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Título: Improving Full-Duplex MAC Protocols for Wireless Ad Hoc Networks with Many-to-Many Multiuser Communication

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Trabalho apresentado ao Programa de Pós-graduação em Ciência da Computação do Centro de Informática da Universidade Federal de Pernambuco, como requisito parcial para obtenção do grau de Mestre em Ciência da Computação.

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Ata da defesa/apresentação do Trabalho de Conclusão de Curso de Mestrado do Programa de Pós-graduação em Ciências da Computação - CIN da Universidade Federal de Pernambuco, no dia 21 de dezembro de 2023.

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Ao vigésimo primeiro dia do mês de dezembro do ano de dois mil e vinte e três, às quinze horas, no Centro de Informática da Universidade Federal de Pernambuco, teve início a duas milésima centésima vigésima primeira defesa de dissertação do Mestrado em Ciência da Computação, intitulada Improving Full-Duplex MAC Protocols for Wireless Ad Hoc Networks with Many-to-Many Multiuser Communication, na área de Redes de Computadores e Sistemas Distribuídos, do candidato Wilton Pereira Santos Santana o qual já havia preenchido anteriormente as demais condições exigidas para a obtenção do grau de mestre. A Banca Examinadora, composta pelos professores Kelvin Lopes Dias, pertencente ao Centro de Informática desta Universidade, Marcelo Menezes de Carvalho, pertencente à Ingram School of Engineering da Texas State University e Renato Mariz de Moraes, pertencente ao Centro de Informática desta Universidade, sendo o primeiro presidente da banca examinadora e o último orientador do trabalho de dissertação, decidiu: Aprovar o trabalho. E para constar lavrei a presente ata que vai por mim assinada e pela Banca Examinadora. Recife, 21 de dezembro de 2023.

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WILTON PEREIRA SANTOS SANTANA

Mestrando(a)

To my beloved parents and brothers.

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"If you want to find the secrets of the universe, think in terms of energy, frequency, and vibration." (Nikola Tesla)

"Be joyful in hope, persevere in hardship; keep praying regularly;" (Romans 12: 12).

RESUMO

A comodidade proporcionada pela comunicação sem fio tornou esta tecnologia cada vez mais prevalente em nossa sociedade moderna nas últimas décadas e, com isso, a necessidade de melhorias constantes. Os rádios full-duplex podem aprimorar as redes sem fio, ou seja, a capacidade de receber informações enquanto transmite dados na mesma largura de banda de frequência, tecnologia que vem crescendo principalmente devido aos seus benefícios. A perspectiva de alcançar o dobro da taxa de transferência e uma utilização mais eficiente da largura de banda podem ser os benefícios previstos devido aos requisitos das aplicações que frequentemente exigem transferência de dados com mais eficiência. Antes que o full-duplex sem fio fosse viável, uma forma de melhorar esses aspectos era empregar técnicas multiusuários de comunicação. Em relação à abordagem multiusuários, o Many-to-Many MAC (M2MMAC), um protocolo de controle de acesso ao meio (MAC), aumentou significativamente o desempenho da vazão da rede. O presente trabalho explora os desafios e oportunidades nos aspectos principais da subcamada MAC ao empregar tecnologia full-duplex. Pensando nisso, este trabalho revisa o estado da arte dos protocolos MAC full-duplex, e também propõe dois novos protocolos, o FD-M2MMAC (Full-Duplex Many-to-Many MAC) e sua versão melhorada, o EFD-M2MMAC (Enhanced Full-Duplex Many-to-Many MAC), que combinam tecnologia full-duplex com técnicas multiusuários.

Os resultados obtidos mostram que a aplicação das abordagens M2MMAC full-duplex promove significativa melhoria no desempenho em termos de vazão em cada nó da rede. Mais especificamente, os protocolos propostos demonstraram maior eficiência na utilização do meio de comunicação, gerando maior vazão nos cenários avaliados. Especificamente, o protocolo FD-M2MMAC alcançou um aumento de 50% na taxa de transferência agregada em comparação com o M2MMAC quando uma duração da janela ATIM de $40ms$ é empregada. Além disso, o FD-M2MMAC melhorado (EFD-M2MMAC) exibiu um aumento de 56% na vazão agregada em comparação com o FD-M2MMAC sob as condições de uma duração de janela ATIM de $40ms$ empregando seis antenas.

Palavras-chaves: Protocolos MAC. full-duplex. comunicação multiusuários. estratégia muitos-para-muitos.

ABSTRACT

The convenience delivered by wireless communication has made this technology increasingly prevalent in our modern society in the last decades, and with that, the word appeals for constant improvements. The full-duplex radios can enhance wireless networks, i.e., the ability to receive information while transmitting data in the same frequency bandwidth, which has been growing mainly because of its benefits. The prospect of achieving double throughput and more efficient bandwidth utilization might be the most envisioned benefits due to application requirements that frequently demand more data transfer with more efficiency. Before the wireless full-duplex was feasible, one way to improve these aspects was to employ a multi-user technique. Regarding the multi-user approach, the Many-to-Many MAC (M2MMAC), a medium access control (MAC) protocol, has significantly increased the network throughput. This work focuses on the challenges and opportunities in the MAC layer aspects while employing full-duplex technology. With that in mind, this work reviews the full-duplex MAC protocols state-of-art. This work presents two protocols, the FD-M2MMAC (Full-Duplex Many-to-Many MAC) and its improved version, the EFD-M2MMAC (Enhanced Full-Duplex Many-to-Many MAC) that combines full-duplex technology with multi-user techniques to increase network throughput.

The obtained results show that the application of our MAC full-duplex approach promotes improvement in the throughput. More specifically, our protocol demonstrated enhanced efficiency in utilizing the communication medium, yielding higher throughput in the assessed scenarios. Specifically, the FD-M2MMAC protocol achieved a 50% increase compared to the M2MMAC with a $40ms$ Announcement Traffic Indication MAP (ATIM) window duration.Furthermore, the Enhanced FD-M2MMAC (EFD-M2MMAC) displayed a 56% increase in aggregated throughput compared to FD-M2MMAC under the conditions of a $40ms$ ATIM window duration and six antennas.

Keywords: MAC protocols. full-duplex. Multi-user communication. Many-to-Many.

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LIST OF ABBREVIATIONS AND ACRONYMS

ACK	Acknowledgment
ADC	Analog-to-Digital Converter
ARQ	Automatic Repeat Requests
ATIM	Ad hoc Traffic Indication Message
ATIM-BRD	ATIM Broadcast
ATIM-RES	ATIM Response
ATIM-NACK	ATIM Negative Acknowledgement
ATIM-ACK	ATIM Acknowledgment
BS	Base Station
CAB	Channel Allocation Bitmap
CSMA/CA	CSMA - Colision Avoidance
CTS	Clear to Send
CUB	Channel Usage Bitmap
DAC	Digital-to-Analog Converter
DCF	Distributed Coordination Function
DIFS	DCF Interframe Space
DSP	Digital Signal Processing
EIFS	Extended Interframe Space
FD	Full-Duplex
FDD	Frequency Division Duplexing
GFDO	Spatial group-based multi-user full-duplex OFDMA
HD	Half-Duplex
HPA	High-Power Amplifier
LNA	Low-Noise Amplifier
LPF	Low-Pass Filter

M2MMAC	Many-to-many Mutichannel MAC Protocol
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
MMAC	Multichannel MAC
MU	Multi-user
NOMA	Non-Orthogonal Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PHY	Physical
PR	Primary Receiver
PSM	Power Saving Mode
PT	Primary Transmitter
RTS	Request to Send
SIC	Successive Interference Cancellation
SIFS	Short Inter-frame Space
SR	Secondary Receiver
ST	Secondary Transmitter
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TMMAC	TDMA based Multichannel MAC
V-BLAST	Vertical-Bell Laboratories Layered Space-Time
WLAN	Wireless Local Area Network

LIST OF SYMBOLS

n	Number of nodes
B	Number of reception antennas
M	Number of channels/sub-carriers
R	Transmission rate
R_{basic}	Basic transmission rate
l_{atim}	ATIM window duration
l_{beacon}	Beacon interval
$NCOM_{max}$	Maximum number of slots in a Communication window
N_{succ}	Number of successful negotiation
l_{slot}	Slot duration
$DATA$	Data packet length
H_M	MAC header packet length
H_P	PHY header packet length
P_{busy}	Probability of channel is in busy state
P_{succ}	Probability of a successful transmission
T_s	Duration of successful negotiation
T_c	Duration of collision
S	Throughput
$S_{non\_full\_duplex}$	Throughput of non-full-duplex component
S_{full_duplex}	Throughput of full-duplex component
σ	Time slot duration
δ	Propagation delay

CONTENTS

1 INTRODUCTION

In today's dynamic landscape, wireless networks have seamlessly integrated into our daily routines, evolving into a pervasive technology that increasingly connects a growing number of devices in various scenarios. The users of wireless networks and their applications drives a constant evolution in the wireless communications area by requiring more device capabilities and expecting more data bandwidth with less latency, and utilization efficiency.

Considering this, many strategies have been proposed to improve wireless network performance metrics. The Multi-user (MU) technique is one successful approach that brings advances to these networks. In this approach, the network nodes are capable of communicating with multiple other nodes simultaneously. In this way, the network throughput and bandwidth utilization efficiency are enhanced by MU methods.

Another outstanding technology is Multiple Input Multiple Output (MIMO) which enables data with multiple users by using an array of antennas. The potential of MIMO radios can be further optimized through integration with Orthogonal Frequency Division Multiple Access (OFDMA). Additionally, leveraging a multi-user variant of Orthogonal Frequency Division Multiplexing (OFDM) proves to be a promising strategy, as demonstrated in the IEEE 802.11ac protocol and the recently proposed IEEE 802.11ax (DALDOUL; MEDDOUR; KSENTINI, 2020).

Moreover, the recent advances in electronic semiconductors and signal processing enable bidirectional communication between wireless devices concurrently; in other words, a node can transmit and receive data at the same time and frequency bandwidth which characterizes Full-Duplex (FD) communication (KIM; LEE; HONG, 2015). Although wired communication widely employed this technology for decades, full-duplex communication was considered a significant challenge in wireless networks. This challenge was due to the transmitting circuit negatively affecting the receiving one, which listens to the transmitted signal as noise, and, therefore, is considered as a self-interference signal. Nonetheless, the self-interfering cancellation could be suppressed by a series of processes involving analog and digital cancellation.

From a MAC design perspective, employing full-duplex radios in the network brings some advantages. Kim *et al.* (KIM; LEE; HONG, 2015) and Thilina *et al.* (THILINA et al., 2015) described some of those. The first advantage is that this technology provides a significant increase in network transmission capacity since it allows two transmissions to happen simultaneously on the same frequency bandwidth (JU et al., 2011; JU et al., 2012a; KIM et al., 2014).

Also, full-duplex allow devices to sense the channel to identify the circumstance of additional communications and, consequently, quickly identify collisions in their data packets enabling collision detection feature in wireless network. In the same way, receiver nodes can adopt strategies that allow the immediate acknowledgment of a packet. In this way, the transmitter can quickly react to scenarios when data transmission fails. In these scenarios, the transmitter might opt to abort the data exchange to save power and allow the content to the channel to start sooner.

Allowing the reception of feedback's signals employed in Automatic Repeat Requests (ARQ) protocols, in channel status information and ACKs and so on during the transmission process make it possible to reduce network latency in networks that employ full-duplex technology (KIM et al., 2014). Additionally, the capability to forward the data in a re-transmission manner contributes to a reduction in the end-to-end delay (JU; OH; HONG, 2009; JU et al., 2012b).

Additionally, full-duplex communications also increase network security. Two transmissions in progress make it more difficult to intercept information, known as eavesdropping since the two data exchanges in progress are perceived to be interference to any node that is not part of the full-duplex communication (ZHENG et al., 2013; VISHWAKARMA; CHOCKALINGAM, 2015; CEPHELI; TEDIK; KURT, 2014).

Besides that, unlike Half-Duplex (HD) technologies, full-duplex technology enables a recharging process even during ongoing transmissions. Research has shown that wireless devices can potentially harvest energy from the transmissions of other equipment, a phenomenon known as Energy harvesting (KANG; HO; SUN, 2015).

Moreover, full-duplex technologies enable innovative solutions to address the hidden terminal problem. In the literature, one common strategy to mitigate this issue is the simultaneous exchange of data packets and the use of busy tones emitted by the receiver to signal channel occupation.

Furthermore, many studies have reported a significant increase in network throughput and utilization efficiency by employing full-duplex radios. The majority of work has employed FD and OFDMA to achieve a MU protocol and reduce bandwidth utilization.

On the other hand, Many-to-many Mutichannel MAC Protocol (M2MMAC) is a many-to-many multi-channel approach based on IEEE 802.11 Power Save Mode (PSM) (GHOBAD, 2017; GHOBAD; MORAES, 2017). In this scenario, nodes reserve a channel to receive data packets from multiple transmitters simultaneously. This characteristic is possible due to the

V-BLAST radio architecture that enables devices to explore multi-user detection approaches.

To take advantage of full-duplex, multiuser, and many-to-many benefits, this work proposes new MAC protocols based on M2MMAC strategy using self-interference cancellation to achieve full-duplex technology to improve overall network performance.

To evaluate the benefits of the proposed protocol, a mathematical model was developed for the aggregated throughput which is the number of successfully transmitted data packets over all network terminals averaged over time. In this way, we can compare with M2MMAC protocol in different scenarios given that the nodes are provided with the same number of antennas.

1.1 OBJECTIVES

This work presents the following objectives:

1. Review of the fundamental concepts regarding multi-user protocols;
2. Summary of the full-duplex radios concepts;
3. Review of the full-duplex protocols with emphasis on multi-user strategies;
4. Proposal of two Full-duplex Many-to-Many protocols;
5. The development of a mathematical model to evaluate the throughput performance of the proposed protocols.

1.2 WORK STRUCTURE

In Chapter 2, we introduce the works that are related to our research. In the Chapter 3, we summarize the full-duplex radios concepts to introduce the main challenges and opportunities of employing this technology. The full-duplex protocols that inspired this study are briefly described in Chapter 4. Chapter 5 describes our main contribution, a new many-to-many protocol process that employs Orthogonal Frequency Division Multiple Access (OFDMA) and Full-Duplex (FD) radios to increase aggregated throughput in the network. Chapter 6 presents the enhanced version of the previous chapter protocol. Finally, in Chapter 7 we present the main conclusion of our work and future developments that can be derived from our contributions.

2 FUNDAMENTALS

This chapter presents some basic definitions, concepts, and protocols, which will be constantly referred to throughout this work. The IEEE 802.11 protocol is one of the most popular protocols for implementing Wireless Local Area Network (WLAN) and, currently, has been widely used in many wireless communication devices in the industry. The success of IEEE 802.11 has inspired many other protocols design which usually employs parts of its mechanisms such as the CSMA - Colision Avoidance (CSMA/CA) to avoid collision in wireless scenarios. Considering that, our protocols have also adopted this mechanism to avoid collision during the control packet exchange. Moreover, its Power Saving Mechanism is a compelling and simple strategy to manage the energy capability between devices that rely on limited sources of power such as batteries.

