to significantly improve the capacity of future wireless networks [Bellalta, 2016], [Cheng and Shen, 2016]. In particular, more efficient WLANs shall supply ongoing traffic load with On-Demand Spectrum Allocation (ODSA) capabilities [Herzen et al., 2013]. Also, such capability is expected to benefit from the spectrum utilization improvement enabled by novel prominent technologies. One of these is In-Band Full-Duplex (IBFD), an emerging technology that improve throughput by (potentially) doubling spectrum efficiency [Sabharwal et al., 2014], [Hong et al., 2014].

1.1 Context

The electromagnetic spectrum is a basic resource for the construction of wireless networks. It can be represented by the axis of frequencies (or wavelength) of all known electromagnetic waves [Halliday et al., 2012]. The characteristics of the electromagnetic waves – amplitude, phase or frequency – are changed by a radio transmitter in a process called 'modulation' to represent and convey digital data [Rappaport, 2009]. The modulated wave(s) is(are) referred to as signal. A successful 'demodulation' depends on how strong the received signal is with respect to the level of noise intrinsic to the radio receiver a.k.a. noise floor [Frenzel, 2013]. In the IEEE 802.11 terminology, the level of signal power measured at the radio is termed Received Signal Strength Indication (RSSI) [IEEE, 2012]. The ratio between the RSSI and the noise floor gives the Signal to Noise Ratio (SNR)[1]. Since the noise floor level is strongly influenced by technological factors that may vary across manufacturers [Frenzel, 2013], the IEEE 802.11 standard specifies the requirements for different (de)modulation schemes in terms of minimum RSSI [IEEE, 2012, Table 18–14]. This way, Wi-Fi radio manufacturers must design radio in a way that the resulting noise floor accomplishes the minimum standard RSSI specifications for a 'successful' demodulation.

The major limiting factor of a radio communication reception is (destructive) interference [Rappaport, 2009]. Destructive interference is nothing but the simultaneous reception of different signals received on a non-orthogonal set of frequencies. The sum RSSI of all unwished signals plays the role of noise for the RSSI of the signal of interest. The very first countermeasure against interference usually results from governmental decisions. To enable co-existence of different radio-based systems in a territorial space, nation-wide regulatory bodies such as the "Federal Communications Commission" (FCC) in USA [FCC, 2016] and the "Agência Nacional de Telecomunicações" (ANATEL) in Brazil [ANATEL, 2016], assign portions of spectrum to specific services and activities. These portions are called frequency bands. Wireless communication standards such as IEEE 802.11 arrange its assigned frequency band into a set of narrower portions of spectrum called channels. The width of a channel (a.k.a. bandwidth) given in Hertz (Hz) results from the difference between the upper and lower frequencies of the channel [Frenzel, 2013]. The IEEE 802.11b standard [IEEE, 1999], for instance, defines thirteen 20 MHz mandatory channels on the 2.4 GHz sub-band of the Industrial, Scientific and Medical (ISM) frequency band. A later amendment of the standard also considers 10 MHz and 5 MHz channels as well as different frequency bands such as the "Public Safety Band" and the "Unlicensed National Information Infrastructure" (U-NII) that operate on 4.9 GHz and 5 GHz, respectively [IEEE, 2012].

In a wireless network, the interference resulting from simultaneous transmissions can cause collision. A collision prevents the receiver to discern the gathered signals, wasting

[1] In decibel (dB), the SNR rewrites as $10\log(RSSI/Noise) = 10\log(RSSI) - 10\log(Noise)$. Thus SNR (dB) is the difference between signal and the noise power levels, respectively.

spectrum resources and impairing network throughput. Managing channel utilization across the different transmitters of a wireless network is a task of the Medium Access Control (MAC) layer [Kurose and Ross, 2012]. In WLANs, all nodes wishing to transmit an unit of data – known as data frame – deliver their respective frame to a protocol of the MAC layer. The MAC protocol running in each device enters in contention mode to determine when to trigger the data frame transmission in the channel. The design of MAC protocols shall consider maximizing network throughput by minimizing both frame collisions and channel idleness. If ODSA is a required feature, the MAC protocol is expected to match spectrum resources to the transmitters demands [Gummadi and Balakrishnan, 2008], [Chandra et al., 2008]. In this case, the total bandwidth granted at the end of each contention round can vary according to traffic load. The design of wireless MAC protocols is also affected by several others factors like network geographic coverage e.g., personal, local, metropolitan [Kurose and Ross, 2012], nature of data traffic pattern e.g., bursty, continuous [Forouzan, 2012], energy constraints [Verma et al., 2015], node mobility [Dong and Dargie, 2013], and ability to opportunistically get access to third-party frequency bands, a.k.a. cognitive networks [Mitola III et al., 2008]. Of several factors, considering the mode in which the channel can operate – i.e., transmission (Tx), reception (Rx), both (Tx/Rx) – is a mandatory design requisite for any MAC protocol, since it determines the available transmission possibilities to be exploited by the protocol [Gummalla and Limb, 2000].

With respect to the operation mode, an wireless communication channel is classified as either unidirectional (a.k.a. “simplex”) or bidirectional [Frenzel, 2013], [Rappaport, 2009]. In a simplex channel communication happens only in one direction – one side can receive but cannot transmit signals e.g., analog TV receptors. In turn, bidirectional channels can be either half-duplex or full-duplex. A half-duplex channel supports transmissions in both directions but cannot perform them simultaneously. To mimic simultaneous transmissions on a half-duplex channel, one may perform Time-Division Duplexing (TDD). With TDD, the spectrum is shared in time so that a portion of time it is used to transmit in one direction and in other portion of time it is used to transmit in the other direction. A Full-Duplex (FD) channel supports two simultaneous transmissions i.e., in an FD channel radios can transmit while receiving. FD channels are classified into Out-of-Band (OBFD) or In-Band (IBFD) [Hong et al., 2014]. With an OBFD channel, radios can Tx and Rx simultaneously but only over orthogonal channels. In this case, narrow portions of spectrum called *guard-bands* are kept inactive in-between the channels to help filtering out adjacent channel interference. Under such conditions, the simultaneity achieved in the channel is termed Frequency-Division Duplexing (FDD) [Rappaport, 2009]. With an IBFD channel, radios can Tx and Rx simultaneously within the same channel. Throughput this work, the term IBFD will be referred to as “FD” unless differently specified.

1.2 Motivation

FD radios depend on Self-Interference Cancellation (SIC) techniques, a recent scientific achievement compared to OBFD radios, specially for IEEE 802.11-like signals [Duarte and Sabharwal, 2010], [Choi et al., 2010]. SIC techniques are designed to suppress the Self-Interference (SI), the interference a radio causes on its own signal reception chain while keeping active its signal transmission circuit. As remarked by [Bharadia et al., 2013], the feasibility of FD radios invalidates a long-held statement that, differently from wired devices, "*It is generally not possible for radios to receive and transmit on the same frequency band because of the interference that results*".

In theory, FD radios can double the capacity of an one-direction wireless link by enabling an extra simultaneous communication in the *same* frequency band. Such improvement is popularly referred to as *the FD gain*. FD radios has attracted the attention from both industry and academia in an attempt to bring the FD gain to current wireless networks. The challenge requires advances spanning different domains of networking research. In this sense, although some issues still fall exclusively in the radio design research field [Sabharwal et al., 2014], [Xie and Zhang, 2014a] remark that the design of a solid FD protocol stack for WLANs also depends on a question that is out of the exclusive scope of radio frequency design, namely, *is it possible to scale the FD gain in a wireless network*? In other words, one wonders whether it is possible to double the capacity of an entire network (rather than a single channel) by replacing half-duplex radios by FD radios. Considering that an FD radio does not eliminate collisions resulting from multiple simultaneous receptions (i.e., third-party interference), the answer for that challenge falls in the MAC design field [Thilina et al., 2015], once MAC protocols can manage the wireless bandwidth contended by an arbitrary number of nodes.

1.3 Problem Statement

The first FD Wi-Fi MAC protocol [Singh et al., 2011] was proposed almost two decades after the first claim of a wireless SIC technique [Tsubouchi et al., 1993]. That achievement matches the evolution of the waveform characteristics SIC techniques can handle. SIC proposals have evolved from low power, low frequency and narrow-band wireless systems [Chen et al., 1998], [Bliss et al., 2007], [Radunovic et al., 2010], [Choi et al., 2010], [Duarte and Sabharwal, 2010] to higher frequency, power and wideband wireless systems such as Wi-Fi [Sahai et al., 2011], [Jain et al., 2011], [Duarte et al., 2012], [Bharadia et al., 2013]. In face of this quite recent achievement, the field of FD Wi-Fi MAC protocols can still be considered at an embryonic stage and research efforts are expected towards an effective FD protocol stack.

At its current phase, the FD MAC design field has demanded deeper understanding about structural MAC design issues limiting the FD scalability gain. This posits the need for the identification of general MAC design guidelines rather than proposing monolithic MAC solutions. Such a set of MAC guidelines is a key challenge to the design of scalable FD MAC protocols in the near future [Xie and Zhang, 2014a].

In addition to doubling spectral efficiency (thus capacity) by means of FD, an effective MAC protocol is also expected to support ODSA capabilities. The ODSA feature has been considered by the WLAN research community over the past few years [Chandra et al., 2008]. However, most of the ODSA proposals evolved before the development of FD radios. Thus, current ODSA MAC protocols can not benefit from the double of throughput expected with FD radios since they are designed assuming only the half-duplex operation mode. Coupling both ODSA and FD into a single MAC protocol has been pointed out as a promising way to handle the increasing traffic demands of future wireless networks. An USA National Science Foundation report about "future directions in wireless networking" for "the next decade and beyond" [Banerjee and Wu, 2013], concludes that:

> "*We require new PHY layer technologies such as . . . full duplex technologies coupled with new MAC layer protocols to increase network throughput by a few orders of magnitude. Further, new models for spectrum access are needed to significantly increase the spectrum reuse efficiency.*"

In this work we focus on general guideline(s) to support the design of MAC protocols. The resulting design guideline(s) shall play a two-fold role, (1) enabling the support for ODSA feature at the MAC layer and (2) facilitating the FD gain scalable capacity at the MAC layer by achieving better capacity *upper-bound*.

1.4 Goals

The overall goal of this work is to increase the available capacity of single-cell IEEE 802.11 WLANs by exploiting FD and ODSA radio features at the MAC layer. Specifically, we aim to:

- *survey* the related literature to *identify* the set of factors that plays against the FD gain scalability.
- *propose* MAC design guideline(s) to enable the development of scalable FD MAC protocols for WLANs; more precisely, the design guideline shall provide current state-of-the-art FD Wi-Fi MAC protocols with a better capacity upper-bound; moreover, it shall offer support to the ODSA feature;
- *redesign* the standard IEEE 802.11a MAC protocol to match it to the proposed design guideline(s) or *propose* a novel FD MAC protocol based on those guidelines; in any case, the resulting FD MAC protocol must keep the same random access nature of the IEEE 802.11 MAC protocol;

- *evaluate* the adapted/proposed IEEE 802.11-based FD MAC protocol to *check* whether – and under which conditions – it can scale the FD gain against the half-duplex counterpart. This goal relies on classic MAC protocol capacity models ([Bianchi, 2000], [Bianchi, 1998]) that best suit theoretical scalability studies;

- *present* a theoretical study to calculate the capacity upper-bound for MAC protocols under the proposed design guideline; also, present a proof-of-concept radio experiment to validate the theoretical result.

1.5 Thesis Outline

The remainder of this work is organized as follows. Chapter 2 reviews MAC protocols and capacity models; Chapter 3 reviews the related literature in the field of ODSA strategies and FD MAC protocols for WLANs; Chapter 4 describes the proposal of this work comprising, description, models and protocols. Chapter 5 presents theoretical and software defined radio proof-of-concept experiments to validate this work. Finally, Chapter 6 summarizes this proposal and discusses its impact on future research directions.

Chapter 2

Background

This chapter presents the background for the current work. Section 2.1 reviews the classic approaches for the design of MAC protocols. Section 2.2 presents Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA), the random access MAC protocol standardized for IEEE 802.11 WLANs.

Section 2.3 cares on the performance evaluation of IEEE 802.11 WLANs. Firstly, it takes the Shannon theorem [Shannon, 1949] as base to formalize the maximum gain FD can bring to IEEE 802.11 channels. Next, it reviews the performance model due to [Bianchi, 2000] to estimate the IEEE 802.11 saturation throughput accounting the number of nodes and MAC contention overheads. Section 2.4 summarizes the chapter.

2.1 Medium Access Control Protocols

In wireless networks the channel is shared among several nodes wishing to transmit. The task of allocating the shared medium among different nodes is performed by the MAC layer. Generally, MAC proposals have been broadly classified as either "channelization" or "random access" access methods [Forouzan, 2012].

2.1.1 Channelization MAC Protocols

Channelization access methods are inspired in classical physical layer multiplexing techniques, in which a multiplexer conveys multiple different signals into a single physical medium. By contrast, with multiple access techniques, signals from different nodes share the medium without a multiplexer. These techniques can be classified in the categories we summarize below or combinations thereof. For further details about these and other multiple-access or multiplexing techniques, please refer to networking textbooks e.g. [Kurose and Ross, 2012], [Forouzan, 2012], [Tanenbaum, 2011], [Rappaport, 2009].

- Frequency-Division Multiple Access (FDMA): based on the Frequency-Division Multiplexing (FDM) principle. FDMA shares bandwidth among nodes by dividing it in the frequency domain. Each node is permanently assigned to an orthogonal sub-channel. Guard-bands and filters make negligible the interference among sub-bands;

- Time-Division Multiple Access (TDMA): based on the Time-Division Multiplexing (TDM) principle. TDMA shares bandwidth among nodes by dividing it in units of orthogonal *time slots*. Each node uses the bandwidth entirely during its assigned time slot. Guard-times and synchronization techniques make negligible the interference among nodes;

- Code-Division Multiple Access (CDMA): based on the Code-Division Multiplexing (CDM) principle. CDMA enables all nodes to transmit simultaneously in the same bandwidth. The nodes modulate signals using specific codes, whose mathematical properties enable the receiver to correctly demodulate the signal of each node it communicates with.

2.1.2 Random Access Protocols

Networks such as WLANs are characterized by bursty traffic rather than continuous streams, which causes waste of bandwidth resources in MAC channelization approaches [Tanenbaum, 2002]. This lead to the development of random access MAC protocols, in which nodes send one unit of data called 'packet' or '*frame*' after winning a *contention round*. In each contention round nodes wait a random period of time before transmitting. The idea of randomness derives from the "pure" ALOHA MAC protocol proposed by [Abramson, 1970]. With pure ALOHA nodes transmit whenever they receive a packet from upper layers. Thus pure ALOHA is classified as *unslotted* because the beginning of a transmission only depends on packet arrival rather than being scheduled into discrete units of time. After transmitting a packet, nodes wait a given amount of time for an acknowledgement; if the ACK is not received, the frame is assumed to be *collided* at the receiver and nodes missing the acknowledgement wait a random period of time before starting the contention process again.

Beyond the idea of random access channel, pure ALOHA was also the base for two other ideas that shaped current WLAN MAC protocols. One of these ideas was born with the *slotted* ALOHA, in which the time is discretized into units called *slots*. Each time slot is as wide as the duration of one frame and nodes must transmit only at the beginning of a time slot. Thus, if a node receives a packet to send during a slot, it has to wait until the next slot. On one hand, this idea requires node synchronization on the beginning of a slot. On the other hand, the risk of overlapping transmissions is reduced since frame collisions are restricted to the beginning of a slot time [Roberts, 1975].

The slotted ALOHA evolved to the *Carrier Sense Multiple Access* (CSMA) protocol, which is characterized by the addition of the carrier sense mechanism. The carrier sensing mechanism forces nodes to listen to the medium before transmitting in order to detect possible ongoing transmissions. A node initiates a transmission only after it detects the medium as idle.

The MAC protocol adopted in the IEEE 802.11 standard is based on the carrier sense mechanism, and random discrete waiting time slots.

2.2 The IEEE 802.11 Distributed Coordination Function

The IEEE 802.11 protocol stack offers a service of transmission for upper-layers. [Tanenbaum, 2011] explain that the Logical Link Control (LLC) layer is a ‘glue’ between typical upper-layers (such as the Internet Protocol, IP) and the IEEE 802.11 stack. LLC multiplexes data from IP adding an 8-byte header to the IP datagram. Then it ‘hires’ the IEEE 802.11 transmission services The service consists in the transmission of the units of data called MAC Service Data Unit (MSDU) [Gast, 2013]. After receiving an MSDU from the LLC layer, the IEEE 802.11 MAC adds it a header consisting of control informations such as source and destination addresses. The resulting unit is called MAC Protocol Data Unit (MPDU). The MAC layer itself is a client of other layer, in the IEEE 802.11 standard it is the Physical Layer Convergence Protocol (PLCP). The PLCP adopts similar terminology for the data it receives from/forwards to other layers. This way the MPDU is the PLCP’s payload, which is termed as Physical Service Data Unit (PSDU). The PLCP introduces its header on the PSDU, yielding a unit of data called PLCP Protocol Data Unit (PPDU). Finally, the PHY layer is a client of the channel, through which the PPDU is sent after the wireless node wins a contention following a contention function of the IEEE 802.11 standard.

The IEEE 802.11 standards establishes the Distributed Coordination Function (DCF) and the Point Coordination Function (PCF) as two possible MAC techniques. Of these, the present work focuses on DCF, since it is mandatory while PCF is optional [IEEE, 2012]. The DCF comprises a slotted *binary exponential back-off* algorithm (or “back-off procedure”) and the CSMA protocol with a *Collision Avoidance* (CSMA/CA) technique. To enable the joint operation of these procedures, the IEEE 802.11 standard defines the following elementary time intervals (usually in μs):

- $SLOT$: the duration of time slot (we refer to as σ). As with ALOHA, transmissions starts only at the beginning of a time slot. The duration of a data frame transmission usually lasts several units of σ;

- $SIFS$: the duration of the Short Inter-Frame Space (SIFS). It is used to prioritize the transmissions of ACKnowledgements (ACK) frames over data frames;

- $DIFS$: the duration of the DCF Inter-Frame Space (DIFS), the *minimum* waiting time before data frame transmissions. It is calculated as $2SLOT{+}SIFS$.

2.2.1 Basic Access: Carrier Sensing and Exponential Back-off Algorithm

With the DCF basic access (also known as "2-way handshake"), a node wishing to transmit – be either a STAtion (STA) or an Access Point (AP) – must sense the medium during DIFS. If the amount of sensed energy is as weak as needed to declare the channel idle (in a process called Clear Channel Assessment, CCA), the node starts transmitting. Otherwise, it defers transmission and enters the first *back-off stage*. In the back-off procedure, each stage corresponds to a *Contention Window* (CW), an interval of integers from which nodes pick a *random uniform back-off time*. The back-off time represents the number of time slots a node must wait before transmitting; it is calculated according to the Eq. 2.1, where W_i is the largest possible back-off time STAs may pick in the i-th back-off stage and U represents a random uniform variable over the given interval.

$$\text{BackoffTime} \quad = \quad U(0, W_i) \times SLOT \tag{2.1}$$

During the back-off procedure, the node keeps sensing the medium to decrease its back-off time by one unit whenever channel is declared 'idle' during $SLOT$. If the channel is sensed busy, the node suspends this count-down process but keeps sensing the channel to resume the counter if the channel is declared idle during $DIFS$. When the back-off time reaches zero, the node starts transmitting and waits for an ACK during a period of time called ACK timeout. If the destination node successfully receives the data frame, it checks whether the channel is idle by $SIFS$ to start sending an ACK back to the data frame transmitter. If the ACK timeout expires for any reason (e.g. channel error, frame collision) the node assumes a collision and updates CW following the Eq. 2.2 (i.e., goes to the next back-off stage $i + 1$) and restarts the transmission process.

$$W_{i+1} \quad = \quad 2(W_i + 1) - 1 \tag{2.2}$$

All parameters related to the back-off process may vary across different version of the IEEE 802.11 standard. In particular, the largest back-off time values W and W_{max} in the first and last back-off stages, respectively, depends on traffic class of the frame to be sent. In the IEEE 802.11a/g/ac [IEEE, 2012],[IEEE80211ac, 2013], they are determined by the Enhanced Distributed Channel Access (EDCA) according to the traffic class the frame to be sent belongs to. These values are shown on Table 2.1 for some traffic classes.

Table 2.1: Largest back-off time values defined in the first and last back-off stages of EDCA.

Class/Back-off values	W	W_{max}
Best-effort	15	1023
Video	7	15
Voice	3	7

2.2.2 Virtual Carrier Sensing

The physical carrier sensing strategy of the basic access mode cannot prevent collisions when nodes are out of each other's interference range. In fact, while one of these nodes (let us say, the STA S_1) transmits to the AP, the other node (let us say, the STA S_2) keeps decrementing its back-off time since it is not sensing S_1's carrier. Thus, both STAs can send to the AP causing a collision. This is a classical problem known as *the hidden node problem*, because S_2 is said to be hidden from S_1.

In order to mitigate collisions caused by the hidden node problem the IEEE 802.11 DCF defines an optional access mode known as the 4-way handshake. The main difference in comparison to the basic 2-way access mode is that each data frame transmission is prepended with a couple of control frames respectively named as Request to Send/Clear to Send (RTS/CTS). After finishing the back-off time, a node sends an RTS control frame instead of a data frame. The node the RTS frame is addressed to waits $SIFS$ before sending the CTS frame. After this, the process follows as in the DATA-ACK two-way handshake. Neighbors STAs that overhear the RTS or CTS control frames, suspend the back-off process by a period of time indicated in the "duration" field of the control frames. The value in this field is an estimation for the time duration of the scheduled data transmission and is used to set the *Network Allocation Vector* (NAV) in the neighbors STAs. Until the time set in NAV has elapsed, the STA is not allowed to perform carrier sensing. This process is also known the *virtual carrier sensing*.

2.3 MAC Saturation Throughput and Channel Capacity

2.3.1 Half- and Full-Duplex Capacities

It is a matter of fact that the throughput of any MAC protocol is bounded by the capacity of the bandwidth B_w it manages. FD radios are expected to double the total capacity a half-duplex bandwidth delivers to the MAC layer. To measure the capacity C_{hd} of a half-duplex bandwidth measuring B_w Hz, the present work refers to the Hartley-Shannon theorem [Shannon, 1949]. Assuming a half-duplex receiver disturbed by an Additive White Gaussian Noise (AWGN), Shannon predicts the capacity C_{hd} according to the Equation2.3.

$$C_{hd} = B_w \log_2(1 + SNR) \tag{2.3}$$

In the Equation 2.3, SNR is the unitless ratio that expresses how stronger the signal level is in comparison to the noise. To express it in decibel (dB), one refers to the Equation 2.4 [Frenzel, 2013]. Considering the signal strength S in dBm and the noise floor $\mathcal{N}_{hd}$ as the noise active in the (half-duplex) bandwidth demodulating the signal of interest, one gets the Equation 2.5. From this, the unitless SNR in Equation 2.3 can be rewritten in terms of the noise floor experienced in the bandwidth, as shown in Equation 2.6. With this, one rewrites Equation 2.3 as Equation 2.7.

$$SNR_{dB}(dB) = 10\log(SNR) \quad (2.4)$$

$$(S - \mathcal{N}_{hd})(dB) = 10\log(SNR) \quad (2.5)$$

$$SNR = 10^{(S-\mathcal{N}_{hd})_{dB}/10} \quad (2.6)$$

Based on Equation 2.6, C_{hd} rewrites as in Equation 2.7.

$$C_{hd} = B_w \log_2(1 + 10^{(S-\mathcal{N}_{hd})_{dB}/10}) \quad (2.7)$$

According to the classical literature [Rappaport, 2009], the noise floor $\mathcal{N}_{hd}$ (dBm) experienced by a half-duplex radio can be estimated in terms of the bandwidth B_w, as shown in the Equation 2.8.

$$\mathcal{N}_{hd}(dBm) = -174 + 10\log(B_w) \quad (2.8)$$

According to [Hong et al., 2014] “true full duplex theoretically doubles the link capacity with respect to traditional half duplex, because the available spectral resources can be fully utilized in time and frequency”. In other words, it means that FD can enable two simultaneous transmission within B_w. Thus, from the above quote, FD gives a new *theoretical* capacity bound for a bandwidth measuring B_w (Hz). This capacity upper bound consists in twice the capacity of a half-duplex bandwidth, as shown in Equation 2.9 under the assumption of an ideal FD radio.

$$C_{fd} = 2B_w \log_2(1 + 10^{(S-\mathcal{N}_{hd})_{dB}/10}) \quad (2.9)$$

Equation 2.9 assumes that both receiver in an FD bandwidth has the same SNR of the single receiver in a half-duplex bandwidth. Although this assumption provides us with a bound for the FD capacity, it might not hold in practice. In fact, [Sabharwal et al., 2014] remark that FD radios are subject to Residual Self-Interference (RSI), i.e., an amount of self-interfering energy that real-world FD radios may not manage to suppress. [Bharadia et al., 2013] say that RSI causes the radio to experience a noise floor $\mathcal{N}_{fd}$ that stronger than $\mathcal{N}_{hd}$. Thus, removing the assumption of an ideal FD radio, one has to replace $\mathcal{N}_{hd}$ by $\mathcal{N}_{fd}$ in the Equation 2.9, yielding Equation 2.10.

$$C_{fd} = 2B_w \log_2(1 + 10^{(S-\mathcal{N}_{fd})_{dB}/10}) \quad (2.10)$$

[Bharadia et al., 2013] equates RSI to the difference between $\mathcal{N}_{fd}$ and $\mathcal{N}_{hd}$. These values refer to the noise floor verified in the radio reception chain after and before the SIC, respectively.

$$
\begin{aligned}
RSI(dB) &= \mathcal{N}_{fd} - \mathcal{N}_{hd} && (2.11)\\
\mathcal{N}_{fd}(dBm) &= \mathcal{N}_{hd} + RSI && (2.12)
\end{aligned}
$$

Considering a non ideal FD radio, one must add the RSI to the half-duplex noise floor. Hence, Equation 2.10, rewrites as Equation 2.13 assuming an AWGN RSI.

$$
C_{fd} = 2B_w \log_2(1 + 10^{(S-\mathcal{N}_{hd}-RSI)_{dB}/10}) \quad (2.13)
$$

2.3.2 IEEE 802.11 MAC Saturation Throughput

The Hartley-Shannon theorem establishes a limit to the capacity of MAC protocols in single-cell WLANs but it does not account for MAC layer overheads such as collision and control frames. To understand how the IEEE 802.11-based MAC protocols scale we need to consider such overheads. We refer to a theoretical performance model due to [Bianchi, 2000], [Bianchi, 1998]. The so-called "Bianchi model" assesses the saturation capacity of WLANs taking into account the random nature of CSMA/CA. The model computes the capacity upper-bound by assuming ideal channel conditions (all packet losses are due to collisions the protocol cannot manage to avoid), saturated traffic (nodes always have data frames to send) and single transmission range domain (absent hidden nodes). The model is structured in two parts. The first part consists of a Markov chain that abstracts the states of CSMA/CA operating in a single node. This helps to form the system of Eqs. 2.14 from which the probabilities τ and p that a single STA transmits and collides, respectively, can be computed. In the Eqs. 2.14, W and m denote the length of the minimum contention window interval and the number of back-off stages set for a given n-node CSMA/CA-based network scenario, respectively. For further details on how to build the system of Eqs. 2.14 please, consult the section A.1 in the Appendix A.

$$
\begin{cases}
\tau = \dfrac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^m)} \\
p = 1 - (1-\tau)^{(n-1)}
\end{cases}
\quad (2.14)
$$

The second part of the model consists in a function that predicts the MAC throughput S from the probabilities τ and p. Next we review all Bianchi model equations to compute the saturation throughput S for an n-nodes WLAN.

Channel events

To assess the saturation capacity S, the Bianchi model firstly identifies all possible "slot times" related to a CSMA/CA channel. In the terminology of the current work, "slot time" is renamed to "channel events" in order to avoid confusion with the standard IEEE 802.11 time slot σ. The possible CSMA/CA channel events are 'success', 'collision' or 'idle' (empty slot). These events happen with probabilities P_{suc}, P_{col} and P_{idl} and take T_{suc}, T_{col} and T_{idl} absolute time units, respectively. Of these, T_{idl} is obtained from the standard waiting time slot [IEEE, 2012]. Moreover, only the first event carries an expected amount of useful payload, that we denote as $E[L]$.

Probabilities of channel events

To compute P_{suc}, P_{col} and P_{idl}, let n be the number of wireless nodes in a IEEE 802.11 cell. Assuming each node competes for accessing the channel with the same probability τ, the probability that a single node does not transmit is $(1-\tau)$. The probability that the channel is idle is P_{idl}=$(1-\tau)^n$ (Eq. 2.19), when all n nodes are simultaneously silent. The probability $P_{tr}(\tau)$ that the channel is not idle is given by Equation 2.15.

$$P_{tr}(\tau) = 1-(1-\tau)^n \tag{2.15}$$

$$P_s(\tau) = \begin{cases} \dfrac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} = \dfrac{n\tau(1-\tau)^{n-1}}{P_{tr}(\tau)} & \text{if } \tau > 0 \\ 0 & \text{if } \tau = 0 \end{cases} \tag{2.16}$$

$$P_{suc}(\tau) = P_s(\tau)P_{tr}(\tau) \tag{2.17}$$

$$P_{col}(\tau) = (1-P_s(\tau))P_{tr}(\tau) \tag{2.18}$$

$$P_{idl}(\tau) = 1-P_{tr}(\tau) \tag{2.19}$$

The transmission of a single STA succeeds if the remainder $n-1$ STAs remain silent while it transmits. This happens with probability $\tau(1-\tau)^{n-1}$. Of all possible events in which the channel is not idle (what happens with probability P_{tr}), n accounts for an STA successfuly transmitting. Therefore, the probability $P_s(\tau)$ that a transmission *occurring* on the channel succeeds is defined as $n\tau(1-\tau)^{n-1}$ over $P_{tr}(\tau)$ (Eq. 2.16). Of course, a transmission needs to occur to succeed. Thus, the probability $P_{suc}(\tau)$ that a transmission succeeds in the channel is given by Eq. 2.17. The probability $P_{col}(\tau)$ that a packet collides during a time slot is defined by Eq. 2.18.

Duration of a successful transmission and collisions

Let H_1 and L_1 be the PHY-MAC headers and (MSDU) payload sizes of an IEEE 802.11 transmission, respectively. Also, let T_H and T_L be the time taken to transmit H_1 and L_1 under given control and data rates, respectively. Considering that the total IEEE 802.11 time to acknowledge a data frame is $SIFS$ plus T_{ACK} and δ as the physical propagation delay, the overall duration T_{suc} of a successful transmission under the IEEE 802.11 two-way handshake is given by equation 2.20a [Bianchi, 2000]. Note that T_{suc} also comprises $DIFS$ because this is the minimum time interval a node must sense the channel as idle before transmitting, or resuming the back-off counter. If the 4-way handshake is triggered, T_{suc} increases by the time T_{RTS} and T_{CTS} to transmit both the RTS and CTS control frames, plus the $SIFS$ time interval in-between them (Eq. 2.20b).

$$T_{suc} = \begin{cases} DIFS + T_H + T_L + \delta + SIFS + T_{ACK} + \delta & \text{2-way handshake} \quad (2.20a) \\ DIFS + T_{RTS} + 2SIFS + T_{CTS} + T_H + T_L + T_{ACK} + 4\delta & \text{4-way handshake} \quad (2.20b) \end{cases}$$

The time the IEEE 802.11 MAC protocol wastes in collisions depends on the handshake employed. It is estimated for the two-way and 4-way handshakes in Eqs. 2.21 [Bianchi, 2000], respectively.

$$T_{col} = \begin{cases} T_H + T_L + \delta + DIFS & \text{2-way handshake} \quad (2.21a) \\ T_{RTS} + \delta + DIFS & \text{4-way handshake} \quad (2.21b) \end{cases}$$

IEEE 802.11 Saturation Capacity

The saturation capacity S for the IEEE 802.11 can be derived from the (Eq. 2.22). S is the ratio between the channel event expected payload and the channel event expected time. If all data frames are assumed to have the same fixed MSDU payload size L_1, then $E[L]$=L_1. Also, T_i is set to the time slot σ and the other time-related parameters are set according to the handshake employed.

$$S = \frac{P_{suc}(\tau)E[L]}{P_{suc}(\tau)T_{suc} + P_{col}(\tau)T_{col} + P_{idl}(\tau)T_{idl}} \tag{2.22}$$

2.4 Summary of the Chapter

This chapter reviewed the classic categories for the design of MAC protocols reported in the literature, namely, channelization and random access. According to the literature, the bursty nature of data traffic led the IEEE 802.11 to adopt the random approach for WLANs. The performance of WLANs were discussed with respect to its maximum bandwidth capacity and network level. In the first case, were reported models to measure the maximum capacity of a wireless bandwidth under half- and full-duplex modes. In the second case, it was reviewed a model to measure WLAN throughput accounting the overheads of the MAC layer.