2.1 IEEE 802.11

The IEEE 802.11 is based on CSMA/CA. In the CSMA/CA, nodes sense the medium aiming to verify if the channel is busy before any transmission. In this way, the protocols avoid unnecessary collisions and re-transmissions in the network.

The Distributed Coordination Function (DCF) mode might use control packet Request to Send (RTS) and Clear to Send (CTS) to avoid collision in the medium. RTS/CTS packets not only perform a collision verification but also a transmission check, since it indicates to the transmitting node that the process should be repeated if a CTS packet is not received. As a result, the RTS/CTS is a faster process than sending a data packet and receiving its acknowledgment.

2.1.1 IEEE 802.11 Power Saving Mode

The IEEE 802.11 Power Saving Mode (COMMITTEE et al., 1997), better known as IEEE 802.11 PSM, is a mechanism based on the IEEE 802.11 DCF to save power over the network devices by suspending the power supply of devices' physical layer that the carrier sensing is unnecessary, therefore, going into a stage known as *doze* mode. As illustrated in Fig. 1, the power management is done based on the division of the inter-beacon interval into two phases giving a Split Phase aspect to the protocol. In the first phase, the ATIM Window, network devices are awake overhearing the default channel. In this phase, nodes that have data to exchange transmit a control packet named Ad hoc Traffic Indication Message - ATIM following the IEEE 802.11 DCF mechanism to engage in communication in the next phase. The communication between nodes A and B shows this behavior in the figure. First, Node A transmits ATIM packet to Node B. In a second moment, Node B might accept the incoming stream by sending back an ATIM Acknowledgment packet addressed to its transmitter (Node A). In the Communication Window, nodes that have established communication during the ATIM period exchange data and confirmation packets. Therefore, the data from Node A to Node B is transmitted after the ATIM Window, as shown in the center part of Fig. 1. The receiving node (Node B) acknowledges the data reception by sending ACK.

On the other hand, nodes that neither transmitted nor received a packet, thus, not involved in a communication, enter a doze mode until the next inter-beacon interval. This scenario is illustrated in Fig. 1 by Node C on the bottom part.

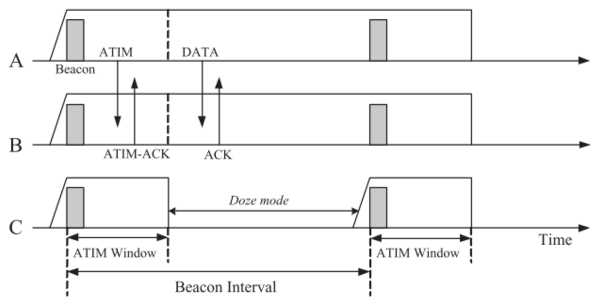

Figure 1 – Operation of IEEE 802.11 Power Save Mode (SO; VAIDYA, 2004).

The Power Save mode mechanism previously described is modified by Multichannel MAC (MMAC) to establish communication in a multi-channel scenario. The adaptation considered in MMAC became a widely used method to address multi-channel issues in ad hoc networks.

2.2 MULTI-CHANNEL PROTOCOLS

This section presents multi-channel protocols that have guided the majority of multi-user protocols.

2.2.1 Multichannel MAC Protocol

The Multichannel MAC (MMAC) (SO; VAIDYA, 2004) protocol combines the IEEE 802.11 PSM with a multi-channel approach to increase the network throughput. As in the IEEE 802.11 PSM, nodes contend to access a control channel ("*default channel*") to negotiate a transmission channel with their destination nodes. Fig. 2 presents a communication sequence of the MMAC protocol.

In the MMAC nodes announce their intent to transmit data in the communication phase by acquiring access to the channel and transmitting an ATIM packet addressed to its destination node. This packet includes a list of channels that are preferable to the transmitter to communicate. Fig. 2 shows that Node A is the first node to acquire the channel by sending an ATIM packet. Whenever a node listens to an ATIM packet addressed to itself, it evaluates the possibility of receiving data in one of the channel lists sent by the transmitter and indicates the selected channel in the ATIM-ACK packet, as illustrated by Node B. In this scenario, the dashed line from Node B to Node C represents the overhearing behavior. Therefore Node C is aware of B's selected channel (Channel 1) and avoids selecting this channel when it receives an ATIM packet as shown in the bottom part. If there is no channel available, the destination node indicates the failure in the channel selection by transmitting an ATIM Negative Acknowledgement packet. After receiving an ATIM-ACK packet the source node evaluates the possibility of transmitting in the selected channel and confirms the agreed configuration with an ATIM Response (ATIM-RES) packet. Fig. 2 shows this behavior in the communication initiated (and terminated) by Node A and Node D. The ATIM-RES is introduced by MMAC to notify neighbor nodes of the ongoing transmission. Similarly, the ATIM-ACK packet notifies nodes of data communication in the receiver vicinity. Since during the ATIM window, all network nodes overhear the default channel, both packets reduce the hidden terminal issue.

In the Communication Window nodes that did not receive an ATIM packet enter in a power save mode. Otherwise, i.e. nodes that successfully negotiated channels, switch to the selected channel and exchange RTS/CTS packets before transmitting data to ensure that any other node in the channel is aware of the communication, as presented in the right side of the Fig. 2.

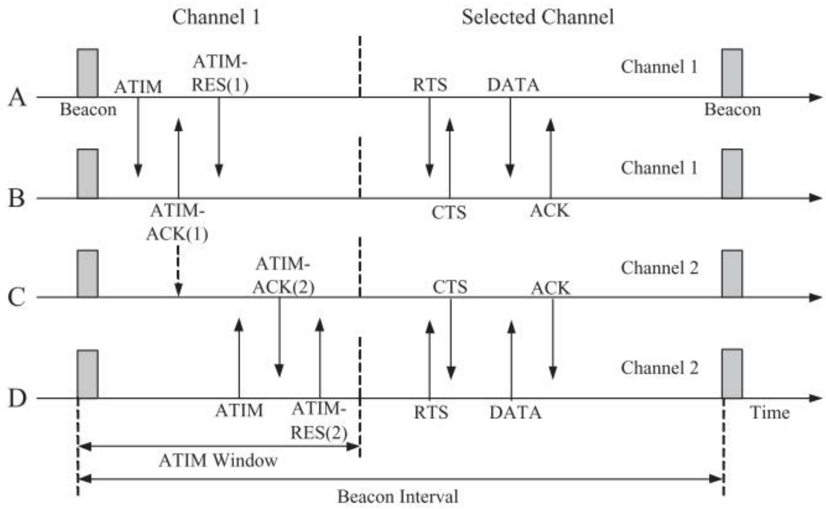

Figure 2 – MMAC communication sequence (SO; VAIDYA, 2004).

2.2.2 Many-to-Many Multichannel MAC Protocol

The Many-to-many Mutichannel MAC Protocol (M2MMAC) (GHOBAD, 2017; GHOBAD; MORAES, 2017) employs many-to-many communication technology to increase the MMAC aggregated throughput. The many-to-many technology allows devices to receive data streams from multiple users simultaneously. Due to that capability, different from MMAC, which requires a channel for each communication, the protocol determines that nodes select a channel in the ATIM Window to receive incoming data during the Communication Window. In that way, nodes secure a reception bandwidth for a later stage by announcing the selected channel in ATIM or ATIM-ACK packets.

Besides that, before sending an ATIM packet, nodes that do not have a previously assigned channel must choose randomly among those available ones. Considering that, in M2MMAC, during the ATIM window the nodes overhear all communication in a predefined control channel, each node knows available channels. Since M2MMAC sets bidirectional communications per negotiation, the transmitting node must verify if it can accommodate an additional receive stream.

The channel reserved by each node is exploited by multiple transmitting nodes that when to address data for a particular device. Therefore, receiving nodes must confirm if they have already reserved a channel for receiving data in the subsequent phase during the ATIM window. Otherwise, it follows a similar process to the transmitter node, checks if channels are available, and randomly selects one among them. After that, it certifies that its receiving chain might afford the additional stream. In mild cases, the node answers with an ATIM-ACK packet. Otherwise, it transmits an ATIM Negative Acknowledgement indicating to neighbor nodes that it can no longer receive additional streams.

In the communication window, nodes that have successfully established communication in the previous window switch their receiver radio to the selected channel. Concurrently to the multiple user detection, nodes transmit data to multiple users in their channels. The data exchange is performed by consecutive transmission and reception of data packet.

The communication sequence for a three-node network is demonstrated in Fig. 3. In the figure, nodes exchange control packets in the ATIM window on the left side of the illustration. On the right side is the communication window in which the different colored lines in the node's time axis illustrate Fig. 3. channel. For instance, node "A" has a reserved "yellow" channel to receive data. Therefore, all packets addressed to node A are also marked with a yellow color.

Network nodes acknowledge the received packets by sending ACK packets at the end of each slot, as shown in Fig. 3. The M2MMAC also exploits Power Save Mode mechanisms. Therefore nodes that did not settle a communication, i.e., do not have packets to transmit or receive, enter doze mode to save power.

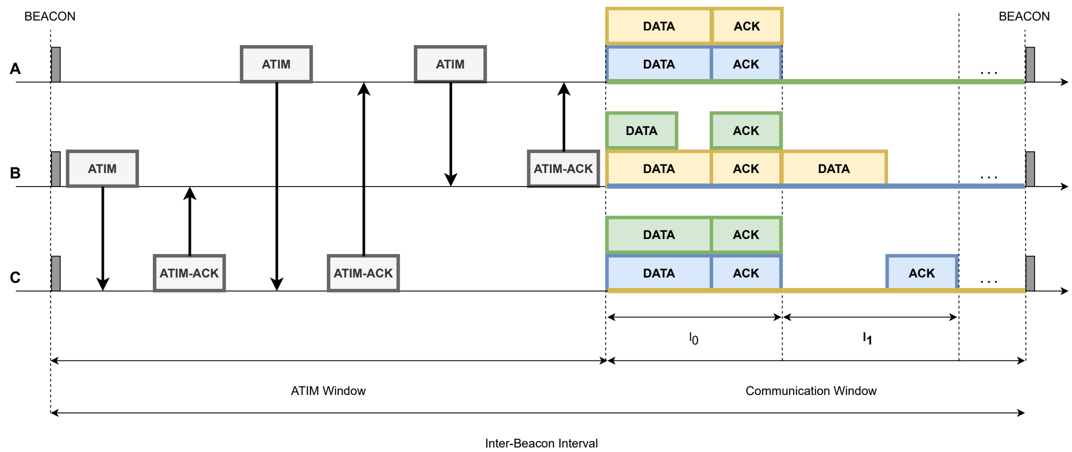

Figure 3 – M2MMAC communication sequence (Adapted from (GHOBAD, 2017)).

The M2MMAC also supports broadcast transmission, which occurs not in the communication window but in the control channel during the ATIM Window. In this scenario, the node sends an ATIM-BRD packet which does not require an ATIM-ACK packet as an answer from target stations. The transmitter node proceeds with its intended broadcast transmission after a Short Inter-frame Space, given that the ATIM-BRD did not suffer any interference.

The authors point out that one must use this communication cautiously since it significantly impacts the communication window.

2.2.3 TMMAC

The TMMAC is a multi-channel MAC protocol based on the MMAC that targets energy efficiency. The protocol dynamically adjusts the ATIM window size and splits the communication window into slots, thus employing a TDMA. Accordingly, nodes in TMMAC have to choose a channel and time slots to communicate in the Communication Window.

Aiming to track channel and slot allocation during ATIM window negotiations, the TMMAC adds the Channel Usage Bitmap (CUB). CUBs indicate that a previous communication reserved a particular channel in a given time slot with a bit. In TMMAC, sending nodes should transmit all their CUBs along with ATIM packets, which includes the number of intended packets to be transmitted in the communication window. Nodes that receive an ATIM packet should combine their CUBs and the received ones to select the channels and slots that will accommodate the communication. Both receiving and transmitter nodes should update their CUBs with agreed resources. In the protocol, CUBs are reset to 0 when a node is powered up or at the beginning of an inter-beacon interval.

Additionally, the TMMAC presents the Channel Allocation Bitmap (CAB) packet. It has the same structure as the CUB packet but differs from the late one by its usage. The CABs are transmitted with ATIM-ACK and ATIM-RES packets to advertise to neighboring nodes that the current negotiation has agreed with a collection of channels and time slots. Therefore, any network neighbor that overhears ATIM-ACK or ATIM-RES packets updates the CUB based on the packet indications.

2.3 PROTOCOL ANALYSIS

To evaluate our protocol improvements regarding the throughput we used an analytical model proposed by Tinnirello *et al.* (TINNIRELLO; BIANCHI; XIAO, 2009). Accordingly, this section presents some works that developed methods to evaluate the IEEE 802.11 DCF through mathematical analysis.

2.3.1 Performance Analysis of the IEEE 802.11 Distributed Coordination Function (BIANCHI, 2000)

In its work, the author defines the stochastic process $b(t)$ as the representation of the backoff time counter for a given station. Furthermore, the $s(t)$ defines the stochastic process that represents the backoff stage $(0, ..., m)$ of a station in a given time t.

The time between the beginning of two consecutive slots is also defined by t and $t+1$ since it adopts a discrete time scale. Bianchi also adopts the notation $W = CW$ and $W_i = 2^i W$ where $i \in [0, m]$, therefore m represents the maximum backoff stage.

The modeling of a bidirectional process $\{s(t), b(t)\}$ is only possible by assuming that each packet collides with a constant and independent probability p in a slot time as constant. The yield discrete-time Markov state machine is shown in Fig. 4.

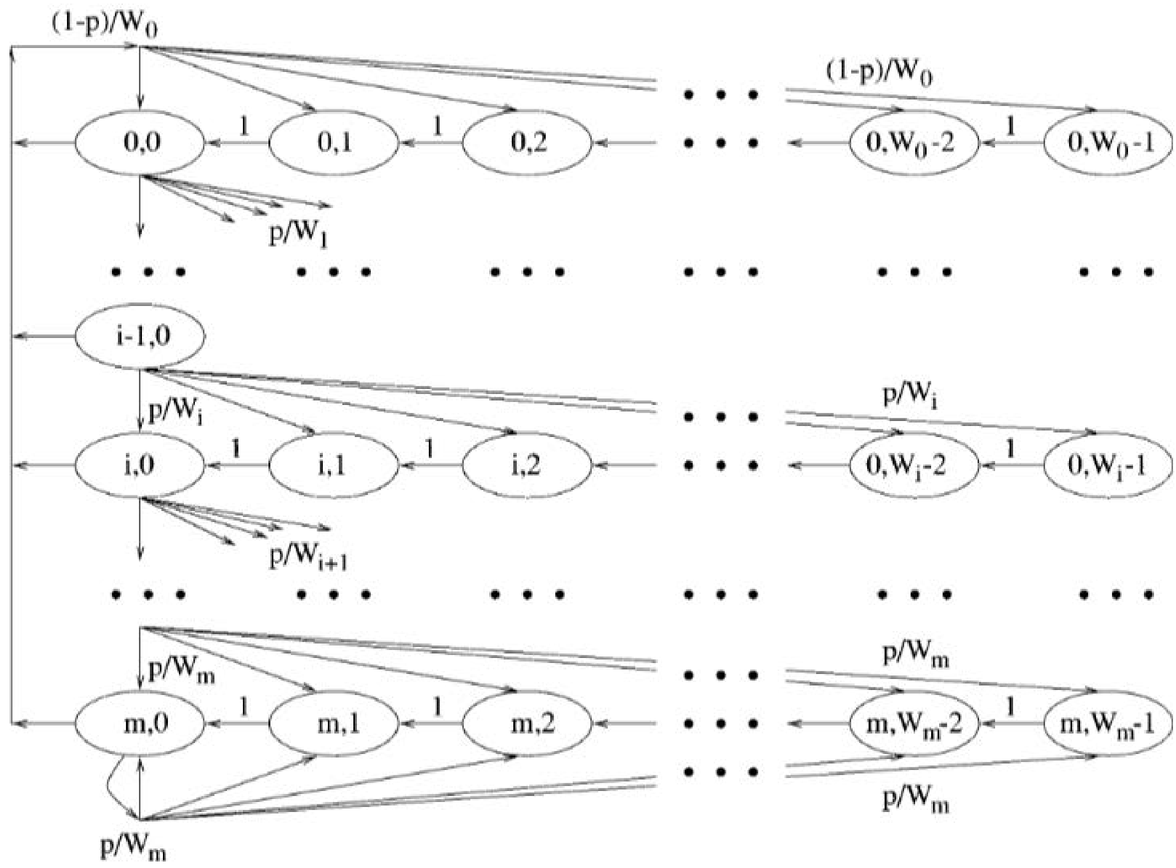

Figure 4 – State Machine in Bianchi analytical model (BIANCHI, 2000).