Chapter 3

Literature Survey

This chapter reviews the MAC protocol literature concerning both On-Demand Spectrum Allocation (ODSA) and Full Duplex proposals. These respective studies are presented in Sections 3.1 and 3.2. Section 3.3 discusses the main problems identified by the literature about the classification and issued of FD MAC protocols. In particular, it discusses the main problems that can prevent MAC protocols to reach the double of throughput of half duplex WLANs, i.e. the FD gain scalability. A novel categorization for FD MAC protocols is proposed. Section 3.4 summarizes the Chapter.

3.1 On-Demand Spectrum Allocation WLANs

The study of ODSA features for WLANs has been mostly focused for half-duplex MAC protocols. This Section overviews the main contributions for ODSA WLANs.

3.1.1 Proposals

The use of static-width channels has been a long-held assumption for the design of MAC protocols. Earlier versions of the IEEE 802.11 MAC protocol, like the IEEE 802.11b [IEEE, 1999], always operate on fixed-width wireless channels managed by CSMA/CA channel access technique. As a result, spectrum allocation does not track users' demands. This can under-utilize spectrum for low-demand traffic or create a bottleneck if available bandwidth does not fit current traffic demands. The ODSA proposals aim to cope with that problem.

The preliminary insights in favor of ODSA are based on ACW proposals from industry. Some proprietary devices e.g. [Sheet, 2001], [Atheros, 2004] provide their users with the feature of setting the radio's channel width (e.g. 20 MHz or 40 MHz). However, the channel width remains static during network operation unless manually changed by the network administrator.

The first work to track WLANs spectrum demands based on ACW [Chandra et al., 2008]. The authors modify a Wi-Fi open-source driver to set radio channel width on-demand according to a given performance policy. They report the firsts performance evaluation experiments about the impact of different channel widths on IEEE 802.11 links. The authors affirm that wide channels increase throughput but penalizes energy-consumption. Based on this they propose policy-driven ODSA algorithms. When the policy is 'throughput maximization', their channel-width adaptation algorithm attempts to widen the channel width in a per-frame basis. When power-consumption reduction is more important than throughput , the ODSA algorithm assign links with narrower channels. The insight of performing channel width adaptation to achieve ODSA became seminal and has been the base for many MAC protocol designs.

[Moscibroda et al., 2008] proposed the first load-balancing work for multi-link WLANs. The authors formulate the adaptive-width channel-assignment problem considering the self-fragmentation challenge. This formulation leads to an NP-complete problem. They proposed three centralized heuristics that determine the channel widths of APs according to their reported loads.

[Yang et al., 2008] formulate the channel-width assignment problem as an NP-complete combinatorial optimization problem. They alleviate the per-AP computational load by means of heuristics that assume the existence of a dedicated radio control channel between APs and their conflicting neighbors. [Li and Zhang, 2009] also propose a combinatorial formulation by means of the joint mixed 0-1 integer linear optimization problem. Similarly, non-optimal heuristics are used to alleviate the computational load. In turn, [Raman and Caesar, 2009] focus on a similar channel adaptation problem, but consider QoS constraints in multichannel ad-hoc networks.

[Gummadi et al., 2008] propose an analytical study to investigate the benefits of occupying the network frequency band with orthogonal channels. Based on this idea, they develop a protocol that attempts to adapt the number and the width of sub-channels within the frequency band to the number of concurrent transmissions in the network. The authors devise an exponential $O(7^n)$ worst-case algorithm to assign channel-widths for n nodes. They also propose an heuristic to prune the search space, but defer the study of a more efficient algorithm, its effectiveness and stability to future work.

Similarly to [Gummadi et al., 2008], [Maheshwari et al., 2009] present a preliminary analytical study to advocate that the number of orthogonal channel within the frequency band should be proportional to the number of interfering links. The authors consider the 802.11 CSMA/CA protocol to analytically calculate the throughput of each spectrum arrangement. Based on such study, they develop a MAC protocol that adapts the number and the width of multiple sub-channels based on an estimation of the number of competing nodes.

[Halperin et al., 2010] focus on the main energy consumption aspects of IEEE 802.11n (e.g. channel width, transmit power, rates, MIMO streams). Unlike the conclusions of the first ODSA performance study for WLANs [Chandra et al., 2008], they state that the use of wide channels has a negligible impact on power consumption. They justify this by saying that [Chandra et al., 2008] "increased the NICs clock frequency and PHY-layer parameters, but IEEE 802.11n simply adds sub-carriers keeping clocks the same". Further, the authors present experiments to show that the extra energy consumption of wide channels can be kept low in comparison to narrow channels if clock and modulation parameters are kept the same.

[Arslan et al., 2010] and [Arslan et al., 2012] analyze the benefits and drawbacks of the channel bonding technique, where two narrow channels are merged to achieve a wider one. They claim that wide channels can impair link performance due to problems of interference and higher SNR requirements. Thus, the authors consider these constraints to formulate an NP-complete channel allocation problem and propose a heuristic to approximate a solution for it.

[Tan et al., 2010] and [Fang et al., 2013] present a joint PHY-MAC solution to divide the wireless channel into narrower orthogonal sub-channels. The solution rely on standard WLAN mechanism such as carrier sensing and control frame exchange to enable concurrent orthogonal transmissions in the channel. Since the work is designed under the half-duplex constraint, all narrow channels must either transmit or receive, not both simultaneously.

[Yang et al., 2011] develop a software-defined radio architecture to support the development of adaptive bandwidth proposals. The resulting radio solution can combine multiple non-contiguous portions of spectrum into a single-wide channel, improving the spectrum reuse efficiency.

[Herzen et al., 2013] present an ACW distributed algorithm to assign both the center frequency and the channel width for residential APs, considering other WLANs under different third-party administrative entities. The algorithm's is based solely on single radio overhearing rather than control messages.

Finally, another important issue in ACW networks concerns the channel width negotiation overhead, since the link communication can not succeed unless the nodes involved are aware of the spectrum settings of each other. Research in this sense includes novel preamble designs that allow the receiver to determine the sender's spectrum configuration during an ongoing frame transmission [Yun et al., 2013], [Zhang and Shin, 2011].

3.1.2 The Standard WLAN Dynamic Bandwidth Channel Access

The current IEEE 802.11ac WLAN standard [IEEE80211ac, 2013] supports ODSA by means of the dynamic bandwidth channel access algorithm. Throughout this work, this algorithm is referred to as the standard IEEE 802.11 ODSA algorithm (or similar terminologies thereof)

This protocol operates together the CSMA/CA protocol to determine the channel width of a winning STA at the end of the contention round. The algorithm negotiates the channel with the destination from a set of supported widths. Although it became mandatory in the IEEE 802.11ac, the algorithm can be set to work in other set of bandwidths in which narrower adjacent channels can be joined into a wider one, as [Park, 2011] discuss.

The mandatory channelization for the ODSA algorithm is shown in Figure 3.1.. The IEEE 802.11n/ac 5 GHz frequency band arrangement is specified on the Fig. 3.1. The narrowest available channel is as wide as 20 MHz to keep co-existence and backward compatibility with

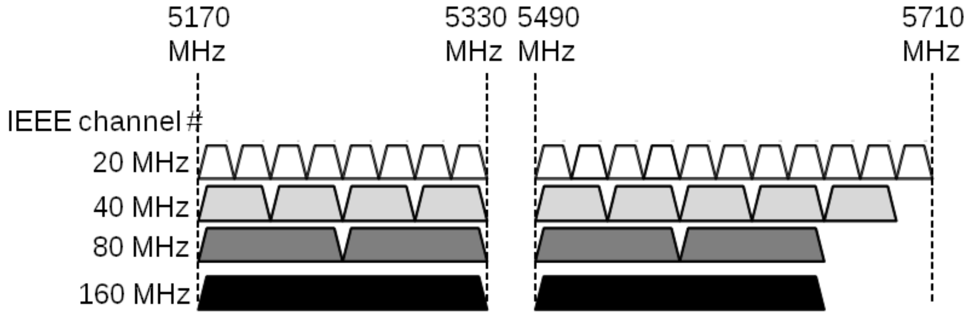


Figure 3.1: IEEE 802.11ac frequency band arrangement over the 5 GHz Frequency Band for the Europe, Japan and Global operating class tables.

legacy Wi-Fi devices. Wider channels can be access depending on the medium availability during the contention process. In particular, it is possible to bond two, four or eight contiguous 20 MHz channels to achieve transmissions as wide as 40, 80 and 160 MHz, respectively. In the "first generation" (so-called "first wave"), the widest mandatory channel (we denote as B_w) is 80 MHz-wide, while 160 MHz channels are optional. Keeping in mind the reservation of channels becomes harder as width becomes wider, the Wi-Fi designers also allow the optional 80+80 channel mode in which two orthogonal 80 MHz channels are accessed simultaneously.

In order to access the widest possible channel, the IEEE 802.11ac ODSA algorithm classifies channels into either primary and secondary. The *primary channel* P_c is where CSMA/CA is performed. If, before a node starts sending the RTS frame on the P_c, one or three secondary channels are sensed idle during a time equal to the PCF Inter-Frame Space (PIFS) time interval, then the secondary channels are also reserved, and transmission occurs in a contiguous 40 MHz or 80 MHz channel, respectively. Note that all transmissions will be as wide as 80 MHz if there is no source of interference nearby the WLAN. Otherwise, the winning node narrows the channel width accordingly and postpones the 80 MHz attempt until the next contention round.

3.2 Wireless FD MAC Protocols

In this section, we summarize the terminology introduced by [Singh et al., 2011] for the design of IEEE 802.11-based FD MAC protocols. Then we overview some of the main FD MAC protocol proposals for WLANs.

3.2.1 Terminology

The ultimate goal of any FD MAC protocol is to take advantage of FD opportunities within a given wireless channel to maximize capacity. It means the protocol attempts to activate two collision-free arbitrary transmissions in the channel to maximize channel utilization then throughput. In Wi-Fi compliant WLANs, the *Primary Transmitter* (PT) is the first node to start transmitting a data frame after winning a typical CSMA/CA contention round. The node to which PT transmits is called *Primary Receiver* (PR). During the primary [1] transmission, the FD MAC protocol may start a secondary transmission in the channel. In this case, the sender and receiver are called *Secondary Transmitter* (ST) and *Secondary Receiver* (SR), respectively.

The FD opportunities can be classified into either *symmetric* or *asymmetric* dual-links. In symmetric dual-links, PT and PR coincide with SR and ST, respectively i.e. [PT=SR]⇄[PR=ST], where the direction of each arrow denotes the destination of a transmissions. In asymmetric dual-links, there must be a *third* node involved in the secondary communication. Such node is either an SR or an ST. In the former case, the PR coincides with the ST i.e. PT→[PR=ST]→*SR*. Otherwise the PT coincides with SR, i.e. PR←[PT=SR]←*ST*. Note the two possible asymmetric dual-links are not different views of the same scenario. Indeed, in one case an already *receiving* node starts transmitting while in the other an already *transmitting* node starts receiving.

3.2.2 Proposals

The first distinctive usage of the FD ability at the MAC layer is for effectively mitigating the hidden node problem, as presented in the "Contraflow" FD MAC protocol by [Singh et al., 2011]. This idea consists in replacing the RTS/CTS control frames by either a busy tone or a data frame if this latter is available. Just after receiving and processing the frame's header from an arbitrary STA, the AP checks whether it has a data frame enqueued to that same STA. If yes, the AP starts a symmetric dual-link which almost doubles channel capacity and protects the ongoing STA's primary transmission from hidden nodes. If the AP has no frame either to the ongoing PT or to other STA then it starts transmitting a predetermined busy-tone to mitigate collisions from hidden nodes. Finally, the proposal computes the probability of success for each possible asymmetric dual-link of a node based on the proportions of past transmissions.

[Jain et al., 2011] present a joint SIC and MAC design to establish symmetric dual-links in real-time. The authors mostly focus on the design of a real-time SIC circuitry and implement symmetric dual-links according to the Contraflow FD MAC protocol [Singh et al., 2011]. The part for the establishment of asymmetric dual-links is not implemented. In particular, the authors present an FPGA-based logic that achieves $11\mu s$ to fetch and transmit the secondary frame (or a busy-tone in the absence of data frames) upon processing the incoming PT's header. With this, *the employment of symmetric dual-links have been consolidated as a potencial replacement for RTS/CTS to combat the hidden node problem*.

[Sahai et al., 2011] propose "FD-MAC", an FD MAC protocol based on CSMA/CA. FD-MAC comprises a header-based discovery mechanism in which nodes with frames addressed to each other share their backoff to maximize full-duplex opportunities. In order to avoid a couple of nodes from starving the entire network, they synchronize the shared backoff counter to allow the channel to be accessed by other nodes. The authors report an improvement of $0.7\times$ over the half-duplex CSMA/CA MAC protocol.

[1] please, note that this does not relate to "primary channel" IEEE 802.11ac terminology.

[Hong et al., 2012] and [Krishna et al., 2012] propose different PHY and radio design strategies to support independent narrow orthogonal channels on a single IEEE 802.11 radio. [Hong et al., 2012] explain this is not feasible on half-duplex radio can because of the high-powered level of the transmitted signal causes strong self-interference on the reception chain of the radio. Thus, no incoming signal can be 'heard' on the reception chain of the *transmitting* device. To cope with this problem both [Hong et al., 2012] and [Krishna et al., 2012] rely on approaches reminiscent to the out-of-band radio technology. In the first work, authors propose a SIC technique that enable a transmitting radio to simultaneously receive on an an orthogonal narrow channel. The technique is complemented with a guard-band set between 1 MHz to 2 MHz to assure near-optimal interference isolation in the most challenging interference scenario i.e. Rx/Tx mode. In the second work, the authors describe the design of a filter capable of working along with guard-bands as small as 100 KHz, one order lower in comparison to the former work. Although these works concentrate on the design of out-of-band FD PHY layers, their results are important to support the design of multi-channel FD MAC protocols.

[Cheng et al., 2013] argue that, although symmetric FD links can naturally mitigate the hidden node problem as firstly discussed by [Singh et al., 2011], at least one end-point of an asymmetric dual-link may be subject to collision because of hidden nodes. To mitigate such a problem they propose RTS/FCTS (Full Duplex CTS), an extended version of the RTS/CTS handshake that is based on three control frames (instead of the standard two frames). They take advantage of the resulting control frame exchange to identify the opportunity to establish an FD link as well as its type (i.e. symmetric or asymmetric). Also, the authors propose an analytic model to study the scalability of the protocol. They achieve their best results for small networks (up to 10 nodes) and lower transmission probability. Indeed, despite the fact that the RTS/CTS handshake (or variants thereof) minimize the time spent in collisions (because RTS frames are usually much shorter than data frames), they slow down all successful transmissions. Thus, the average FD capacity performance over half-duplex's decreases with an increasing traffic in the network.

[Kim et al., 2013] propose "Janus", a receiver-initiated FD MAC protocol for infrastructure WLANs. Under the receiver-initiated MAC design guideline, the round for negotiation of data transmission is triggered by the receiver (the AP, in this case). During the negotiation round, STAs report to the AP information about the data transmission they intend to perform as well as the level of interference they sense from other STAs. After gathering information, the AP creates an interference map to determine which STA(s) can transmit. In order to maximize the FD opportunities, Janus also allows for partially interfering STAs to transmit simultaneously. To minimize Frame Error Rate (FER) in these cases, Janus relaxes SNR requirements by assigning STAs with lower data rate modulation schemes. The authors claim a gain of 2.5× over CSMA/CA considering a 10 MHz FD out-of-band scenario with three nodes. However, it is not clear whether the receiver-initiated design guideline can scale the FD gains. Indeed, with such a design, the time or spectrum overheads wasted during the negotiation round grow with the number of STAs. The authors plan to deal with such limitation in future works.

[Zhang et al., 2014] concern on the channel switching problem in multi-channel networks. Particularly, the authors approach the multi-channel hidden problem in IEEE 802.11 networks. This problem may happen when a node can not sense an ongoing data transmission in a new channel it switches to. According to authors, typical solutions for the problem rely on control channels that are exclusively allocated to support signaling among nodes. They design an FD-based MAC protocol to eliminate the spectrum overhead associated to control channels. The solution helps each node to find the resident channel of its respective destination while avoiding hidden nodes. The channel switching algorithm does not implement ODSA policy.

[Duarte et al., 2014] propose a joint PHY-MAC FD solution for multi-antenna Wi-Fi networks. Similarly to [Jain et al., 2011], the work is mostly focused on FD PHY layer aspects and consider FD communications only between two nodes i.e., symmetric dual-links. The main difference is that FD opportunities are managed based on RTS control frames instead of the header of data frames. Upon the reception of an RTS, the SR inspects its frame queue to check whether there is a data frame to be sent back to the PT. If the SR has a frame to the PT then a symmetric FD link is established a period of $SIFS$ after the CTS control frame is sent.

[Kim et al., 2015b] propose an FD version for the Orthogonal Frequency Division Multiple Access (OFDMA). With the solution, a pair of nodes negotiate several parameters for data communication. The protocol assigns non-overlapping channels for pair of nodes and determines the communication mode for each pair i.e., full or half duplex. The channel assignment negotiation depends on specific control channels shared by all nodes. The control channel is managed following a typical binary exponential backoff random algorithm. The proposal achieves a maximum gain of 150% (i.e. 2.5×) over a half-duplex MAC protocol as the traffic rate increases in a wireless network. Although this is an efficient solution, it is not clear whether such result scale the FD gain for at least two reasons. Firstly, all experiments are carried for a fixed 25-node network. Secondly, and most important, the success of FD data frame transmissions depends on the negotiations carried on the control channel. The control, by its turn, is managed in a random way based on the binary exponential back-off algorithm. As any random access channel, the rate of collision might increase with the number of nodes. Thus, the achieved gain might decrease accordingly. For this reason further study is needed to assure scalability of the FD gain.

[Choi et al., 2015] design a power controlled FD MAC protocol for IEEE 802.11 WLANs. To estimate the inter-client level of interference, the proposed MAC protocol assesses the signal strength of overheard control frames. Based on the gathered information, the backoff procedure is adjusted in a way that nodes with lower mutual-interference are given higher priority to establish asymmetric FD links. Also, transmission power is adjusted to avoid collision on such links. In the best-case scenario (i.e. from 10 to 20 contending STAs), the achieved gain is less than 1.8× the half-duplex CSMA/CA throughput.

[Liao et al., 2015] propose an FD MAC protocol that attempts to maximize the capacity gain over the CSMA/CA half-duplex by minimizing the time duration of collisions. In this sense, the FD functionality enables a node to sense and transmit over the same channel. If a node detects a channel as busy then it suspends its own transmission to minimize the duration of some possible ongoing collision. The proposal's gain depends on the time CSMA/CA wastes in collisions. The authors compare their proposals only against the two-way handshake CSMA/CA in which the collision duration is proportional to the data frame size. The claimed gain is expected to further reduce if the half-duplex CSMA/CA is set to the four-way handshake once the collision time is proportional to a small RTS control frame in this case.

[Al-Kadri et al., 2016] consider the design of energy-constrained FD MAC protocols. The authors extend the RTS/FCTS MAC protocol by [Cheng et al., 2013] with techniques to reduce transmission power of data and ACK frames in order to save energy. With this, their design outperforms RTS/FCTS energy consumption while keeping a similar throughput.

3.3 What Hinders the FD MAC Protocol Scalability?

By surveying the FD MAC protocol literature one can find that scaling the FD gain is far from being a closed question for random access wireless networks, specially for the single-cell scenarios. Also, little progress has been made to enable the ODSA feature in FD WLANs.

To design an effective FD MAC protocol for WLANs one needs to keep in mind what can prevent it to scale the FD gain. Next, we discuss the available literature in this sense. Thus, we enhance this knowledge by presenting an yet undiscovered limitation. We then propose a novel classification for FD MAC protocols.

3.3.1 Self-Interference Cancellation Imperfection

The maximum gain an FD PHY layer delivers to the MAC layer is affected by the amount of SIC achieved by the FD radio design. If the SIC is not effective, the residual self-interference (RSI) after cancellation can cause the noise floor to increase and, consequently, the capacity to decrease. A too high RSI can lead an FD radio to perform worse than an half-duplex radio in terms of capacity, even with the advantage of an extra link.

Consider a 10 MHz-wide AWGN half-duplex channel set to a transmit power of 20 dBm. Considering a noise floor and RSSI levels of -95 and -60 dBm, respectively, the resulting link SNR is $-60 - (-95) = 35$ dB. According to the Shannon-Hartley theorem, the maximum capacity the link delivers to the MAC layer is about 116.27 Mbps. To enable an FD-capable link, each radio should suppress the transmit SI in such a way as to assure the same level of noise floor experienced by the counterpart half-duplex link. The SI should be canceled by $20 - (-95) = 115$ dB [Sabharwal et al., 2014]. If the FD radios in the example can manage to cancel 85 dB at most, the SNR of each link endpoint will decrease from the previously assumed

35 dB to 35 − (115 − 85) = 5 dB. Thus, the FD capacity will be 41.14 Mbps, a performance about 3× worse than the half-duplex case.

To date, the best known SIC result are due to [Bharadia et al., 2013] and [Korpi et al., 2016a], who claim cancellation levels of *up to* 110 dB, a fair improvement over designs proposed no longer than few years before e.g. [Duarte et al., 2012], [Everett et al., 2011], [Choi et al., 2010], [Duarte and Sabharwal, 2010]. One setup considered by [Korpi et al., 2016a] consists of a 20 MHz bandwidth in an outdoor scenario. With transmit power set to 29 dBm and considering a (half-duplex) noise-floor of −88 dBm, the author claim a total cancellation of 110 dB, causing the RSI to reduce to the same noise-floor of the half-duplex operating mode.

[Bharadia et al., 2013] also claim a negligible RSI in a 20 MHz channel. In another setup, the authors consider a 80 MHz bandwidth set to a transmit power of 20 dBm and with a (half-duplex) noise-floor of −90 dBm. In this setup, the authors claim to achieve an RSI of up to 1 dB, resulting in (FD) noise-floor of up to −89 dBm. This translates into an FD capacity gain of 1.87× over the throughput of an IEEE 802.11ac half-duplex PHY layer. The authors clarify that an FD MAC design is out of their scope but recognizes it is a mandatory requisite to fully "realize and taking advantage" of the full duplex technology. Additionally, in spite of the promising results, RSI reduction has been under investigation for a variety of different requisites such as radio miniaturization for small form-factor devices [Reiskarimian and Krishnaswamy, 2016], [Debaillie et al., 2014], interaction with standard Wi-Fi technology such as Multiple Input, Multiple Output (MIMO) [Bharadia and Katti, 2014], [Aryafar et al., 2012]; cancellation efficiency in very wide bandwidths [Huusari et al., 2015] and node mobility [Korpi et al., 2016b].

As other proposals in the field of design and performance evaluation of FD MAC protocols [Al-Kadri et al., 2016], [Liao et al., 2015], [Cheng et al., 2013], [Kim et al., 2013], the present work builds on the outcome of the FD radio design field to focus on the design and performance evaluation of a novel FD MAC layer. For a comprehensive study about SIC techniques, the reader is kindly asked to consult the specific literature e.g., [Kim et al., 2015a], [Sabharwal et al., 2014], [Korpi et al., 2014].

3.3.2 Networking Design Aspects

Aside from the challenges in the field of SIC radio design, [Thilina et al., 2015] remark that scaling the FD gain in a WLAN – i.e., doubling throughput of a half-duplex WLAN for an arbitrary number of STAs – requires advances falling the in the field of networking, particularly those handled at the MAC layer. In this same sense, [Xie and Zhang, 2014a] bring a new perspective to the FD gain scalability problem at the MAC layer. Instead of proposing an FD MAC protocol itself, they attempt to gain deeper insights about the structural factors limiting random-access protocols to scale the IBFD gain. They describe the first design guidelines a MAC protocol must attend to meet the scalability goal in a multi-cell IEEE 802.11 deployment.

These are the need for both *spatial reuse* and *asynchronous contention*. In the first case, the total interference range spread by FD is wider than in half-duplex links. Thus, nodes around both endpoints of a dual-link have to defer transmission to avoid collisions. With a half-duplex link (let us say, from S_1 to S_2), two other simultaneous links can be activated: a transmission within S_1's range (but out of S_2's range) and a receiver within S_2's range. In turn, the asynchronous contention may dramatically limit FD gain at because, ideally, FD transmissions should start simultaneously to maximize FD gain. However, this is not likely to happen because of the random uniform nature of CSMA/CA. Keeping in mind the desire for fully profiting from the FD gains, the belief for a joint PHY-MAC design approach has been defended in the research community by [Thilina et al., 2015], [Bharadia et al., 2013].

Currently, the mechanisms FD MAC protocols employ to establish dual-links have been classified into the following categories [Thilina et al., 2015], [Zhang et al., 2016]:

- *Shared-Random Back-off* (SRB) enables nodes to exchange the back-off counter to synchronize dual-link transmissions. After winning a contention, the PT sets two specific fields on the data frame to negotiate future symmetric dual-link communications with its corresponding PR. One field indicates whether it has more data frames addressed to the PR. The other field shares a random back-off value the PT proposes to the PR for the future dual-link communication. If the PR has an enqueued frame that is addressed to the PT, it opportunistically informs that through the ACK frame. e.g. [Sahai et al., 2011]. As [Thilina et al., 2015] remark, in any SRB-based FD MAC protocol, the first transmission is always half-duplex;

- *Header snooping* leads node to overhear and decode all transmitted frame headers in order to determine whether a collision-free dual-link can be established in the future. For instance, if a STA S_1 overhears an ACK from the AP to the STA S_2 but did not detect a prior corresponding data frame, then S_1 does not need to freeze the back-off counter while the AP transmits to S_2 e.g. [Singh et al., 2011], [Goyal et al., 2013]. Such approach intrinsically assumes the symmetry of a wireless link, which may not hold in some real cases [Kotz et al., 2003];

- *RTS/CTS-based FD mechanisms* somehow exploits the RTS/CTS handshake to also negotiate the establishment of dual-links. For example, [Cheng et al., 2013] adapt CTS frames to also play the role of RTS. This way, the CTS frame also includes the length of the data frame its originator – let us say, the AP – intends to send to a third node – let us say, the STA S_2. Then, a second CTS is sent from S_2 to the AP in order to enable the an asymmetric dual-link involving the AP.

The ODSA and FD capabilities have yet been considered separately from each other in the design of MAC protocols. On one hand, ODSA-capable MAC protocols do not benefit from FD capabilities. On the other hand, although FD MAC proposals work on fixed-width channels,

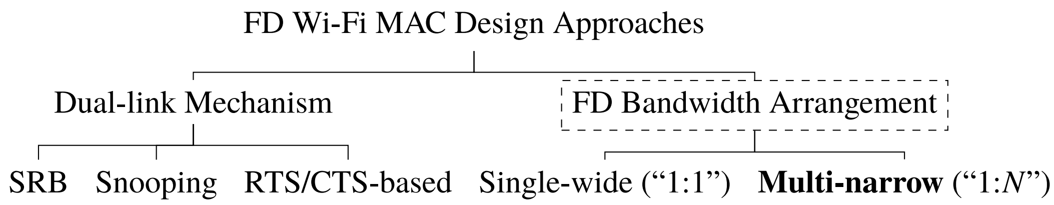


Figure 3.2: FD Wi-Fi MAC protocol design classification.

they implicitly follows the idea of the standard ODSA algorithm, which consists in allocating the widest available bandwidth per contention round. The difference is that, in the FD case, the bandwidth support two simultaneous transmissions. Therefore, despite the lack of a coupled solution, we note that both FD and ODSA research communities have been strongly influenced by a same implicit rationale, namely, "the wider the bandwidth, the higher the throughput".

Based on the above remark, we propose a complementary category to classify FD MAC protocols as illustrated in the dashed box of Fig. 3.2. With this novel category, the protocols are classified according to the design guideline they follow to arrange the available wireless FD bandwidth from the MAC layer perspective. We identify a predominant trend we refer to as the 1:1 MAC design guideline e.g. [Singh et al., 2011], [Jain et al., 2011], [Sahai et al., 2011], [Hong et al., 2012], [Miura and Bandai, 2012], [Cheng et al., 2013], [Kim et al., 2013], [Duarte et al., 2014], [Xie and Zhang, 2014b], [Kim et al., 2015b], [Choi et al., 2015], [Liao et al., 2015], [Al-Kadri et al., 2016]. Under the 1:1 guideline a MAC protocol 'sees' the wireless bandwidth through a *single* FD PHY layer. The protocol attempts to occupy the bandwidth with two arbitrary collision-free simultaneous transmissions. The resulting dual-link range may result in poor spatial reuse, dramatically hindering the FD gain scalability in some scenarios [Xie and Zhang, 2014a]. Furthermore, conditioning the whole FD bandwidth to a single PHY layer hampers the development of on-demand spectrum policies at the MAC layer since all transmissions allocates the same channel width regardless of traffic demands. To cope with these problems, the next chapter describes 1:N, an FD MAC design guideline based on which the FD bandwidth must be arrange into more than one narrower channel.

3.4 Summary of the Chapter

This Chapter reviewed On-Demand Spectrum Allocation (ODSA) algorithms and Full Duplex (FD) MAC protocols. It was verified that most of ODSA algorithms evolved before the achievement of FD radios. The aspects that can prevent FD MAC protocols to scale the FD gain were discussed. In particular, it was identified a novel common practice in the design of FD MAC protocols based on which the FD bandwidth is 'seen' through a single PHY layer.

Chapter 4

Proposal

This chapter presents a novel guideline for the design of FD MAC protocols. It is structure as follows. Section 4.1 presents the project requisites that guides the proposal. Section 4.2 describes the proposal in terms of advantages, drawbacks, performance indicators and novelty in comparison to the state of the art. Section 4.3 presents and discusses case studies of FD MAC protocols under the 1:N design guidelines. Section 4.4 discusses models to assess the saturation throughput of the 1:N FD MAC protocols presented in the chapter. Finally, Section 4.5 summarizes the chapter.

4.1 Project Requisites

The present work aims to propose and evaluate the performance of an alternative solution for the 1:1 FD MAC design guideline. To overcome the structural limits the 1:1 design guideline impose on current FD MAC protocols, the novel design guideline is expected to outperform or – be as effective as – the 1:1 design guideline with respect to the following features:

- Degree of spatial reuse;
- Support for the ODSA strategies;
- Theoretical capacity upper-bound.

In addition to the above-described requisites, the proposed design guideline shall be enough generic to support random access protocols such as the Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA) protocol of IEEE 802.11 WLANs.

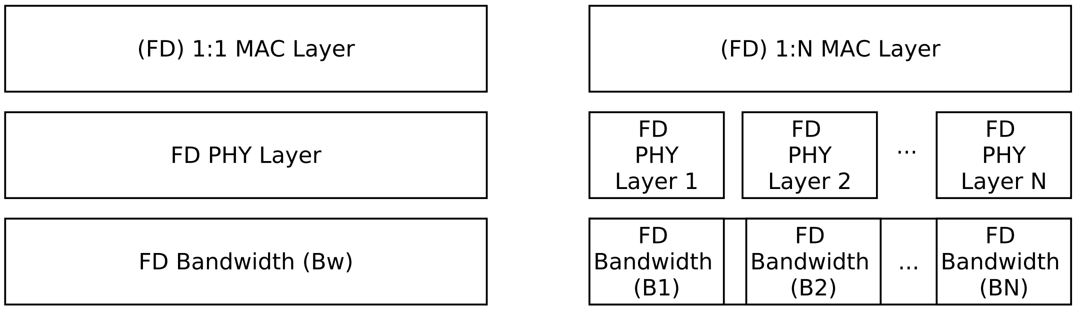


Figure 4.1: FD MAC design guideline layering comparison over a bandwidth of B_w Hz: 1:1 (left-hand side) vs. 1:N (right-hand side).

4.2 The 1:N FD MAC Design Guideline

4.2.1 Description and Characteristics

In order to meet the requisites described in section 4.1, we propose the 1:N FD MAC design guideline as an alternative proposal for the 1:1 MAC design guideline. Any MAC protocol designed under the 1:N shall 'see' the FD bandwidth of B_w Hz through $N > 1$ PHY layers. Each PHY layer is assigned to a sub-channel that is narrower than the whole available FD bandwidth and orthogonal to the sub-channel of the others PHY layers. Figure 4.1 illustrates the layering structure resulting from the 1:N FD MAC design guideline (right-hand side) in comparison to its 1:1 counterpart (left-hand side).

If the supported FD bandwidth measures B_w Hz, then the 1:N guideline establishes that there must be N independent narrow orthogonal channels each measuring B Hz. Each pair of adjacent narrow channels shall be separated by a guard-band of g Hz to suppress channel leakage at the destination. The total spectrum G (Hz) employed for guard-bands is given by the Equation 4.1.

$$G(Hz) = (N-1)g \tag{4.1}$$

The 1:N FD MAC design guideline mandates that the available bandwidth shall be equally divided across the N narrow channels. After discounting the guard-band overhead G, the width B of each narrow channel in the 1:N design guideline is given by the 4.2.

$$\begin{aligned} B(Hz) &= \frac{B_w - G}{N} \\ B(Hz) &= \frac{B_w - (N-1)g}{N} \end{aligned} \tag{4.2}$$

Table 4.1: Possible 1:N channel arrangements considering typical IEEE 802.11 channelizations.