Using the short notation:

$$P\{i, k \mid i_0, k_0\} = P\{s(t+1) = i_1, b(t+1) = k_1 \mid s(t) = i_0, b(t) = k_0\}.$$

The transition probabilities of the Markov chain is given by

$$\begin{cases} P\{i,k \mid i,k+1\} = 1, & k \in [0, W_i - 2], i \in [0,m] \\ P\{0,k \mid i,0\} = (1-p)/W_0, & k \in [0, W_0 - 1], i \in [0,m] \\ P\{i,k \mid i-1,0\} = p/W_i, & k \in [0, W_i - 1], i \in [1,m] \\ P\{m,k \mid m,0\} = p/W_m, & k \in [0, W_m - 1]. \end{cases} \tag{2.1}$$

Representing the fact that the counter is decremented at the beginning of each slot. Following the case that occurs after a successful transmission in the second equation. In this case, the backoff stage is always 0 and the backoff is uniformly chosen between 0 and $W_0 - 1$. The third equation represents failure scenarios before the backoff stage achieving the value m. In these scenarios, the counter is chosen uniformly between 0 and W_m. The last equation represents transmission failure scenarios in which the backoff stage achieved the value m. In these scenarios, the contention window is not increased in the subsequent transmission attempts.

The author defines the stationary distribution of the chain as

$$b_{i,k} = \lim_{x \to \infty} P\{s(t) = i, b(t) = k\}, i \in (0,m), k \in (0, W_i - 1).$$

Accordingly, the probability τ that a station transmits in a randomly chosen slot time can be obtained as

$$\tau = \sum_{j=1}^{m} b_{i,0} = \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-2p^m)}. \tag{2.2}$$

The probability that p that a packet encounters a collision is the probability at least one of the remaining $n-1$ station transmits in a slot time is

$$p = 1 - (1-\tau)^{n-1}. \tag{2.3}$$

The value of variables τ and p can be solved numerically by equations 2.2 and 2.3

In RTS/CTS mechanisms a collision can occur only on RTS packet, thus, is the average time spent in collision events T_c is

$$T_c = RTS + DIFS + \delta, \tag{2.4}$$

where RTS is the duration of transmitting an RTS packet, DIFS is the time that any station should wait before sending any packet, known as DCF Interframe Space (DIFS), and δ is the propagation delay.

On the other hand, the average time of successful transmissions in the channel T_s is calculated by considering H as the sum of PHY and MAC packet header length and $E[P]$ as the average packet payload. The average time on successful transmissions is given by the sum of the duration required to transmit all control packets (RTS, CTS, and ACK), spaces DIFS, the space required before transmitting any packet, known as Short Inter-frame Space (SIFS), the propagation delays required, the H which is the sum of PHY and MAC packet headers length and the average packet payload $E[P]$, hence,

$$\begin{aligned} T_s = RTS + SIFS + \delta + CTS + SIFS + \delta \\ + H + E[P] + SIFS + \delta + ACK + DIFS + \delta. \end{aligned} \tag{2.5}$$

The probability P_{tr} that at least one transmission occurs in the slot time can be obtained by noting that each station transmits with τ probability and there is n station in the networking. Hence,

$$P_{tr} = 1 - (1 - \tau)^n . \tag{2.6}$$

The probability P_s that a successful transmission occurs is equal to the probability that only one transmission happened in the time slot given that at least one transmission occurred in the time slot. Therefore,

$$P_s = \frac{n\tau (1 - \tau)^{n-1}}{1 - (1 - \tau)^n}. \tag{2.7}$$

Considering that the slot time is empty with the probability of $(1 - P_{tr})\,\sigma$ in which σ is the duration of an empty slot. A successful transmission occurs with the probability of $P_{tr}P_sT_s$ in a slot time. And a collision happens in a given slot time with the probability of $P_{tr}(1 - P_s)\,T_c$.

Thus, the throughput per node is given by

$$S = \frac{P_s P_{tr} E[P]}{(1 - P_{tr})\,\sigma + P_{tr}P_sT_s + P_{tr}(1 - P_s)\,T_c}. \tag{2.8}$$

2.3.2 Refinements on IEEE 802.11 Distributed Coordination Function Modeling Approach (TINNIRELLO; BIANCHI; XIAO, 2009)

The first contribution in the refinement is to enlighten that the previous model assumed that the backoff counter is decremented at the beginning of a slot time. The backoff procedure is suspended whenever the medium is busy.

Tinnirello et al. point out that decreasing the backoff counter at the end of each slot would be more in line with the IEEE 802.11 protocol. The work also reminds us that backoff counter is suspended whenever the medium is identified as busy. In its model the backoff counter is uniformly chosen between $[0, CW]$ where CW is the current backoff window size that is initially set to CW_{min}. Every time that a transmission fails the backoff window size should be set to the value $CW = 2(CW + 1) - 1$ until it reaches its limit which is CW_{max} where the window size should remain. The contention window size remains CW_{max} until a successful transmit happens or the re-transmission counter reaches its predefined limit (V). In these cases, the CW is reset to CW_{min}.

Additionally, the issue of anomalous slots that occurs after any transmission. The authors indicate that the only station that might transmit in the slot immediately after successful transmissions is the transmitting station since its new counter is chosen uniformly between $[0, CW_{min}]$ while others stations had frozen their counter, thus are not 0 yet. The anomalous slot also occurs after a collision. In this case, no station can transmit, since the stations involved in the collision must resume the backoff process after the Extended Interframe Space (EIFS) interval.

To address the anomalous slot and the backoff decrement, the authors demonstrate an easy adaptation in the Bianchi (BIANCHI, 2000) model. It indicates that a transition in the state occurs when any non-transmitting station decrements its backoff counter. Therefore, a slot time corresponds to (i) an idle backoff slot or (ii) a time interval including one or multiple transmissions followed by an extra backoff period, or (iii) a time interval that includes a collision followed by an EIFS interval and the extra backoff slots.

Following a similar approach to its precursor, let the backoff counter random process be $b(t)$ and the backoff stage random process be $s(t)$.

The discrete-time Markov chain considering the backoff counter is decremented at the end of the backoff slot and the probability of a transmitting frame collides is independent of backoff procedure is shown in Fig. 5.

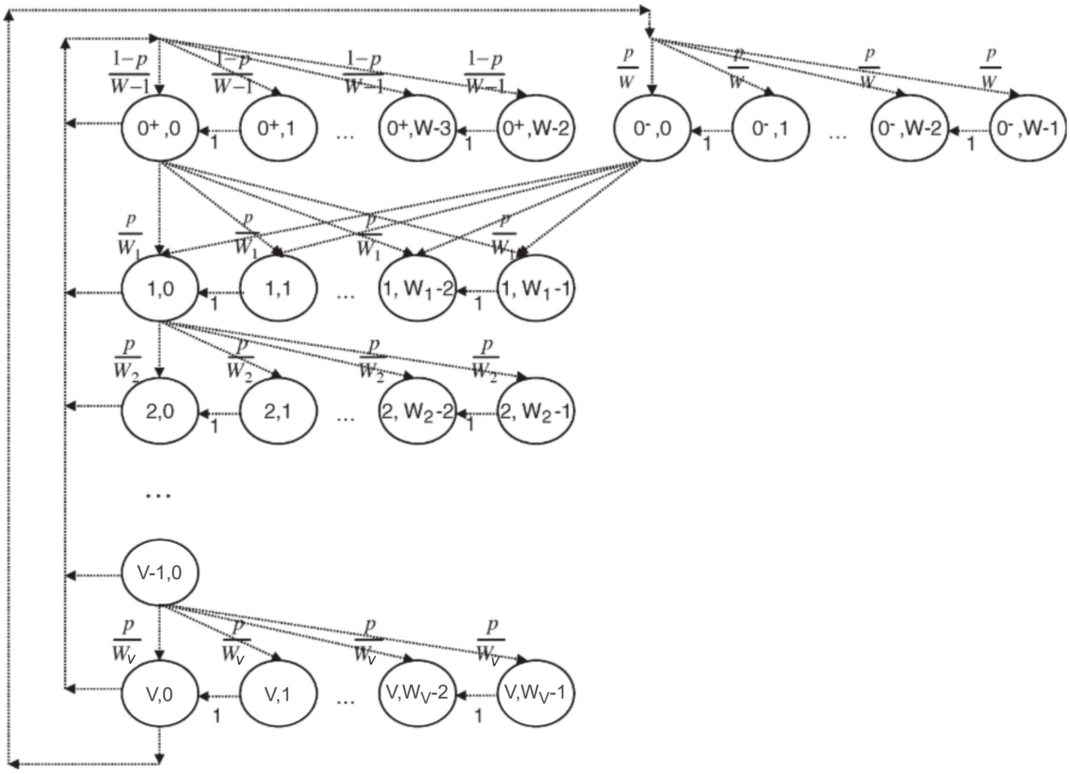

Figure 5 – State Machine in Tinnirello *et al.* analytical model (Adapted from (TINNIRELLO; BIANCHI; XIAO, 2009)).

The transition probabilities result in

$$\begin{cases} P\{i,k \mid i,k+1\} = 1, & k \in [0, W_i - 2], i \in [1, V] \\ P\{0^-,k \mid 0^-,k+1\} = 1, & k \in [0, W_0 - 2] \\ P\{0^+,k \mid 0^+,k+1\} = 1, & k \in [0, W_0 - 3] \\ P\{0^-,k \mid V,0\} = p/W_0, & k \in [0, W_0 - 1] \\ P\{0^+,k \mid i,0\} = (1-p)/(W_0 - 1), & k \in [0, W_0 - 2]\, \forall i \\ P\{i,k \mid i-1,0\} = p/W_i, & k \in [0, W_i - 1], i \in [1, V]. \end{cases} \tag{2.9}$$

The probability τ that a station transmits in a randomly chosen slot is

$$\tau = \sum_{j=1}^{V} b_{j,0} + b_{0^-,0} + b_{0^+,0} = \frac{1 - p^{V+1}}{1-p} b_{0,0}. \tag{2.10}$$

Replacing the probability of the state $b_{0,0}$ from the Markov chain results in

$$\tau = \frac{1}{1 + \frac{1-p}{2(1-p^{V+1})}\left[\sum_{j=0}^{V} p^j \cdot (2^j W - 1) - (1 - p^{V+1})\right]}. \tag{2.11}$$

The collision probability p that a station might encounter by another transmission from at least one of the contending stations is

$$p = 1 - (1 - \tau)^{n-1}. \tag{2.12}$$

The value of variables τ and p can be solved numerically by equations 2.11 and 2.12

Finally, the throughput per node is given by the formula:

$$S = \frac{P_s E(P)}{(1 - P_b)\delta + P_s T_s + (P_b - P_s) T_c}. \tag{2.13}$$

2.3.3 M2MMAC Agreggated Throughput Evaluation

The M2MMAC authors have presented the protocol performance analysis based on Bianchi (BIANCHI, 2000) and Tinnirello *et al.* (TINNIRELLO; BIANCHI; XIAO, 2009) works among others. The M2MMAC performance can be analyzed by noting that data exchange is contention-free in the communication window. Therefore, the performance can be calculated by observing the number of data packets that can be transmitted in the communication along with the number of streams that can be negotiated in the ATIM window.

The maximum number of data packets that can be exchanged in a Communication Window is given by

$$NCOM_{max} = \left\lfloor \frac{l_{beacon} - l_{atim}}{l_{slot}} \right\rfloor, \tag{2.14}$$

where l_{slot} is the duration of a slot in the communication window. The slot duration is determined by the time required to transmit the largest protocol data packet allowed followed by its acknowledgment considering also the propagation delay and the required inter-frame spaces. Therefore, it yields

$$l_{slot} = \frac{DATA - H_P}{R} + \frac{H_P}{R_{basic}} + SIFS + \delta + \frac{ACK - H_P}{R} + \frac{H_P}{R_{basic}} + \delta + SIFS, \tag{2.15}$$

where $DATA$ is the largest payload that is possible to transmit, R is the transmission rate, H_p is the physical layer header length and R_{basic} is the transmission rate employed in headers transmission which is lower than the payload to greater reach in the network. Additionally, SIFS is the time required prior to transmitting any packet, ACK is the length of an acknowledgment packet, and δ is the propagation delay.

Besides that, the network is limited by the number of communications that might be established. Considering that the network is composed of N devices, the number of streams cannot overcome $N(N-1)$ streams. However, the number of streams is also limited by the number of channels C available to the network that can be used by nodes to transmit data which can be less than the number of devices. In that case, if we consider $M = min\{N, C\}$, the number of communications is given by $M(M-1)$.

Another throughput limitation arises from the number of streams that each node can fit in the reception chain, given that each receiving radio is provided with B reception antennas. Therefore, the multiple-user detection technology limits the nodes up to $B-1$ reception streams that limit the protocol to the total of $M(B-1)$ yields.

Finally, the throughput is also limited by the number of streams that can be successfully negotiated during the ATIM Window. Derived from Bianchi (BIANCHI, 2000), the network stations have the probability P_{idle} to find the channel idle, Given that, the average number of successful negotiations per virtual slot time unit is given by

$$N_s = \frac{P_{succ}}{P_{idle}\tau + P_{succ}T_s + P_{coll}T_c}, \tag{2.16}$$

where the duration of a successful negotiation T_s is given by the sum of the control packets' transmission duration, along with their propagation delay and the inter-frame spaces required by CSMA/CA mechanism. In addition, P_{succ} is the probability of a successful transmission given that a transmission occurs, and P_{coll} is the probability that occurs a collision. Therefore,

$$T_s = \frac{ATIM - H_P}{R} + \frac{H_P}{R_{basic}} + SIFS + \delta + \frac{ATIMACK - H_P}{R} + \frac{H_P}{R_{basic}} + DIFS + \delta, \tag{2.17}$$

where $ATIM$ is the length of an ATIM packet and H_p is the physical layer header length, where $ATIMACK$ is the length of an ATIM-ACK packet, $DIFS$ is the time required by any station to sense the medium as idle before starting transmission and $SIFS$ is the spacing required before sending any packet. In this context, it is important to notice that while the packet content is sent in a R transmission rate the packet headers are transmitted in a lower rate R_{basic}.