	IEEE 802.11a/g	IEEE 802.11n	IEEE 802.11ac
Supported Bandwidths	20, 10, 5	40, 20	80, 40, 20
B_w	20 MHz	40 MHz	80 MHz
Possible 1:N Arrangements	2x10, 4x5	2x20	2x40, 4x20

The width limit $B_{g\to 0}$ of each narrow channel in the 1:N design guideline stems from getting g narrower and narrower from the Equation 4.2. The resulting value is given by the Equation 4.3.

$$\begin{aligned} B_{g\to 0}(Hz) &= \lim_{g\to 0} B \\ B_{g\to 0} &= \lim_{g\to 0} \frac{B_w - (N-1)g}{N} \\ &= \lim_{g\to 0} \frac{B_w}{N} \\ B_{g\to 0} &= \frac{B_w}{N} \end{aligned} \tag{4.3}$$

Both N and g shall be defined as networking configuration parameters. Valid parameters of N and g shall comply the Equation 4.4.

$$B_w(Hz) = NB + (N-1)g \tag{4.4}$$

The value of B_w must be fixed to meet regulations of a given network technology. It may vary only across different network standards. For example, the IEEE 802.11a/g standards support 20 MHz, 10 MHz and 5 MHz channels. Therefore, B_w = 20 MHz and N can be set to 2 and 4 yielding, two 10 MHz PHY layers or four 5 MHz PHY layers, respectively. If the IEEE 802.11 changes the 1:N configuration values may change accordingly. The Table 4.1 exemplifies possible 1:N parameters under the IEEE 802.11a/g [IEEE, 2012], IEEE 802.11ac [IEEE80211ac, 2013] and IEEE 802.11n [IEEE, 2009] standards.

It is worthy to note that, in spite of the fact that the channel arrangement implied by 1:N matches the IEEE 802.11 channelization, as one can infer from Table 4.1, the way the bandwidth is accessed changes. Different from the IEEE 802.11 standards, *no transmission as wide as B_w shall happen under 1:N*. This way, *the node that wins a contention never modulates a single data frame on the entire FD bandwidth.*

4.2.2 Key Overheads

This section concerns on the key generic overheads the 1:N FD MAC design guideline brings in comparison to its 1:1 counterpart. The term ‘generic’ is meant by overheads that incur no matter how clever is the MAC strategy over the N channels of the 1:N design guideline. Instances of MAC protocols under 1:N as well as the particular overheads they introduce are discussed in Section 4.3. The current section discuss two generic overheads, namely, total spectrum spent with guard-band and the impact caused by channel reduction on timing parameters of the network.

Guard-band Overhead

The guard-band spectrum required by the 1:N design guideline is a critical overhead of the system because it turns off spectrum for channel separation. Some of the 1:N expected advantages described in subsection 4.2.3 benefit from an increasing value of N. However, arbitrarily large N might neutralize those expected advantages because of the ‘waste’ of spectrum that results. In fact, because B_w is fixed, if one increases the number N of narrow channels, the width of each one of them must be narrowed to accommodate more guard-band spectrum within B_w. Thus, the width B of each particular narrow channel becomes narrower as the number of channels increase. Alternatively, one should increase the total spectrum allocated for the WLAN from B_w Hz to $B_w + G$ Hz to enable the operation of an 1:N FD MAC protocol. Anyway, the 1:N FD MAC design guideline is more expensive in terms of spectrum resources than its 1:1 counterpart. A topic of study of this work is to investigate some condition (if any) under which such a cost leads 1:N to outperform the 1:1 FD capacity upper-bound.

Impact of Channel Reduction on Timing Parameters

When channel width reduces, capacity might reduce accordingly. In the IEEE 802.11 WLAN standards, this is reflected by slowing all MAC and PHY layer timing parameters. With the exception of the IEEE 802.11 time slot σ and parameters thereof, all other MAC and PHY timing parameters doubles whenever channel width halves [IEEE, 2012, section 18.3.8.7 and Table 18-5]. The values for some of these parameters are illustrated on Table 4.4.2. Consequently, events like data frame transmission and collision might take longer in a narrow channel.

Table 4.2: Some IEEE 802.11a MAC timing parameters across channel widths.

	Timing Parameters (μs)		
Bandwidth	$SIFS$	$SLOT$	$DIFS$
20 MHz	16	9	34
10 MHz	32	13	58
5 MHz	64	21	106

4.2.3 Expected Advantages and Capacity

This section overviews the main potential expected advantages of the 1:N FD MAC design guideline compared to its 1:1 counterpart.

Increased Spatial Reuse Factor

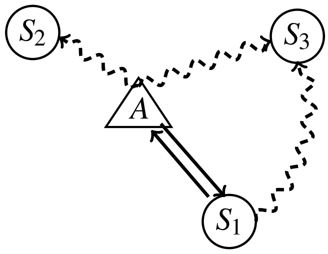
The 1:N FD MAC design guideline is expected to outperform the 1:1 guideline in terms of spatial reuse offer in the network. This stems from the fact that channel orthogonality can multiply the possibilities for the establishment of dual-links in the bandwidth, as comparatively illustrated in the Figures 4.2. When an 1:1 FD MAC protocol establish a dual-link – as illustrated in the Figure 4.2a through the couple of solid straight arrow between the AP A and the STA S_1 – all other STAs (S_2 and S_3) must remain silent because of the resulting interference, as represented by the dashed waved arrows in the Figure. On one hand, this can prevent a hidden node (like the STA S_2) to start transmitting (and colliding) with the ongoing transmission ($S_1 \rightarrow A$). On the other hand, the increased dual-link interference range sacrifices the spatial reuse offer, which has been pointed as a key issue that hinders the FD gain scalability at the MAC layer [Xie and Zhang, 2014a]. In the same scenario, the 1:N design guideline (with N set to two) can enable an extra dual-link in the bandwidth. A possible mix of simultaneous dual-links is illustrated in the Figure 4.2b, in which channel orthogonality is shown by means of different colors (gray and black). The way each narrow channel is allocated depends on the MAC protocol strategy, as section 4.3 discusses. In general, by arranging the FD bandwidth into N *orthogonal* narrow-channel PHY layers, the 1:N FD MAC design guideline enable the co-existence of $N-1$ extra simultaneous dual-links in the same space. However, the guard-band spectrum overhead G is also a function of N, as previously shown in Equation 4.1. The balance between the spatial reuse factor and the guard-band overhead on capacity is a fundamental trade-off for investigation in the present work.

Improved Signal to Noise Ratio under 1:N

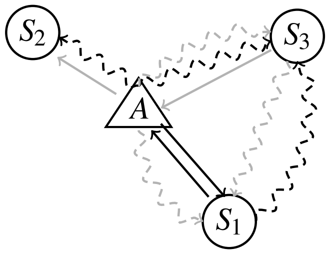
With channel width reduction one might expect the noise floor to reduce accordingly, as suggested by Equations 2.8. Along with the FD feature that enables narrow channels to operate concurrently, the reduced noise floor experienced by a narrow channel is also expected to compensate the capacity loss imposed by guard-band overheads.

The SNR gain $\Delta\mathcal{N}$(dB) of each channel in the 1:N design guideline against the single channel of the 1:1 guideline is defined as the difference between the noise-floor experienced by a demodulation across the entire FD bandwidth measuring B_w MHz and a demodulation experienced within the narrower bandwidth measuring B MHz, respectively. This is given by Equation 4.5.

$$\Delta\mathcal{N}(dB) \quad = \quad \mathcal{N}_{fd}(B_w) - \mathcal{N}_{fd}(B) \tag{4.5}$$



(a) Poor spatial reuse under the 1:1 single-band MAC design.



(b) Instance of spatial reuse opportunities enabled under the 1:N=2 MAC design guideline.

Figure 4.2: Spatial reuse factor in the 1:1 (a) and 1:N (b) FD MAC design guidelines.

Recalling the Equation 2.12 to calculate the noise floor in an FD receiver and the width B of each narrow channel in the 1:N design guideline (Equation 4.2), Equation 4.5 rewrites as 4.6, which yields the Equation 4.7. In the Equation, g is the guard-band that separates an arbitrary pair of narrow channels of the 1:N design guideline.

$$
\begin{aligned}
\Delta\mathcal{N}(dB) &= (-174 + 10\log(B_w) + RSI) - [-174 + 10\log(B) + RSI] &\quad (4.6)\\
&= (-174 + 10\log(B_w) + RSI) - \\
&\quad \left[-174 + 10\log\left(\frac{B_w - (N-1)g}{N}\right) + RSI\right] \\
&= 10\log(B_w) - 10\log\left(\frac{B_w - (N-1)g}{N}\right) \\
&= 10\log\left(\frac{B_w}{\frac{B_w - (N-1)g}{N}}\right) \\
\Delta\mathcal{N}(dB) &= 10\log\left(\frac{NB_w}{B_w - (N-1)g}\right) &\quad (4.7)
\end{aligned}
$$

In order to understand the *minimum SNR gain* $\Delta\mathcal{N}_{g\to 0}$ possible to achieve in each channel of the 1:N design guideline, one needs to refer to the maximum width of the channels. In fact, the Equations 2.8 and 2.12 for the noise floor tell us that widening a channel causes its noise floor to increase, so the SNR. Thus, the minimum SNR gain $\Delta\mathcal{N}_{g\to 0}$ results from the maximum width of channels in the 1:N design guideline. For a given value of N, the maximum width of channels

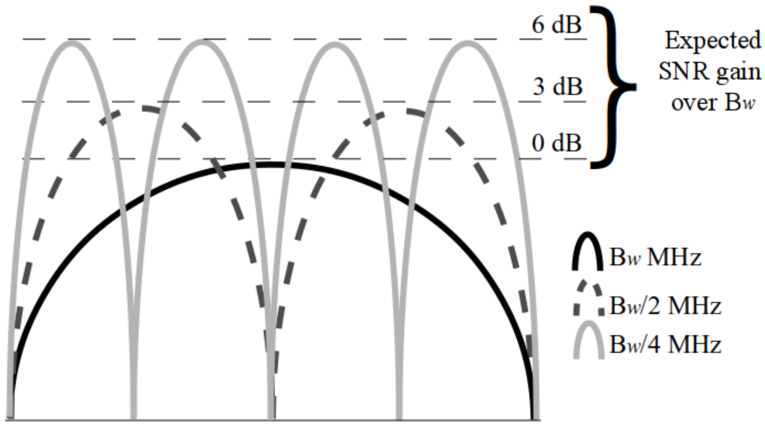


Figure 4.3: Channelization and expected SNR gain ($SNR_{\mathcal{G}}$) of 1:N channels over an FD bandwidth of B_w (Hz) for $N = 2$ and $N = 4$.

in the 1:N design guideline is given by the width limit $B_{g\to 0}$ (Equation 4.3), which results from getting g narrower and narrower. Thus, $\Delta\mathcal{N}_{g\to 0}$ is calculated by Equation 4.8.

$$\Delta\mathcal{N}_{g\to 0}(dB) = \lim_{g\to 0} \Delta\mathcal{N} \tag{4.8}$$

From Equation 4.7, Equation 4.8 rewrites as Equation 4.9.

$$\begin{aligned} \Delta\mathcal{N}_{g\to 0}(dB) &= \lim_{g\to 0} 10\log\left(\frac{NB_w}{B_w - (N-1)g}\right) \\ &= 10\log\left(\frac{NB_w}{B_w}\right) \\ \Delta\mathcal{N}_{g\to 0}(dB) &= 10\log(N) \end{aligned} \tag{4.9}$$

Considering the Equation 4.9 with N set to 2 and 4, the minimum SNR gain experienced by each narrow channel in comparison to the entire bandwidth B_w is about 3 dB and 6 dB, respectively. The gains are illustrated in Figure 4.3. Also, these values are consistent with the minimum IEEE 802.11 RSSI requisites for a successful demodulation across different bandwidths.

The IEEE 802.11 standard presents its supported data rates in Table 18-4 of page 1590 [IEEE, 2012]. Also, in Table 18–14, page 1612, the standard lists the minimum reference RSSI for each modulation (data rate). For the sake of readability, both mentioned Tables are merged in Table 4.3. In the IEEE 802.11, each line in the Table 4.3 says that one needs an RSSI *improvement* of at least 3 dB to provide a modulation scheme with the double of bandwidth. This is an 'horizontal reading'. The 1:N design guideline reads Table 4.3 'diagonally' (as highlighted in gray on the Table). Meaning that the minimum RSSI requisite for a demodulation scheme *relaxes* by 3 dB whenever channel width halves. One may argue that channel width reduction may not be interesting under the half-duplex constraint – as is the case of the IEEE 802.11 standards – because capacity may reduce accordingly. However, under the full duplex assumption, this

Table 4.3: IEEE 802.11 minimum RSSI across modulations and channel widths.

Weaker RSSI

Modulation	20 MHz		10 MHz		5 MHz	
	Mininum RSSI (dBm)	Maximum Rate (Mbps)	Mininum RSSI (dBm)	Maximum Rate (Mbps)	Mininum RSSI (dBm)	Maximum Rate (Mbps)
BPSK 1/2	-82	6	-85	3	-88	1.5
BPSK 3/4	-81	9	-84	4.5	-87	2.25
QPSK 1/2	-79	12	-82	6	-85	3
QPSK 3/4	-77	18	-80	9	-83	4.5
16 QAM 1/2	-74	24	-77	12	-80	6
16 QAM 3/4	-70	32	-73	18	-76	9
64 QAM 2/3	-66	48	-69	24	-72	12
64 QAM 3/4	-65	54	-68	27	-71	13.5

Denser Rate

argument no more holds. In fact, in-band and out-of-band radio technologies enable independent simultaneous transmissions within a given bandwidth. This leads to the central argument of this proposal, which is that *a narrow channel benefits from better SNR because noise weakens accordingly while FD compensates for the spectrum reduction by enabling the simultaneous activation of other narrow channels within the bandwidth*. Consider the following example to clarify the potential improvements of such proposal.

Suppose BPSK 1/2 is the densest modulation scheme possible to set in an IEEE 802.11 20 MHz channel. According to Table 4.3, this yields a 6 Mbps transmission and means the maximum RSSI is -82 dBm. Under this same RSSI, one can narrow the channel by a factor of two – leading to 10 MHz – or a factor of four – leading to 5 MHz – and set the modulations QPSK 1/2 or QPSK 3/4 in each respective case. This yields 6 Mbps or 4.5 Mbps, respectively. Under the assumption of an FD radio, the 20 MHz can be split into two 10 MHz channels paying an overhead of g Hz. Thus, in the example, it is possible to replace a single 6 Mbps transmission (1×20 MHz) by two 6 Mbps transmissions (2×10 MHz) or four 4.5 Mbps transmissions (4×5 MHz) paying an extra overhead of g Hz and $3g$ Hz, respectively.

In some cases of Table 4.3, narrowing a channel does not translate to a denser data rate. In all these cases the SNR improves, which may be valuable in hostile environments. If, for instance, the 'channel quality' is -74 dBm, then the densest rates for 20 MHz, 10 MHz and 5 MHz channels are 24 Mbps, 12 MBps and 9 Mbps, respectively. In this example, there is a leftover of 3 dB for 10 MHz and 2 dB for 5 MHz. With this the wireless link may sustain longer distances or react better against sudden changes in the quality.

Bandwidth Capacity

As discussed in Section 2.3, the throughput of any MAC protocol is bounded by the capacity of the bandwidth it manages. Recalling the Equations 2.8 and 2.13 discussed in that section, the maximum expected capacity the 1:1 design guideline delivers to the MAC layer is given by the Equations 4.10–4.12. In the Equation, RSI is the level of Residual Self-Interference (RSI) that the radio can not manage to suppress in its own reception chain while transmitting.

$$C_{fd} = 2B_w \log_2 \left(1 + 10^{(SNR_{dB} - RSI)_{dB}/10}\right) \tag{4.10}$$

$$C_{fd} = 2B_w \log_2 \left(1 + 10^{(S - N_{hd} - RSI)_{dB}/10}\right) \tag{4.11}$$

$$C_{fd} = 2B_w \log_2 \left(1 + 10^{(S - (-174 + 10\log(B_w)) - RSI)_{dB}/10}\right) \tag{4.12}$$

The capacity upper-bound shown in Equation 4.12 serves as base to calculate the bandwidth of the 1:N FD MAC design guideline. The same assumptions about the RSI level and the total bandwidth B_w are taken. However, *the way* 1:N *arranges* B_w*, affects the way both the bandwidth reduction and the noise floor account for the capacity of each 1:N narrow-channel*. The capacity C_{Bfd} of a *single* portion of FD spectrum B (given by Equation 4.2) within B_w is given by the Equation 4.13. Note that this is the Equation 4.12 with B_w replaced by the value of B.

$$C_{Bfd} = 2\left[\left(\frac{B_w - (N-1)g}{N}\right) \log_2 \left(1 + 10^{\left(S - \left(-174 + 10\log\left(\frac{B_w - (N-1)g}{N}\right)\right) - RSI\right)_{dB}/10}\right)\right] \tag{4.13}$$

Note that the guard-band g reveals a critical trade-off for 1:N MAC protocols. If one increases g to avoid inter channel leakage, the width of B decreases and the noise-floor level becomes weaker. On one hand, a narrower B causes the capacity C_{Bfd} to decrease. The mathematical explanation for such decrease is highlighted as gray box throughout the Equations 4.14–4.15. On the other hand, the same decision of turning B narrower, leads the capacity C_{Bfd} to increased because of the reduced noise-floor. The mathematical explanation for such increase is highlighted with underlines Equations 4.14–4.15.

$$C_{Bfd} = 2\left[\left(\frac{B_w \colorbox{lightgray}{$-(N-1)g$}}{\colorbox{lightgray}{N}}\right) \log_2 \left(1 + 10^{\left(S - \left(-174 + 10\log\left(B_w - \underline{(N-1)g}\right) - \underline{10\log(N)}\right) - RSI\right)_{dB}/10}\right)\right] \tag{4.14}$$

$$C_{Bfd} = 2\left[\left(\frac{B_w \colorbox{lightgray}{$-\underline{(N-1)g}$}}{\colorbox{lightgray}{N}}\right) \log_2 \left(1 + 10^{\left(S + \underline{10\log(N)} - \left(-174 + 10\log\left(B_w \underline{-(N-1)g}\right)\right) - RSI\right)_{dB}/10}\right)\right] \tag{4.15}$$

As a side note, if let $g \rightarrow 0$, B tends to its width limit $B_{g\rightarrow 0}$ i.e., the wider possible channel width in the 1:N design guideline. Consequently, the noise floor within $B_{g\rightarrow 0}$ is stronger than in B. Precisely, the noise-floor sensed by $B_{g\to 0}$ is the strongest in comparison to the noise floor sensed in all other possible values of N in the 1:N design guideline. Even so, the noise floor sensed within $B_{g\to 0}$ is weaker than in the entire bandwidth B_w, since the minimum N is 2 and $B_{g\to 0} = B_w/2 < B_w$. Thus, imposing $N > 1$ implies in a gain in SNR. As discussed before, the minimum noise-floor improvement $\Delta\mathcal{N}_{g\to 0}$ resulting from adopting the 1:N design guideline instead of its 1:1 counterpart is $10\log(N)$. Therefore, letting $g \to 0$ in the Equation 4.15, the capacity limit $C_{g\to 0}$ results, as shown in Equation 4.16. The meaning in the highlighted terms are the same as in 4.15. The capacity limit is defined as the capacity in which the width of each narrow channel is maximum and the improvement in the noise floor in comparison to 1:1 FD MAC protocols is minimum, as one clearly see by comparing Equations 4.10 and 4.17.

$$C_{g\to 0} = \lim_{g\to 0} C_{Bfd} \tag{4.16}$$

$$\begin{aligned}
C_{g\to 0} &= \lim_{g\to 0}\left\{2\left[\left(\frac{B_w \underline{-(N-1)g}}{N}\right)\log_2\left(1 + 10^{\left(S\underline{+10\log(N)}-\left(-174+10\log\left(B_w\underline{-(N-1)g}\right)\right)-RSI\right)_{dB}/10}\right)\right]\right\} \\
&= 2\left[\left(\frac{B_w}{N}\right)\log_2\left(1 + 10^{\left(S\underline{+10\log(N)}-(-174+10\log(B_w))-RSI\right)_{dB}/10}\right)\right] \\
&= 2\left[\left(\frac{B_w}{N}\right)\log_2\left(1 + 10^{\left(S\underline{+10\log(N)}-\mathcal{N}_{hd}-RSI\right)_{dB}/10}\right)\right] \\
&= 2\left[\left(\frac{B_w}{N}\right)\log_2\left(1 + 10^{\left(S-\mathcal{N}_{hd}-RSI\underline{+10\log(N)}\right)_{dB}/10}\right)\right]
\end{aligned}$$

$$C_{g\to 0} = 2\left[\left(\frac{B_w}{N}\right)\log_2\left(1 + 10^{\left(SNR_{dB}-RSI\underline{+10\log(N)}\right)_{dB}/10}\right)\right] \tag{4.17}$$

If one assumes B_w as in-band – as in 1:1 MAC design guideline – than it is possible to perform bidirectional transmissions under a the assumption of an additional noise measuring RSI. Whether all sub-carriers within B_w means a single MAC data frame or multiple independent MAC data frames is a decision of the client of the bandwidth B_w. The client in this case is the MAC protocol. Thus, from the perspective of a MAC protocol under the 1:N design, there exists N independent bidirectional transmissions. However, from the perspective of the physical FD bandwidth, there exist only a bidirectional transmission. Thus, under the assumption of an in-band Full Duplex bandwidth measuring B_w and that the guard-band g is enough wide to turn level of leakage (between adjacent channels) as weak as the noise-floor, the overall capacity upper-bound the 1:N design guideline can deliver to the MAC layer is given by the Equation 4.18.

$$C_{fdN} = NC_{Bfd} \tag{4.18}$$

Support for ODSA

The set of channels 1:N exposes to the MAC layer enable the overall bandwidth to be accessed on demand. As in the IEEE 802.11 ODSA algorithm, the largest amount of spectrum accessed by a 1:N MAC protocol depends on the widest allowed bandwidth B_w (as already illustrated in the Table 4.1). The number of channels a node contend to, varies according to its demands. Also, the way channels are allocated to supply node's demands is left to the MAC protocol designer. Upon winning a contention, a node can access the channels instantaneously, sequentially, etc.

4.2.4 How Does this Proposal Relate to Prior Works?

The idea of splitting the wireless bandwidth of a network into narrower orthogonal channel is not new. In fact, the present work builds on the contributions and lessons learned from prior works that investigate the design and/or the performance of narrow-channels in WLANs [Fang et al., 2013], [Krishna et al., 2012], [Hong et al., 2012], [Arslan et al., 2012], [Arslan et al., 2010], [Tan et al., 2010], [Chandra et al., 2008]. Even an off-the-shelf half-duplex radio can serve as base to implement multiple orthogonal channels[1], as is the case of the design proposed by [Tan et al., 2010], [Fang et al., 2013]. Roughly speaking, these solutions are feasible because an IEEE 802.11 "channel" is nothing but a set of frequency sub-carriers that can be partially allocated to different nodes in a network. Nonetheless, the half duplex constraint limits the possible mix of concurrent transmission/reception achieved in such kind of design. In other words, proposals under the half duplex constraint can manage to either transmit or receive (not both) over orthogonal channels.

As already cited in this work, [Hong et al., 2012] and [Krishna et al., 2012] rely on approaches reminiscent to the out-of-band radio technology to enable a single radio to implement narrow orthogonal channels in a half-duplex bandwidth. Thus, although each narrow channel can send or receive independently from each other, they operate under the half-duplex constraint. [Krishna et al., 2012] remark that, under the in-band FD feature, each narrow channel can operate concurrently in the FD mode. However, to the best of the author's knowledge, no prior work investigates the performance of concurrent narrow channels under the IBFD assumption, specially considering the FD gain scalability at the MAC layer. As already mentioned, this work identifies a designing trend based on which current FD MAC protocols see the FD as 'a whole'. In this trend, the lack of spatial reuse resulting from the increased interference range of a dual link plays against the FD gain scalability [Xie and Zhang, 2014a] In order to fill such gap, the present work relies on the recent advances in both fields of in-band FD [Bharadia et al., 2013], [Korpi et al., 2016b], [Korpi et al., 2016a] and out-of-band

[1]A IEEE 802.11n/ac half-duplex radio also can transmit/receive up to two and four simultaneous handshake frames, respectively [Gast, 2013].

FD [Krishna et al., 2012] to propose and study a novel category of FD MAC protocols based on concurrent narrow orthogonal FD channels.

4.3 Case Study of 1:N FD MAC Protocols

This section presents two case studies to illustrate how an FD MAC protocol can operate under the 1:N FD MAC design guideline. The case study presented in subsection 4.3.1, consists in adapting the MAC protocol proposed by [Jain et al., 2011] to the 1:N FD MAC design guideline. The original MAC protocol and its adapted version are labeled as 1:1 Full-Duplex Busy Tone (FDBT) and 1:N FDBT, respectively. The resulting 1:N FDBT design exemplifies an ODSA strategy in which the node that wins a contention access all narrow channels simultaneously with N concurrent transmissions.

The case study presented in subsection 4.3.2 proposes an alternative ODSA strategy in which the winning node performs a sequence of transmissions across the N narrow channels. The resulting MAC protocol is termed Piece-by-Piece Enhanced Distributed Channel Access (PbP-EDCA) [Queiroz and Hexsel, 2015], a mnemonic to the ODSA strategy it employs and the back-off settings of the standard IEEE 802.11 EDCA (as previously shown in Table 2.1).

4.3.1 Case Study 1: The FD Busy Tone MAC Protocol

The 1:1 FDBT protocol is a random access MAC based on the symmetric dual-link mechanism proposed by the Contraflow FD MAC protocol [Singh et al., 2011]. Thus 1:1 FDBT handles only symmetric dual-links. From a practical perspective, 1:1 FDBT may not be the best starting point to compare with 1:N because it misses all opportunities for the establishment of asymmetric dual-links. However, 1:1 FDBT is a reference for performance evaluation studies because its best-case overhead to achieve a dual-link is nearly close to the overhead of an ‘ideal’ FD CSMA/CA MAC protocol, as described by [Xie and Zhang, 2014a]. According to the authors, an ‘oracle’ can lead CSMA/CA to always establish a dual-link just after finishing the back-off procedure, *adding no extra overhead to double the number of transmissions* per contention round. To nearly represent such condition with 1:1 FDBT, one has to assume the AP always has a cached data frame addressed to the winning STA, as [Jain et al., 2011] remark. Under this assumption, author claim that 1:1 FDBT can establish a dual-link between the STA and the AP by adding a constant time overhead of 75μs to the overall CSMA/CA back-off procedure. This extra overhead comprises the overall time the AP needs to process the STA’s incoming header, fetching and start sending a data frame to the STA. Therefore, the performance of 1:1 FDBT is chosen as reference for the upper-bound throughput study of this work.

Fig. 4.4 presents the worst and best cases attainable with the FDBT MAC protocol. An arbitrary STA starts a primary transmission to the AP at the time t_0 after winning a CSMA/CA contention. The STA also starts a ‘PT timer’ during which it will wait for a signal from the

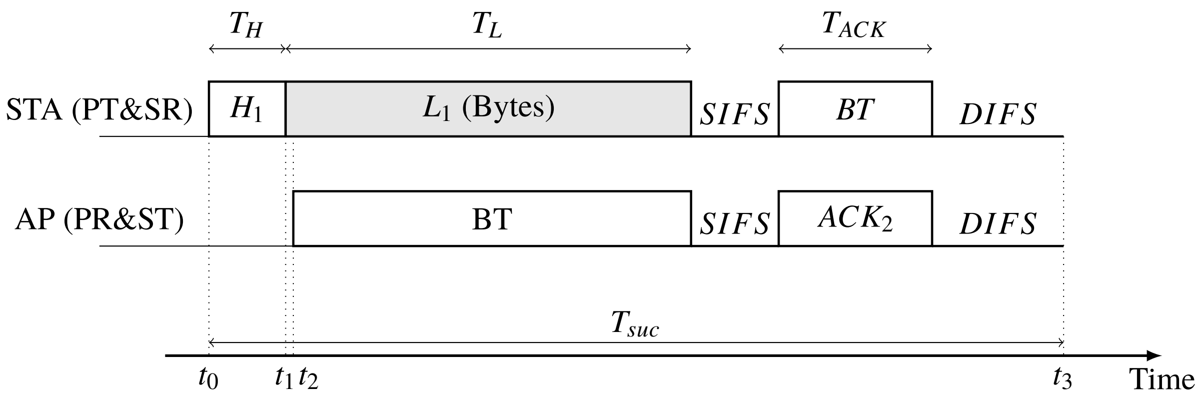
AP. Upon receiving and processing H_1, the AP checks whether there is an enqueued data frame addressed to the PT. In the worst-case (Fig. 4.4a), such frame is absent and the AP starts sending a Busy Tone (BT) (at time t_2) to avoid hidden node collisions while receiving the PT's frame. If the STA's PT timer expires before it detects a signal from the AP, the STA assumes a collision and handles it following the CSMA/CA procedure. In turn, the PT STA starts sending a BT to protect the ACK frame from collisions as well. In the best-case (Fig. 4.4b), the AP has an enqueued data frame addressed to the STA. Then it fetches the data frame and starts a secondary transmission at time t_2. In the best-case, the FDBT MAC protocol profits from a FD gain inversely proportional to Δ_t, the time interval between the start time of both transmissions. In Fig. 4.4b, Δ_t corresponds to $t_2 - t_0 > 0$. Note, however, that FD becomes profitable only at t_3, the time at which useful data starts being transferred. The BTFD protocol always ensures both transmissions finish simultaneously to protect collisions from hidden nodes [Singh et al., 2011]. Then the maximum secondary payload L_2 (bytes) for the capacity upper-bound is dimensioned accordingly. This process is based on the data frame size information carried in the header of the STA's frame. The other parameters on the Figs. 4.4 are helpful for the capacity model we return to these in section 4.4.

In the present work, the original FDBT MAC protocol is classified as 1:1 since it always transmits data frames across the whole available bandwidth. A possible way of adapting it to 1:N consists in replacing the single transmission to $N>1$ narrow-channel transmissions keeping the CSMA/CA operation unchanged. This way, a node performs *up to N* simultaneous transmissions instead of a single wide transmission.

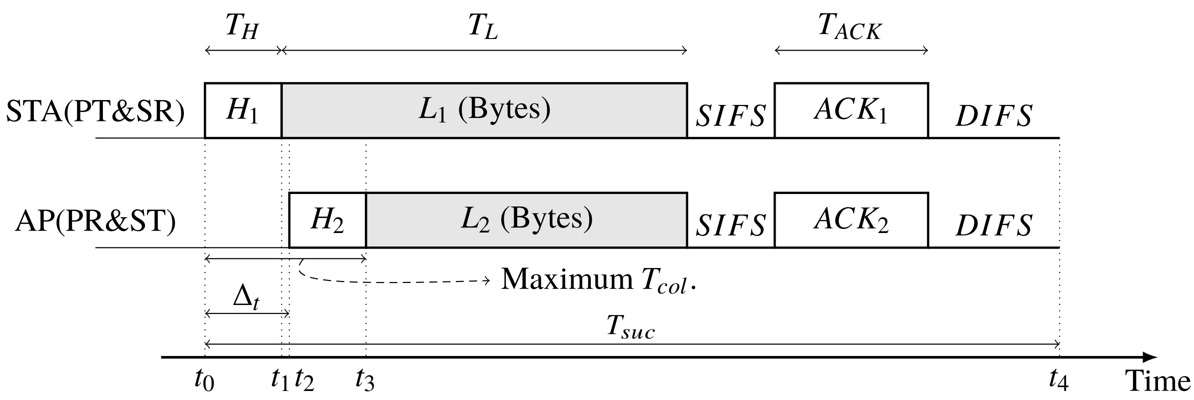
4.3.2 Case Study 2: The Piece by Piece EDCA MAC Protocol

With PbP-EDCA, a winning node performs a *sequence* of narrow-channel transmissions instead of accessing all bandwidth at once. PbP-EDCA can operate in accordance with CSMA/CA as well as the EDCA channel access timing parameters. The flowchart in Figure 4.5 presents a general guideline to implement PbP-EDCA from the standard transmission procedure (Tx) of IEEE 802.11. The establishment of dual-links with FD busy tone replies operates just as in the FDBT protocol described in section 4.3.1. For the sake of readability, we omit the steps regarding 1:1 FDBT in the flowchart.

In PbP-EDCA, one among the N available channels must be set as the Primary channel P_c. Following the terminology of the IEEE 802.11 standard ODSA algorithm, P_c is where the CSMA/CA contention happens and the other channels are called secondary channels. Nodes of a given cell must be set to the same P_c. The winning contender must not access the widest available bandwidth B_w at once even if it is detected as idle by the carrier sense mechanism of CSMA/CA. Instead, upon winning a contention in P_c (c=0), the winner STA S_1 sends its data frame to the AP, and also requests another contention-free transmission by asserting the *Channel Negotiation Bit* (CNB). If S_1's queue does not empty after it dequeues an MSDU (say a_1) to be



(a) Worst-case: FD employed to send a Busy Tone (BT).



(b) Best-case: FD employed to send another data frame.

Figure 4.4: Establishment of a symmetric dual-link by the FDBT MAC protocol. At time t_2, the AP (ST) starts sending a signal to the STA (SR) upon receiving and processing the primary transmission header (during $[t_0,t_2]$). In the worst-case (4.4a), it is a busy tone. In the best-case (4.4b), the signal is a data frame.

sent through P_c, S_1 sets CNB in a_1 to manifest its intention to transmit another frame after a_1, in the next secondary channel.

After processing a_1, the AP sets CNB in its ACK frame to indicate whether it acknowledges or rejects the extra transmission request from S_1. After sending the ACK back to S_1 with CNB set to 1 through P_c, the AP *waits* for another data frame from S_1 in the channel $c = 1$ during time interval T_α. This releases the AP A to keep working the primary channel to start receiving frames from other STAs. Note that this strategy is not feasible under the half-duplex assumption. In fact, with PbP-EDCA, the AP can establish another dual-link transmission in P_c concurrently with other dual-links in the secondary channel.

Once S_1 processes the ACK from the AP, it sends another data frame on the first secondary channel (c=1), but employs its FD capabilities to enable other incoming transmissions in P_c. The STA S_1 asserts the channel c=1 is idle during the time interval $T_\beta < T_\alpha$ before transmission. The parameter T_β is needed to avoid collision with third-party entities operating on the same frequency band, and may be set to $DIFS$.

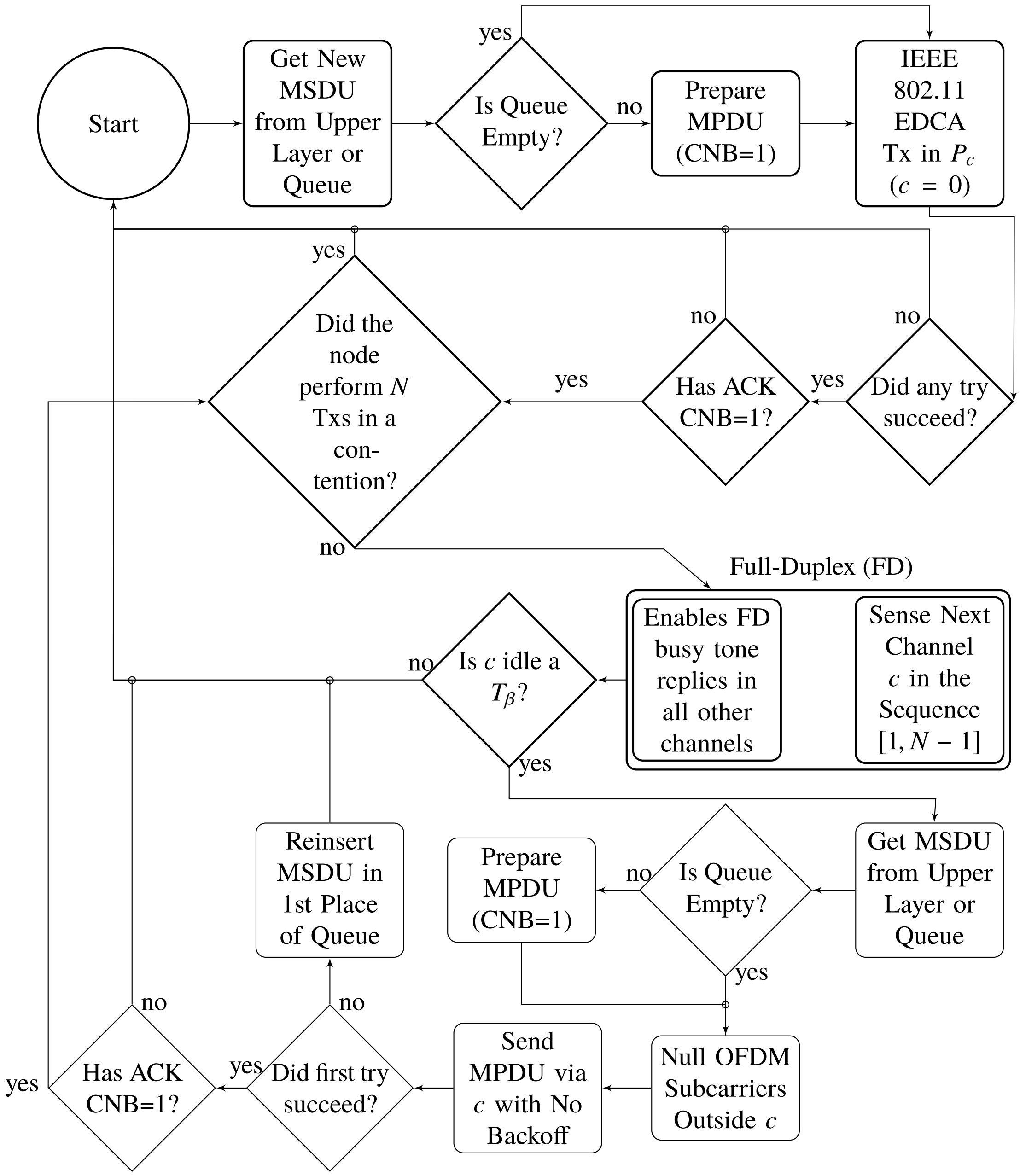


Figure 4.5: PbP-EDCA transmission procedure (Tx) from the standard IEEE 802.11 EDCA.

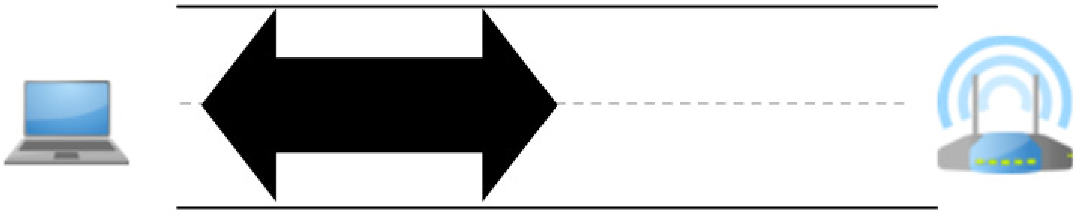
In general terms, a data transmission ongoing in the narrow channel number c can serve as base to negotiate another data transmission in the channel $c + 1$. Since the maximum number of transmissions of a winning STA is N, the AP always set the CNB bit to 0 in the ACK sent through the last channel. Based on this process, a node can perform up to N narrow transmissions after winning a single contention in the primary channel. If a secondary channel transmission encounters a failure, such as a time limit expiration or transmission error, PbP-EDCA re-enqueues the victim frame and restarts normal CSMA/CA contention in P_c.

4.3.3 Comparative Analysis of the MAC Protocols

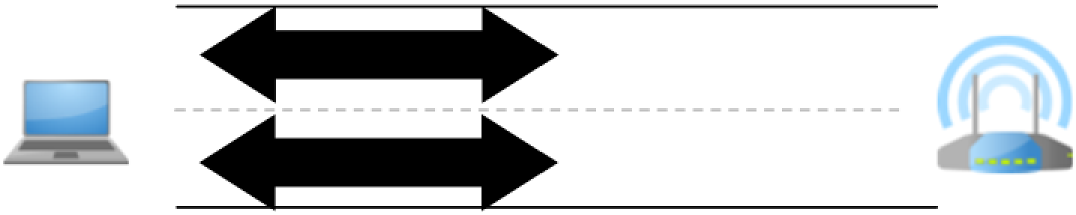
Both the 1:N FDBT and the PbP-EDCA relies on CSMA/CA to handle contention among nodes. The main difference refers to their respective ODSA strategies over the 1:N channel arrangement. The Figure 4.6 illustrates each ODSA strategy in comparison to the ODSA algorithm adopted by the IEEE 802.11n/ac standards. It is shown how each ODSA strategy works just after the STA (left-hand side) finishes the back-off process to send a data frame to the AP (right-hand side). In all cases, it is assumed the AP can create a symmetric dual-link to the STA just after receiving the STA's frame header. Also, it is considered an arbitrary FD channel arranged into two narrower orthogonal channels. In the case of the standard IEEE 802.11 ODSA algorithm (Figure 4.6a), both narrower channels are bonded into a wider one, following the 1:1 approach. This results in a wide bandwidth dual-link illustrated by means of a bidirectional black arrow. Note that this example consists in the best-case for the standard ODSA algorithm. Such best-case happens when no third-party source operates in the secondary channels of the bandwidth. Under such assumption, the ODSA algorithm always performs transmissions as wide as the entire available bandwidth, be it 20 MHz, 40 MHz or 80 MHz.

The 1:N FDBT ODSA strategy occupies the entire bandwidth (Figure 4.6b) as the standard ODSA does, but the 1:N design guideline forces the 1:N FDBT to transmit over narrow channels. In the example, two narrow-width symmetric dual-links are formed instead of a wide one. The 1:N FDBT can not improve over the spatial reuse factor of of the standard IEEE 802.11 ODSA algorithm because it also allocates the entire bandwidth in each contention round. However, the expected increase in the SNR (as shown by Equation 4.9), may enable higher data rates, which might increase throughput.

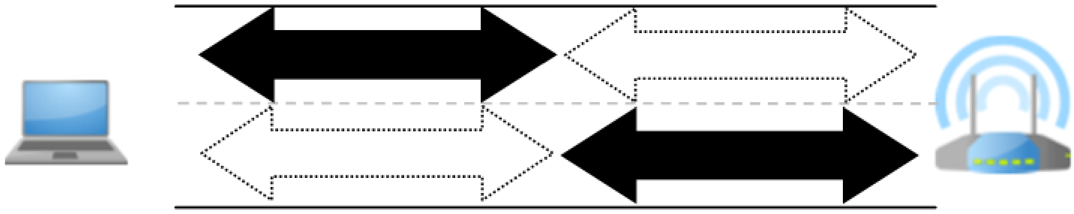
With PbP-EDCA (Figure 4.6c), the ODSA algorithm follow a novel approach in which the winning node *never* gets access to the entire available bandwidth, even if the bandwidth is idle when the node is granted access. In this case, the node's demands is supplied by means of a sequence of narrow-width transmissions, up to N. While a node establishes a dual-link through a channel, other node can do the same in other different channel. The transmissions of the winning node are shown as black bidirectional arrows in Figure 4.6c. Note they do not happen simultaneously in the bandwidth. The extra transmissions that may happen simultaneously to the ongoing transmission are shown through white bidirectional arrows in the Figure. On one hand,



(a) Standard IEEE 802.11 ODSA (FD assumed).



(b) 1:N FDBT ODSA.



(c) 1:N PbP-EDCA ODSA. Other STA may occupy the idle channel.

Figure 4.6: On-demand Spectrum Allocation (ODSA) strategies in different MAC protocols *after* a node wins a CSMA/CA contention.

the PbP-EDCA ODSA strategy can benefit from an improved spatial reuse factor in comparison to both the 1:*N* FDBT and the standard ODSA algorithm. On the other hand, such a increase in concurrency penalizes the total time a particular node takes to get access to the entire bandwidth.

Note that all MAC protocols presented in this section do not handles asymmetric dual-links, as assumed in some prior works [Duarte et al., 2014],[Jain et al., 2011]. For the throughput scalability study proposed in the present work, considering the worst and best cases for each MAC protocol suffice to understand their respective lower and upper performance boundaries. The 'worst-case' and 'best-case' designate whether each MAC protocol transmit in half- or full-duplex modes after winning a CSMA/CA contention, respectively.

4.4 Assessing Throughput Scalability of 1:N FD MAC Protocols

This section explains how to predict the saturation capacity for the FDBT and the PbP-EDCA MAC protocols from the Bianchi model.

4.4.1 FDBT MAC Protocol Saturation Capacity

The FDBT MAC protocol behaves just like the standard IEEE 802.11 MAC in the worst-case. They differ only with respect to the length of a collision and the extra payload L_2 FDBT handles in its best-case. Therefore, predicting FDBT's capacity with the Eq. 2.22 of the Bianchi model is just a matter of computing these values, as we explain in the next paragraphs.

Payload of a successful FD dual-link transmission

To compute the FDBT payload in the best-case we recall that a half-duplex transmission corresponds to an FD primary transmission. Therefore, let H_1 and L_1 correspond to the PHY-MAC headers and payload sizes of a primary transmission, respectively. Similarly, H_2 and L_2 have equivalent meaning for a secondary transmission as illustrated on Figs. 4.4. Also, let T_H and T_L be the time taken to transmit H_1 (or H_2) and L_1 under given control and data rates, respectively.

The total payload FDBT carries in a successful channel event depends on whether it benefits from an extra data frame transmission. In the worst-case (Eq. 4.19a), a BT is employed (as illustrated on Fig. 4.4a), so no payload is added to the channel event beyond the PT's one. Note this corresponds to the same performance achieved by the IEEE 802.11 MAC protocol as we discussed in section 2.3.2. In the worst-case, the total payload carried by the 1:N FDBT MAC protocol is calculated according to the Eq. 4.19b. In the best-case for FD (Eq. 4.19c), FDBT always benefits from two data frame transmissions (as illustrated in Fig. 4.4b). The total payload is computed by Eq. 4.19d for the 1:N FDBT MAC protocol. As previously mentioned, the gains and losses an increasing N causes on the capacity of bandwidth B_w is matter of investigation of the present work.

$$E[L] = \begin{cases} L_1 & \text{IEEE 802.11 or FDBT worst-case} \quad (4.19a) \\ L_1 N & 1{:}N \text{ FDBT worst-case} \quad (4.19b) \\ L_1 + L_2 & \text{FDBT best-case} \quad (4.19c) \\ (L_1 + L_2)N & 1{:}N \text{ FDBT best-case} \quad (4.19d) \end{cases}$$

As in the Bianchi model, the transmission triggered by the CSMA/CA counter is set to a fixed payload L_1. We calculate the amount of bytes due to the secondary payload L_2 with Eq. 4.20.

$$L_2 = L_1 - f_L(\Delta_t + H_2) \quad (4.20)$$

In Eq. 4.20, $f_L(t)$ gives the amount of payload (in Bytes) the ST's can transmit during the time interval t under a given data rate. In our case, this comprises the time to fetch and transmit H_2 which is $[t_1, t_3]$ as shown Fig. 4.4b.

Duration of a collision

In the FDBT MAC protocol, the duration T_{col} of a collision depends on the time elapsed until the protocol detects the collision. The PT starts a timer just after pushing the last symbol header into the channel. If no signal is detected from the PR before the timer expires, the PT interrupts the transmission and assumes a collision. If the PT detects an incoming header, it finishes the reception to check whether the header comes from the ST. In case of a collision, the received header is unintelligible or is not the expected one. Only after this process, the PT interrupts its transmission. Hence, in the worst-case, the duration of a collision for the FDBT MAC protocol must account the transmission of two headers (with their respective propagation delays δ) plus Δ_t (Eq. 4.21c). Therefore, Equation 2.21 rewrites as Eq. 4.21 to also consider the case of FDBT. As mentioned in subsection 4.2.2, the channel width reduction causes the MAC and PHY layer parameters to increase. Such overhead shall be considered when 1:N MAC protocols take place.

$$T_{col} = \begin{cases} T_H + T_L + \delta + DIFS & \text{2-way handshake} \quad (4.21a) \\ T_{RTS} + \delta + DIFS & \text{4-way handshake} \quad (4.21b) \\ 2(T_H + \delta) + \Delta_t & \text{FDBT} \quad (4.21c) \end{cases}$$

Among the values in Eq. 4.21c, only Δ_t depends on technological and implementation issues. Particularly, [Singh et al., 2011] and [Jain et al., 2011] claim to achieve a Δ_t of 1μs and 11μs for IEEE 802.11 and IEEE 802.15 networks, respectively.

4.4.2 Markovian Analysis of the PbP-EDCA Node

The PbP-EDCA MAC protocol manages the primary narrow channel P_c according to CSMA/CA. Thus, the Bianchi model can predict the performance PbP-EDCA achieves in P_c. However, the probability τ_c that a STA gains access to secondary channel c is different (though dependent) of the probability that it transmits in P_c. To calculate the transmission probability τ_c for secondary channels of PbP-EDCA, the current work enhances the Markov model presented in [Bianchi, 2000].

The Bianchi model calculates the probability τ that a STA transmits in a CSMA/CA-based network. In PbP-EDCA, the probability that a STA transmits in the channel c is denoted as τ_c. Since PbP-EDCA is based on 1:N, there must exist N channels within the bandwidth. These channels are numbered from zero until $N - 1$. Therefore, $c \in [0, N - 1]$ where the primary channel P_c is designated by $c = 0$ and the secondary channels falls in the interval $[1, N - 1]$. Since PbP-EDCA nodes contend in the primary channel following CSMA/CA, the probability τ_0 that a node transmits in the primary channel is equal to the probability τ that CSMA/CA STA transmits in a IEEE 802.11 WLAN (Equation 4.22.

$$\tau_0 = \tau \tag{4.22}$$

To assess the maximum capacity of PbP-EDCA, one must take the same assumptions of the Bianchi model, namely, saturated traffic conditions and no propagation loss. In the model, packet losses are only due to the MAC protocol. Particularly, the Bianchi model calculates the probability p that a *transmitted* packet collides in a n-node network according to the Equation 4.23. The Equation stems from the fact that a single STA is 'silent' (waiting in the back-off procedure) with probability $(1 - \tau_0)$. The fundamental condition for a successful transmission is that all other $n - 1$ STAs are simultaneously. This happens with probability $(1 - \tau_0)^{(n-1)}$. If the condition *is not* met, more than one STA transmits, leading to collision in the channel.

$$p = 1 - (1 - \tau_0)^{(n-1)} \tag{4.23}$$

Under saturation conditions, the winning STA always set the CNB bit to schedule a transmission in the next narrow channel c in the sequence $1, 2, \cdots, N - 1$. The transmission in the first secondary channel is subject to a successful transmission in the primary channel. Since a PbP-EDCA STA transmits with probability τ_0 and a successful transmissions means it does not collides i.e., $(1 - p)$, a PbP-EDCA STA transmits in the secondary channel $c = 1$ with probability τ_1, as given by the Equation 4.24.

$$\tau_1 = (1 - p)\tau_0 \tag{4.24}$$

To predict the saturation throughput upper-bound of PbP-EDCA, one has to assume that the STA is granted access to all secondary channels. In other words, if a node does win a CSMA/CA contention and does not collide in the primary channel, then it should be granted access to all other (secondary) channel $c \in [1, N - 1]$. Thus, the probability τ_c that a node successfully transmit in an arbitrary secondary channel $c \in [1, N - 1]$ is conditioned to a successful transmission in the primary channel, yielding the Equation 4.25.

$$\tau_c = (1 - p)\tau_0,\ c \in [1, N - 1] \tag{4.25}$$

With probabilities τ_0, p and τ_c one can calculate the saturation throughput achieved in primary and secondary channels by referring to the Bianchi Capacity formula explained in the Section 2.3.2. Recall that all IEEE 802.11 timing parameters present in that formula rescales according to the assumed channel width, as discussed in subsection . Finally, for a detailed discussion about probabilities of the PbP-EDCA Markovian model, please consult the model presented in the Appendix A.

4.5 Summary of the Chapter

This chapter presented 1:N, an alternative proposal for the 1:1 FD MAC design guideline. The novel guideline forces MAC protocols to “see” the available Full Duplex (FD) bandwidth through $N > 1$ equally-spaced orthogonal FD PHY layers. The presented proposal was analyzed with respect to its key overheads and expected advantages. The key identified overheads are the spectrum spent with guard-bands and the slowed timing MAC-PHY parameters resulting from channel width reduction. With N narrow channels, the total spectrum overhead is $(N-1)g$ (Hz), where g is the guard-band needed to separate a pair of adjacent channels. It was verified that a counter-measure to keep g low consists in relying on some kind of Out-of-Band FD technology such as [Krishna et al., 2012], which reports $g = 100$ KHz. Among the identified expected advantages are the support for the On-Demand Spectrum Allocation (ODSA), the increased spatial reuse factor and noise floor reduction within each particular narrower channel. Particularly, it was verified that protocols under the 1:N design guideline can benefit from spatial reuse factor of N in comparison to protocols under the 1:1 design guideline. Also, the minimum gain in the Signal-to-Noise ratio experienced within each narrow channel is $10\log(N)$. The chapter also described and compared two random access protocols under 1:N, namely, 1:N FDBT and PbP-EDCA. Both rely on CSMA/CA and differ only with respect to the ODSA strategy employed by the node that wins a contention With 1:N FDBT all narrow channels are accessed instantaneously while with PbP-EDCA they are accessed sequentially. Finally, the chapter discuss analytical models to predict the saturation capacity of the discussed 1:N FD MAC protocols.

Chapter 5

Results

This Chapter presents saturation throughput results for 1:N FD MAC protocols, namely, PbP-EDCA and 1:N FDBT. For comparison purposes, we also present saturation throughput for the 2-way and 4-way IEEE 802.11 half-duplex standard and the 1:1 FDBT MAC protocol [Jain et al., 2011]. The performance comparison of the protocols are detailed in section 5.1. Section 5.2 evaluates the bandwidth capacity of each MAC design guideline across different parameters. Also, it is presented a software defined radio study to validate the theoretical model proposed for the 1:N design guideline.

5.1 Performance of FD MAC protocols

5.1.1 Scenarios and Methodology Review

Common network parameters

For the saturation throughput experiments reported in this section all MAC and PHY timing parameters are set according to the IEEE 802.11a standard. The standard ODSA algorithm is set to a bandwidth measuring B_w = 20 MHz, meaning the primary and secondary channels measures about 10 MHz. Hence, for 1:N MAC protocols N is set to 2. It is assumed that each station that wins a CSMA/CA contention can benefit from the entire bandwidth of 20 MHz following the ODSA strategy of each MAC protocol. It translates into a single 20 MHz transmission for both the IEEE 802.11 MAC protocols and the 1:1 FDBT MAC protocol and two 10 MHz transmissions for the 1:N MAC protocols. In the case of 1:N FDBT, both transmissions are simultaneous. While for the PbP-EDCA the transmissions are performed sequentially, as discussed in the Section 4.3.3 (Figure.4.6). In the best case of all FD MAC protocols, successful transmission lead to dual-links, doubling the number of sent data frames.

Also, it is assumed that 1:N MAC protocols pay an additional guard-band overhead of 100 KHz to separate the narrow channels. This means that 1:N FD MAC protocols assumes Out-of-band FD radio such as the one shown in [Krishna et al., 2012]. Thus, the total required

Table 5.1: Common Parameter Values Set for Both IEEE 802.11 and PbP-EDCA.

Data Frame Payload L_1 (for Half-duplex of FD primary transmission)	536 bytes
Data Frame Payload L_2 (for FD secondary transmission)	refer to Eq. 4.20
MAC Header	224 bits
ACK Length	112 bits
Minimum Contention Window Size W	16 slots
Number of Backoff Stages m	6
Control Frame Modulation Scheme	BPSK 1/2
Time slot (σ)	$9\mu s$
SIFS	$16\mu s$
DIFS	$34\mu s$
Full-Duplex Bandwidth B_w	20 MHz
Number of Narrow Orthogonal Channels for 1:N Protocols	2
Handshake	2-way
Propagation Delay δ	1 μs

bandwidth is 20.1 MHz. Section 5.2 studies the impact of allocating the guard-band overhead within the bandwidth $B_w = 20$ MHz as well as the impact of larger N on the total bandwidth capacity under the 1:N design guideline. The common parameters for all scenarios in this section are shown in Table 5.1. The MAC and PHY timing parameters in the Table 5.1 are shown with respect to a 20 MHz channel. Recall that those IEEE 802.11 parameters doubles when channel width halves [IEEE, 2012]. The exception for this rule is the time slot σ, as previously shown in Table 4.4.2.

The Appendix C provides the reader with scripts and instructions to facilitate the reproduction of all results reported in this section.

Variable Parameters and Full Duplex

The payload size L_1 of the MAC Service Data Unit (MSDU) plays a fundamental role for the saturation throughput of CSMA/CA based protocols because it may determine the duration of a collision and the useful transferred payload [Bianchi, 2000]. In preliminary tests of this work (reported in Section B.1 of the Appendix B), it was verified that larger L_1 strongly penalizes the IEEE 802.11 2-way protocol. At the same time, increasing L_1 causes L_2 to increase too. Since L_2 is present only in FD MAC protocols, larger L_1 is clearly expected to favor only FD MAC protocols. For this reason, the results discussed in this section refers to a MSDU payload of L_1 of 536 bytes (of which 36 bytes account for headers before the MAC layer, namely, 8 bytes for the UDP header, 20 bytes for the IP header and 8 bytes for the Logical Link Control).

Table 5.2: Highest data rate supported across different bandwidths for a given RSSI.

Bandwidth	**Assumed RSSI (Mnemonic)**		
	-82 dBm ("Weak")	**-74 dBm ("Medium")**	**-65 dBm ("Strong")**
20 MHz	6 Mbps	24 Mbps	54 Mbps
10 MHz	6 Mbps	12 Mbps	27 Mbps

Note L_1 is equal for both half-duplex and FD primary transmissions. The amount L_2 of bytes transferred per FD secondary transmission depends on L_1 (Eq. 4.20). As explained in the Section 4.3, the FD MAC protocols dimension L_2 such that both primary and secondary transmissions finish simultaneously. The information L_1 is known just after the reception of the primary transmission header. The FDBT MAC protocol was chosen as a representative of the 1:1 FD MAC design guideline. This is because its best-case overhead to establish a dual-link is nearly close to zero, as discussed in Section 4.3.1. Then, 1:1 FDBT establishes a reference for throughput scalability studies.

For the scalability study, it is considered an increasing number $n > 0$ of stations (STA) served by the Access Point (AP) of an infrastructure WLAN. Only STAs play the role of primary transmitter upon winning a contention. With FD MAC protocols, the AP processes the primary transmission's header and starts a secondary transmission to the STA. We evaluate the FD MAC protocols considering two cases. In the worst-case, the AP's secondary transmission consists of a Busy-Tone (BT) which carries no useful payload. In the best-case that transmission consists of another data frame. These respective cases are depicted in the Figs. 4.4a and 4.4b.

In addition to the worst and best FD cases, the modulation scheme (data rate) is also a key parameter for MAC protocol performance. However, the RSSI a given modulation scheme requires for a successful demodulation also depends on channel width. Since the channel width is not the same among the protocols, modulation schemes are determined by considering different signal strengths per scenario. Particularly, the assumed RSSIs are shown in Table 5.2. These values are in accordance to the IEEE 802.11 standard [IEEE, 2012], as discussed in Subsection 4.2.3 (Table 4.3). For convenience of the reader, Section C.3 of Appendix C presents lookup algorithms that select the highest possible data rate for FD MAC protocols given the highest supported rate assumed for an IEEE 802.11 half-duplex MAC protocol.

Under the same conditions, the RSSI experienced by each side of an FD link might be weaker than the RSSI of a half-duplex receiver because of the Residual Self-Interference (RSI). For the present study it is assumed an RSI of 1 dB, as observed by [Bharadia et al., 2013] in bandwidths > 20 MHz. It is worthy to note that some work have claimed to reduce the RSI of a 20 MHz channel to the same level of the noise floor in different scenarios (indoor [Bharadia et al., 2013], outdoor [Korpi et al., 2016a], size-constrained devices [Korpi et al., 2016b]). These results were for the bandwidth of 20 MHz, enabling the setup of the present Section.

A summary of all parameters varied in this section to calculate MAC protocol saturation throughputs are shown in Table 5.3.

Table 5.3: Summary of all variated parameters to calculate network saturation throughput.

MAC Protocols		**Assumed RSSI**	**FD Cases**	***n***
Half Duplex	**Full Duplex**	– "Weak" (−82 dBm)	– "Worst":	10, 20,
– IEEE 802.11 with the 2-Way handshake	– 1:1 FDBT		data frame + busy-tone	
		– "Medium" (−74 dBm)		30, ...,150
	– 1:N FDBT		– "Best":	
– IEEE 802.11 with the 4-Way handshake		– "Strong" (−65 dBm)	data frame + data frame	
	– (1:N) PbP-EDCA			

Methodology to Calculate MAC Protocol Saturation Throughput

In order to estimate the scalability and the capacity upper-bound of each MAC protocol, we follow the methodology and assumptions of the Bianchi model [Bianchi, 2000]. We assume all nodes are within the transmission range of each other, present saturated traffic and transmit over an ideal channel in which frame losses result only from collisions the MAC protocol cannot manage to avoid. These assumptions ensure one estimates "the most each MAC protocol can do" when provided with the best conditions to reach the saturation throughput upper-bound. However, it is worthy to note that any FD MAC protocol under the 1:N design guideline might perform better in noisy environments paying an overhead of $(N-1)g$ (as verified in Section 4.2.3, Equation 4.9).

To calculate the saturation capacity S of a MAC protocol following the Bianchi model, recall that one needs to estimate the expected data frame payload $E[L]$ transferred in each successful transmission – which is calculated according to the Eq. 4.19, being L_1 and L_2 set according to the Table 5.1 – and the time duration of following network events: successful transmission T_{suc} (Eq. 2.20a), collision T_{col} (Eq. 4.21) and the idle slot time T_{idl} as defined by the IEEE 802.11 standard. The probabilities P_{suc} (Eq. 2.17), P_{col} (Eq. 2.18) and P_{idl} (Eq. 2.19) of these respective network events depend on the probability τ that STA transmits in the channel.

To calculate τ for all evaluated protocols (except PbP-EDCA) one has to solve the system of Eqs. 2.14 by means of numeric techniques. With similar procedure, one computes the probability of transmission in each PbP-EDCA secondary channel by solving the system of Eqs. (A.12). Finally, one can calculate the saturation throughput S for each MAC protocol according to the Eq. 2.22. To facilitate the reproduction of all saturation throughput results presented in this section, please refer to the Appendix C.

5.1.2 MAC Protocols Overheads

A key overhead in CSMA/CA-based MAC protocols is the data frame collision. Figure 5.1 plots the probability of collision of each considered MAC protocol over an increasing number of nodes. As expected, the IEEE 802.11 MAC protocols as well as both FDBT MAC protocols present the same probability of collision. This results from the fact those protocols employ the CSMA/CA contention mechanism exactly in the same way. They differ only with respect to either the handshake mechanism – RTS/CTS or Busy-Tones (BT) – or the ODSA strategy through which a winning node get access to the channel, as previously illustrated in the Figure 4.6. These differences cause each MAC protocol to experience different collision time, as shown in Table 5.4. As one can see in the Table, the time duration T_{col} of a collision is affected by the data rate each protocol can set given the RSSI conditions. The IEEE 802.11 2-way MAC protocol presents the largest collision time because it collides the entire data frame. Thus, if data rate improves, collision time improves accordingly. The IEEE 802.11 4-way collides an RTS control frame that is sent at a constant control rate of 6 Mbps [IEEE, 2012]. The 1:1 FDBT MAC only a portion of the primary transmitter payload is subject to collision. This portion comprises the frame header and a fraction of the data frame, as previously illustrated in Figure 4.4b (in the time interval t_1 and t_3). Hence, the time 1:1 FDBT experience in collision improves for higher data rates. Both the 1:N FD MAC protocols presented the worst collision time duration. The reason is that channel width reduction causes MAC and PHY timing parameter to double. In spite of that, PbP-EDCA can improve the collision probability in comparison to all other protocols. The reason is that its ODSA strategy leads winning STAs to access spectrum sequentially rather than instantaneously. Than, when a STA is in the secondary channel, the probability of collision slightly decreases in the primary channel. Note, however, this increases the time a particular STA gets to access the entire bandwidth after winning a contention.

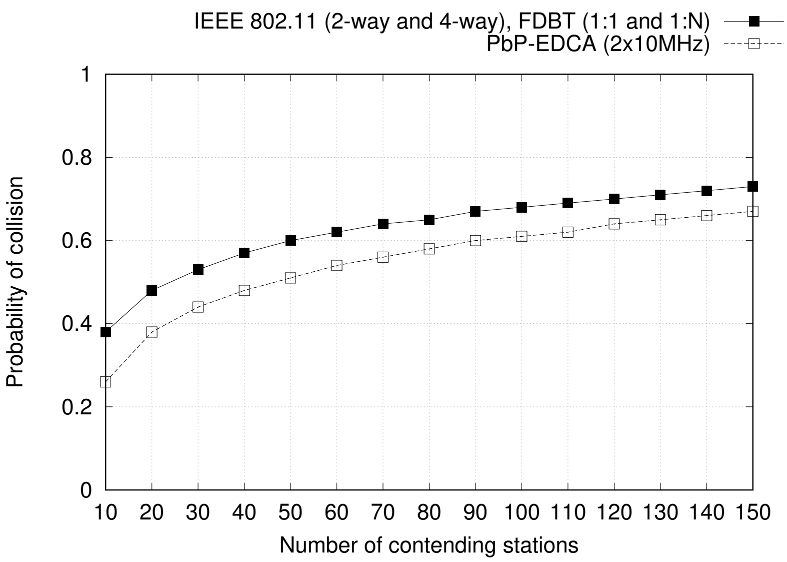


Figure 5.1: Probability of collision.