Accordingly, the collision duration is given by

$$T_c = \frac{ATIM - H_P}{R} + \frac{H_P}{R_{basic}} + DIFS + \delta. \tag{2.18}$$

Thus, the maximum number of streams that might be negotiated on the ATIM Window is given by

$$N_{atim} = 2N_s l_{atim}, \tag{2.19}$$

where the total number of communications is multiplied by two, since each negotiation establishes two communications, one from the ATIM transmitter node to its addressed node and the other way, to the address node to its recipient.

With the previous factors the M2MMAC's aggregated throughput is

$$S_{aggregated} = \frac{min\left\{M(M-1), M(B-1), N_{atim}\right\} NCOM_{max} DATA}{l_{beacon}}. \tag{2.20}$$

2.4 CHAPTER SUMMARY

This chapter has presented the IEEE 802.11ac, the IEEE 802.11 Power Save Mode, Multi-channel MAC, and the TMMAC protocols. We also presented the throughput performance analysis of IEEE 802.11 and M2MMAC protocol that has inspired our work.

3 FULL-DUPLEX RADIOS

This chapter presents a summary of full-duplex radio in the hope of assisting readers to understand better the benefits and challenges inherent in full-duplex MAC protocol designing. Therefore, this chapter presents the basic concepts of a full-duplex wireless radio.

The full-duplex communication might be defined as concurrently bidirectional communication. The full-duplex communication might be classified as out-band or in-band full-duplex. The first one is the more common and has been used until recently, it either uses Time Division Duplexing (TDD) or Frequency Division Duplexing (FDD) approaches to achieve full-duplex communication. On the other hand, in-band communication is the technology that enables bidirectional communication in the same frequency band. In this work, full-duplex communication refers to the latter one.

3.1 FULL-DUPLEX BASICS

To provide a concurrently in-band simultaneous bidirectional communication, full-duplex radios must address the self-interference issue. This issue arises from the effects that the transmitted signal causes in the receiving signals. As the nature of the environment affects both, transmitted and received signals, refined approaches are required to suppress the self-interference signals which makes the signal subtraction inefficient in the signal process.

A crucial subject in full-duplex radios is developing techniques to suppress the self-interfering signal efficiently. Self-interfere methods can be classified as passive and active cancellation. Passive cancellation focuses on preventing the transmitting signal from spreading from the transmitting circuit to the receiver chain of the radio; thus, it is also known as the isolation method. In Fig. 6 this method is represented by the distance between antennas. Nonetheless, active cancellations target to obliterate the transmitting signal and its effects on the received one. In Fig. 6 it is represented by the cancellation circuit block (SABHARWAL et al., 2014).

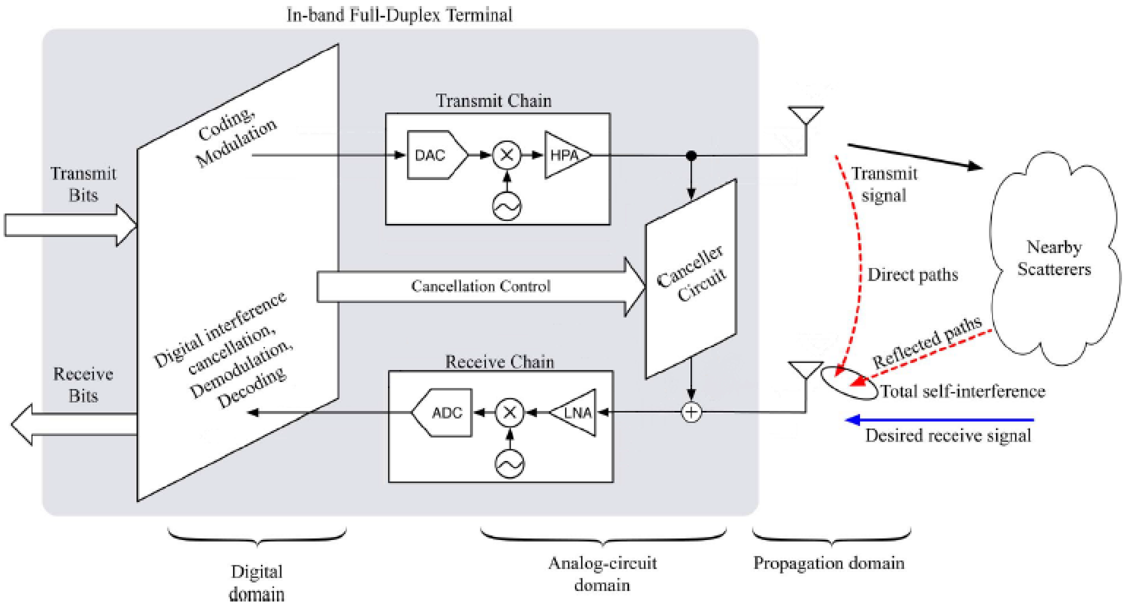

Figure 6 – Self-interference signal cancellation (SABHARWAL et al., 2014).

3.2 PASSIVE CANCELLATION

Passive self-interference cancellation methods, also known as self-interference suppression in the propagation domain or just isolation, are techniques that aim to isolate the receiving circuit chain electromagnetically from transmitting circuit chain effects to suppress the effects of the self-interference signal before its manifestation in the receiving signal (SABHARWAL et al., 2014).

The technique employed by Choi et al. (CHOI et al., 2010), one of the predecessors in full-duplex radio for wireless networks, is called Antenna Cancellation. This strategy uses three antennas, two transmitting signals, and a single receiving antenna positioned in the middle of the others. This scenario intends to yield destructive interference in the receiving signal.

The antenna spacing consists of using medium attenuation. This technique can be summarized by placing receiving and transmitting antennas away from each other for a distance of about 20 to $40cm$. Hence, the radio takes advantage of the medium's propagation losses to mitigate self-interference effects. Employing this approach allowed the authors of (DUARTE; SABHARWAL, 2010; DUARTE; DICK; SABHARWAL, 2012) to achieve a self-interference cancellation from $39dB$ up to $45dB$. Although this technique is simple and practical, it is limited to the size of the devices used for communication since its effect is proportional to the spacing applied.

Bharadia *et al.* presents the use of a circulator device. This device consists of three ports that allow the passage of current in a particular direction, i.e., clockwise or counterclockwise, between two consecutive ports (POZAR, 2009). Because of this, Bharadia *et al.* suggests connecting the transmitting circuit, the antenna, and the receiving circuit in a circulator to avoid the transmitting current leaking to the receiving signal while allowing the latter one to receive signals from the antenna. Although inspiring, this technique obtained a reduction of only $15dB$ possible.

3.3 ACTIVE CANCELLATION

As previously mentioned, active cancellations target mitigating the effects of the transmitting signal on the received one. It can be made by two types of cancellation, analog and digital. As the name suggests analog cancellation aims to process the analog signal while digital cancellation targets the digital one. In this section, we present the procedures that enabled full-duplex communication.

3.3.1 Analog Cancellation

Analog cancellation techniques, or analog cancellation, aim to suppress self-interference in the analog circuit chain before the Analog-to-Digital Converter (ADC). This cancellation can occur before or after the Low-Noise Amplifier (LNA) (SABHARWAL et al., 2014).

Radunovic *et al.* (RADUNOVIC et al., 2009) proposed a straightforward analog cancellation system that was later adopted in the work of Choi *et al.* (CHOI et al., 2010). In this procedure, a copy of the signal after the High-Power Amplifier (HPA) is created as a reference signal to subtract from the signal obtained at the beginning of the receiver circuit.

Applying the reference signal to a series of parallel transmission lines to obtain variable delays and adjustable attenuation is another method (BHARADIA; MCMILIN; KATTI, 2013; BHARADIA; KATTI, 2014; KNOX, 2012; PHUNGAMNGERN; UTHANSAKUL; UTHANSAKUL, 2013). An alternative to this strategy is to apply a method known as *Balun* (JAIN et al., 2011). This technique includes the balancing and unbalancing of the copy of the signal to be transmitted so that the adjustments of delays and attenuation are applied to the signal and, finally, the cancellation of self-interference in the analog domain.

Another approach is to process a copy of the signal in the digital domain to apply necessary adaptations digitally, such as gain, phase, and delay adjustments. Performing a digital-to-analog conversion to perform the analog signal cancellation in the receiver circuit (DUARTE; SABHARWAL, 2010; DUARTE; DICK; SABHARWAL, 2012; DUARTE et al., 2014). This approach is more straightforward since performing attenuation and delay operations on signals in the digital domain is less complicated than in the analog domain (KIM; LEE; HONG, 2015).

3.3.2 Digital Cancellation

Cancellation procedures in the digital domain or simply digital cancellation are intended to cancel self-interference after the analog-to-digital converter. This process applies advanced Digital Signal Processing (DSP) techniques making sophisticated processing systems relatively easier (SABHARWAL et al., 2014).

Digital cancellation techniques are usually the last procedure to engage in self-interference mitigation. For this reason, these strategies must eliminate the remaining interference that the isolation and analog cancellation processes left. Nonetheless, digital cancellation techniques have been introduced previously in the wireless communications literature. They are employed to eliminate interference in signals, as performed in the strategies of Successive Interference Cancellation (SIC) (HALPERIN; ANDERSON; WETHERALL, 2008), analog network coding (ANC) (KATTI; GOLLAKOTA; KATABI, 2007) and ZigZag decoding (GOLLAKOTA; KATABI, 2008) in an attempt to recover packets in situations of collisions between signals.

Choi *et al.* points out that these techniques can be employed in *full-duplex* radios. However, since the radio knows the symbols of the interfering signals, since it is the signal transmitted, decoding the signal would be unnecessary to facilitate signal recovery. Nevertheless, predicting delays and phase shifts is a significant challenge in full-duplex radio designs and, for this reason, is the scope of several state-of-the-art works.

Kim *et al.* (KIM; LEE; HONG, 2015) indicates some works that employ schemes such as Maximum Squared Error (BLISS; PARKER; MARGETTS, 2007) and multiple antenna strategies, such as *zero-forcing beamforming* (ZF), null space projection (NSP) and mean square error filters are some methods adopted by (RIIHONEN; WERNER; WICHMAN, 2009) and (RIIHONEN; WERNER; WICHMAN, 2010).

3.4 NETWORK SYMMETRY

Regarding the full-duplex capabilities, MAC protocols can be divided into symmetric and asymmetric protocols (PENG et al., 2020). In asymmetric protocols, the base station and access point are the only nodes capable of full-duplex communication, while other network stations employ a Half-Duplex radio to communicate. Symmetric protocols consider that all network nodes are equipped with the same wireless radio. Therefore, full-duplex communication is achievable by all network nodes, while other network stations employ a half-duplex radio to communicate.

3.5 MULTI-USER FULL-DUPLEX

MIMO has been the foremost strategy adopted in full-duplex radios to deliver a multi-user capability (ARYAFAR et al., 2012). This approach replicates the full-duplex chain, allowing devices to accept multiple incoming and outgoing data in different channels. Although this method is more straightforward, it does not efficiently use the bandwidth since it allocates a channel for each full-duplex communication, rapidly consuming the physical layer resources.

The Spatial group-based multi-user full-duplex OFDMA (GFDO) (PENG et al., 2020) is an asymmetric strategy to allow full-duplex multi-user widely used in infrastructure MAC protocols. In this strategy, the access point is provided with a full-duplex radio positioned in the center, while other devices use a half-duplex to communicate as shown in Fig. 7. The process gathers stations into groups called spatial groups (SG) to avoid inter-node interference. In this way, the GFDO BS designates a Group Header (GH) to collect channel information about nodes in the SG called Group Members (GM) and interferences between other SG. With the interference information between group members, the AP can allocate the same channel as an uplink in a spatial group and a downlink resource in another group without interference between the transmitter and receiver devices.

In (SHAYOVITZ; KRESTIANTSEV; RAPHAELI, 2022), Shayovitz et al. present an algorithm of autoregressive filters employing an alternating minimization combined with an approximate joint maximum likelihood estimation of the signal leakage and AR filters using alternating minimization. This approach enables stations to decode signals from weak users in the uplink channel while in the presence of a strong narrow-band user.

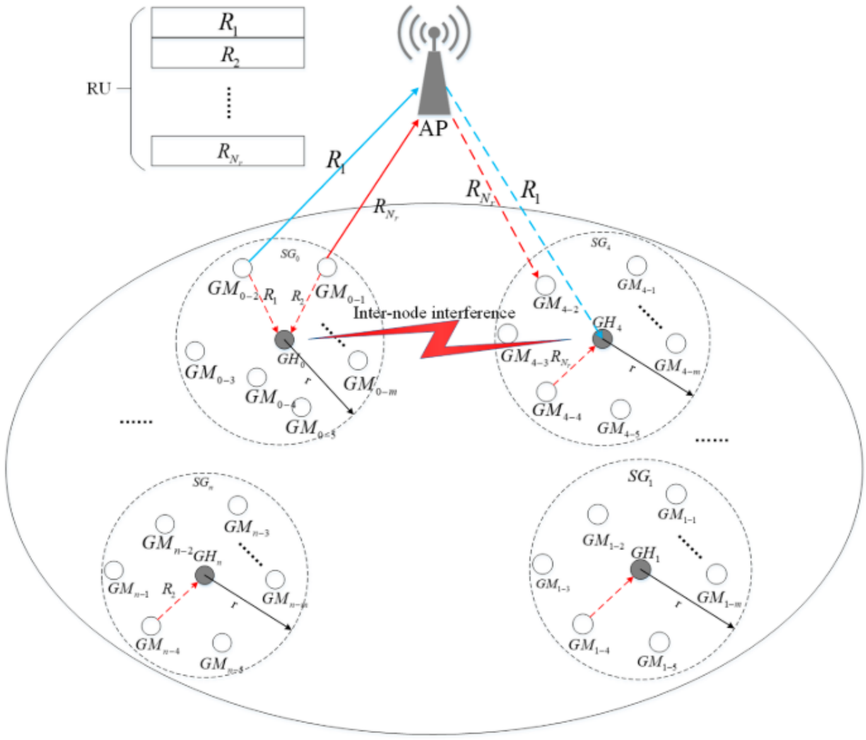

Figure 7 – Spatial Group-Base Multi-User Full-Duplex (PENG et al., 2020).

3.6 CHAPTER SUMMARY

In this chapter, we presented the basic concepts regarding full-duplex radios. The mechanisms that enable this communication, such as passive and active cancellation were also presented. Additionally, we presented the multi-user full-duplex communication principles that empowered our protocol proposal.

4 FULL-DUPLEX MAC PROTOCOLS AND RELATED WORK

In the following sections, we discuss the scenarios that are presented in full-duplex communication along with the terminology commonly used in full-duplex protocols. In addition, we briefly present relevant protocols in the field. Finally, we arrange the protocols in a table to summarize the protocols in their main characteristics.

4.1 NETWORK TOPOLOGY

The capability of concurrent communication, i.e., the presence of two simultaneous transmitting and two receiving nodes, requires the definition of new communication medium access control protocols. Therefore, in the literature, the two pairs of communicating nodes employ the role of primary and secondary communications. The first one is defined by the communication yield by the node that has first acquired the channel. The second one is the result of the second communication allowed to happen, given that it does not interfere with the primary one.

As two communications occur simultaneously, this implies that more than one node is transmitting, as well as more than one node receives data. With that in mind, the literature has assigned the name of the Primary Transmitter (PT) to the node that is first granted to transmit and its receiver as the Primary Receiver (PR). The secondary communication is composed of a Secondary Transmitter (ST) which is the node allowed to transmit along with the primary transmitter and, analogously, a Secondary Receiver (SR) which is the secondary transmitter's receiving node.

The two previously described communication, primary and secondary, raises some particular scenarios in the protocol topology. A fundamental case involves only two nodes. In that case, the primary transmitter also plays the role of a secondary receiver while its receiver also transmits data configuring bi-directional communication. The Fig. 8 presents a layout of a bi-directional full-duplex communication.

Figure 8 – Bi-Directional Full-Duplex topology (Adapted from: (GOYAL et al., 2013)).

On the other hand, uni-directional communication is formed when the primary receiver does not address data to its transmitter. In this case, the communication can be classified into two communications based on the secondary transmitter.

Target-based topology arises when the primary receiver intends to transmit to a third node as shown in Fig. 9. In that case, similar to the bidirectional scenario, the primary receiver (blue node) is the secondary transmitter, and its receiver is the secondary receiver.

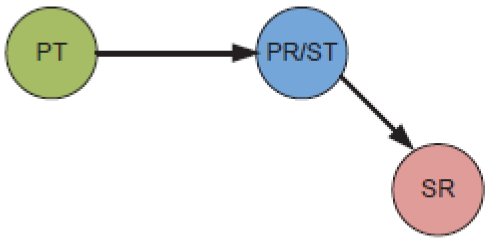

Figure 9 – Unidirectional Full-Duplex topology based on target (Adapted from: (GOYAL et al., 2013)).

In the sourced-based scenario, nodes overhearing the channel identify the opportunity to transmit to the primary transmitter without interfering with the reception of its transmitted data. In this case, the secondary transmitter must ensure that his signal will not affect the reception of the primary receiver node. That requirement is commonly ensured by noting that the secondary transmitter must be able to receive the primary transmission without any interference that would arise from a secondary transmission from the primary receiver. This scheme is shown in Fig. 10 in which the red node transmission does not interfere with the PT-PR communication.

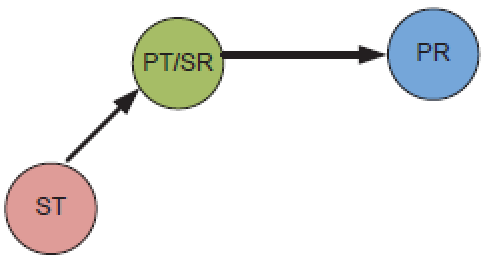

Figure 10 – Unidirectional Full-Duplex topology based on source (Adapted from: (GOYAL et al., 2013)).

In addition to these scenarios, there is also the case that a third node is assigned or allowed to transmit to another. Thus, neither node in the secondary communication takes a role in the primary one. This scenario is more complex to achieve since the transmitters must be coordinated and both secondary nodes should be determined to avoid interference between the signals.

4.2 INFRASTRUCTURE-BASED PROTOCOLS

This section introduces some full-duplex protocols that rely on infrastructure-based architecture.

Jain *et al.*

Jain *et al.* (JAIN et al., 2011) proposed a protocol based on CSMA/CA in which whenever a receiving node has data addressed to its transmitter, it is capable of sending during data reception. A busy tone signal should protect the channel in case of asymmetric data. This behavior is repeated on the occasion that the receiving node has no data to exchange with the proposal which avoids the hidden terminal problem.

Sahai *et al.*

Sahai *et al.* (SAHAI; PATEL; SABHARWAL, 2011) introduces an asynchronous version of Jain *et al.* (JAIN et al., 2011) protocol. In this way, Sahai *et al.* suggest a 45-bit modification in the IEEE 802.11 packet. In this protocol, the communication always starts in a half-duplex mode, as presented in Fig. 11. Accordingly, whenever a device has data to the access point it can transmit synchronously.

A starvation problem may arise in cases where the access point and a node have data to exchange frequently. To avoid this scenario, Sahai *et al.* determined that the two nodes agree to halt communication with each other, so other network devices have the opportunity to transmit, this mechanism was called shared random backoff.

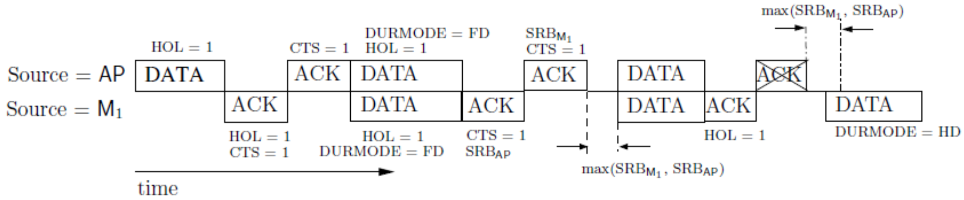

Figure 11 – Sahai et al. transmission diagram (Reprinted from: (SAHAI; PATEL; SABHARWAL, 2011)).

In the Snooping to Leverage FD Mode mechanism in Sahai *et al.* the nodes overhear the channel to identify the network topology and by so identify whether another device is a hidden terminal. This approach enables nodes to explore scenarios in which the access point is only a transmitter allowing data reception in a unidirectional full-duplex communication.

Finally, Sahai *et al.* proposes that the access point only extends data exchange with one given node with a probability that decays in a geometric pattern. Similarly, nodes only explore unilateral communication with the access point with a probability that is based on an aggression factor and the maximum size of the contention window. These strategies, combined, compose the scheme of Virtual Contention Resolution.

AC-MAC

The AC-MAC (OASHI; BANDAI, 2012) determines that before securing the channel, a node should backoff for a random period between zero and the minimal contention window value. The primary receivers should verify if contain data to primary transmitters, in affirmative cases it establishes a full-duplex communication. Despite that, the communication should proceed in a half-duplex fashion.

AC-MAC/DCW

AC-MAC/DCW (OASHI; BANDAI, 2012) is an AC-MAC adaptation and intends to improve the previous protocol when, frequently, the client nodes have much more data to the access point. In these scenarios, the AC-MAC/DCW adopts two sizes of contention windows for base stations, large and small. After successfully transmitting a packet, the access point should decide which contention window to be applied based on its transmission queue.

Transmission queues that have lower sizes than a given threshold lead to a larger contention window selection. Otherwise, the stations embrace a small window size so they can be privileged in the network.

Duarte *et al.*

Duarte *et al.* (DUARTE et al., 2014) proposed an adaptation in IEEE 802.11 DCF protocol for full-duplex radios. In this protocol, the primary receivers should examine the transmission queue before sending a CTS packet. On the occasion that there is a packet addressed to its transmitter, the receiver sends the CTS and waits a SIFS period, similar to IEEE 802.11 DCF protocol. After that, it initiates the data transmission in a full-duplex bidirectional communication as shown in Fig. 12.

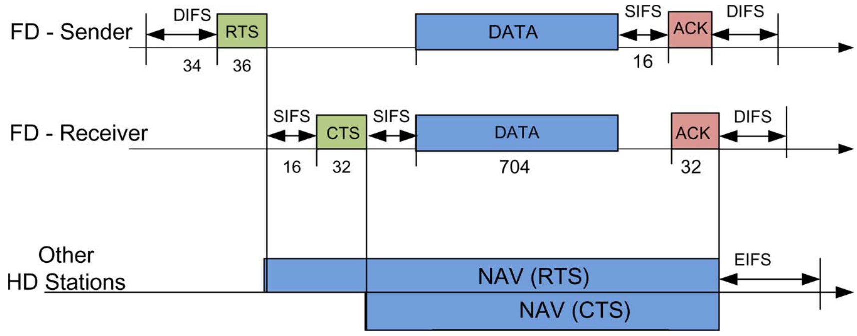

Figure 12 – Duarte et al. transmission diagram (Reprinted from: (DUARTE et al., 2014))

In a successful data exchange, the nodes must acknowledge the transmission in a full-duplex communication. In that scenario, asymmetric communication requires that the device with the shorter data packet wait until the end of transmission to acknowledge.

Duarte *et al.* is also concerned about network justice. It pointed out that devices in full-duplex communication have an advantage in acquiring the channel again because these nodes wait a DIFS period while other networks' nodes should wait for a more extended period before channel contention, i.e. an EIFS, as these nodes are incapable of packet decode. To bring justice to the network, Duarte *et al.* proposed that primary and secondary transmitters involved in full-duplex communication must wait for an EIFS period likewise.

Tang and Wang

The approach proposed by Tang and Wang (TANG; WANG, 2014) restricts the full-duplex technology to access point (AP) nodes. Therefore, user stations should communicate in the traditional half-duplex manner. With this strategy, the full-duplex approaches are simplified so the technology adoption and migration are facilitated, since only the base station is aware of bidirectional capabilities. The protocol determines that the access point can transmit packets to any network node while another node is transmitting to it. Fig. 13 shows the two possible scenarios that might occur in Tang and Wang. In Fig. 13 (a) a unidirectional communication is established as the access point transmits to a third node. However, the packet sent from AP to its receiver is shorter than the one sent from node A. Therefore, the AP transmits a busy tone to ensure that both transmission finishes at the same time. In Fig. 13 (b) the ending of both communications is ensured by node A which delays its transmission after receiving the CTS packet from AP including the duration of the secondary transmission.

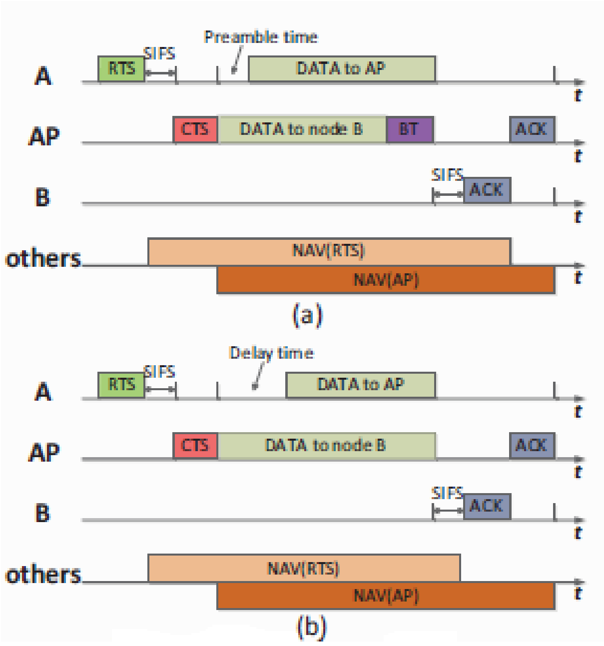

Figure 13 – Transmission diagram from Tang and Wang: (a) a bidirectional full-duplex scenario (b) a unidirectional (Reprinted from: (TANG; WANG, 2014)).

PoCMAC

In PoCMAC (CHOI; LIM; SABHARWAL, 2015) protocol the CTS and ACK packets are modified to differentiate the recognized packet from the access point to other nodes and from the common node to the access point so it can manage unidirectional communication.

The PoCMAC follows the Tang and Wang's strategy (TANG; WANG, 2014). The only node capable of full-duplex communication is the base station. Different from Tang and Wang, the common nodes are aware of this capability and should receive and send the proper CTS and ACK packets.

FuPlex

The FuPlex (QU et al., 2015) explores both scenarios of unidirectional full-duplex. In the scenario in which the access point is the primary receiver, the base station initiates a secondary transmission to another network node. Otherwise, if the access point is the primary transmitter, all nodes contend to transmit as a secondary transmitter to the access point, except the primary receiver.

Mu-FuPlex

Mu-FuPlex (QU et al., 2017) is based on the OFDMA process adopted by IEEE 802.11ax. The protocol is an adaptation of FuPlex (QU et al., 2015) and intent to avoid the interference between nodes by first grouping nodes that are near each other and employing different sub-carries for downlink and uplink channel for each group while it re-uses the sub-carries in an access point full-duplex communication.

PC Mu-FuPlex

PC Mu-FuPlex adds transmission power control to the previous version to avoid even further interference between uplink and downlink full-duplex nodes. (QU et al., 2018)

MB-FDMAC

In the Multi-Band Full-Duplex MAC protocol (ALKHRIJAH; CAMP; RAJAN, 2023) the authors adopt two frequency bands during the data transmission which one of them is a microwave range (sub 6 GHz) that provides a higher cover area and the other one is in millimeter wave (60 GHz) that provides a higher data transfer rates as shown in Fig. 14.

The MB-FDMAC protocol employs a unidirectional full-duplex in the access point to allow frequency reuse between uplink and downlink channels. Initially, the MB-FDMAC promotes mmWaves adopting μWaves only when the user equipment is not in the mmWave range.

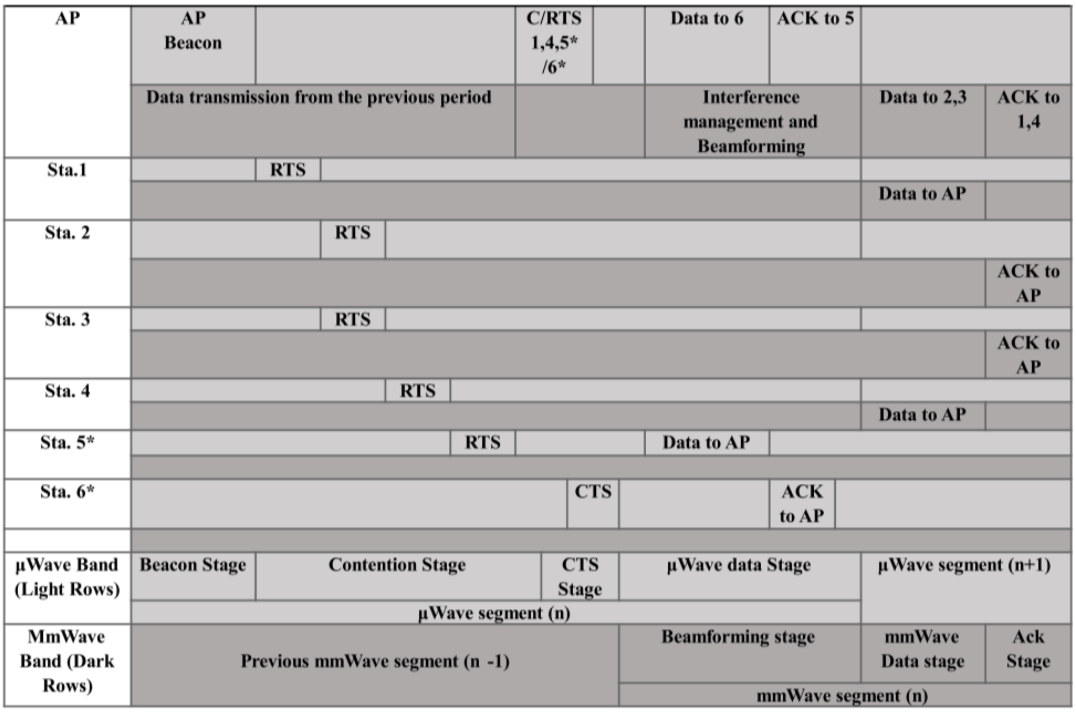

Figure 14 – Transmission diagram from FD-MBMAC (Reprinted from: (ALKHRIJAH; CAMP; RAJAN, 2023)).