Table 5.4: Time duration (μs) of data frame collisions for each MAC protocol across different RSSI (data rates).

RSSI	2-way	4-way	1:1 FDBT	1:N MAC
‘Weak’	815	87	125	173
‘Medium’	251	87	77	141
‘Strong’	147	87	69	125

5.1.3 Saturation Throughput Results

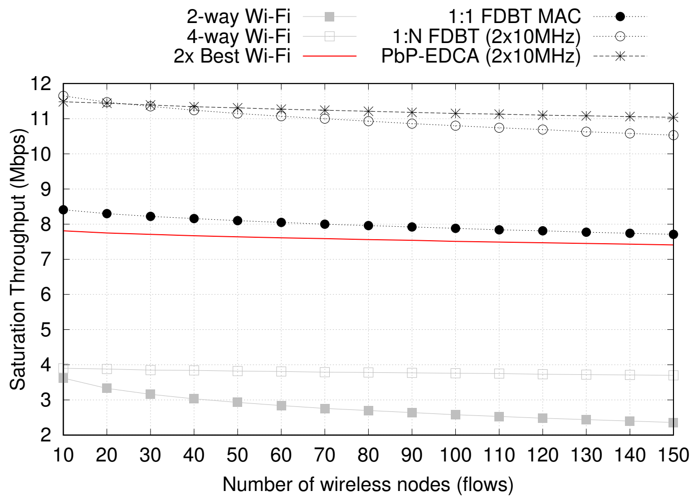
This section presents MAC saturation throughput results in Figures 5.3 and 5.2. In the Figures, results are grouped according to the "FD cases" parameter, namely, "worst" and "best" cases, respectively. In each group, is presented one Figure of results per assumed RSSI, namely, "Weak", "Medium" and "Strong". Each Figure plots one saturation throughput curve per MAC protocol over n STAs. Moreover, it is plotted a continuous non-dotted curve[1] labeled as "2× Best Wi-Fi" that corresponds to 2× the best IEEE 802.11 throughput. Such curve considers the largest out of the 2-way and 4-way throughput over the number of STAs.

On the FD Gain Scalability of FD MAC Protocols

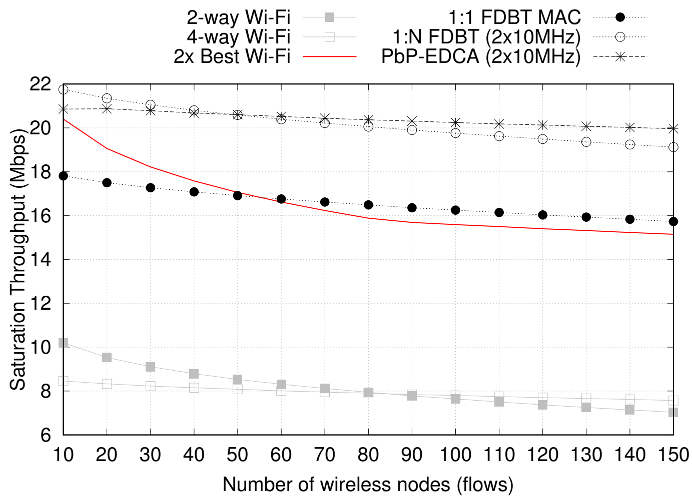
In the FD worst-case – when the secondary FD transmission is a Busy-Tone (BT) rather than a data frame – this prevents all FD MAC protocols to scale the double of throughput achieved by the half-duplex MAC protocols. In the case of the 1:1 FDBT MAC protocol, this happens because it operates on the same bandwidth of the half-duplex MAC protocols but has stronger noise because of RSI, so lower data rate. Thus, it can neither improve the number of simultaneous transmissions – because BT is not useful data – nor the total data rate of the channel. The reason why it outperforms the IEEE 802.11 MAC protocols is because not successful transmission is penalized with the RTS/CTS handshake, since the built-in BTs sent by the AP naturally protects the STAs transmission. Also, since BTs can be sent at the same rate of data frames, 1:1 FDBT improves its own collision time as data rates increases. These times are $125.00\mu s$, $77.00\mu s$ and $69.00\mu s$ when RSSI is "Weak", "Medium" and "Strong", respectively. This source of improvement is not enough to lead 1:1 FDBT to scale the FD gains in the worst-case.

In case of 1:N MAC protocols (worst-case), the increased noise-floor caused by the RSI is less damaging. Assuming the noise-floor spans uniformly across the bandwidth $B_w = 20$ MHz, each 10 MHz narrow channel sees only part of the increased noise. In Section 4.2.3 it was shown that such improvement is at least $10\log(N)$. Thus, the RSSI of -82 dBm of the "Weak" scenario relaxes by $10\log(2) \sim 3$ dB. Considering the 1 dB of RSI, 1:N MAC protocols can set a data rate of 4.5 Mbps in a 10 MHz channel. Also, paying an overhead of $g = 100$ KHz as previously discussed, 1:N MAC protocols can sustain one 4.5 Mbps per 10 MHz within the bandwidth $B_w = 20$ MHz. Thus, even in the FD worst-case scenario with the 'Weak' RSSI of -82 dBm, all 1:N MAC protocols can outperform the IEEE 802.11 MAC protocol in terms of both *number of simultaneous transmissions* – two against one – and *sum data rate* – 2×4.5 Mbps against 1×6 Mbps. In 'Medium' and 'Strong' scenarios, each channel of 1:N FD MAC protocols can sustain 12 Mbps and 27 Mbps, respectively. The number of simultaneous transmissions and sum data rate reveal more important than MAC overheads for saturation throughput performance. In fact, excepting the 2-way protocol, both the 1:N MAC protocols present the longest duration of collision T_{col} in all scenarios. Particularly in the 'Weak'-RSSI scenario, T_{col} is $173.00\mu s$ for 1:N

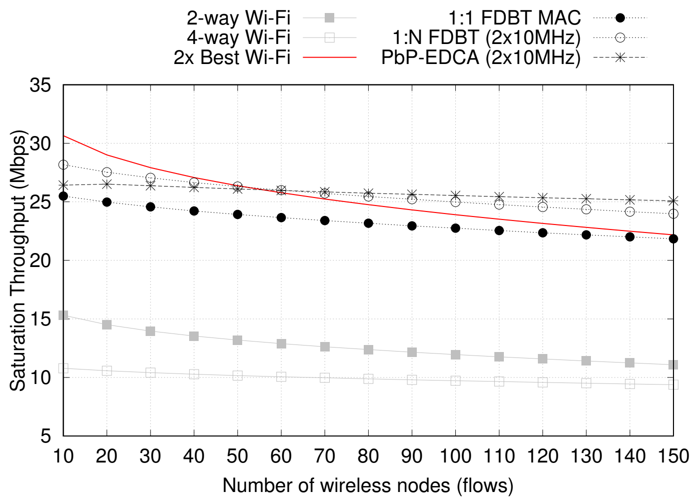
[1] in red for color prints.



(a) RSSI=−82 dBm (“Weak”)



(b) RSSI=−74 dBm (“Medium”)



(c) RSSI=−65 dBm (“Strong”).

Figure 5.2: Saturation throughput considering the ‘best-case’ for FD MAC protocols under residual self-interference.

MAC protocols and 815.00μs, 87.00μs and 125.00μs for the 2-way, 4-way and the 1:1 FDBT MAC protocols, respectively. Similarly to 1:1 FDBT, this value improves for 1:N MAC protocols as data rates get better. But not enough to avoid the penalization imposed by the channel width reduction.

The above rationale verifies for the other 'Medium' and 'Strong' scenarios in the 'FD worst-case' as well as in the 'FD best-case'. In other words: *it is more important to outperform the IEEE 802.11 MAC protocols in terms of simultaneous transmissions and sum data rate rather than in terms of contention overheads*. Although lower contention overheads may help to scale 2× the best half duplex throughput i.e., the 'FD gain'). In fact, in the 'FD best-case', all FD MAC protocols doubles their number of concurrent transmissions with respect to the 'FD Worst-case' scenario. This reason, along with the improvement of the MAC overheads, causes the 1:1 FDBT MAC protocol to scale the FD gains for larger n. As already said, it can improve T_{col}. Also, it does not penalize successful transmissions with RTS/CTS overhead. By its turn, the 1:N FD MAC protocols keep the same previously explained advantages and drawbacks unless by the fact they can 4× more simultaneous transmission in comparison to the IEEE 802.11 MAC protocol and 2× in comparison to 1:1 FDBT.

5.2 Capacity Upper-Bound of FD MAC Design Guidelines

The MAC protocol performance study presented in section 5.1 suggests that *the capacity upper-bound of an arbitrary* 1:1 *FD MAC protocol can improve if it can be adapted to operate under the* 1:N *design guideline*. To check whether that assertion is valid, this Section proposes an analytical study in subsection 5.2.1 and a proof-of-concept software-defined radio experiment in subsection 5.2.5.

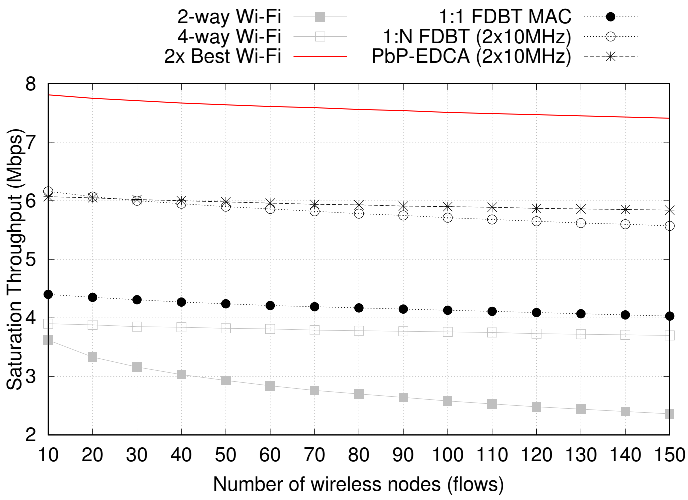
5.2.1 Theoretical Capacity Upper-Bound

All results reported in this Subsection are based on the bandwidth capacity formula developed in Section 4.2.3.

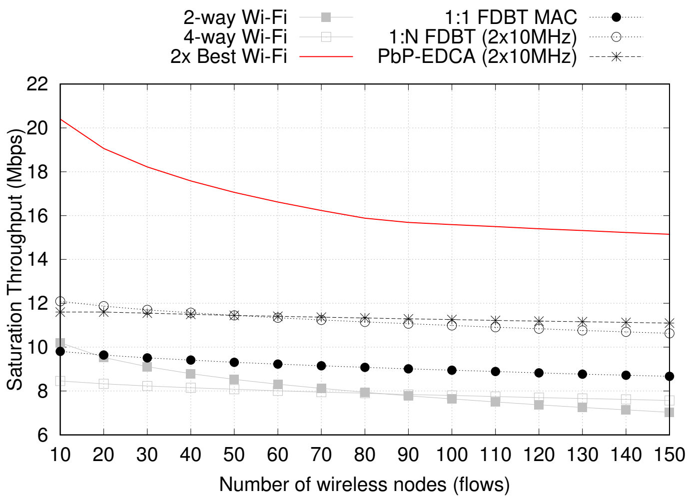
Novel Bandwidth Upper-bound

Section 2.3.1 discusses the theoretical bandwidth capacity upper-bound for an FD channel measuring B_w. A key topic of investigation of this work is to check whether the 1:N bandwidth arrangement can outperform current known FD limits. For this reason, this Section refers to Equations 4.18 and 4.10 to report and compare the capacity limits of 1:N and 1:1, respectively.

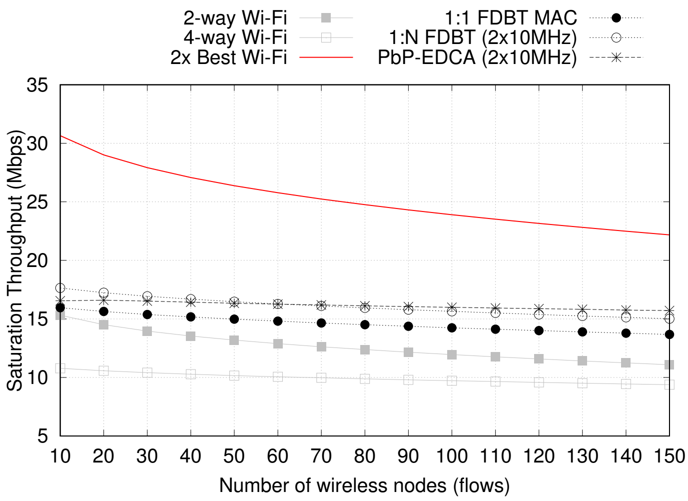
Firstly, the proposals are compared assuming negligible Residual Self Interference (RSI). This is valuable from a theoretical point of view to fix upper-bound limits. Secondly, from a practical perspective, different works have reported to reduce the RSI to the noise-floor



(a) RSSI=−82 dBm (“Weak”)



(b) RSSI=−74 dBm (“Medium”)



(c) RSSI=−65 dBm (“Strong”).

Figure 5.3: Saturation throughput considering the ‘worst-case’ for FD MAC protocols under residual self-interference.

level [Bharadia et al., 2013], outdoor [Korpi et al., 2016a], [Korpi et al., 2016b]), as already mentioned.

Figure 5.4 plots the capacity upper-bound for the 1:1 and the 1:N=2 guidelines across different SNRs. The half-duplex capacity is also plotted for comparison purposes. The total bandwidth is B_w = 20 MHz so 1:N corresponds to two 10 MHz channels. Each 10 MHz channel is separated by a guard-band g=100 KHz, that can be achieved by actual Out-Of-Band FD Wi-Fi radios [Krishna et al., 2012]. The expected theoretical gain of an FD radio is 2× the half-duplex capacity. However, the 3 dB gain induced by the bandwidth reduction leads two narrow FD channels to outperform a single wide FD channel. The Appendix B.2 present MAC saturation throughputs for the scenarios considered in this Section under ideal RSI.

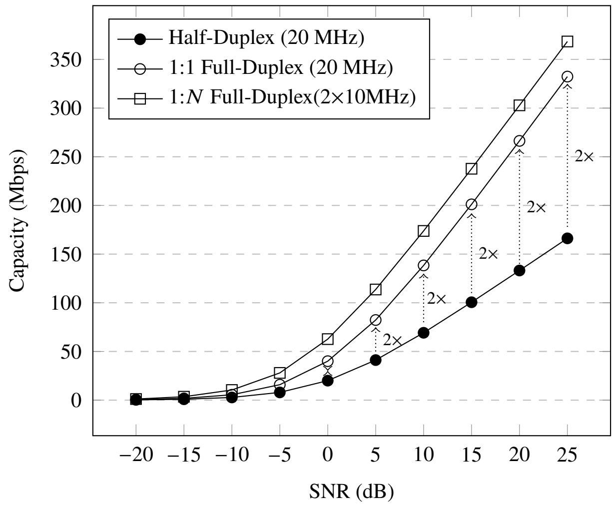


Figure 5.4: Maximum theoretical capacity delivered to the MAC by each design guideline. RSI assumed negligible.

5.2.2 Impact of Residual Self-Interference

Figures 5.5 and 5.6 show bandwidth capacity results for the 1:1 and 1:N design guidelines considering different levels of RSI. The Figures consider an RSI of 25 dB and 30 dB, respectively. According to [Bharadia et al., 2013], these values corresponds to the design proposed by [Jain et al., 2011] and [Everett et al., 2011], respectively. Under such strong RSI, no FD design can outperform a single Half-Duplex link. Note, however, that the 1:N FD design guideline reacts better against the residual noise, because the way it arranges the bandwidth reduces exposition to noise.

5.2.3 Impact of Wide Guard-bands

Figures 5.7 and 5.8 show bandwidth capacity results for the 1:1 and 1:N design guidelines considering ideal RSI and wide guard-bands g. The Figures considers guard-bands of 2 MHz

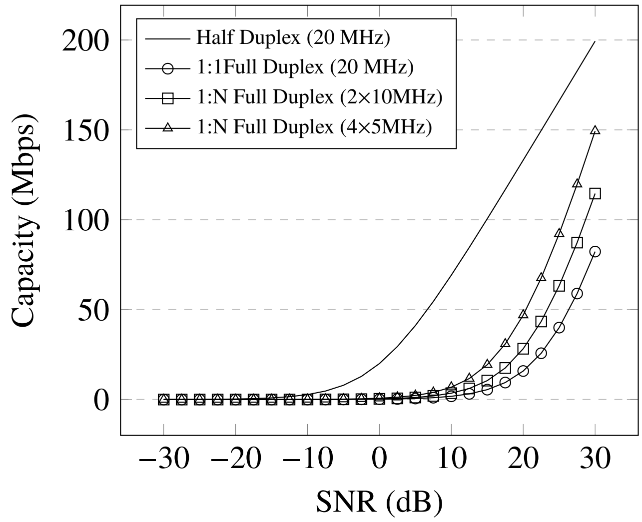


Figure 5.5: Impact of RSI on FD Bandwidth Capacity: RSI 25 dB, g=100KHz.

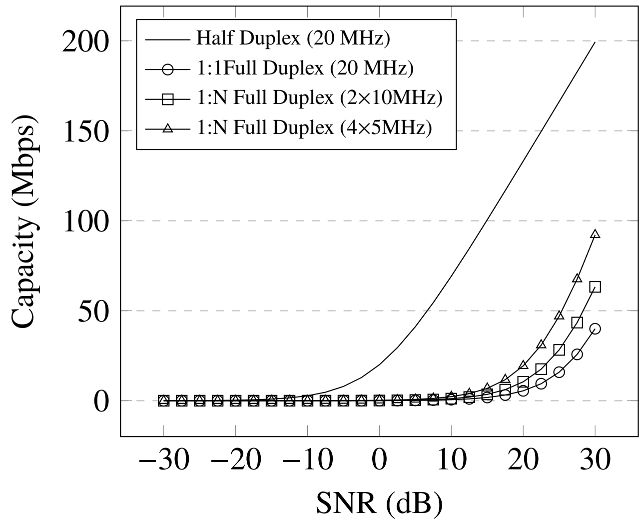


Figure 5.6: Impact of RSI on FD Bandwidth Capacity: RSI 30 dB, g=100KHz.

and 3.4 MHz. [Yang et al., 2010] remark that IEEE 802.11a channelization places a 3.4 MHz guard-band between adjacent channels to avoid co-channel leakage. It means that IEEE 802.11 compliant radios may see stronger leakage for guard-bands narrower than that value. Figures shows that the SNR range on which the 1:N design guideline can outperform 1:1 shortens for wider and wider guard-bands. In each case, such observed SNR ranges are about $[-15, 25]$ and $[-15, 10]$. As channel quality gets better, spectrum becomes more valuable. Then, under high quality channels, the negative impact of guard-bands on 1:N worsens. Similar results are seen in the equivalent Figures 5.9 and 5.10 where an RSI of 1 dB is assumed.

5.2.4 What If N Grows?

Figures 5.11 and 5.12 show bandwidth capacity results if one increases N assuming negligible RSI. The guard-band g is set to 1 MHz and 100 KHz, respectively. The Figures

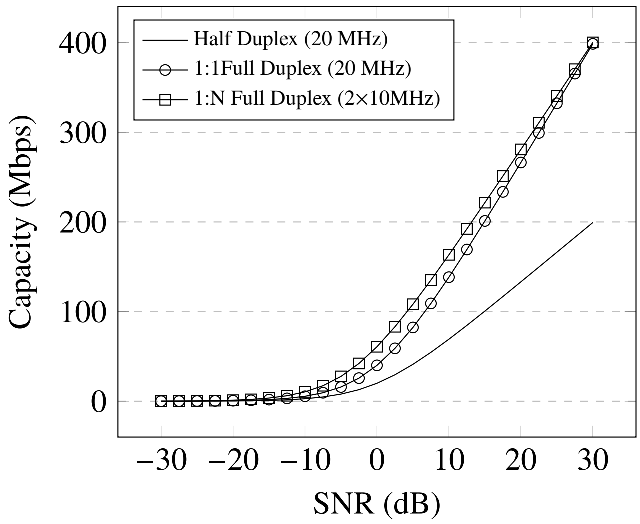


Figure 5.7: Impact of Guard-band on FD Bandwidth Capacity: Ideal FD, g=2MHz.

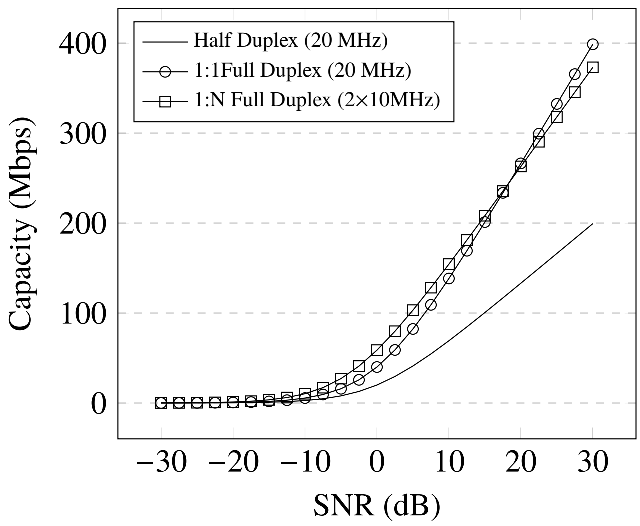


Figure 5.8: Impact of Guard-band on FD Bandwidth Capacity: Ideal FD, g=3.4 MHz.

reveal that capacity grows over N if the radio can sustain very efficient guard-bands as narrow as 100 KHz. Otherwise, larger N penalizes the bandwidth capacity because of the waste of spectrum. Figures 5.13 and 5.14 are homologous to Figures 5.11 and 5.12 but assuming an RSI of 1 dB.

5.2.5 Validation

This Section investigates the practical feasibility of two key aspects of the current work through testbed experiments. The first one regards noise-floor reduction within a bandwidth. It is referred to as the 'RSSI experiment'. It is known from the related literature that narrower channels benefits from weaker noise floor. However, the premise of this work does not consists in reducing the entire bandwidth but dividing it. In fact, the entire bandwidth keeps active but through independent portions of orthogonal spectrum. Hence, the first experiment answers

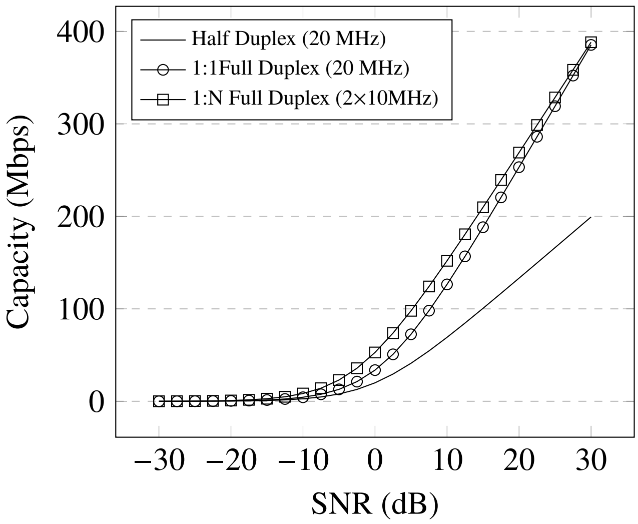


Figure 5.9: Impact of Guard-band on FD Bandwidth Capacity: RSI=1dB, g=2MHz.

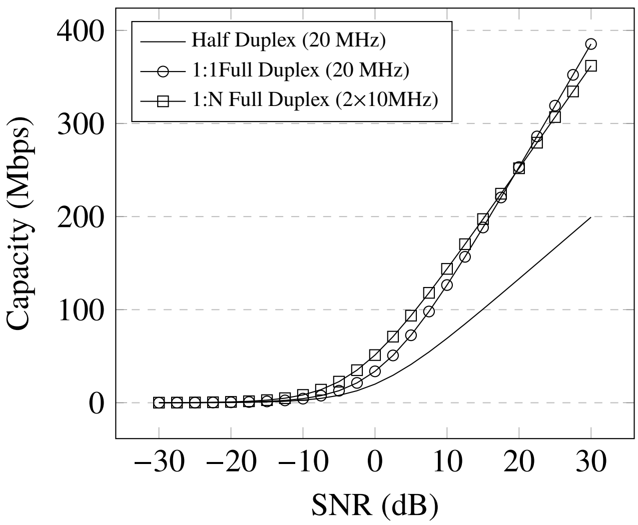


Figure 5.10: Impact of Guard-band on FD Bandwidth Capacity: RSI 1dB, g=3.4 MHz.

whether it is possible to keep the entire bandwidth active and, at the same time, benefiting from the stronger noise within each independent orthogonal piece of it.

The second experiment regards the possibility of breaking through the so-called FD gain, i.e., 2× the half-duplex capacity. If FD radios can really manage to suppress RSI to the noise-floor level, than the 1:1 FD bandwidth might double the half-duplex bandwidth capacity. If there exist at least one scenario in which the 1:N bandwidth arrangement outperform 1:1 then it may be possible to break through the FD gain.

In order to check whether it is possible to break through the expected FD gain under the assumption of an RSI as weak as the noise-floor, this Section proposes a proof-of-concept software defined radio experiment.

Both experiments were based on a pair of two-antennas Ettus Universal Software Radio Peripheral (USRP) B210 devices and the gr-ieee80211 GNURadio module [Bloessl et al., 2013].

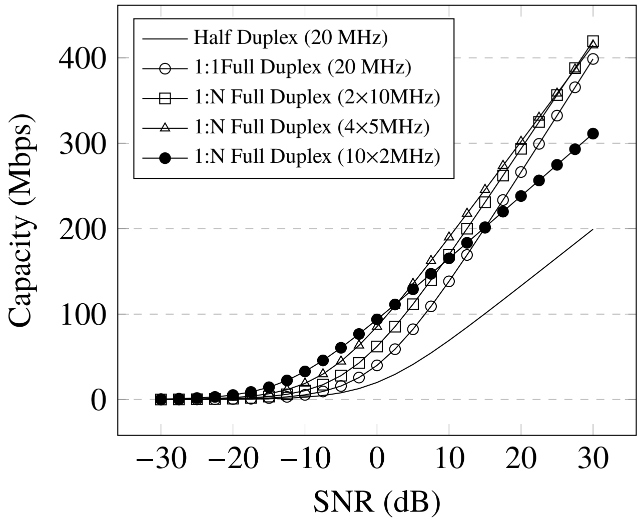


Figure 5.11: FD Bandwidth Capacity on Large N: Ideal FD, g=1MHz.

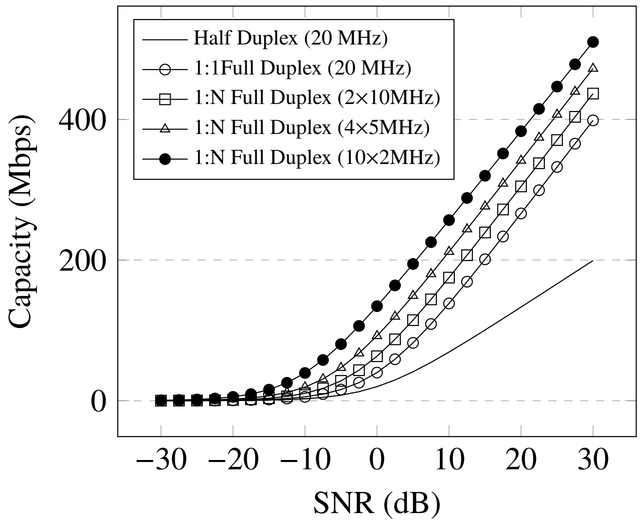


Figure 5.12: FD Bandwidth Capacity on Large N: Ideal FD, g=100KHz.

Each B210 device was attached to an Intel i7 computer through an USB 3.0 port[2] and placed about 1.5 meter away from the other. The testbed is shown in Figure. 5.15.

In both experiments the signal waveform complies the IEEE 802.11a PHY layer of the `gr-ieee80211` GNURadio module [Bloessl et al., 2013]. The total available bandwidth B_w = 10 MHz. For 1:N, N is set to 2 i.e. two 5 MHz channels.

Validating Equation 4.2.3

For the RSSI experiment, the testbed was set in the simplex mode. One USRP B210 was set as receiver and the other as transmitter. Two experiments were performed: one representing

[2]although the connection between USRP and the PC adds a time overheads to the experiments, the B210 `benchmark_rate` utility reported that the performance of the USB controllers matched the sampling rate required for OBFD 10 MHz experiments.

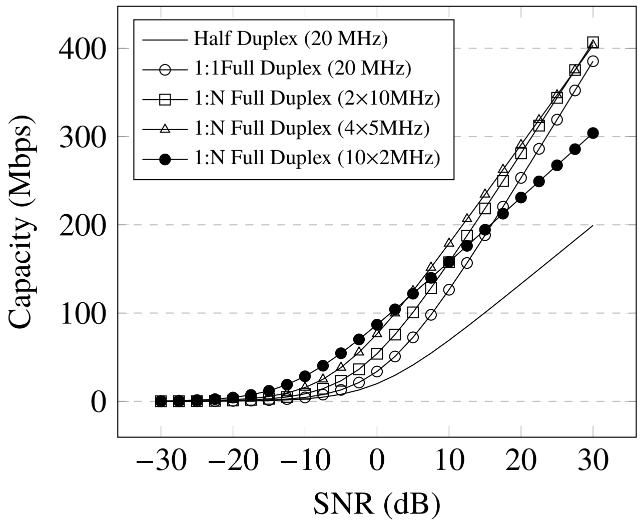


Figure 5.13: FD Bandwidth Capacity on Large N: RSI=1dB, g=1MHz.

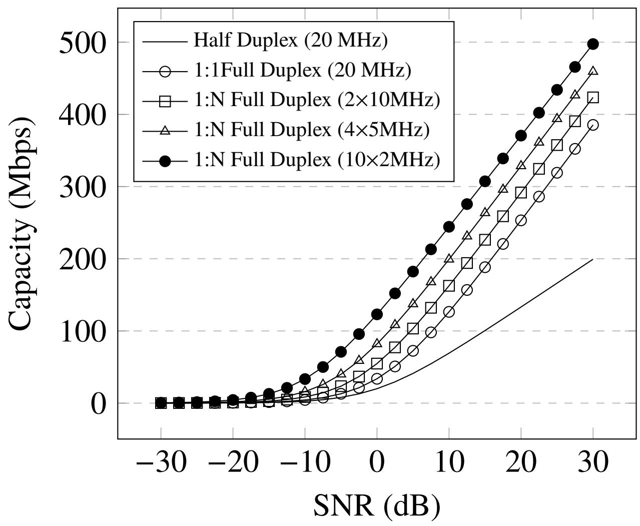


Figure 5.14: FD Bandwidth Capacity on Large N: RSI=1dB, g=100KHz.

the 1:1 design guideline and the other the 1:N design guideline. In each case it was gathered Power Spectrum (PS) samples.

Fig. 5.16 plots average PSs of the strongest signals as reported by a couple of single-antenna Ettus USRP B210 platform. The average PS samples is estimated based on the Matlab's `pwelch` procedure. From the plots, one can see that concurrency does not prevent the two narrow channels from gaining about 3 dB over the wider channel. This validates the Equation 4.2.3 proposed in Section 4.2.3. In fact, although narrow channels occupy the same 10 MHz spectrum, they are employed independently. Thus, the noise floors experienced within a channel do not account substantially for the demodulation processing in the other.

Figure 5.15: Software-defined radio testbed.

Breaking through the Full-Duplex Wi-Fi Capacity Gain

The second experiments consists in showing at least one practical scenario (if any) under which an nearly ideal FD radio can *more-than-double* over an half duplex link. Unfortunately, FD radios are still not commercialized nowadays. Also, the design of an FD radio is out of the scope of this proposal. For this reason, USRP B210 were employed to mimic an ideal FD radio.

Preliminary, it was verified that the USRP B210 radio works poorly in the in-band FD mode[3]. Then, to mimic an ideal FD radio, this experiment relies on the OBFD feature of USRP B210. This feature assure one can send and receive simultaneously through the *different* bandwidths. Then two different 10 MHz orthogonal channels were set in each device, yielding a total of 20 MHz. In each radio, one channel is only for receptions and the other only for transmissions. Thus each radio transmits and receives simultaneously but through different channel. This may increase the noise floor slightly in the receiver channel. Thus, to mimic the channels as in-band FD, they were separated from each other by 60 MHz. *Note this does not correspond to the guard-band required by the* $1{:}N$ *guideline* but is just a workaround to suppress the cross channel interference in each radio.