4.3 AD HOC BASED PROTOCOLS

Here we review some full-duplex protocols based on ad hoc architecture.

ContraFlow

The ContraFlow protocol (SINGH et al., 2011) is one of the first protocols designed for full-duplex wireless communication. In this protocol, a node acquires the channel via the CSMA/CA protocol. Whenever receiving a packet, the receiver chooses between protecting the transmission with a busy tone or sending data to another node.

The selection of a second receiver is based on a weighted list related to the success rate in the transmission. This approach is intended to minimize interference due to primary and nearby communication. At the end of transmission, nodes wait for acknowledgment sending a busy tone signal to protect the channel.

Goyal et al.

Goyal et al. (GOYAL et al., 2013) proposed two bits modifications on CSMA/CA protocol called full-duplex acknowledgment(FDA) to indicate the full-duplex mode to be operated or the impossibility of such communication. In this approach, after an RTS packet, the transmitter protects the channel by sending a busy tone signal until it receives an FDA packet.

Whenever a primary transmitter is free to receive a packet while transmitting, the node indicates it by setting a transmission flag. Neighbor nodes interested in transmitting to the primary transmitter can express it by sending a busy tone after evaluating that its communication does not affect the primary one.

RFD-MAC

The RFD-MAC protocol intends to apply full-duplex radios in a multi-hop environment. In this scenario, unidirectional full-duplex communication is a good approach to improve overall network throughput. The RFD-MAC (TAMAKI et al., 2013) brings to the primary transmitter the responsibility of finding another node in which a secondary communication would not interfere with its own. In this way, since both communications should not interfere with each other, the selection of receiver nodes is the main challenge faced by RFD-MAC protocol.

DAFD-MAC

The DAFD-MAC (SUGIYAMA et al., 2014) intends to improve the success rate of establishing unidirectional communication. Since a secondary receiver may be prevented from communicating due to a neighbor transmission, DAFD-MAC proposes a combination of placement recognition and directional antennas on the nodes. In this fashion, the transmitted signal affects a reduced area and hence a minimal number of nodes are involved.

Vermeulen *et al.*

Vermeulen *et al.* (VERMEULEN; POLLIN, 2014) proposed a protocol based on IEEE 802.15.4. The strategy adopted every node should listen to the channel during two time intervals enabling nodes to identify a collision in the transmission process during the initial intervals of this process.

Additionally, the protocol requires receiver nodes to transmit a dummy packet to announce a communication in progress to neighbor nodes. Whenever a receiver verifies a packet interference, it halts the dummy packet transmission allowing the transmitter to identify this scenario.

RTS/FCTS-MAC

The RTS/FCTS-MAC protocol (CHENG; ZHANG; ZHANG, 2013) modifies CTS packets to include the sender and receiver addresses. Whenever a receiver node has a packet for its transmitter, it sends the transmitter address in both fields. In this case, before exchanging packets, the sender must reply with another FCTS indicating that the operation may proceed in a bidirectional full-duplex mode.

Otherwise, if another node is desired, the receiver address is set to this device which should respond with an FCTS before communication starts. At the end of the process, the ACK packet is exchanged in full-duplex mode.

FD-MMAC

The FD-MMAC (ZHANG et al., 2014) is a multi-channel procedure to avoid the hidden terminal problem and allow transmission even in exposed terminal situations. Despite that, the FD-MMAC suggests each node determines its capabilities based on a region division.

The FD-MMAC grounds on the fact that other nodes either can only decode one of the two signals transmitted on a full-duplex communication or any of those due to a collision of primary and secondary communication signals. Based on that, the receiver nodes should transmit a beacon allowing other devices to classify their region.

Whenever a node cannot decipher the signal, it is assumed to be in a collision region where it cannot operate. In case a device can only listen to a beacon signal, it is determined that it is in a receive-only region. On the other hand, if the node can decode the data transmitted, it is allowed to send data since it does not interfere with the primary communication. Therefore, to be discovered by a transmitter, the Transmission-Only nodes should select another residing channel.

4.4 PROTOCOLS SUMMARY

This section presents the previous refereed protocols summary in the format of Table 1. The reader might consult the protocol name along with the year and its reference work. In the second column, it is presented the architecture or its topology. After, that we list the protocols used as a base for each work followed by the column that describes the evaluated metrics. Additionally, the major characteristics, advantages, and disadvantages Finally, the validation or evaluation mechanism is described in the last column. We also added to the table our two protocols (FD-M2MMAC and EFD-M2MMAC) proposed in this dissertation to compare with the literature.

Table 1 – Full-Duplex MAC Protocols

Protocol/ Year	**Architecture/ Topology**	**Protocol Based**	**Metrics**	**Major Characteristics**	**Main Advantages**	**Main Disadvantages**	**Validation**
ContraFlow (SINGH et al., 2011)	Ad hoc (Distributed)	CSMA/CA	Utility and Throughput	Transmission protection by busy tone and receiver selection	Selection based on transmission success rate	Secondary transmission vulnerable of hidden terminal problem.	Simulation
Jain *et al.* (JAIN et al., 2011)	Infra-structured (Centralized)	CSMA/CA	Throughput, fairness and capacity	First protocol implemented in a real full-duplex radio	Simplicity	Handle exclusively bilateral connections	WARP V2 Implementation
Sahai *et al.* (SAHAI; PATEL; SABHARWAL, 2011)	Infra-structured (Centralized)	IEEE 802.11 DCF	Throughput	Nodes are allowed to start asynchronous uni-lateral connections	Nodes may start communication with a half-duplex communication ongoing	complexity and overhearing	WARP Implementation
AC-MAC (OASHI; BANDAI, 2012)	Infra-structured (Centralized)	CSMA/CA	Throughput	Contention Window Control		Exclusively bidirectional full-duplex communications	NS3 Simulation
AC-MAC/DCW (OASHI; BANDAI, 2012)	Infra-structured (Centralized)	CSMA/CA	Throughput	Dynamic Contention Window Control	Avoid excessive information transmitted	Exclusively bidirectional full-duplex communications	NS3 Simulation
Goyal *et al.* (GOYAL et al., 2013)	Infra-structured (Centralized) e Ad hoc (Distributed)	IEEE 802.11 CSMA/CA	Throughput	Interference evaluation between the full-duplex communications	More probable of success in unilateral communications	Overhearing	OPNET Simulation

Table 1 – Full-Duplex MAC Protocols (continuation)

Protocol/ Year	**Architecture/ Topology**	**Protocol Based**	**Metrics**	**Major Characteristics**	**Main Advantages**	**Main Disadvantages**	**Validation**
Janus (KIM et al., 2013)	Infra-structured (Centralized)	Any	Throughput, fairness, and overhead	Transmission in low interference scenarios	Explores well the opportunities in full-duplex and nodes does not suffer from collision during transmission period	Overhearing and overhead. Are not based on any existing protocol	WARP Implementation
FD-MAC (KIM; STARK, 2013)	Ad hoc (Distributed)	IEEE 802.11	Throughput and bandwidth efficiency	IEEE 802.11 adaptation to full-duplex radios	Simplicity	Only employs bilaterals transmission, secondary ones are limited primary time.	Mathematical Analyses
RFD-MAC (TAMAKI et al., 2013)	Ad hoc (Multi-hop)	IEEE 802.11	Throughput and full-duplex connection rate	Secondary receiver selection algorithm	Transmitter selection to avoid interference in receiver nodes	Overhearing and requires that devices maintain data from neighbor nodes.	Simulation
RTS/FCTS-MAC (CHENG; ZHANG; ZHANG, 2013)	Ad hoc (Distributed)	IEEE 802.11 DCF	Throughput	Secondary receptor indication by CTS	Robustness against hidden terminal problem	overhead in control packet exchange and overhearing	Statistical Analyses
DAFD-MAC (SUGIYAMA et al., 2014)	Ad hoc (Multi-hop)	CSMA/CA	Throughput and Collision rate	Directional antennas to avoid interference between communication	More successful chance in secondary transmission	An complex algorithm that involves nodes localization	Simulation

Table 1 – Full-Duplex MAC Protocols (continuation)

Protocol/ Year	**Architecture/ Topology**	**Protocol Based**	**Metrics**	**Major Characteristics**	**Main Advantages**	**Main Disadvantages**	**Validation**
Vermeulen *et al.* (VERMEULEN; POLLIN, 2014)	WSN (Multi-hop)	IEEE 802.15.4	Bit energy, throughput e delay	CSMA/CD version to WSN	Collision detection and hidden terminal mitigation	Do not explore full-duplex to improve network throughput. Raises the energy consumption in receiver nodes	Matlab Simulation
Tang and Wang (TANG; WANG, 2014)	Infra-structured (Centralized)	IEEE 802.11 DCF	Throughput	Full-duplex communications in even with collision	Uni-lateral transmission with nodes that are not mutually hidden terminals	Does not explore all full-duplex possibilities, such as bi-lateral e a uni-lateral communication based on source	Matlab Simulation
Duarte *et al.* (DUARTE et al., 2014)	Infra-structured (Centralized)	IEEE 802.11 DCF	Goodput	Queue search to apply full-duplex	Co-existence between half-duplex and full-duplex comunications	Does not explore full-duplex uni-laterals connections	OPNET Simulation
FD-MMAC (ZHANG et al., 2014)	Multi-User Ad hoc (Distributed)	CSMA/CA	Throughput, delay, fairness and load balance	Transmission in exposed terminals and reception in hidden ones	Robustness against Hidden and Exposed terminal problems	Does not handle unilateral *full-duplex* connection	OPNET Simulation
PoCMAC (CHOI; LIM; SABHARWAL, 2015)	Infra-structured (Centralized)	IEEE 802.11	Throughput and fairness	Transmission power optimization in order to avoid interference	Greater success rate in secondary transmission	Does not handle bilateral *full-duplex* connections and complexity	MatLab Simulation and WARP Implementation

Table 1 – Full-Duplex MAC Protocols (continuation)

Protocol/ Year	**Architecture/ Topology**	**Protocol Based**	**Metrics**	**Major Characteristics**	**Main Advantages**	**Main Disadvantages**	**Validation**
FuPlex (QU et al., 2015)	Multi-User Infra-structured (Centralized)	IEEE 802.11DCF	Throughput	Full-Duplex based on source and on target	Explore both Unidirectional Full-Duplex	Inter-node interference	NS2 simulation
Mu-FuPlex (QU et al., 2017)	Multi-User Infra-structured (Centralized)	IEEE 802.11ax OFDMA	Throughput and Efficency	Nodes are grouped	Avoids interference between nodes	Unidirectional Full-Duplex	NS2 simulation
PC Mu-FuPlex (QU et al., 2018)	Multi-User Infra-structured (Centralized)	IEEE 802.11ax	Throughput and Efficency	Power Control over MU FD	Avoids interference between nodes	Complexity	NS2 simulation
FD-M2MMAC (SANTANA; MORAES, 2022)	Multi-User Ad hoc (Distributed)	M2MMAC	Throughput	MU Many-to-Many FD	Exchange data with multiple nodes	FD with a single node per interval	MatLab
EFD-M2MMAC (SANTANA; MORAES, 2023)	Multi-User Ad hoc (Distributed)	FD-M2MMAC	Throughput	MU Many-to-Many FD	Exchange data with multiple nodes	Complexity in FD schedule exchange	MatLab

4.5 CHAPTER SUMMARY

In this chapter, we presented the full-duplex protocols that have guided our work. To better introduce them, the chapter is mainly divided into their network target architecture, i.e. if the network is provided with a coordinator node and/or infrastructure or rather if it is self-configured with the independent nodes.

Among those, it is important to highlight the protocols FuPlex, Mu-FuPlex, MB-FDMAC, and FD-MMAC which have inspired us in our proposal with their multi-user full-duplex approaches.

Besides that, this chapter also summarizes the protocols presented in a table format to favor readers by making it more convenient to consult the protocols' main aspects.

5 FULL-DUPLEX MANY-TO-MANY MULTICHANNEL MAC PROTOCOL

In this chapter, we present a new MAC protocol based on M2MMAC which uses self-interference cancellation to achieve full-duplex communication to improve the aggregated throughput. Accordingly, to evaluate the benefits of the proposed protocol, a throughput analysis is developed so the aggregated throughput is compared with the M2MMAC protocol in different scenarios given that the nodes are provided with the same number of antennas. The multiple scenarios are related with the number of antennas for each device, the number of available channels and sub-carriers. Finally, we evaluated the effect of the Announcement Traffic Indication MAP (ATIM) window size parameter.

The new protocol combines the M2MMAC approach, and its many-to-many nature, with full-duplex radio to improve the overall network throughput. Also, the protocol adopts an OFDMA approach, providing that it has been widely used in the wireless network communication industry. Thus, we propose a new protocol named Full-Duplex Many-to-Many Multichannel MAC (FD-M2MMAC) (SANTANA; MORAES, 2022), which is the main contribution of this chapter.

5.1 ASSUMPTIONS

The following list summarizes the assumptions considered in the protocol:

- The Channel State Information (CSI) is well known for M orthogonal sub-carriers. The CSI knowledge allows nodes to detect channel information, and combine multiple reception antennas to detect distinct signals from multiple sources.
- The network nodes are provided with two radio interfaces capable of multi-user detection. This can be achieved by employing radios such as described in (LEE; LEE; LEE, 2006).
- The network nodes are provided with an array of B reception antennas. Those antennas are divided between two radio interfaces: the primary one is devoted to receiving data from multiple transmitters, while the secondary one is dedicated to receiving data from a node in its reserved channel.
- Each node in the ad hoc network Each node must reach and be reached by all other nodes of the network, being the communication always in single-hop fashion, and they

are synchronized.

- In the ATIM window, nodes exchange control packets employing CSMA/CA in the control channel in half-duplex way. In the Communication window, nodes employ OFDMA full-duplex to exchange data packets.

- The network is considered to be saturated. Therefore, the network nodes always have packets to be transmitted to each other.

A sample of the topology for which the FD-M2MMAC is presented is in Fig. 15. In this topology, each node is provided with six antennas, which are grouped as three to the primary and three to the secondary V-BLAST radios allowing each node to detect two streams in the primary radio. Each node reserves a singular sub-carriers that cannot be reserved by any other node to receive incoming data. The node's reserved sub-carriers are shown as different colors in each node to illustrate that each node has reserved a different sub-carrier in the ATIM Window. A transmission of data is represented by a solid line and the arrows indicate the flow. The full-duplex transmission is indicated by dashed lines.

It is important to notice that the secondary radio requires the same configuration as the primary one so the network nodes can receive in a full-duplex manner. For example, in Fig. 15 for node A to detect incoming data from node C in "red" frequency (reserved by node C), node A must first eliminate its self-interference signal which is the result of all transmitted signals, including the one in "red". Afterwards, node A has to detect the signal that comes from C in the "red" frequency. However, the signal from node B addressed to node C in "red" frequency also reaches node A producing a noise that should be detached from the C signal and ignored.

Fig. 16 presents the same scenario previously described with the target sub-carrier for primary radios (P) and secondary radios (S). In that illustration, node B presents the primary radio focusing on the sub-carrier that has been selected by this node, sub-carrier "yellow", in the ATIM window. The secondary radio is required to node B to detect the incoming full-duplex communication from node A in the "blue" sub-carrier. Notice that in this case, node B suffers interference from the signal that node C is transmitting to A in the "blue" sub-carrier. Therefore, node B needs to detect, in the "blue" sub-carrier, two signals and ignore the one that is not coming from node A.

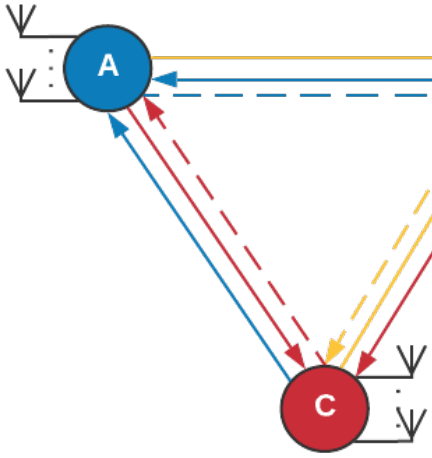

Figure 15 – FD-M2MMAC example topology. Three nodes communicate in a multi-user approach with full-duplex technology during a communication window slot. (Reprinted from: (SANTANA; MORAES, 2022))

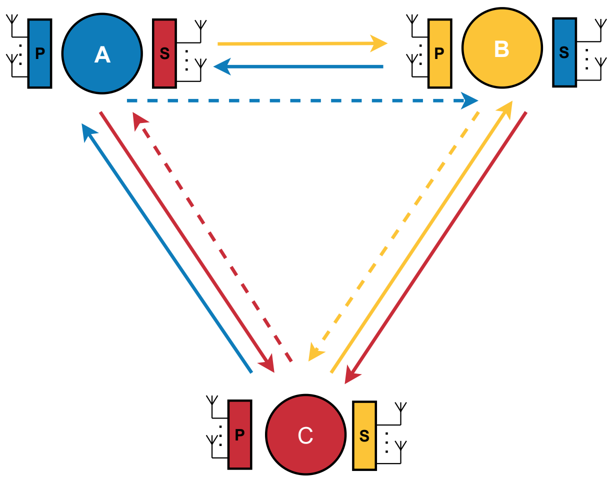

Figure 16 – FD-M2MMAC topology receiver radios details with the different sub-carriers that are the target for the primary radio (P) and secondary radio (S).

5.2 SIMPLIFIED HARDWARE ARCHITECTURE

Fig. 17 presents a simplified architecture of the transceivers provided in every node in the FD-M2MMAC. Fig. 17 shows that to transmit to different users, each node should store a different buffer of the packets to be transmitted in the recipient frequency.

However, before reaching the Digital-to-Analog Converter (DAC), the digital signals that are targeted by both receives are collected to be used in the digital cancellation process. After the DAC, all the signals are combined to be transmitted. Before the signal reaches the antenna, the resulting signal is collected to be used in the analog cancellation in the Circuit Canceller.

This module aims to mitigate the repercussions of the self-interference signal in the analog domain.

In the receiver chain, the incoming signal is first analogically canceled and before being filtered by a Low-Pass Filter (LPF). The LPF targets a single sub-carrier frequency. After the filtering, the signal is converted to its digital form where it can be digitally canceled to withdraw the self-interference signal that is aimed. Finally, the V-BLAST radio, a MIMO detector, is responsible for identifying the multiple users that are transmitting in the same frequency.

Notice that both, the primary and secondary, receivers have the same capabilities. The self-interference cancellation mechanisms are required in both since the primary radio allows transmitting for another device in a previously selected reception frequency, therefore, a full-duplex transmission. The secondary radio provides the capability to receive the signal from a neighbor node that is transmitting in full-duplex.

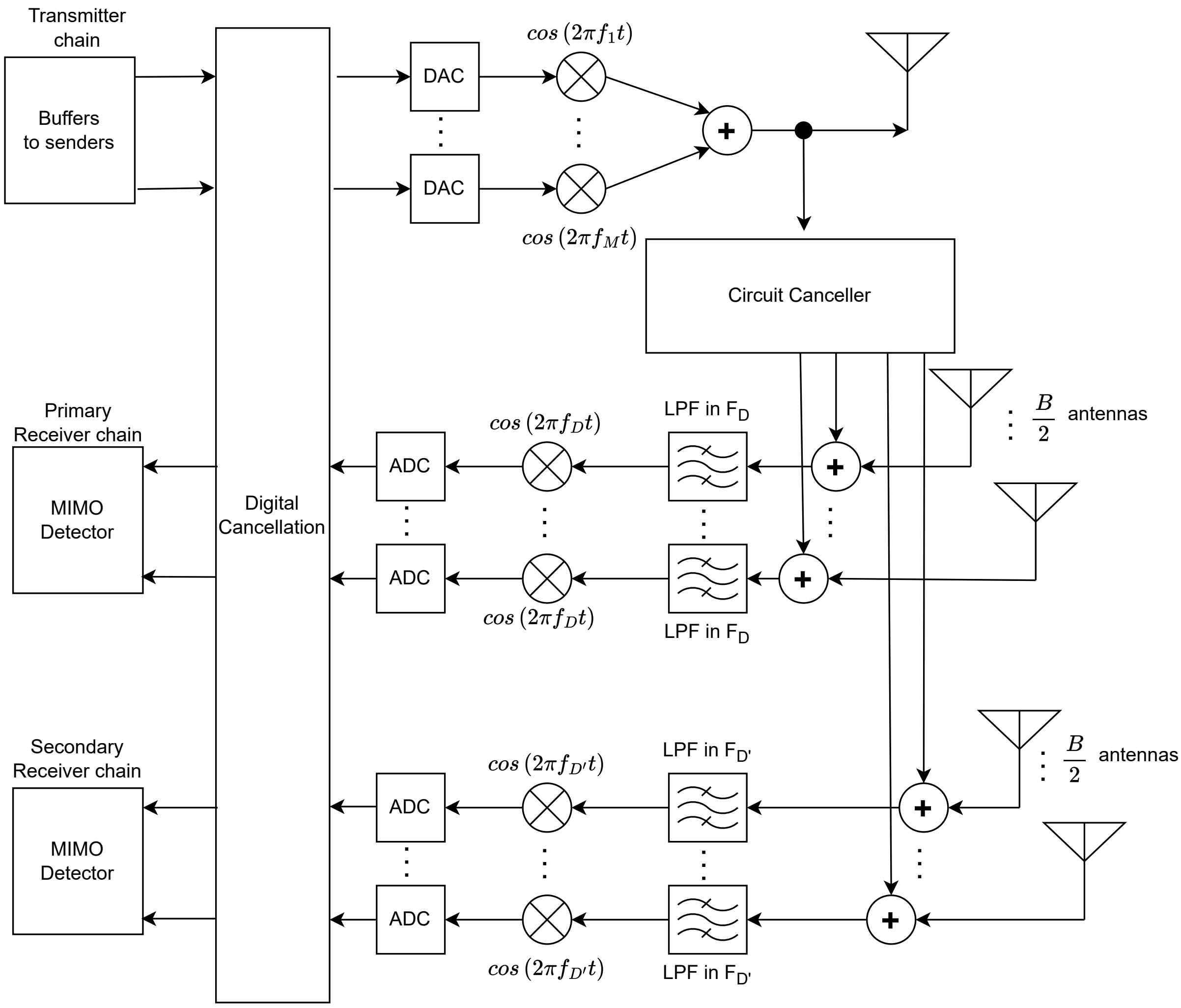

Figure 17 – Simplified transceivers hardware architecture used in FD-M2MMAC.

5.3 PROTOCOL DESCRIPTION

Similar to its precursors, the FD-M2MMAC establishes that, in the ATIM window, network devices indicate the node they intend to transmit data by sending an ATIM packet employing CSMA/CA in the control channel. During this window, nodes exchange control packets in a half-duplex manner and are broadcast through the network. It is important to notice that in this phase the nodes are awakened and overhearing a default channel similar to MMAC. This packet should include the recipient's MAC ID and useful sender information, including its reserved sub-carrier and the full-duplex reception.

In every network node, an available sub-carrier is randomly selected upon each node's first ATIM transmission or reception. Therefore, before sending an ATIM packet, the node must verify if it has already selected its sub-carrier to receive data and if there is a flow available to accommodate the next communication flow.

Nodes that receive the ATIM packet must also have their sub-carrier secured to accept any incoming data stream. In other words, each node that will take a role in the Communication Window must select a distinct sub-carrier to receive data. If it has already reserved a sub-carrier, the node proceeds with the stream availability check. Otherwise, the node has not reserved a sub-carrier yet during the ATIM window, it follows a similar process of random selection that its transmitter performed. If there is no sub-carrier available, the node refuses the communication by replying to the ATIM with an ATIM-NACK packet.

After sub-carrier selection, receiving nodes should verify if it has an available incoming stream to concede. In the positive case, the nodes accept the communication by sending an ATIM-ACK packet. Otherwise, it transmits an ATIM-NACK packet indicating to neighbor nodes that it is no longer available to receive data.

Finally, while receiving an ATIM-ACK, the transmitter should ensure that neighbor nodes are aware of the established communication and agenda. Therefore, the node broadcasts an ATIM-RES packet that includes its full-duplex transmission, the ID of the node that it intends to address in a full-duplex manner, and its reserved sub-carrier.

Fig. 18 summarizes the previously described process for the three-node network. In this example, node A is the first to acquire the control channel, retaining the *blue* sub-carrier and then sending an ATIM packet addressed to node B. Since the network is saturated (i.e., a node has packets to any other node), node A indicates in the ATIM packet that it intends to transmit in a full-duplex mode. The B device reserves its reception sub-carrier (*yellow*) and responds to node A with an ATIM-ACK packet, accepting the main flow and the full-duplex mode. With a full-duplex communication established, the B secondary radio is dedicated to detecting packets from A addressed to B in the A sub-carrier (*blue*). Therefore, node B is receiving data in both sub-carrier (*blue* and *yellow*).

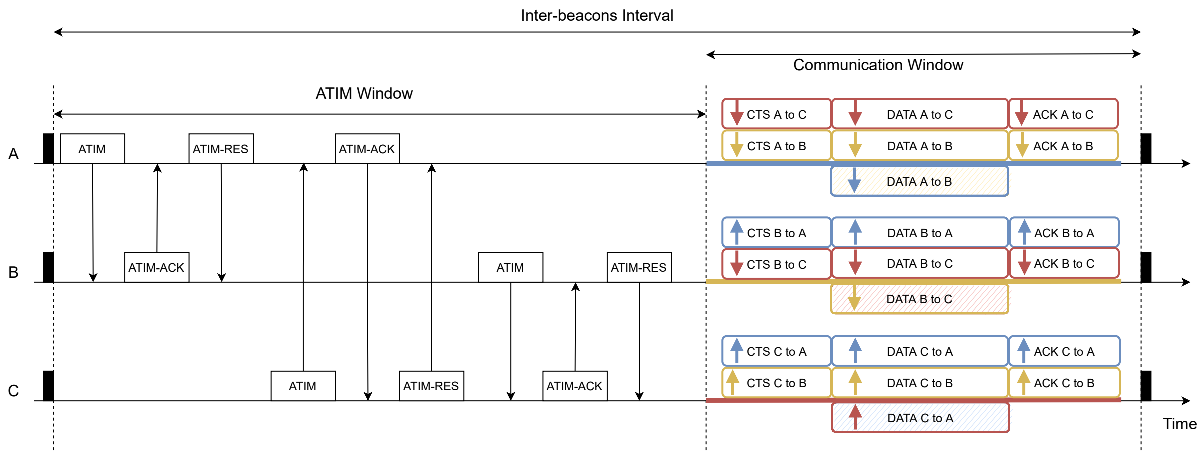

Figure 18 – FD-M2MMAC Communication Sequence. Reprinted from: (SANTANA; MORAES, 2022).

Similarly, node C acquires the control channel and sends its ATIM packet to node A which responds with an ATIM-ACK packet, since it has an idle reception flow. Additionally, node A secondary radio is available to receive; therefore, node A answers with a positive flag for any full-duplex mode request. Lastly, node B follows a similar process as the others to establish communication with node C.

Data transmission occurs in the Communication window. In this window, each data packet is preceded by a clear-to-send (CTS) packet sent in a half-duplex manner to each target node in their reserved sub-carrier. CTS packets not only indicate which node the CTS transmitter expects to receive data but also indicate the node that is allowed to transmit in full-duplex manner to the CTS sender, i.e., the node that is provided an additional stream. In case the data is received successfully, the receiver replies with an ACK packet to each transmitter in their sub-carriers confirming the data reception including data received by full-duplex streams.

5.4 MATHEMATICAL MODEL

We evaluate the aggregated (*i.e.*, from all stream flows) throughput performance by developing a mathematical model that enforces the protocol constraints similar to the related predecessor protocol (GHOBAD; MORAES, 2017). The analysis considers the maximum data sent in the Communication window. Since the FD-M2MMAC employs a split-phase mechanism, the nodes only transmit data in the communication phase. Also, we partitioned the non-full-duplex and full-duplex components for simplicity.

Following the M2MMAC, the first constraint to be analyzed is the number of data packets each node transmits in an inter-beacon interval. To calculate that, we must obtain the time period that the protocol spends on the ATIM phase and extract the maximum number of slots that a Communication window, *i.e.*, the remaining inter-beacon duration, can fit. Accordingly, the consecutive data transmission through the communication window slots that have been established in the ATIM window yields that

$$NCOM_{max} = \left\lfloor \frac{l_{beacon} - l_{atim}}{l_{slot}} \right\rfloor, \tag{5.1}$$

where l_{beacon} is the beacon interval, l_{atim} is the ATIM window duration, and l_{slot} is the minimum time slot required to transmit a packet with the maximum possible length.

Furthermore, the number of network devices is an essential aspect of the throughput evaluation. Considering that n node composes the single-hop network, even if the physical layer provides more data stream capability, each node can only communicate with the other $n-1$ nodes. Therefore, the network is limited to $n(n-1)$ potential connections.

Another constraint is the number of concurrent transmissions that are possible to occur during the Communication window. Again, the physical layer capacities determine the concurrent transmissions that network nodes are capable of. In our protocol, the number of signals the receiving chain can decode specifies the number of simultaneous transmissions; hence, each successful negotiation in the ATIM window establishes two streams, one per direction. To successfully decode multiple concurrent users, the devices can accept up to $B-1$ incoming streams in a single sub-carrier which is the one selected to receive data, where B is the number of receiving antennas on the V-BLAST radio. In summary, each node can transmit up to other $B-1$ devices (KIM; LEE, 2015).