As in the RSSI experiment, here two setups are considered: one representing the 1:1 design guideline (10 MHz) and the other the $1{:}N$ design guideline (2×5 MHz). In the $1{:}N$ experiment, each 10 MHz signal is re-sampled as a 5 MHz signal in software by means of

[3]The B210 specification sheet [Ettus Research, 1997] claims "Full-Duplex" capability but does not clearly specifies whether it is in-band. According to an official response the author got in the Ettus mailing list, the native FD support is restricted to the out-of-band FD mode [Queiroz, 2016a]

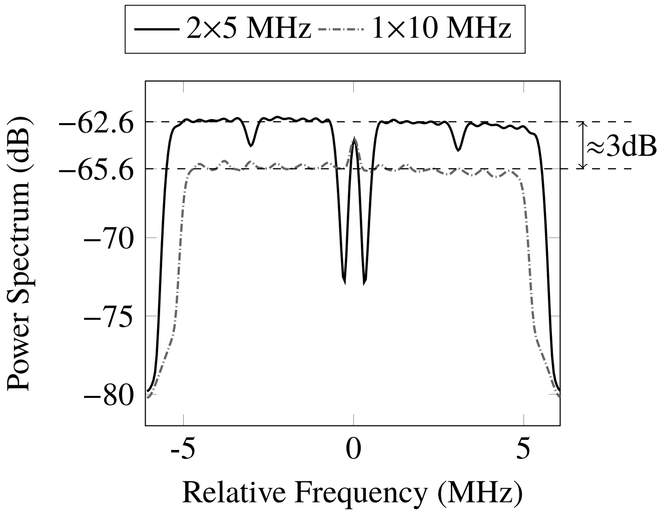


Figure 5.16: Each concurrent 5 MHz-wide channel can outperform a single 10 MHz channel about 3 dB even under the same output power.

GNURadio. The signal is then duplicated and each copy is shifted to one half of the 10 MHz channel. Since each signal correspond to an IEEE 802.11 data frame, each radio sends two '5 MHz wide' data frames within the 10 MHz channel. Thus, in the 1:N design, a total of 4 frames is sent through the bandwidth. In the 1:1 design a total of two 10 MHz frame are sent.

The IEEE 802.11 data rates were 9 Mbps and 6 Mbps for 10 and 5 MHz channels, respectively. The radios operated in saturated conditions. Since SDR experiments are affected by CPU load and OBFD doubles the processing demand, the half-duplex link was assessed from the best FD link. For each experiment it was gathered as many samples as needed to calculate mean throughput $\overline{X}$ with a confidence of 95% and a relative error < 5%, following the statistical procedures of Akaroa [Ewing et al., 1999]. The points plotted in Fig. 5.17 are repeated in Table 5.5. In that table, $\overline{X}$ is the throughput mean corresponding to the steady-state stochastic process of the testbed, CI the half width of confidence interval, s is the total of measured samples and d^* is the number of discarded transient samples.

Table 5.5: Steady-state best-case throughput of MAC design guidelines.

MAC Guideline	$\overline{X}(Kbps)$	CI	s	d^*
Half-duplex	26.03	0.003	3486	581
1:1 FD	52.06	0.035	2436	406
1:N FD	57.48	0.304	1920	320

From the plots on Fig. 5.17 one can see that the capacity upper-bound of the 1:1 design guideline corresponds to about 2× the capacity of half-duplex, as expected. Under same conditions, the 1:N design guideline present a throughput gain of about 2.2× the half-duplex throughput.

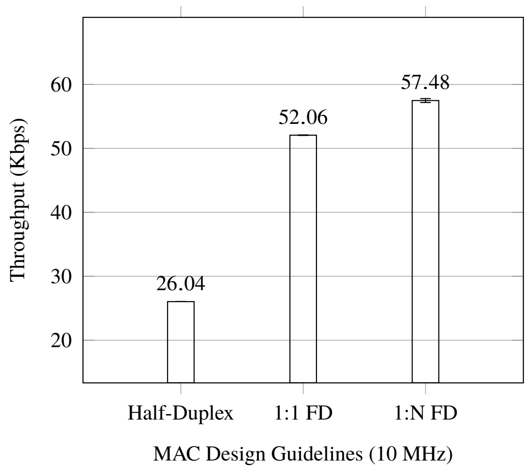


Figure 5.17: Best-case throughput of each FD MAC design guideline assessed on the USRP B210 platform.

5.3 Summary of Results

This chapter evaluated the performance of the 1:1 and 1:N FD MAC design guidelines. The study was organized into two categories. Firstly, it was presented the MAC protocols saturation throughput. Then it was studied the bandwidth capacity achieved under each FD MAC design guideline.

In the presented MAC saturation throughput studies, it was verified that the key factors to explain the performance of each MAC protocol (in order of relevance) are:

i) higher number of simultaneous transmissions;

ii) higher total data rate;

iii) lower MAC overheads.

Table 5.6 summarizes the saturation throughput results discussed in Subsection 5.1.3 with respect the performance factors. The main outcome of the Table is to say the reasons that lead each FD MAC protocol to either scale, not scale or outperform the expected FD gain – i.e. 2× the best half duplex throughput. Reading the Table from left to right, one firstly sees the causes that explain the final result of each protocol. In the last column, the reader is provided with the information about whether a given MAC protocol scale the FD gain.

The bandwidth capacity studies showed that it is possible for the 1:N design guideline to outperform the capacity of a 1:1 FD bandwidth. In fact, the 1:N design guideline presented better results than 1:1, even under strong residual self-interference. Also, it was shown that an increasing N translates into an increasing capacity if guard-band can be set enough narrow e.g. 100 KHz [Krishna et al., 2012]. For guard-bands wider than 2 MHz, the 1:N performance impairs, specially for large N. Considering the RSI level claimed by state of art FD radio designs, the 1:N improved over the 2× theoretical FD capacity gain. The performance limits of 1:N were

Table 5.6: FD Gain Scalability of MAC Protocols: Summary of Results under 1 dB of RSI.

FD Cases	**FD MAC Protocol**	**Kind of improvement over the IEEE 802.11 Half-Duplex**			**Comparison to 2x the best IEEE 802.11 throughput**		
		More simultaneous transmissions (TXs)?	**Higher total data rate?**	**Lower MAC Overheads?**	**Weak RSSI**	**Medium RSSI**	**Strong RSSI**
Worst	1:1 FDBT	no	no, because of residual SI.	yes. Can reduce time wasted in collisions; dispenses RTS/CTS	*Cannot Scale*	*Cannot Scale*	*Cannot Scale*
	1:*N* FDBT	yes, 2x but requires guardband	Depends on RSSI	no/yes. Enlarges time wasted in collisions but dispenses RTS/CTS	*Cannot Scale*	*Cannot Scale*	*Cannot Scale*
	1:*N* PbP-EDCA	yes, 2x but requires guardband	Depends on RSSI	Same as above and reduces collision probability but increases time to access spectrum	*Cannot Scale*	*Cannnot Scale*	*Cannnot Scale*
Best	1:1 FDBT	yes, 2x	no, because of residual SI.	Same as in the worst-case.	*Can Scale*	*Can scale for large n*	*Can scale for large n*
	1:*N* FDBT	yes, 4x but requires guardband	Same as in the worst-case.	Same as in the worst-case.	*Can Outperform*	*Can Outperform for large n*	*Can scale for large n*
	1:*N* PbP-EDCA	yes, 4x but requires guardband	Same as in the worst-case.	Same as in the worst-case.	*Can Outperform*	*Can Outperform*	*Can outperform for large n*

validated based on proof-of-concept software-defined radio experiments. In particular, it was reported an experiment in which the 1:1 and 1:N MAC design guidelines presented capacity upper-bound gains of 2× and 2.2× the half-duplex capacity, respectively.

As a final remark, It is worthy to note that the reported results are not meant to close the FD MAC protocol field. Contrary to this, the current proposal is meant to open novel possibilities of improving the FD gains at the MAC layer. Future works are expected to study the 1:N design guideline under different network constraints and scenarios.

Chapter 6

Conclusion and Future Directions

This work investigates the scalability of the Full-Duplex (FD) capacity gain in WLANs. It is identified the need for novel Medium Access Control (MAC) design guidelines. Considering the need for improving spectrum resources, the design guidelines are expected to facilitate the support for On-Demand Spectrum Allocation (ODSA) techniques.

6.1 Summary

This work studies the reasons that prevent MAC protocols to scale the FD gain in WLANs. After surveying the literature, it was identified some works advocating that the maximum gain due to FD cannot be reached if PHY and MAC layer designs are conceived separately. Indeed, [Bharadia et al., 2013] remark that the historical separation between MAC and PHY communities must be overcome for FD systems to come to fruition. [Thilina et al., 2015] believe that achieving maximum gain by full-duplexing requires a joint FD-MAC design. In addition, [Xie and Zhang, 2014a] provide a theoretical result showing that FD random-access MAC protocols (such as the IEEE 802.11 MAC) cannot double WLAN performance unless "network-level mechanisms such as spatial reuse and asynchronous contention are carefully addressed". We *advance* such contributions by identifying a novel class of FD MAC protocols, which this work termed as 1:1 FD MAC design guideline [Queiroz et al., 2016].

Under the 1:1 design guideline an FD MAC protocol 'sees' the whole FD bandwidth through a single PHYsical layer. Managing the FD bandwidth as an indivisible portion of spectrum as in the 1:1 guideline causes poor spatial reuse and needs higher RSSI for successful demodulation. These aspects can hinder the FD gain scalability of 1:1 MAC protocols. The single bandwidth approach also hampers the development of on-demand spectrum policies at the MAC layer. To overcome such limitations, it was *proposed* the 1:N FD MAC design guideline. Under 1:N, the MAC layer arranges the FD bandwidth into $N>1$ FD PHY layers. Each PHY layer is assigned to a portion of spectrum that is narrower than the available FD bandwidth and orthogonal to the other PHY's spectrum portions. The 1:N design guideline provides

MAC protocols with an increased spatial reuse offer and denser modulation schemes. These advantages result from the channel orthogonality and the RSSI gain enabled by narrower Wi-Fi channels. Additionally, arranging the FD bandwidth into independent PHY layers facilitates the implementation of on-demand spectrum policies at the MAC layer.

By means of novel bandwidth models and experiments, it was *shown* that 1:N FD MAC protocols exploit the FD gain more efficiently than 1:1 FD MAC protocols. Also, it was *presented* MAC protocols that scale to more-than-double throughput in comparison to the IEEE 802.11 standard MAC protocol. Also, It was *proposed* a theoretical capacity study to *demonstrate* that an *arbitrary* FD Wi-Fi MAC protocol benefits from a more efficient best-case if designed under the 1:N guideline rather than the 1:1 guideline. Such statement was *validated* through a proof-of-concept software-defined radio experiment. Particularly, it was shown that the proposed design guideline could outperform the 1:1 counterpart reaching a gain of $\approx 2.2\times$ the half-duplex capacity.

6.2 Contributions

The presented work achieved the following contributions

- Literature review and enhancement of the prior proposed classification for the field of Full Duplex MAC protocols. In particular, in Chapter 3 it is introduced a novel category based on which FD MAC protocols are classified with respect to the number of channels they arrange the Full Duplex bandwidth. Also, the reasons that prevent MAC protocols to scale the FD gain are presented;

- Proposal of a novel design guideline for IEEE 802.11 FD MAC protocols. In particular, Chapter 4 presents the following contributions with respect to the proposed guideline: description of bandwidth capacity limit, case studies of novel FD MAC protocols and saturation throughput models to evaluate the proposed case studies;

- Presentation of novel FD bandwidth capacity upper-bounds and identification of key factors for the scalability of the FD gain at the MAC layer (as detailed in Chapter 5);

- Proposal of a Software-Defined Radio experiments to validate the claimed FD performance gains;

- Implementation and publication of software for the proposed FD MAC saturation throughput models.

The present work also achieved the following results with respect to the related research community:

- Conference publication [Queiroz et al., 2016];

- Conference publication [Queiroz and Hexsel, 2015];
- Journal publication [Queiroz, 2013];
- Presentation in the "mentoring moments – formal session" of the ACM SIGCOMM 2016;
- 1 Citation: After the literature review of [Wang, 2016, pg. 57], that author acknowledges the claimed innovation of this work as published in [Queiroz and Hexsel, 2015];
- Doctoral exchange program in the Departments of Informatics Engineering of the University of Coimbra (Portugal) under co-supervision of professor Dr. João Vilela.

6.3 Future Research Directions

Next, are listed some possible research directions from this work.

- Energy-constrained FD networks: reduction of energy consumption is important for energy-constrained devices and green networking. Doubling network capacity by means of FD increases energy consumption because the radio needs energy for transmission and reception. Energy saving and throughput maximization are conflicting policies for wireless networks [Chandra et al., 2008] and further research effort is needed to balance these performance metrics for FD networking. We believe the 1:N MAC design guideline can be helpful for two reasons. Firstly, its superior throughput relies on the properties of narrow orthogonal channels and does not require the radio output power to increase. Secondly, some energy-aware MAC protocols have to trade-off between radio availability maximization and energy-consumption minimization [Tsao and Huang, 2011]. These proposals set the whole wireless bandwidth into either the "wakeup" or "sleepy" state. The multi-PHY nature of 1:N may bring larger granularity to the process enabling partial states of the bandwidth;
- Standardization bodies: the IEEE 802.11 task groups have adopted co-existence and backward compatibility with prior Wi-Fi standards as mandatory requisites for future amendments. The 1:N guideline fully matches the mandatory channel arrangement of the current IEEE 802.11ac standard. The standard association handshake can be exploited by an station to determine whether the corresponding access point support the 1:N (PbP-EDCA) or the legacy access guideline;
- The 1:N guideline and FD MIMO radios: some authors have demonstrated the feasibility of FD MIMO radios [Bharadia and Katti, 2014],[Aryafar et al., 2012]. All these works follow the 1:1 guideline. A possible research direction consists in studying the feasibility of MIMO radios together with the 1:N FD MAC guideline. For instance, if an FD MIMO radio supports M transmission streams within an FD bandwidth measuring B MHz, is it

possible to support a total of $2M$ streams in two orthogonal channels measuring $B/2$ MHz each, or two transmission streams per narrow channel?

- Jointly In-Band and Out-Of-Band Full Duplex Radio Design: This work identified that current in-band FD radio prototypes are mostly 1:1-driven. They do not account for interference caused among adjacent orthogonal channels at the receiver. The simplest way to deal with that problem is to increase guard-bands. This is a reasonable solution for proof-of-concept studies but is not for real-world scenarios because of the resulting waste of spectrum. An alternative solution consists in a joint design of SIC techniques and advanced filters to save spectrum. Therefore our results suggest further research in the FD radio design.

- Impact on future FD MAC design: this work focused only on symmetric FD dual-links to assess the capacity upper-bound of the considered MAC protocols. Future work builds on the 1:N design guideline to facilitate the discovery of asymmetric FD dual-links. In this sense, it is an author belief that the superior capacity upper-bound presented by the 1:N MAC design guideline can inspire a new generation of FD MAC protocols.

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Appendix A

PbP-EDCA Markovian Model

To assess the capacity of PbP-EDCA in a secondary channel c, in this appendix we explain how to compute the probability of accessing c. The PbP-EDCA manages the primary channel according to the CSMA/CA protocol. For this reason, the Bianchi model can predict the PbP-EDCA performance in the primary channel. The present work generalizes the Markovian chain of the Bianchi model to work with N channels. The channels are assumed to be accessed sequentially according to the On-Demand Spectrum Allocation (ODSA) strategy of PbP-EDCA. The generalization accounts for the fact that PbP-EDCA becomes the standard CSMA/CA when N is set to 1. Therefore, the general Markovian PbP-EDCA model considers adds the stochastic process $h(t)$ – to account the numer of the channel in which a given STA is at a given instant – in addition to the stochastic processes $s(t)$ and $b(t)$, that refer to the back-off stage and back-off number of a STA at a given instant, respectively. The resulting PbP-EDCA analytic model is derived in what follows according to [Queiroz, 2013].

A.1 Probability of Accessing Secondary Channels

The back-off stage $i \in [0, m]$ of a STA at time t refers to the increments in the length of the contention interval W_i upon collisions. We follow the same notation of the Bianchi model where W (or W_0) stands for the *number* of possible back-off count values in the first back-off stage. Then, in each stage i, we have W_i=$2^i W$ and a STA picks a random uniform number from the interval $[0, W_i - 1]$. The last back-off stage m is such that W_m=$2^m W$. When the back-off count of a STA reaches zero (regardless of the stage) it transmits in the primary channel P_c with probability of collision p. If such transmission succeeds (what happens with probability $1-p$), the STA also performs a sequence of transmissions in each secondary channel $c \in [0,N-1]$, where N is the number of channels.

The three-dimensional PbP-EDCA process $\{s(t), b(t), h(t)\}$ consists in a discrete-time Markov chain, in which the non-null one-step transition probabilities are those given in Eqs. A.1.

$$\begin{cases} P_{i,k,0|i,k+1,0} = 1, & k \in [0, W_i - 2]; i \in [0, m] \\ P_{i,0,1|i,0,0} = 1 - p, & i \in [0, m] \\ P_{i,0,c|i,0,1} = 1, & i \in [0, m]; c \in [2, N - 1] \\ P_{0,k,0|i,0,N-1} = 1/W_0, & i \in [0, m]; k \in [0, W_0 - 1] \\ P_{i,k,0|i-1,0,0} = p/W_i, & i \in [1, m]; k \in [0, W_i - 1] \\ P_{m,k,0|m,0,0} = p/W_m, & k \in [0, W_m - 1] \end{cases} \tag{A.1}$$

In the equations, $P_{s_a|s_b}$=x denotes that a transition from the state s_b to the state s_a occurs with probability x. A depiction of the model is shown in Figure A.1.

Let $b_{i,k,c} = \lim_{t\to\infty} P\{s(t) = i, b(t) = k, h(t) = c\}$, $i \in [0, m]$, $k \in [0, W_i - 1]$ and $c \in [0, N - 1]$ be the stationary distribution of the chain. A corresponding closed-form solution can be obtained by firstly noting that our protocol behaves just like the IEEE 802.11 EDCA *while a data frame transmission does not succeed* in the primary channel. Under such condition, the Bianchi model becomes an instance of ours and the following equalities hold for $c = 0$ and $k \in [1, W_i - 1]$:

$$\begin{aligned} b_{i,0,0} = b_{i-1,0,0} \cdot p \rightarrow b_{i,0,0} = p^i \cdot b_{0,0,0} \quad & 0 < i < m \\ b_{m-1,0,0} \cdot p = (1 - p)b_{m,0,0} \cdot p \rightarrow b_{m,0,0} = \frac{p^m}{1 - p} \cdot b_{0,0,0} & \end{aligned} \tag{A.2}$$

$$b_{i,k,c} = \frac{W_i - k}{W_i} \cdot \begin{cases} (1 - p) \sum_{j=0}^{m} b_{j,0,N-1} & i = 0 \\ p \cdot b_{i-1,0,0} & 0 < i < m \\ p \cdot (b_{m-1,0,0} + b_{m,0,0}) & i = m \end{cases} \tag{A.3}$$

Upon a successful transmission in the primary channel at any stage $i \in [0, m]$, a node senses the next secondary channel $c \in [1, N - 1]$ during T_β and transmits if CCA detects channel as idle. Following the standard IEEE 802.11 EDCA, all nodes wait for an additional DIFS in the primary channel just after an ACK transmission. Therefore, keeping the same capacity upper-bounds assumptions of [Bianchi, 1998] (e.g. ideal channel, homogeneous transmission length) a station transmits with no contention on secondary channels if it does not collide in the primary channel for each stage i. This translates to:

$$(1 - p)b_{i,0,0} = b_{i,0,1} = b_{i,0,2} = \cdots = b_{i,0,N-1} \tag{A.4}$$

A station goes back to the CSMA/CA contention in the primary channel with probability $\sum_{i=0}^{m} b_{i,0,N-1}$ and it picks zero as its back-off counter with probability $\frac{1}{W_0}$. Therefore a node

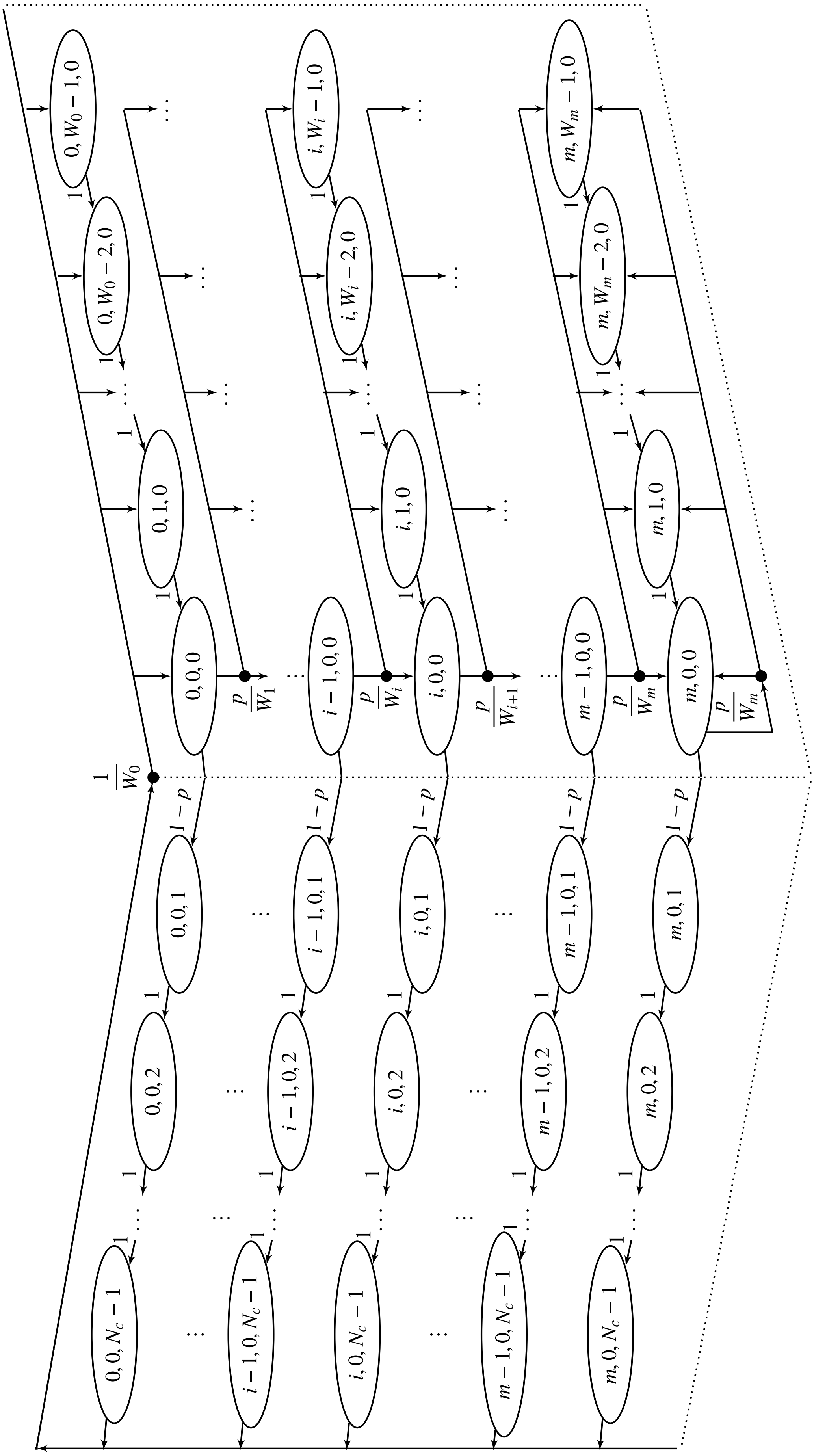


Figure A.1: Markov chain model for the PbP-EDCA MAC Protocol.

arrives at the state $b_{0,0,0}$ with probability $(\sum_{i=0}^{m} b_{i,0,N-1}) \cdot (\frac{1}{W_0})$. However, the transition from any state $b_{0,k,0}$, $k \in [1, W_0 - 1]$, to $b_{0,0,0}$ is a certain event. Hence:

$$b_{0,0,0} = \sum_{i=0}^{m} b_{i,0,N-1} \tag{A.5}$$

From Eq. (A.4), Eq. (A.5) can be rewritten as:

$$\begin{aligned} b_{0,0,0} &= \sum_{i=0}^{m} (1-p) b_{i,0,0} \\ \frac{b_{0,0,0}}{(1-p)} &= \sum_{i=0}^{m} b_{i,0,0} \end{aligned} \tag{A.6}$$

Based on Eqs. (A.2) and (A.6), and considering the chain regularities for each $c \in [0, N-1]$, $i \in [0, m]$ and $k \in [0, W_i - 1]$, Eq. (A.3) becomes:

$$b_{i,k,c} = \begin{cases} \frac{W_i - k}{W_i} b_{i,0,0} & c = 0 \\ (1-p) b_{i,0,0} & 0 < c < N \end{cases} \tag{A.7}$$

By means of Eq. (A.2) and Eq. (A.7) it is possible to express all occurrences of $b_{i,k,c}$ in terms of the collision probability p and $b_{0,0,0}$. This latter can be determined by imposing the normalization condition, as follows:

$$\begin{aligned} 1 &= \sum_{c=0}^{N-1} \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} b_{i,k,c} = \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} \sum_{c=0}^{N-1} b_{i,k,c} = \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} \left(\frac{W_i - k}{W_i} b_{i,0,0} + \sum_{c=1}^{N-1} (1-p) b_{i,0,0} \right) \\ &= \left(\sum_{i=0}^{m} b_{i,0,0} \sum_{k=0}^{W_i-1} \frac{W_i - k}{W_i} \right) + \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} (1-p) \sum_{c=1}^{N-1} b_{i,0,0} \\ &= \left(\sum_{i=0}^{m} b_{i,0,0} \frac{W_i + 1}{2} \right) + \sum_{i=0}^{m} (1-p) \sum_{k=0}^{W_i-1} \sum_{c=1}^{N-1} b_{i,0,0} \\ &= \left(\sum_{i=0}^{m} b_{i,0,0} \frac{2^i W + 1}{2} \right) + (1-p) \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} \sum_{c=1}^{N-1} b_{i,0,0} \\ &= \frac{b_{0,0,0}}{2} \cdot \left[W \left(\frac{1-(2p)^m}{1-2p} + \frac{(2p)^m}{1-p} \right) + \frac{1}{1-p} \right] + (1-p) b_{0,0,0} (N-1) W \left[\frac{1-(2p)^m}{1-2p} + \frac{(2p)^m}{1-p} \right] \end{aligned}$$

from which

$$b_{0,0,0} = \frac{2(1-2p)(1-p)}{[W - pW(1+(2p)^m)][1+2(1-p)(N-1)] + 1 - 2p} \tag{A.8}$$

We present Eq. (A.8) as a generalization of that proposed by Bianchi [Bianchi, 2000] in Eq. (A.9). In fact, PbP-EDCA becomes the standard single-channel IEEE 802.11 EDCA when N=1.

$$b_{0,0,0} = \frac{2(1-2p)(1-p)}{(1-2p)(W+1)+pW(1-(2p)^m)+(N-1)(1-p)(2W)[1-p(1+(2p)^m)]} \tag{A.9}$$

Let τ_c be the probability that a station transmits in the channel $c \in [0, N-1]$ within a randomly chosen time slot. The probability τ_0 that a station transmits in the primary channel comes from all states in which the back-off counter k and channel c are both zero. From the chain, we have $\tau_0 = \sum_{i=0}^{m} b_{i,0,0}$. Based on Eq. (A.6), τ_0 can be rewritten as:

$$\tau_0 = \sum_{i=0}^{m} b_{i,0,0} = \frac{b_{0,0,0}}{(1-p)} \tag{A.10}$$

Following the chain regularities, a node transmits in a given a secondary channel $c \in [1, N-1]$ with probability $\tau_c = \sum_{i=0}^{m} b_{i,0,c}$. Taking the Eqs. (A.4), τ_c re-writes as follows:

$$\begin{aligned} \tau_c &= \sum_{i=0}^{m} b_{i,0,c} \\ &= \sum_{i=0}^{m}(1-p)b_{i,0,0} = (1-p)\sum_{i=0}^{m} b_{i,0,0} \end{aligned}$$

then, from Eq. (A.10)

$$\tau_c = (1-p)\tau_0,\ c \in [1, N-1] \tag{A.11}$$

Considering that a collision happens when more than one node transmits simultaneously in the primary channel, p is given by $1-(1-\tau_0)^{n-1}$ [Bianchi, 2000]. Taking this equality and Eq. A.10, one forms the system of Eqs. (A.12).

$$\begin{cases} \tau_0 = +\dfrac{2(1-2p)}{(1-2p)(W+1)+pW(1-(2p)^m)+(N-1)(1-p)(2W)[1-p(1+(2p)^m)]} \\ p = 1-(1-\tau_0)^{(n-1)} \end{cases} \tag{A.12}$$

By solving the system of Eqs. (A.12) with numeric techniques, one finds τ_c, $c \in [1, N-1]$ from Eq. A.11. Finally, these probabilities serve as base to calculate the PbP-EDCA according to the Bianchi capacity formula (Eq. 2.22).

A.2 Model Accuracy for Capacity Prediction of PbP-EDCA

To assess the PbP-EDCA capacity achieves in the secondary channel we refer to the Bianchi's saturation capacity (Eq. 2.22) with probability τ_c (Eq. A.11). The capacity in the primary channel is calculated based on the probabilities τ_0 (Eq. A.10) and p=1−$(1-\tau_0)^{n-1}$. We contrast the results achieved by the Bianchi model along with our enhanced Markov chain, with simulation samples from the Network Simulator 3.14.1 [NS3-Consortium, 2016]. To determine the number of samples needed to reach the steady-state (as intrinsically assumed by the Bianchi model) we employ the "Akaroa tool" with a confidence interval of 95% and relative error <5%. For further details about the Akaroa's statistical procedures refer to [Ewing et al., 1999], [Pawlikowski et al., 2002].

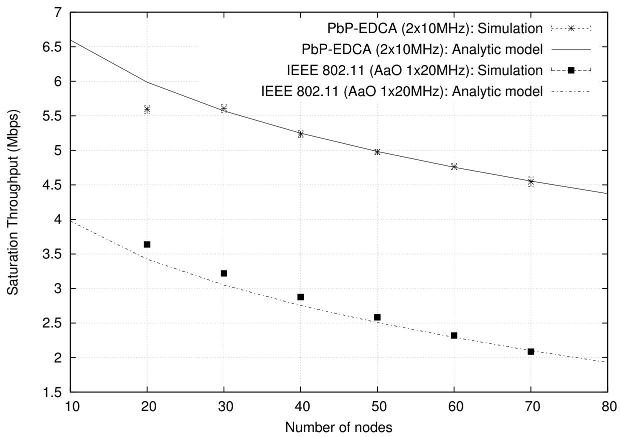


Figure A.2: Saturation throughput for the IEEE 802.11a basic access mode with m=3 and W=16.

In Fig. A.2 we show simulation (points) and analytical (lines) results for both the standard AaO IEEE 802.11 MAC protocol and PbP-EDCA. The widest supported channel is B_w=20 MHz and PbP-EDCA is set to N=2, with primary and secondary channels being 10 MHz wide. We employ the data modulation scheme BPSK 1/2 for the 20 MHz channel, which yields a 6 Mbps data rate. The RSSI required for such a configuration is enough to employ BPSK 3/4 in each 10 MHz channel [IEEE, 2012], resulting in 4.5 Mbps per channel. In both cases, the control rate is BPSK 1/2, which yields 6 Mbps and 3 Mbps for 20 MHz and 10 MHz channels, respectively. The remainder MAC and PHY parameters are shown in Table A.1.

The points in Fig. A.2 are repeated in Table A.2. In that table, S is the analytic saturation throughput, $\overline{S}$ is the steady-state simulation throughput mean, CI the half width of confidence interval, s is the total of simulated samples and d^* is the number of discarded transient samples. As one can see, the saturation capacity function of the Bianchi model yields accurate results along with the probabilities of our Markov model. As pointed out by [Bianchi, 2000], the model accuracy improves for an increasing number of nodes, since the assumption of a constant "independent"[1] collision probability p becomes more precise for larger n. Indeed, the relevance of a large n on p mitigates the influence of other non-modeled parameters.

[1]Independent from all factors other than n.

Table A.1: Common Parameter Values Set for Both (AaO) IEEE 802.11 and PbP-EDCA.

Application Layer Payload	1436 bytes
Application Layer Data Rate	10 Mbps
MAC Header	224 bits
ACK Length	112 bits
Minimum Contention Window Size W	16 slots
Number of Backoff Stages m	3
Control Frame Modulation Scheme	BPSK 1/2
Widest Channel Width B_w	20 MHz
Num. Narrow Orthogonal Channels N (PbP-EDCA)	2
Handshake	2-way
Propagation Delay δ	1 μs

Table A.2: PbP-EDCA vs. IEEE 802.11: Analytic and detailed steady-state simulation throughput for $m = 3$ and $W = 16$.

n	EDCA MAC	S	$\overline{S}$	CI	s	d^*
20	PbP (2×10)	5.98	5.59	0.0603	1482	247
	WiFi (1×20)	3.42	3.63	0.0044	1506	251
30	PbP (2×10)	5.57	5.60	0.0543	1530	255
	WiFi (1×20)	3.05	3.21	0.0052	1548	258
40	PbP (2×10)	5.24	5.23	0.0520	1500	250
	WiFi (1×20)	2.75	2.87	0.0062	1500	250
50	PbP (2×10)	4.98	4.97	0.0384	1494	249
	WiFi (1×20)	2.50	2.58	0.0046	1566	261
60	PbP (2×10)	4.75	4.76	0.0466	1632	272
	WiFi (1×20)	2.29	2.31	0.0048	1446	241
70	PbP (2×10)	4.55	4.54	0.0684	1530	255
	WiFi (1×20)	2.10	2.08	0.0045	1452	242

S and $\overline{S}$ in Mbps.

Appendix B

Additional Results

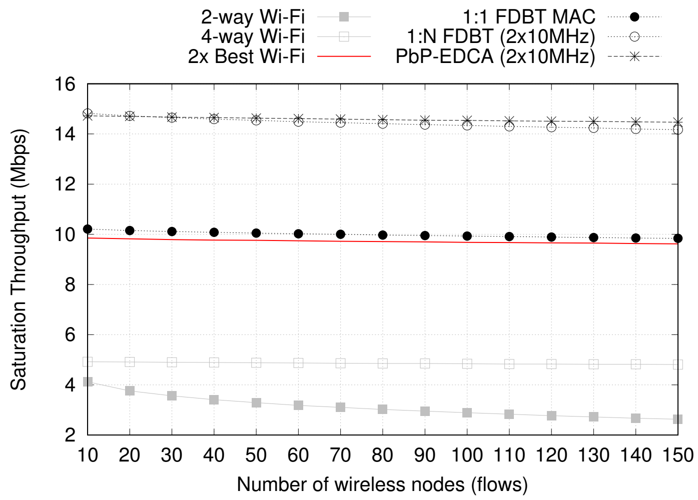
This Appendix presents complementary saturation throughput results for 1:1 FDBT, 1:N FDBT, PbP-EDCA and IEEE 802-11 (2-way and 4-way) MAC protocols. Section B.1 presents results considering larger payloads than in Section 5.1. Section B.2 presents MAC saturation throughput results assuming Residual Self-Interference (RSI) as weak as the noise floor.

B.1 Large Data Frame Payload

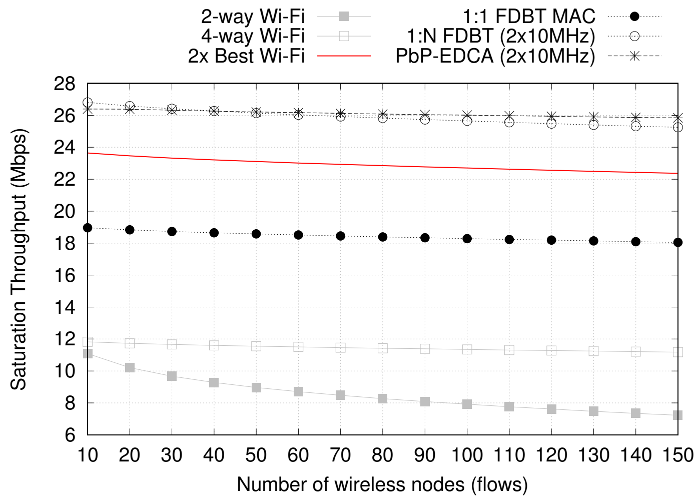
The results of Figures B.1 refers to the same scenario parameters considered to generate the results shown in Figures 5.2. The only exception is for the MAC Service Data Unit (MSDU) payload size L_1, which is set to 1500 bytes in this Subsection. As one can see in Figure B.1, large payload favors the FD MAC protocols in comparison to the half-duplex MAC protocols.

B.2 MAC Saturation Throughput Under Ideal SIC

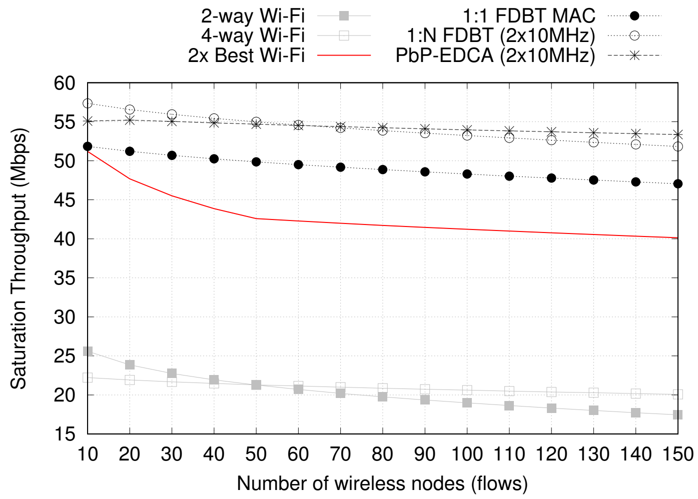
The results on the Figures B.2 and B.3 are homologous for the scenarios assumed for Figures 5.3 and 5.2, respectively. As such, the Table B.1 is equivalent to the Table 5.6. The difference is that the results in this Section builds on the state of the art Full Duplex proposals that claim to reduce the self interference to the noise floor in 20 MHz channels [Bharadia et al., 2013], [Korpi et al., 2016a], [Korpi et al., 2016b]). Under this conditions, the 1:N FD MAC design guideline can scale the FD gains event the the 'FD worst-case' scenarios, in which the secondary transmission consists of protecting Busy Tones rather than useful data. As explained in Section 5.1, this mostly account for the fact the 1:N FD MAC protocols outperform the standard half duplex with respect the number of simultaneous transmissions and sum data rate. For further discussion about each item of the Table B.1 please see Section 5.1. tb:summaryofresults



(a) RSSI=−82 dBm (“Weak”)

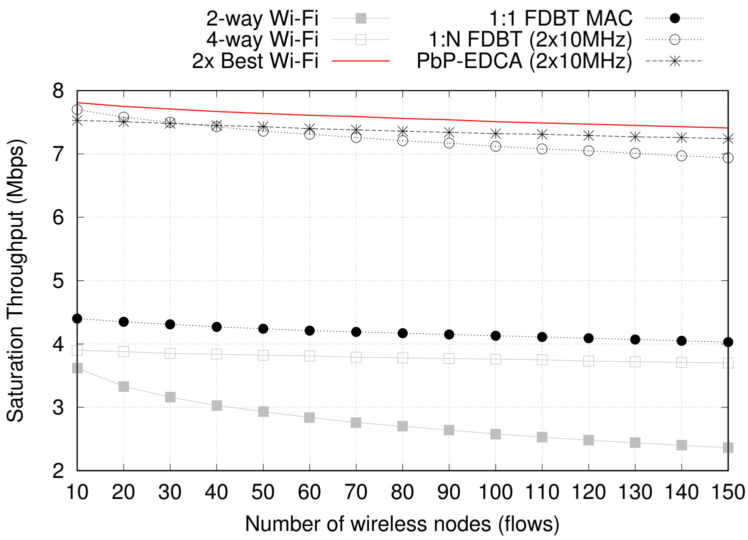


(b) RSSI=−74 dBm (“Medium”)

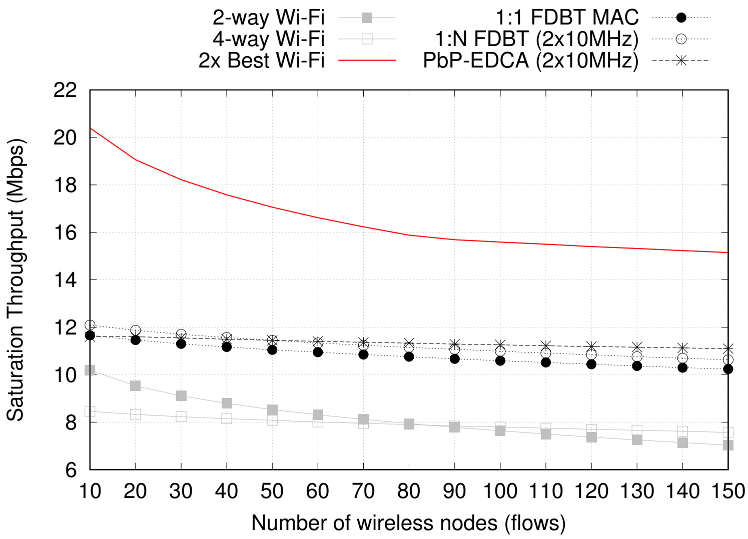


(c) RSSI=−65 dBm (“Strong”).

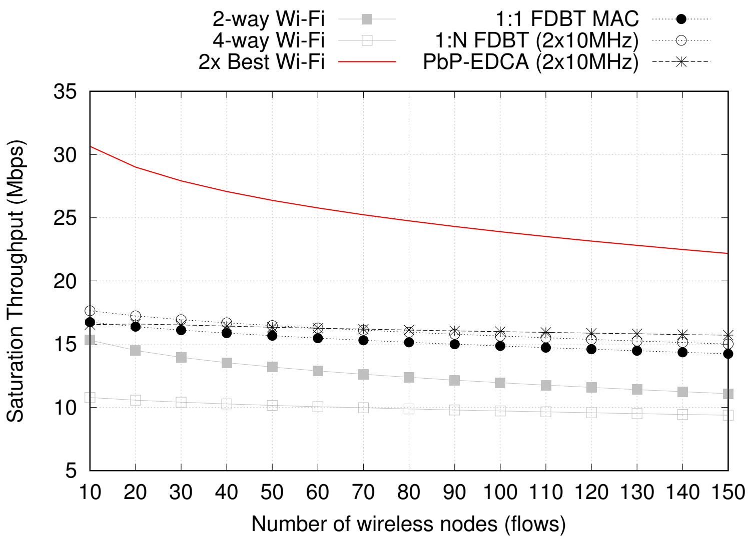
Figure B.1: MAC Protocols Saturation throughput: FD mode=“best-case”, RSI=1dB and MSDU Payload=1536 bytes.



(a) RSSI=−82 dBm (“Weak”)

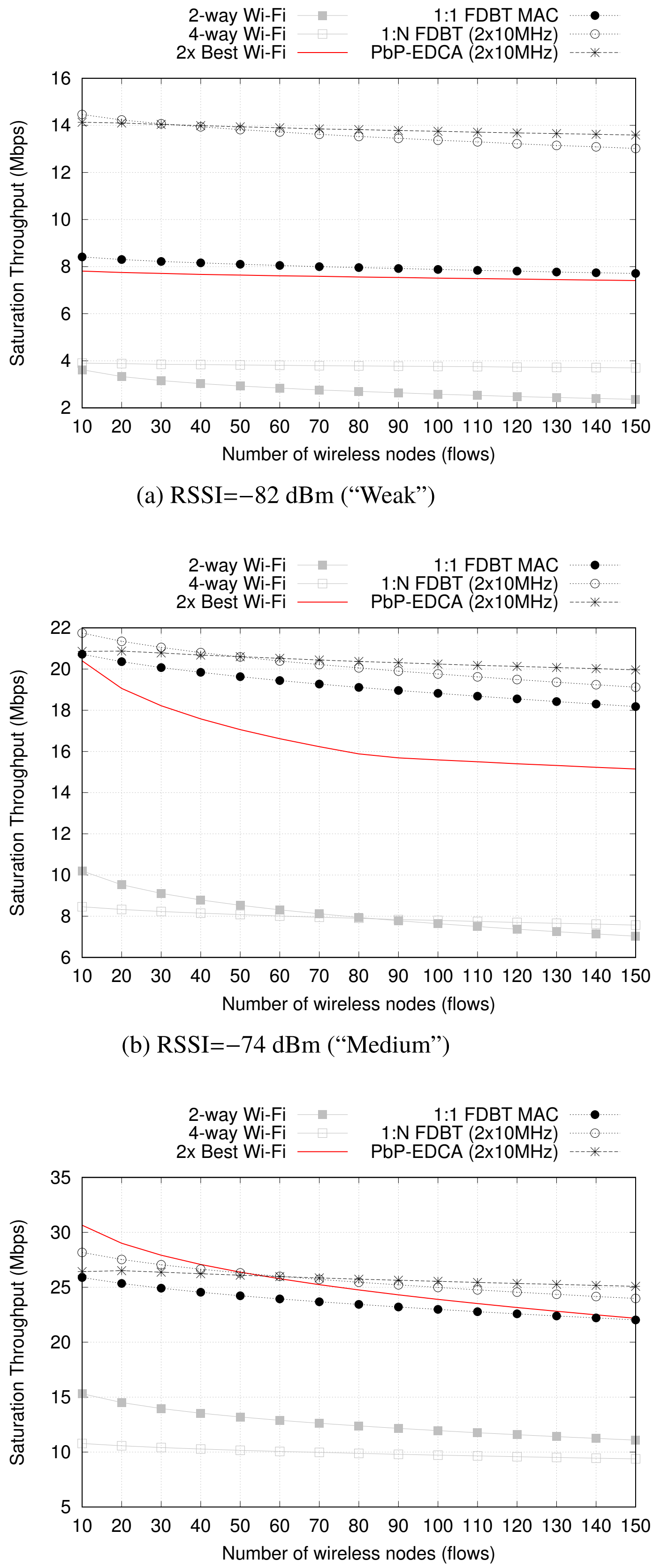


(b) RSSI=−74 dBm (“Medium”)



(c) RSSI=−65 dBm (“Strong”).

Figure B.2: Saturation throughput considering the ‘worst-case’ for FD MAC protocols under ideal SIC.



(a) RSSI=−82 dBm (“Weak”)

(b) RSSI=−74 dBm (“Medium”)

(c) RSSI=−65 dBm (“Strong”).

Figure B.3: Saturation throughput considering the ‘best-case’ for FD MAC protocols under ideal SIC.

Table B.1: MAC Saturation Throughput Under Ideal SIC: Summary of Results.

FD Cases	**FD MAC Protocol**	**Kind of improvement over the IEEE 802.11 Half-Duplex**			**Comparison to 2x the best IEEE 802.11 throughput**		
		More simultaneous transmissions (TXs)?	**Higher total data rate?**	**Lower MAC Overheads?**	**Weak RSSI**	**Medium RSSI**	**Strong RSSI**
Worst	1:1 FDBT	no	no	yes. Can reduce time wasted in collisions; dispenses RTS/CTS	*Cannot Scale*	*Cannot Scale*	*Cannot Scale*
	1:N FDBT	yes, 2x but requires guardband	yes/no depending on the RSSI	no/yes. enlarges time wasted in collisions but dispenses RTS/CTS	*Can Scale*	*Cannot Scale*	*Cannot Scale*
	1:N PbP-EDCA	yes, 2x but requires guardband	yes/no depending on the RSSI	Same as above and reduces collision probability but increases time to access spectrum	*Can Scale*	*Cannnot Scale*	*Cannnot Scale*
Best	1:1 FDBT	yes, 2x	no	Same as in the worst-case	*Can Scale*	*Can Outperform*	*Can scale for large n*
	1:N FDBT	yes, 4x but requires guardband	yes. Same as in worst-case	Same as in the worst-case	*Can Outperform*	*Can Outperform*	*Can outperform for large n*
	1:N PbP-EDCA	yes, 4x but requires guardband	Same as in worst-case	Same as in the worst-case	*Can Outperform*	*Can Outperform*	*Can outperform for large n*

Appendix C

Scripts to Calculate MAC Saturation Throughput

This Appendix presents algorithms to facilitate the reproduction of the MAC saturation throughput reported in this thesis.

Section C.1 presents the function `BianchiPbPEDCAMarkovModel` developed in this work to calculate saturation throughput for the following MAC protocols: IEEE 802.11 2-way and 4-way, Full Duplex FDBT (1:1 or 1:N) and Full-Duplex PbP-EDCA. The entire script is written in the GNU Octave sintax. The saturation throughput for all protocols are calculated based on the probabilities `tau` and `p` that a single station transmits or collides, respectively. The function `BianchiPbPEDCAMarkovModel` calculates `tau` and `p` according to [Bianchi, 2000],[Bianchi, 1998]. In particular for PbP-EDCA, these probabilities are calculated as in [Queiroz, 2013]. The capacity for PbP-EDCA with $N > 2$ channels is calculated following [Queiroz and Hexsel, 2015]. Be aware that the model model does not account guard-bands overheads on MAC layer.

Section C.2 provides the reader with an example of usage of the `BianchiPbPEDCAMarkovModel` function. The function is meant to support all MAC and PHY parameters of IEEE 802.11a/g [IEEE, 2012]. The reader is welcome to enhance (and share) this script with novel models and latter IEEE 802.11 parameters by sending patches to the author's git repository [Queiroz, 2016b].

Section C.3 present lookup algorithms that select the highest possible data rate for FD MAC protocols given the highest supported rate assumed for an IEEE 802.11 half-duplex MAC protocol.

C.1 GNU Octave Function to Calculate MAC Saturation Throughput

```
%    Performance model for the PbP-EEDCA MAC Protocol
%    Copyright (c) 2014 Saulo Queiroz (ssaulojorge@gmail.com).
```

```
%    All rights reserved.
%    This program is free software: you can redistribute it and/or modify
%    it under the terms of the GNU General Public License as published by
%    the Free Software Foundation, either version 3 of the License, or
%    (at your option) any later version.
%    This program is distributed in the hope that it will be useful,
%    but WITHOUT ANY WARRANTY; without even the implied warranty of
%    MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the
%    GNU General Public License for more details.
%    You should have received a copy of the GNU General Public License
%    along with this program.  If not, see <http://www.gnu.org/licenses/>.

%    REMARK. In the below code I focused on readability of the protocol functioning
%         instead of optimality. Notation is as in the paper http://dx.doi.org/10.1145/2695664.2695809
%         Please, cite it if you use this work.

%
%============================>Compute the saturation throughput following the Markovian Bianchi Model
%---------> n = number of nodes
%
%--------->WLANStandard = {0,1,2}
%---> 0 = 802.11a
%---> 1 = 802.11g-only (fast slot duration)
%---> 2 = 802.11g-mixed (slow slot duration, 802.11b legacy)
%
%---------> m = number of backoff stages
%
%---------> W = initial value for the maximum contention window
%
%---------> Tbeta = sensing time the sender node waits before
%                   transmitting in a secondary channel. Zero
%                   for upper-bound studies and for standard EDCA.
%
%--------->channelWidthMHz = {5,10,20} MHz
%
%--------->numberOfChannels integer
%
%--------->dataRateMbps = {6,9,12,18,24,36,48,54}
%    Actually this parameter refers to the modulation scheme
%    employed for data packets. Each modulation scheme is
%    represented by the data rate it achieves in the standard
%    20 MHz wide channel. E.g. BPSK 1/2 => 6Mbps (in 20 MHz).
%    The final data rate also account the channelWidthMHz.
%    E.g. 12 Mbps in 10 MHz leads to 6 Mbps.
%
%--------->controlRateMbps = {6,9,12,18,24,36,48,54}. See dataRateMbps
%
%--------->protectionMode = {0, 1, 2, 3}
%---> 0 no protection. i.e. means two-way handshake (DATA-ACK)
%---> 1 RTS-CTS-DATA-ACK (In all channels in case of PbP-EDCA)
%---> 2 RTS-CTS-DATA-ACK (only on the primary channel either standard of PbP-EDCA)
%---> 3 full-duplex busy-tone (only for PbP-EDCA)
%        references:
%    1)  http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5930070&isnumber=5929998
%    2)  http://doi.acm.org/10.1145/2030613.2030647
%
%--------->btType = {0, 1}
%---> 0 busy-tone carrying no useful data is sent
%---> 1 busy-tone is actually a data packet carrying useful data.
```

```
%       Correspond to the best case for throughput impacting S.
%     REMARK: CHECK IF THROUGHPUT CALCULATION FOR PBP UNDER OPTION 1 IS OK.
%             I STILL DIDN'T NEED THIS SCENARIO.
%
%--------->appLayerPayLoadBytes: size of payload in bytes
%
%--------->transportProtocol = {0,1}
%---> 0 = UDP;
%---> 1 = TCP
%
%--------->ipProtocol = {0,1}
%---> 0 = ipv4;
%---> 1 = ipv6;
%
%====>References
%---> IEEE 802.11-2012 Standard
%---> http://www.oreillynet.com/pub/a/wireless/2003/08/08/wireless_throughput.html?page=1
%---> A Case for Adapting Channel Width in Wireless Networks
function [saturationThroughputMbps, tau, p, Tcol, Ts]= \
         BianchiPbPEDCAMarkovModel(n, WLANStandard, m, W, Tbeta, channelWidthMHz, numberOfChannels, \
          dataRateMbps, controlRateMbps, protectionMode, \
          btType, appLayerPayLoadBytes, transportProtocol, ipProtocol)

  %================>  Preliminaries
  %================>  Preparing MSDU, the MAC payload. It is: app layer + UDP/TCP + IP + LLC
  msduDataBits =  appLayerPayLoadBytes * 8;
  msduDataBits += retTransportProtocolHeaderBits(transportProtocol);
  msduDataBits += retIPHeaderBits(ipProtocol);
  msduDataBits += retLLCHeaderBits();

  %================>  Computing 802.11 Timing Parameters
  % To calculate the time taken by data and headers we need first to
  % calculate the time duration of a single symbol. It depends on the
  % channel width and the WLAN standard.
[TsifsMicroSecs, TdifsMicroSecs, TslotMicroSecs, TsymbolMicroSecs] = compute80211TimingParameters \
(channelWidthMHz, WLANStandard);

  %================>  Computing the Time required to send:
  %  - macpayload (msduDataBits),
  %  - MAC header/fcs and  PHY header of the MSDU frame
  %  - Time taken by ACK, RTS and CTS. Note RTS/CTS returns zero
  %    if they are not enabled.
  [macPayloadTxTimeInMicroSecs, macAndPhyHeadersTxTimeMicroSecs, ackTxTimeInMicroSecs,\
  rtsTxTimeInMicroSecs, ctsTxTimeInMicroSecs] = \
      computeTimeToTx80211FramesWithPhyHeaders (msduDataBits, dataRateMbps, controlRateMbps,\
      TsymbolMicroSecs, channelWidthMHz, WLANStandard, protectionMode);

  %================>  Compute the basic node probabilities: p, tau0, tayC
  % These probabilities refer to the behavio of a node, as capture by the Markov model.
  % p = collision probability (for PbP-EDCA refers to the  primary channel only)
  % tau0 = transmission probability (for PbP-EDCA refers to the  primary channel only)
  % tauC = transmission probability in the C-th secondary channel (zero for standard EDCA)
  % overallTxProbability = system transmission probability
  [p, tau0, tauC, overallTxProbability] = computeMarkovProbabilities (n, m, W, numberOfChannels);
  tau = overallTxProbability;

  %================>  Compute the channel probabilities
  %---------> Basic (preliminary) channel probabilities:
  [Ptr0, Ps0] = basicPreliminaryChannelProbabilities (tau0, n);
```

```
[PtrC, PsC] = basicPreliminaryChannelProbabilities (tauC, n); % zero for standard EDCA
%---------> Channel probabilities
[Psuc0, Pcol0, Pidl0] = basicChannelProbabilities (Ptr0, Ps0);
[PsucC, PcolC, PidlC] = basicChannelProbabilities (PtrC, PsC);


%================>  Computing Saturation Throughput S
%=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-> The denominator of S
%------------------------>  Preliminaries variables
%  H      = duration of phy and mac overheads in microsecs
%  TL     = time in micro secs. to send the MSDU (payload offered by the MAC layer)
%  delta  = prop. delay in microseconds
%  Tack   = duration of ack including its phy overheads
%  Trts   = duration of RTS including its phy overheads
%  Tcts   = duration of CTS including its phy overheads
%  Ts     = Time taken by a successful primary channel transmission
%  Tcol     = Time spent by a collision in the primary channel
%  Tslinha      = Time taken by a successful secondary channel transmission (only PbP)
H = macAndPhyHeadersTxTimeMicroSecs;
TL = macPayloadTxTimeInMicroSecs;
delta = 1; %prop. delay in microsecs (Bianchi)
Tack = ackTxTimeInMicroSecs;
Trts = rtsTxTimeInMicroSecs;
Tcts = ctsTxTimeInMicroSecs;
Ts = H + TL + delta + TsifsMicroSecs + Tack + delta + TdifsMicroSecs;
Tslinha = Ts - TdifsMicroSecs + Tbeta;
Trtsctsprotection = Trts + delta + TsifsMicroSecs + Tcts + delta + TsifsMicroSecs;
% TIME wasted in COLLISIONS also depends on the protection mode
switch (protectionMode)
  case 1
    %-----> RTS/CTS for all PbP channels. You can use this with numberOfChannels==1
    %       for the standard WiFi (PbP extra gains will be zero below) but option
    %       2 is preferable.
    Ts += Trtsctsprotection;
    Tslinha += Trtsctsprotection;
    Tcol = Trts + delta + TdifsMicroSecs;
  case 2
    %-----> RTS/CTS for primary channels either PbP of standard EDCA.
    Ts += Trtsctsprotection;
    Tcol = Trts + delta + TdifsMicroSecs;
  case 3
    %-----> With busy-tones time duration of collisions needs special care ;)
    %       Below function computes Tcol regardless protocol choise: PbP or MAC.
    %       If numberOfChannels==1 then standard IEEE 802.11 with busy tones is
    %       assumed. This works even if the assumed BT is actually data.
    [Tcol, devicesResponseMicroSecs, overallBtHeaderTxTimeMicroSecs] =\
         computeBTCollisionDurationMicroSecs (protectionMode, delta, dataRateMbps,\
         channelWidthMHz, WLANStandard);
  otherwise
    %-----> default: collision with DATA-ACK 2-way handshake mode.
    Tcol = H + TL + delta + TdifsMicroSecs;

    if (protectionMode != 0) % UNEXPECTED CONDITION.
       disp "Protection mode code unknown.";
       if (numberOfChannels > 1)
         disp "Assuming full duplex busy tones for PbP-EDCA";
    [Tcol, devicesResponseMicroSecs, overallBtHeaderTxTimeMicroSecs] =\
       computeBTCollisionDurationMicroSecs (protectionMode, delta, dataRateMbps,\
       channelWidthMHz, WLANStandard);
```

```
      else
        disp "Assuming two-way handshake for standard 802.11 EDCA";
      endif
    endif
endswitch

%  NsigmaTL     = Number of empty time slots that fits into the TL time interval
%  NsigmaSlinha = Number of empty time slots that fits into the Tslinha time interval
NsigmaTL = ceil (TL/TslotMicroSecs);
NsigmaSlinha = ceil (Tslinha/TslotMicroSecs);

%=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=> The numerator of S
%------------------------>  Preliminaries
%---------> Expected payload for primary channels (S numerator part A)
% expectedpayLoad = E[L] = payload in primary channel
L =  msduDataBits;
if (btType == 1)
  if (protectionMode != 3) % UNEXPECTED CONDITION.
    disp "protectionMode should be 3 if btType is 1!!";
    disp "Assuming your protection carries no useful payload!";
  else
    %---------> the FD WiFi MAC protocol "ensures the secondary transmission ends
    %           ends no later than the primary transmission" (contraflow). This means
    %           that the secondary transmission can be completed with busy-tones if
    %           it is transmission is too small.
    %---------> To assess the upper bound capacity one MUST assume the
    %           secondary transmission consists only in useful data. Thus
    %           the payload added to the secondary transmission in a
    %           successful time slot is L (same payload added by PT) MINUS
    %           the payload that the secondary transmiter could add in
    %           in the channel during the time H, i.e. header of the BT.
    %           This is because the secondary transmission starts only
    %

    %------------------------> How long ST wait until starting sending it BT (ST data packet)
    timeBeforeSendingBTInMicroSecs = overallBtHeaderTxTimeMicroSecs + devicesResponseMicroSecs;

    %------------------------> How many OFDM symbols could be sent during the above time
    timeBeforeSendingBTInNumberOfOFDMSymbols = floor(timeBeforeSendingBTInMicroSecs / TsymbolMicroSecs);

    %------------------------> How many bits could be sent during the above time.
    %                           i.e. number of bits per symbol (4R) x symbol duration
    %                           already rescaled by channel width
    timeBeforeSendingBTInBits = 4 * dataRateMbps * timeBeforeSendingBTInNumberOfOFDMSymbols;
    %-- showing how much useful bytes N are wasted in collisions winthin each channel width.
    %  A side note is, when collision does not happen the secondary transmission carries the
    %  same data of bytes of primary’s MINUS N.
    %disp (channelWidthMHz)
    %disp (timeBeforeSendingBTInBits/8);
    %========================> Maximum payload added by the secondary transmission ensuring
    %                           that it finishes no longer than the primary one.
    L += (L - timeBeforeSendingBTInBits);
 endif
endif

%---------> checking whether it is PbP
Ldelta = 0;

%---------> Expected (average) payload in the primary channel.
```

```
  %      We assume a system where all packets have the same size.
  primaryChannelPayload = Psuc0 * L;

  %---------> Most precise model for PbP with N>2 i.e. 5
  % REF:Saulo Queiroz and Roberto Hexsel. 2015. Translating full duplexity
  %     into capacity gains for the high-priority traffic classes of IEEE 802.11.
  %     In Proceedings of the 30th Annual ACM Symposium on Applied Computing (SAC '15).
  %     ACM, New York, NY, USA, 634-639. DOI: http://dx.doi.org/10.1145/2695664.2695809
  if (numberOfChannels > 2)
    %---------> Expected payload for secondary channels (S numerator part B)
    %   Lsuc and Lcol are the expected secondary payLoad when primary channel
    %  either contains a successful transmission or a collision, respectively.
    %   OBS.: This part becomes zero (below) in the throughput for the standard EDCA
    Lcol = Lsuc = L / 2;

    %---------> Expected payload Lsigma for secondary channels when primay is idle
    Lsigma = msduDataBits*(TslotMicroSecs/TL)*(NsigmaTL/NsigmaSlinha);


    %---------> Expected (average) secondary channel payload when
    %  there is a collision in the primary channel and a successful
    %  transmission in the secondary channel c
    secondaryPayloadWhenPrimaryCollides = (Pcol0 * PsucC) * Lcol;

    %---------> Expected (average) secondary channel payload when
    %  there is a successful transmission in the primary and
    %  secondary channels, respectively secondary channel c
    secondaryPayloadWhenPrimarySucceeds = (Psuc0 * PsucC) * Lcol;

    %---------> Expected (average) secondary channel payload when
    %  time slot is empty in the primary channel
    secondaryPayloadWhenPrimayIsEmpty = (Pidl0 * PsucC) * Lcol;

    %---------> Total expected (average) added by all secondary channels
    % Note that Nc = 1 for the standard IEEE 802.11 EDCA, then Ldelta = 0.
    % Note also that, choosing 1 channel (standard WLAN) nullifies the
    % throughput of the PbP secondary channels.
    Ldelta = (numberOfChannels - 1)*(secondaryPayloadWhenPrimaryCollides + \
             secondaryPayloadWhenPrimarySucceeds + secondaryPayloadWhenPrimayIsEmpty);
  endif

  %---------> Numerator/Denominator for IEEE 802.11 and FDBT
  saturationThroughputSNumerator = primaryChannelPayload + Ldelta;
  saturationThroughputSDenominator = Psuc0 * Ts + Pcol0 * Tcol +  Pidl0 * TslotMicroSecs;

  %=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-=-> The EDCA / PbP-EDCA Saturation Throughput S
  %---------> S in bits per micro seconds
   S = saturationThroughputSNumerator / saturationThroughputSDenominator;

  %---------> Most precise model for PbP with N=2
  if (numberOfChannels == 2)
    %---------> Numerator/Denominator PbP-EDCA secondary channel. tdifs=tbetas
    S2 = (PsucC * L)  / (PsucC * (Ts + TdifsMicroSecs) + PcolC * Tcol +  PidlC * TslotMicroSecs);
    S += S2;
  endif
  %---------> S in megabits per second
  %           Online calculator: http://www.endmemo.com/convert/data%20transfer.php
  saturationThroughputMbps = S * 0.953674;
endfunction
```

```
% With full-duplex busy-tones (employed by the primary receiver PR to protect
% primary transmission) time spent in collision depends on how long the
% primary transmitter PT waits the PR’s busy-tone. A too long value implies
% in long collision duration. In turn, too short value leads the PT to
% unnecessarily stop data transmission to the PR. To compute it one estimates
% how long a successful response would be. If, within this time, no BT signal
% is detected by the PT, then it assumes a collision.
%   - H : the duration of PT’s header (MAC and PHY). NOTE THAT, one
%         could guess to not account this value by arguing that PT can start the
%         expiration time just after sending the PT’s header. However if a
%         collision occurs the time taken by header wasted, locking the channel.
%   - delta : the propagation delay of the data header and the expected BT.
%   - H : In the worst-case (regarding time) PR (secondary transmitter ST) will send
%         a data packet instead as BT. Then
%   - btStartTimeLatency: the ("non-negligible") time ST needs to process H and
%              starts the busy-tone transmission (which also takes its own delta).
%              The below references claim to achieve <1us and ~11us respectivelly.
%              1) Efficient and fair MAC for wireless networks with self-interference cancellation
%                 http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5930070&isnumber=5929998
%                 "Once a packet header is RECEIVED by a primary receiver, it is able to transmit the
%                  secondary packet in less than 1 micro-sec, a delay which is acceptable
%                  even for the most advanced PHY layers."
%              2) Practical, Real-time, Full Duplex Wireless
%                 http://doi.acm.org/10.1145/2030613.2030647
function [Tcol, devicesResponseMicroSecs, overallBtHeaderTxTimeMicroSecs] =\
    computeBTCollisionDurationMicroSecs (protectionMode, delta, dataRateMbps,\
                                         channelWidthMHz, WLANStandard)
 %-------> useful parameters
 [TsifsMicroSecs, TdifsMicroSecs, TslotMicroSecs, TsymbolMicroSecs] = compute80211TimingParameters\
 (channelWidthMHz, WLANStandard);

  %=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+> DEVICE CARD RESPONSE TO INCOMMING HEADER
  devicesResponseMicroSecs = 11;

  %=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+> OVER-THE-AIR RELATED PARAMETERS
  %=========================> Computing BT MAC Headers. For further explanations please
  %                           see function computeTimeToTx80211FramesWithPhyHeaders.
  %---------------> FCS trailer bits are overheads but are appended at
  %                 the end of the MSDU. Then they don’t account to
  %                 compute the duration of header for BT purposes.
  [macHeaderBits, macFCSTrailerBits] = ret80211MACOverheadsBits();
  btMacHeaderBits = macHeaderBits;
  %--------------->RECALL that number of symbols remains the same irrespective of
  %                channel width, cw affects only the duration of symbol as well as
  %                other related parameters
  btMacHeaderInNumberOfOFDMSymbols = computeNumberOfOFDMSymbols(btMacHeaderBits, dataRateMbps);
  btMacHeaderTxTimeInMicroSecs = TsymbolMicroSecs * btMacHeaderInNumberOfOFDMSymbols;

  %=========================> Computing BT PHY Headers.
  %---------------> As in the above logic, tail and pad bits don’t account for the
  %                 BT header because they are appended at the end of the PSDU
  %--------------->  Rate dependent PHY overheads
  [servicePhyBits, tailPhyBits] = retRateDependentPhyOverHeadBits();
  btRateDependentPhyHeaderBits = servicePhyBits;
  %---------> Number of symbols for rate dependent phy header bits
  btRateDependentPhyHeaderInNumberOfOFDMSymbols = \
      computeNumberOfOFDMSymbols(btRateDependentPhyHeaderBits, \
      dataRateMbps);
```

```
  %---------> Time to send rate dependent PHY overheads
  btRateDependentPhyHeaderTxTimeInMicroSecs = \
          TsymbolMicroSecs * btRateDependentPhyHeaderInNumberOfOFDMSymbols;

  %--------------->  Constant rate PHY overheads
  %---------> Time to send the PHY overheads
  [plcpPreambleMicroSecs, plcpHeaderMicroSecs, signalExtensionMicroSecs] = \
      retFixedPhyOverheads(channelWidthMHz, WLANStandard);
  btConstantRatePhyHeaderTxTimeInMicroSecs = plcpPreambleMicroSecs + plcpHeaderMicroSecs;

  %--------->  Time duration of overall PHY overheads
  btPhyHeaderTxTimeInMicroSecs = btRateDependentPhyHeaderTxTimeInMicroSecs + \
                                 btConstantRatePhyHeaderTxTimeInMicroSecs;

  %==========================> Time to send all MAC and PHY overheads (H in the paper)
  overallBtHeaderTxTimeMicroSecs = btPhyHeaderTxTimeInMicroSecs + btMacHeaderTxTimeInMicroSecs;

  %=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+> COLLISION DURATION from EXPIRING
  %                                      TIME before declaring collision
  %---------------> To calculate how long wait we estimate how long a normal process
  %                 would take.
  %---------------> PT's header and its propag. time + response time + busy tone
  %                 header and its propag. time. THIS IS REQUIRED TO PREDICT
  %                 THE UPPER-BOUND CAPACITY.
  Tcol = 2*(overallBtHeaderTxTimeMicroSecs + delta) + devicesResponseMicroSecs;
endfunction

function  [Ptr, Ps] = basicPreliminaryChannelProbabilities (tau, n)
  Ptr = 1 - (1 - tau)^n;
  %----> tau = 0 means the probability to access the PbP-EDCA secondary channel
  %      in the standard EDCA, for instance
  if (Ptr != 0)
    Ps  = (n * tau * (1 - tau)^(n-1)) / Ptr;
  else
    Ps = 0;
  endif
endfunction

function  [Psuc, Pcol, Pidl] = basicChannelProbabilities (Ptr, Ps)
  Psuc = Ps * Ptr;
  Pcol = (1 - Ps) * Ptr;
  Pidl = (1 - Ptr);
endfunction

%
function [p, tau0, tauC, overallTxProbability] = computeMarkovProbabilities (n, m, W, numberOfChannels)
  %---------> Solving the non-linear system of equations between tau0 and p
  %           value of p and tau0 will be assigned to x(1) and x(2), respectively.
  [x,info]= fsolve(@(x) tau0pSystemOfEquantions(x, n, m, W, numberOfChannels), [0.00001;0.99999]);
  p = x(1);
  tau0 = x(2);
  if (numberOfChannels == 1)
    tauC = 0;
    overallTxProbability = tau0;
  else
    tauC = (1-p)*tau0;
    overallTxProbability = tau0 + (numberOfChannels-1)*tauC;
  endif
endfunction
```

```
function y=tau0pSystemOfEquantions(x, n, m, W, Nc)
  %p==x(1) and tau0 == x(2) and
  %y(1) = b000/(1-x(1)) - x(2);
  % Note that when Nc=1 (PbP-EDCA becomes the standard EDCA) tau0 becomes
  % Eq. 6 of 'Performance Analysis of the IEEE 802.11 Distributed Coordination Function'
  % G. Bianchi, JSAC 2000.
  y(1) = ((2*(1-2*x(1))) / ((1-2*x(1))*(W+1) + \
         x(1)*W*(1-(2*x(1))^m) + (Nc-1)*(1-x(1))*(2*W)*( 1 - x(1)*(1+ (2*x(1))^m)))) - x(2);

  % Bianchi's transmission probability tau (tau0 for PbP-EDCA)
  % as function of the collision probability:
  % p = 1 - (1 - tau0)^(n-1) => 0 = - p + 1 - (1 - tau0)^(n-1)
  y(2)=-x(1)+1-(1-x(2))^(n-1);
endfunction


% Given bytes from the layer above MAC we compute:
% -> time to send the mac payload (msdu)
% -> time to send the mac overheads (header and trailer-fcs)
% -> time to send the phy overheads (plcp header and preambles
% -> time to send 802.11 overhead frames with their respective
%    PHY overheads (ACK + PHY headers and  RTS/CTS + PHY headers)
function [macPayloadTxTimeInMicroSecs, macAndPhyHeadersTxTimeMicroSecs, ackTxTimeInMicroSecs, \
         rtsTxTimeInMicroSecs, ctsTxTimeInMicroSecs] = \
           computeTimeToTx80211FramesWithPhyHeaders (msduDataBits, dataRateMbps, controlRateMbps,\
                                                     TsymbolMicroSecs, channelWidthMHz, WLANStandard,\
                                                     protectionMode)
  %=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+> Time to send MPDU = MAC HEADERS + MSDU (mac payload)
  %==========================> Preparing the MAC overheads (header and trailer)
  % mac overheads are sent at the same data rate chosen for payload.
  % Note that: mpduDataBits = msduDataBits + macHeaderOfDataBits;
  [macHeaderBits, macFCSTrailerBits] = ret80211MACOverheadsBits();
  macHeaderOfDataBits = macHeaderBits + macFCSTrailerBits;

  %==========================> Computing number of symbols for MPDU
  %---------> Number of symbols for the MAC payload. RECALL number of symbols
  %           remains the same irrespective of channel width, cw affects only
  %           the duration of symbol as well as other related parameters
  msduDataInNumberOfOFDMSymbols = computeNumberOfOFDMSymbols(msduDataBits, \
                                                             dataRateMbps);
  %---------> Number of symbols for MAC overheads
  macHeaderOfDataBitsInNumberOfOFDMSymbols = \
            computeNumberOfOFDMSymbols(macHeaderOfDataBits, dataRateMbps);

  %==========================> Computing the time to send the MPDU symbols
  %---------> Time to send only the MAC payload (denoted as TL in the paper).
  macPayloadTxTimeInMicroSecs = TsymbolMicroSecs * msduDataInNumberOfOFDMSymbols;
  %---------> Time to send MAC (Hmac in Bianchi paper)
  macHeaderTxTimeInMicroSecs = TsymbolMicroSecs * macHeaderOfDataBitsInNumberOfOFDMSymbols;

  %=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+> Time to send PPDU = PHY HEADERS + PSDU (PHY payload)
  % The 802.11a/g PHY layer has two type of overheads:
  % 1) Overheads sent at the data rate chosen for the MPDU i.e. Service field of the PLCP header,
  %  tail and pad bits, this latter is added to the PHY payload to make it multiple of the total
  %  data bits carried in a symbol generated at a given data rate (added later).
  % 2) Overheads sent at a constant data rate i.e. Preamble and firsts 24 bits (of 40) of the PHY header.
  %    are sent at a constant rate (BPSK 1/2 which yields 6 Mbps in 20 MHz).
  %      See section 18.3.2.1 of 802.11-2012.
```

```
% REMARK.: the preamble has its own "tail bits" sent at BPSK 1/2.
%          Below refers to the data rate dependent "tail bits".
%==========================> Preparing rate dependent PHY overheads
[servicePhyBits, tailPhyBits] = retRateDependentPhyOverHeadBits();
rateDependentPhyHeaderBits = servicePhyBits + tailPhyBits;
%---------> Number of symbols for rate dependent phy header bits
rateDependentPhyHeaderInNumberOfOFDMSymbols = computeNumberOfOFDMSymbols(rateDependentPhyHeaderBits, \
                                                                          dataRateMbps);
%---------> Time to send rate dependent PHY overheads
rateDependentPhyHeaderTxTimeInMicroSecs = \
           TsymbolMicroSecs * rateDependentPhyHeaderInNumberOfOFDMSymbols;

%==========================> Constant rate PHY overheads
%--> Time to send the PHY overheads (Hphy in the paper)
[plcpPreambleMicroSecs, plcpHeaderMicroSecs, signalExtensionMicroSecs] = \
        retFixedPhyOverheads(channelWidthMHz, WLANStandard);

constantRatePhyHeaderTxTimeInMicroSecs = plcpPreambleMicroSecs + plcpHeaderMicroSecs +\
               signalExtensionMicroSecs;

%==========================> Time duration of overall PHY overheads
phyHeaderTxTimeInMicroSecs = \
   rateDependentPhyHeaderTxTimeInMicroSecs + constantRatePhyHeaderTxTimeInMicroSecs;

%--> Time to send all MAC and PHY overheads (H in the paper)
macAndPhyHeadersTxTimeMicroSecs =\
   macHeaderTxTimeInMicroSecs + phyHeaderTxTimeInMicroSecs;


%=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+> Preparing ACK ...
%--> The 802.11 ACK is only 14 bytes and doesn't have TCP/UDP, IP and LLC layers.
ackBits = 112;
%--> Passing ACK to PHY also adds service and tail bits.
%    Since ACK "payload" is also overhead, we handle it
%    the others overheads sent under the same (control) rate.
ackBits += (servicePhyBits + tailPhyBits);

%==========================> Computing the number of symbols   XXX
%---------> Number of symbols of the ACK. Note it is sent at rate controlRateMbps
ackInNumberOfOFDMSymbols = computeNumberOfOFDMSymbols(ackBits, controlRateMbps);

%==========================> Computing the time to send the symbols
%---------> Time to send only the ACK without and PHY overheads
ackTxTimeInMicroSecs = TsymbolMicroSecs * ackInNumberOfOFDMSymbols;

%--> Adding the PHY overheads (PLCP and Preamble). Note it is the
%    same as for data frames since it always use same modulation
%    irrespective of the type of 802.11 frame (control,data,mngt.)
ackTxTimeInMicroSecs += constantRatePhyHeaderTxTimeInMicroSecs;

%================>  Computing the Time of one RTS and one CTS if needed.
if (protectionMode == 1 || protectionMode == 2)
  %--> The 802.11 RTS and CTS are 20 and 14 respectively. They don't have TCP/UDP, IP and LLC layers.
  rtsBits = 160;
  ctsBits = 112;
  %--> Passing RTS and CTS to PHY also adds service and tail bits
  rtsBits += (servicePhyBits + tailPhyBits);
  ctsBits += (servicePhyBits + tailPhyBits);
```

```
    %===========================> Computing the number of symbols
    %---------> Number of symbols of RTS and CTS. Note they are sent at rate controlRateMbps
    rtsInNumberOfOFDMSymbols = computeNumberOfOFDMSymbols(rtsBits, controlRateMbps);
    ctsInNumberOfOFDMSymbols = computeNumberOfOFDMSymbols(ctsBits, controlRateMbps);

    %===========================> Computing the time to send the symbols
    %---------> Time to send only the RTS and CTS without and PHY overheads
    rtsTxTimeInMicroSecs = TsymbolMicroSecs * rtsInNumberOfOFDMSymbols;
    ctsTxTimeInMicroSecs = TsymbolMicroSecs * ctsInNumberOfOFDMSymbols;

    %--> Adding the PHY overheads (PLCP and Preamble). Note it is the
    %    same as for data frames since it always use same modulation
    %    irrespective of the type of 802.11 frame (control,data,mngt.)
    rtsTxTimeInMicroSecs += constantRatePhyHeaderTxTimeInMicroSecs;
    ctsTxTimeInMicroSecs += constantRatePhyHeaderTxTimeInMicroSecs;
  else
    rtsTxTimeInMicroSecs = ctsTxTimeInMicroSecs = 0;
 endif
endfunction


% The time taken to send the PLCP header and preamble does not depend
% on the set data rate. The standard mandates that the header (without
% the service bits) must be sent at BPSK 1/2 (which yields 6 Mbps in
% 20 MHz). Thus the PLCP header takes only one symbol (4 micro secs
% in 20 MHz channel).  The PLCP preamble consists in the first set of
% signals sent and are used only for synchronization purposes. It
% takes 16 micro seconds. See sections 18.3.2 'PLCP Frame Format' and
% 18.3.3 'PLCP preamble (SYNC)' in the IEEE 802.11-2012 standard.
function [plcpPreambleMicroSecs, plcpHeaderMicroSecs, \
          signalExtensionMicroSecs] = retFixedPhyOverheads(channelWidth, WLANStandard)
  scalingRatio = 20 / channelWidth;

  plcpPreambleMicroSecs = 16 * scalingRatio;
  plcpHeaderMicroSecs = 4 * scalingRatio;
  switch (WLANStandard)
    case 0
       signalExtensionMicroSecs = 0;
    case 1
      signalExtensionMicroSecs = 6;
  endswitch
endfunction

function [TsifsMicroSecs, TdifsMicroSecs, TslotMicroSecs, TsymbolMicroSecs] = \
    compute80211TimingParameters (channelWidth, WLANStandard)
  % similar to Chandra et al 2008, we use a scalling ratio
  % to recalculate all 20 MHz-based timing parameters to
  % the value corresponding to channelWidth
  scalingRatio = 20 / channelWidth;

  %OBS.: To improve readibility we will set each parameter
  %      aside from each other even if they share some
  %      test conditions.

  %======> Calculating the standard 20MHz SIFS
  %        in microseconds (us).
  %        It depends on the WLAN standard.
  switch (WLANStandard)
    case 0 % 802.11a
```

```
      T_20MHz_sifs = 16;
    case 1 % 802.11g-only
      T_20MHz_sifs = 10;
    case 2 % 802.11g-mixed
      T_20MHz_sifs = 10;
  endswitch

  %======> SLOT duration depends standard and channel width
  %         but cannot be computed from the scaling ratio.
  if (WLANStandard == 2)
    % if there is no legacy, 11g BSS can
    % employ the slow (long) slot duration
    % IEEE 802.11-2012 standard, section 19.4.5
    TslotMicroSecs = 20;
  else
    % In case of 11a or 11g-only, short preamble
    % is enabled for 20 MHz i.e. 9 us. See sections 18.3.8.7
    % and 19.4.5 of IEEE 802.11-2012 standard, respectivelly.
    switch (channelWidth)
      case 20
       TslotMicroSecs = 9;
      case 10
       TslotMicroSecs = 13;
      case 5
       TslotMicroSecs = 21;
    endswitch
  endif

  %======> Symbol duration time for the standard 20 MHz chanel
  T_20MHz_symbol = 4;

  %======> Resizing timing parameters according to channel width (scale)
  TsymbolMicroSecs = T_20MHz_symbol * scalingRatio;
  TsifsMicroSecs = T_20MHz_sifs * scalingRatio;
  TdifsMicroSecs = 2*TslotMicroSecs + TsifsMicroSecs;
endfunction


function [numberOfOFDMSymbols] = computeNumberOfOFDMSymbols(psduDataBits, dataRateMbps)
  % 1. Calculate the number of bits per OFDM symbol at rate dataRateMbps
  %  See Section 18.3.2.3 "Modulation-dependent parameters" Table 18-4
  %  IEEE Std 802.11-2012. Corresponds to N_{DBPS} in the table
  numberOfDataBitsPerSymbol = 4 * dataRateMbps;

  % 2. Calculating the number of OFDM symbols required to transmit psduDataBits bits
  %  (Section 18.3.5.4 "Pad bits (PAD)" Equation 18-11; IEEE Std 802.11-2012)
  % Note that the pad bits are implicit in the ceil function.
  numberOfOFDMSymbols = ceil (psduDataBits / numberOfDataBitsPerSymbol);
endfunction

  % see section 'Pad bits (PAD)' (number 18.3.5.4 or 17.3.5.3 in 802.11-2012,
  % 802.11-2007, respec.)
function [servicePhyBits, tailPhyBits, padPhyBits] = \
         retRateDependentPhyOverHeadBits(psduBits, dataRateMbps)
  servicePhyBits =  16;
  tailPhyBits = 6;
endfunction

function [tpOverheadBits]=retTransportProtocolHeaderBits(transportProtocol)
```

```
  switch (transportProtocol)
    case 0
      tpOverheadBits = 64; % UDP Header in bits: 8 bytes * 8
    case 1
      tpOverheadBits = 160; % TCP Header (without options) in bits: 20 bytes * 8
  endswitch
endfunction

function [ipOverheadBits]=retIPHeaderBits(ipProtocol)
  switch (ipProtocol)
    case 0
      ipOverheadBits = 160; % IPv4 Header (without options) in bits: 20 bytes * 8
    case 1
      ipOverheadBits = 320; % IPv6 Header (without options) in bits: 40 bytes * 8
  endswitch
endfunction

function [llcOverheadBits]=retLLCHeaderBits()
  llcOverheadBits = 64; % 8 bytes * 8
endfunction

function [macHeaderBits, macFCSTrailerBits]=ret80211MACOverheadsBits()
  macHeaderBits = 192; %24 bytes * 8;
  macFCSTrailerBits = 32; % 4 bytes * 8
endfunction

function totalSymbols = numberOfSymbols(totalBits, dataRateMbps)
  % Computing the Ndbps (as established by IEEE 802.11 standards)
  % At least in 802.11g/a, a single symbol encodes 4xR bits
  % given a modulation R = {6,9,12,18,24,48,54}
  % (IEEE Std 802.11-2007, section 17.3.2.2, table 17-3)
  dataBitsPerOFDMSymbol = nominalRate * 4;

  % ceil means: if we need n<1 symbol, we need 1 symbol
  totalSymbols = ceil(totalBits / dataBitsPerOFDMSymbol);
endfunction

%  /* COMPOSITION OF DATA FRAMES
%   * ==================> 1.PPDU = PSDU + PHY Headers/Overheads
%   * | |========================================> 1.1 PSDU = the payload of the PHY Layer i.e. the MPDU
%   * | |=========================> 1.1.1 MPDU = MAC Headers/overheads + MDSU
%   * | |  |===================> 1.1.1.1 MAC Headers/overheads
%   * | |  |  |==========> MAC header  = 24 bytes
%   * | |  |  |==========> MAC Frame Check Sequence (trailer) = 4 bytes
%   * | |  |===================> 1.1.1.2 MSDU i.e. the payload of the MAC frame
%   * | |  |  |==========> Application layer Payload = 1460
%   * | |  |  |==========> UDP/TCP header = 8 bytes
%   * | |  |  |==========> IP header = 20 bytes
%   * | |  |  |==========> LLC header = 8 bytes
%   * |========================================> 1.2 PHY Headers/Overheads
%   * | |==========> 1.2.1 PHY PLCP Preamble = (20/BW)*16 microseconds
%   * | |==========> 1.2.2 PHY PLCP Header = (20/BW)*4  microseconds
%   * OBS: in the 802.11 implementation of NS3 the standard values are in the below methods
%   * WifiPhy::GetPlcpPreambleDurationMicroSeconds e WifiPhy::GetPlcpHeaderDurationMicroSeconds
%   * Total = 1524 corresponde a MACTotalDataFrameSizeInBits
%   */

function [phyHeaderDurationMicroSecs, phyPayloadDurationMicroSecs] = \
         calculatePPDUDurationMicroSecs(a,b)
```

```
        phyHeaderDurationMicroSecs = a;
endfunction

% Compute the Physical Protocol Data Unit in bytes,
% i.e. PSDU (PHY Payload) + PCLP Header + PLCP Preamble
function [psduBytes]=calculatePSDUSize(appLayerPayLoadBytes,transportProtocol)
  % the MPDU (MAC payload + headers) is the PHY payload, i.e. the PSDU
  psduBytes = calculateMPDUSize(appLayerPayLoadBytes,transportProtocol);
endfunction

% Compute the time overhead (in micro-seconds)
% introduced by the PHY Layer, i.e. plcpPreamble, plcpHeader
function [plcpHeaderMicroSecs, plcpPreambleMicroSecs, \
      signalExtensionMicroSeconds]=calculatePhyOverhead(WLANStandard)
  % The 802.11a/g PHY headers are in BPSK 1/2 which
  % yields 6 Mbps in 20 MHz channels
  plcpHeaderMicroSecs =  4;
  plcpPreambleMicroSecs = 16;
  switch (WLANStandard)
  case 0
    % 802.11a
    signalExtensionMicroSeconds = 0;
  case 1
    % 802.11g
    signalExtensionMicroSeconds = 6;
  case 2
    %not working
  endswitch
endfunction


% Compute the MAC Protocol Data Unit in bytes, i.e. MSDU + MAC Header + Trailler
function [mpduBits]=calculateMPDUSize(appLayerPayLoadBytes,transportProtocol)
  % calculate the MAC payload
  msduBits = calculateMSDUSize(appLayerPayLoadBytes,transportProtocol);
  macHeaderBits = 192; %24 bytes * 8;
  macTrailerFCSBits = 32; % 4 bytes * 8
  mpduBits = msduBits + macHeaderBits + macTrailerFCSBits;
endfunction

% Compute the MAC payload (i.e. the MSDU) in Bytes
function [msduBits]=calculateMSDUSize(appLayerPayLoadBytes,transportProtocol)
  msduBits = appLayerPayLoadBytes*8;
  switch (transportProtocol)
    case 0
      % UDP
      msduBits += 64; % 8 bytes * 8
    case 1
      % TCP (standard without optional fields)
      msduBits += 160; % 20 bytes * 8
  endswitch
  msduBits += 64; % LLC Header: 8 bytes * 8
endfunction
```

C.2 Example of Usage

The below script calculates the network saturation throughut (`S`), station probability of collision (`p`) and station probability of transmission (`tau`) in a 50-node IEEE 802.11a WLAN, with 10 MHz bandwidth managed by the 1:1 FDBT in the best case. It requires the function `BianchiPbPEDCAMarkovModel` presented in the Secion C.1. Be aware that the input parameters `dataRateMbps` and `dataRateMbps` must be given with respect to the standard IEEE 802.11 bandwidth of 20 MHz. The function `BianchiPbPEDCAMarkovModel` rescales all standard MAC and PHY parameters internally according to the input parameter `Bw`. The only valid values for `Bw` are those supported in the IEEE 802.11a/g, namely, `20`, `10` and `5` [IEEE, 2012].

```
% -------------------> setting parameters
n=50; Bw=10; N=1; WLANStandard = 0; Tbeta = 0; transportProtocol = 0; ipProtocol = 0;
dataRateMbps = 6; controlRateMbps = 6;
%note that the below variable determines the mac payload along with
%the constant size of all headers (ip, udp/tcp,mac)
appLayerPayloadBytes = 500;
btType = 1; % use FD secondary transmission rather than RTS/CTS.
protectionMode = 3; % FD best-case: protection performed with data frames rather than busy tones
W = 16; % minimum backoff window (random number from 0 to 15)
m = 6;% number of back-off stages
transportProtocolHeaderSize = 0; % udp
ipProtocolHeaderSize = 0; % ip
% -------------------> Calculating the throughput
[S, tau, p, Tcol, Ts] = BianchiPbPEDCAMarkovModel(n, WLANStandard, m, W, Tbeta, Bw, N,\
                   dataRateMbps, controlRateMbps, protectionMode, btType, \
                   appLayerPayloadBytes, transportProtocolHeaderSize, ipProtocolHeaderSize);
```

C.3 FD Data Rate Selection

This Section presents lookup algorithms that give the highest supported data rate for an IEEE 802.11-based FD MAC protocol.The input is the highest supported data rate assumed for a 20 MHz IEEE 802.11 half-duplex channel. Based on the input, the algorithm determines the implicit Received Signal Strength Indication (RSSI) of the channel. Then, for the FD MAC protocols, such RSSI is penalized with the Residual Self-Interference (RSI) proper of FD radios. If one is looking for the highest equivalent data rate in 10 MHz and 5 MHz Wi-Fi channels, the reference RSSI is improved by 3 dB or 6 dB, respectivelly (see Table 4.3). The equivalent RSSIs that result from such calculations determines the highest suported data rate for the FD channel of 20 MHz, 10 MHz and 5 MHz. These respective values are returned in the variables `maxDataRateMbpsFor20MHzFD`, `maxDataRateMbpsFor10MHzFD` and `maxDataRateMbpsFor5MHzFD` of the GNU Octave algorithm `maxModulationGivenHalfDuplex20MHz` presented in subsection C.3.1. **Be aware these returned rates for 10 MHz and 5 MHz are meant as input for the `BianchiPbPEDCAMarkovModel` throughput function. Thus they be rescaled later on.**

If one assumes RSI is negligible – as shown feasible for 20 MHz channel [Bharadia et al., 2013], [Korpi et al., 2016a]) – then FD benefits from the same data rate assumed for half-duplex in the same channel width. Thus, the algorithm C.3.1 makes sense only for channels narrower than 20 MHz being rewritten as the algorithm presented in subsection C.3.2.

C.3.1 Data Rate Selection for FD Channels under RSI of 1 dB

```
%==============> For below discussion see Receiver Minimum Input Sensitivity
%                (RMIS) Table 18-14 (IEEE Std. 802.11-2012)
%--------------- Please, see comments on function maxModulationGiven20MHzRate
function [maxDataRateMbpsFor20MHzFD, maxDataRateMbpsFor10MHzFD, maxDataRateMbpsFor5MHzFD] =\
 maxModulationGivenHalfDuplex20MHz(dataRateMbpsFor20MHzHalfDuplex)
   % We determine a data rate for fd channel from the data rate for half duplex.
   % From the data rate for half duplex we find the asssumed rssi
   % Then we penalizes such rssi with the residual self interference.
   % Below ref claims residual SI < 1dB in the SNR.
   %   Bharadia, D., McMilin, E., and Katti, S. (2013). Full duplex radios. In
   %   Proc of the ACM SIGCOMM 2013, pages 375-386. ACM
  switch (dataRateMbpsFor20MHzHalfDuplex)
    case 6 % implied RMIS = -82 dBm -> penalized RSSI = -83 dBm
      disp "Residual SI imposes data rate below 6 Mbps for 20 MHz FD but there is none. Using 6 Mbps";
      maxDataRateMbpsFor20MHzFD = 6;
      maxDataRateMbpsFor10MHzFD = 9;% RMIS = -84 dBm
      maxDataRateMbpsFor5MHzFD = 18;% RMIS = -83 dBm
    case 9 % implied RMIS = -81 dBm -> penalized RSSI = -82 dBm
      maxDataRateMbpsFor20MHzFD = 6;% RMIS = -82dBm
      maxDataRateMbpsFor10MHzFD = 12;% RMIS = -82dBm
      maxDataRateMbpsFor5MHzFD = 18;% RMIS = -83dBm
    case 12 % implied RMIS = -79 dBm -> penalized RSSI = -80 dBm
      maxDataRateMbpsFor20MHzFD = 9;% RMIS = -81dBm
      maxDataRateMbpsFor10MHzFD = 18;% RMIS = -80dBm
      maxDataRateMbpsFor5MHzFD = 24;% RMIS = -80dBm
    case 18 % implied RMIS = -77 dBm -> penalized RSSI = -78 dBm
      maxDataRateMbpsFor20MHzFD = 12;% RMIS = -79dBm
      maxDataRateMbpsFor10MHzFD = 18;% RMIS = -80dBm
      maxDataRateMbpsFor5MHzFD = 24;% RMIS = -80dBm
    case 24 % RMIS = -74 dBm -> penalized RSSI = -75 dBm
      maxDataRateMbpsFor20MHzFD = 18;% RMIS = -77dBm
      maxDataRateMbpsFor10MHzFD = 24;% RMIS = -77dBm
      maxDataRateMbpsFor5MHzFD = 36;% RMIS = -76dBm
    case 36 % RMIS = -70 dBm -> penalized RSSI = -71 dBm
      maxDataRateMbpsFor20MHzFD = 24;% RMIS = -74dBm
      maxDataRateMbpsFor10MHzFD = 36;% RMIS = -73dBm
      maxDataRateMbpsFor5MHzFD = 54;% RMIS = -71dBm
    case 48 % RMIS = -66 dBm -> penalized RSSI = -67 dBm
      maxDataRateMbpsFor20MHzFD = 36;% RMIS = -70dBm
      maxDataRateMbpsFor10MHzFD = 48;% RMIS = -69dBm
      maxDataRateMbpsFor5MHzFD = 54;% RMIS = -71dBm
    case 54 % RMIS = -65 dBm -> penalized RSSI = -66 dBm
      maxDataRateMbpsFor20MHzFD = 48;% RMIS = -66dBm
      maxDataRateMbpsFor10MHzFD = 54;% RMIS = -68dBm
      maxDataRateMbpsFor5MHzFD = 54;% RMIS = -71dBm
  endswitch
endfunction
```

C.3.2 Data Rates For Narrow FD Channels Under Negligible RSI

```
==============> For below discussion see Receiver Minimum Input Sensitivity
%                (RMIS) Table 18-14 (IEEE Std. 802.11-2012)
%------------> Ex. A dataRateMbpsAt20MHz = 6 Mbps (in 20 MHz) requires
%                  a RMIS of -82 dBm (BPSK 1/2). Under this same RMIS
%                  a 10 MHz wide channel can employ QPSK 1/2 which yields
%                  6 Mbps too. Since we represent each modulation by its
```

```
%                  corresponing data rate in 20 MHz channel, the maximum
%                  data rate achieved by a 10 MHz channel under a RMIS of
%                  -82 dBm is assigned to the symbol '12' i.e. the rate
%                   achieved by QPSK 1/2 in 20 MHz channels.
function [max10MHzDataRateMbps, max5MHzDataRateMbps] = maxModulationGiven20MHzRate(dataRateMbpsAt20MHz)
  switch (dataRateMbpsAt20MHz)
    case {6, 9} % RMIS = -82 dBm and -81 dBm, respectively.
      max10MHzDataRateMbps = 12; % RMIS = -82 dBm
      max5MHzDataRateMbps  = 18; % RMIS = -83 dBm
    case 12 % RMIS = -79 dBm
      max10MHzDataRateMbps = 18; % RMIS = -80 dBm
      max5MHzDataRateMbps  = 24; % RMIS = -80 dBm
    case 18 % RMIS = -77 dBm
      max10MHzDataRateMbps = 24; % RMIS = -77 dBm
      max5MHzDataRateMbps  = 24; % RMIS = -80 dBm
    case 24 % RMIS = -74 dBm
      max10MHzDataRateMbps = 24; % RMIS = -77 dBm
      max5MHzDataRateMbps  = 36; % RMIS = -76 dBm
    case 36 % RMIS = -70 dBm
      max10MHzDataRateMbps = 36; % RMIS = -73 dBm
      max5MHzDataRateMbps  = 54; % RMIS = -71 dBm
    case {48, 54} % RMIS = -66 dBm and -65 dBm, respectively.
      max10MHzDataRateMbps = 54; % RMIS = -68 dBm
      max5MHzDataRateMbps  = 54; % RMIS = -71 dBm
  endswitch
endfunction
```