Nevertheless, the FD-M2MMAC protocol considers that the B reception antennas are split between two receiving radios the primary and secondary radios. In this scenario, the primary radio is dedicated to receiving data from multiple users in a predefined frequency. The secondary radio detects incoming streams from a node that is transmitting in full-duplex, thus other nodes are sending data addressed to the transmitter node which requires that the full-duplex receiver also be capable of detecting multiple users to take the unwanted transmission out. Due to the required split, the number of incoming streams is limited by the primary radio antennas which are $B/2-1$.

The number of connections successfully established during the ATIM window also limits the throughput. It is important to notice that like the IEEE 802.11 PSM, nodes not entangled are arranged to back-off to save power. Since in the ATIM window, the FD-M2MMAC protocol follows the CSMA/CA channel access mechanism employed by IEEE 802.11 (IEEE Computer Society LAN MAN Standards Committee, 1997), we use the analytical model described by (TINNIRELLO; BIANCHI; XIAO, 2009) to evaluate the maximum amount of streams that could be successfully negotiated in the ATIM window. Accordingly, the duration of a successful negotiation is given by

$$\begin{aligned} T_s = {} & \tfrac{ATIM-H_P}{R} + \tfrac{H_P}{R_{basic}} + SIFS + \delta + \tfrac{ATIMACK-H_P}{R} + \tfrac{H_P}{R_{basic}} + SIFS + \delta \\ & + \tfrac{ATIMRES-H_P}{R} + \tfrac{H_P}{R_{basic}} + \delta + DIFS, \end{aligned} \tag{5.2}$$

where $ATIM$, $ATIMACK$, and $ATIMRES$ are the ATIM, ATIM-ACK, and ATIM-RES packet lengths, respectively. R is the data transmission rate, δ is the channel propagation delay, and $SIFS$ is the time duration of Short Inter-frame Space, which is the spacing mandatory before transmitting a packet. $DIFS$ is the time duration of DCF Inter-frame Space that is enforced by DCF protocol to sense the medium as idle before any station acquires the medium with a transmission.

On the other hand, the collision duration is given by

$$T_c = \tfrac{ATIM-H_P}{R} + \tfrac{H_P}{R_{basic}} + DIFS + \delta. \tag{5.3}$$

According to Bianchi (BIANCHI, 2000), the probability of finding the channel in a busy state P_{busy} and the probability of a successful transmission P_{succ} is, respectively, obtained by

$$P_{busy} = 1 - (1-\tau)^n, \tag{5.4}$$

$$P_{succ} = n\tau(1-\tau)^{n-1}, \tag{5.5}$$

where n is the number of nodes and τ is the probability of transmission to occur in a time slot, which can be obtained from (BIANCHI, 2000).

Therefore, the successful number of agreements per time that can occur during the ATIM interval is given by

$$N_{succ} = \tfrac{P_{succ}}{(1-P_{busy})\delta + P_{succ}T_s + (P_{busy}-P_{succ})T_c}. \tag{5.6}$$

The successful negotiation in the ATIM phase establishes two stream flows in the Communication phase, *i.e.*, the communication in the transmitter-receiver direction and in the receiver-transmitter direction. Thus, the maximum number of stream flows negotiated in an ATIM window is

$$NATIM = 2N_{succ}l_{atim}. \tag{5.7}$$

Therefore, the throughput evaluation for the non-full-duplex component is given by

$$S_{non\_full\_duplex} = \frac{min\left\{M(M-1), \frac{B}{2}-1, NATIM\right\}NCOM_{max}DATA}{l_{beacon}}, \tag{5.8}$$

where $DATA$ is the data packet length.

Considering that each full-duplex radio is capable of a single self-interference signal cancellation, each node eligible to accept an additional stream is in a full-duplex fashion.

Since each node is only capable of a single full-duplex connection, the full-duplex component is limited to the number (n) of network nodes. Hence, it follows that

$$S_{full\_duplex} = \frac{min\{M(M-1), n, NATIM\}NCOM_{max} \times DATA}{l_{beacon}}. \tag{5.9}$$

Finally, the aggregated throughput is the combination of non-full-duplex and full-duplex components from (5.8) and (5.9), respectively. Therefore, we have that

$$S_{aggregated} = S_{non\_full\_duplex} + S_{full\_duplex}. \tag{5.10}$$

5.5 RESULTS

The analysis that we presented in this section was evaluated in the MATLAB platform. The parameters utilized in our analysis are detailed in Table 2, primarily drawn from (BIANCHI, 2000) for assessing the IEEE 802.11 protocol.

The model presented in the previous section enables an evaluation of the protocol in similar scenarios as those proposed by M2MMAC. In the first scenario we evaluate the protocol throughput with the varying of the channels, or in our case sub-carriers, available in the network when we employ a $20ms$ and $40ms$ ATIM window.

Fig. 19 presents the throughput evaluation when the ATIM window is fixed in $20ms$. In this scenario, we present the case when the network nodes are employed with six and ten antennas (B).

The results presented in Fig. 19 show that FD-M2MMAC was able to improve the aggregated throughput in 51% in this scenario.

Fig. 20 presents the evaluation results when the protocol employs a $40ms$ ATIM window of a $100ms$ inter-beacon interval. In this disposition, the aggregated throughput in FD-M2MMAC

Table 2 – Parameters and values for performance analysis

Parameters	Values
Number of nodes (n)	60
Number of reception antennas (B)	6
Number of channels/sub-carriers (M)	12
Transmission rate (R)	2 $Mbps$
Basic transmission rate (R_{basic})	1 $Mbps$
Beacon interval (l_{beacon})	100 ms
ATIM window (l_{atim})	20 ms
Data packet length ($DATA$)	512 $Bytes$
MAC header packet length (H_M)	34 $Bytes$
PHY header packet length (H_P)	24 $Bytes$
RTS packet lengths	352 $bits$
CTS packet lengths	304 $bits$
ACK packet lengths	304 $bits$
ATIM packet lengths	352 $bits$
ATIM-ACK packet lengths	304 $bits$
ATIM-NACK packet lengths	304 $bits$
ATIM-RES packet lengths	304 $bits$
SIFS duration	10 μs
DIFS duration	50 μs
time slot (σ) duration	20 μs
Propagation delay (δ)	1 μs

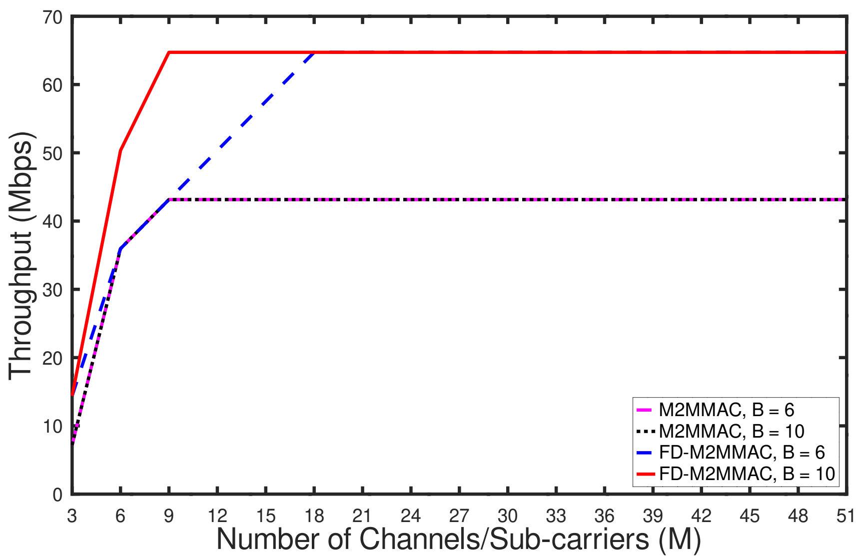

Figure 19 – Aggregated throughput evaluation versus available channels using 20 ms ATIM Window (Reprinted from: (SANTANA; MORAES, 2022)).

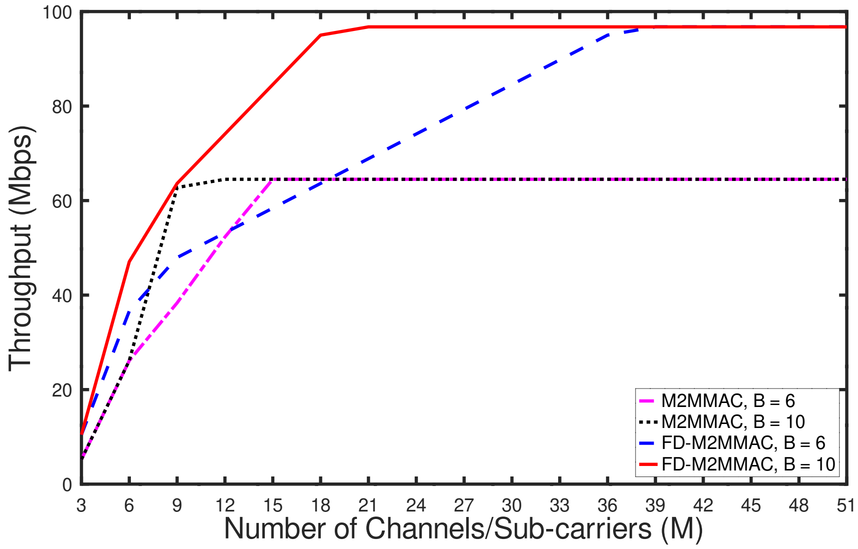

Figure 20 – Aggregated throughput evaluation versus available channels using 40 ms ATIM Window (Reprinted from: (SANTANA; MORAES, 2022)).

achieves $96.76Mbps$, which represents a 50% increase in throughput when compared with M2MMAC.

Fig. 21 displays the evaluation throughput when the ATIM window duration varies in the protocol. In this arrangement, the network nodes have a total of three available channels/sub-carries for scenarios in which the nodes have four, six, and ten antennas available to receive information.

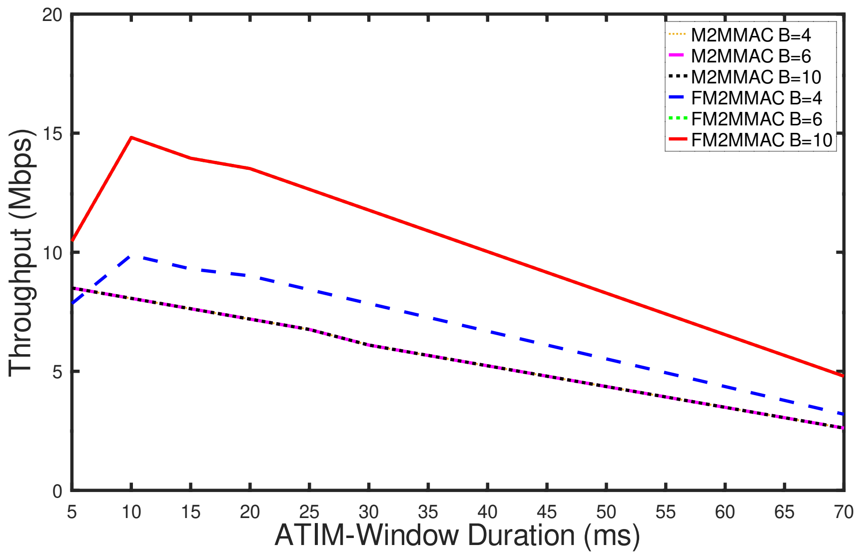

Figure 21 – Aggregated throughput evaluation versus ATIM window size using 20 ms with 3 channels available (Reprinted from: (SANTANA; MORAES, 2022)).

Fig. 22 shows a similar valuation of the aggregated throughput versus ATIM window duration when 12 channels/sub-carriers are available in the network for communication.

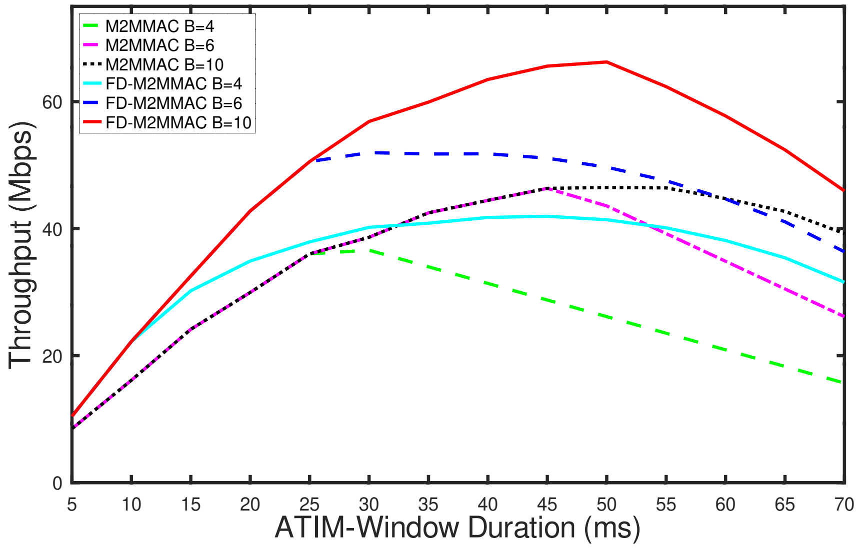

Figure 22 – Aggregated throughput evaluation versus ATIM window size using 20 ms with 3 channels available (Reprinted from: (SANTANA; MORAES, 2022)).

As we noticed in the previous results, the length of the ATIM window, which restricts the number of communication channels opened, and the quantity of receiving antennas directly affect network throughput. As these aspects increase, convergence to a saturation point occurs more quickly. Additionally, our findings demonstrate that FD-M2MMAC outperforms M2MMAC in all tested scenarios.

The results also show that FD-M2MMAC outperforms M2MMAC in the evaluated scenarios achieving a higher throughput due to the full-duplex mechanism.

It is important to notice that the performance presented was a smaller extent than expected for a full-duplex protocol. The main reason for that was the required split in the receiving antennas that allows full-duplex reception.

5.6 CHAPTER SUMMARY

In the previous sections, we presented the FD-M2MMAC a brand-new MAC protocol that was inspired by M2MMAC a multi-user and multichannel protocol.

The analytical model used to evaluate the protocol performance of FD-M2MMAC against its half-duplex was presented in this chapter. In this scenario, the throughput was evaluated considering different numbers of reception antennas in a range of possible ATIM Window lengths, and adopting multiple channels available. The results achieved by FD-M2MMAC show that it has increased the throughput.

6 ENHANCED FULL-DUPLEX MANY-TO-MANY MULTICHANNEL MAC PROTOCOL

In this chapter, we present the Enhanced Full-Duplex Many-to-Many Multichannel MAC (EFD-M2MMAC) that complements the previous protocol and employs a straightforward full-duplex radio (SANTANA; MORAES, 2023).

6.1 ASSUMPTIONS

The assumptions adopted by EFD-M2MMAC are very similar to the ones that we described in the last chapter. They are as follows:

- The full-duplex reception chain is capable of decoding not only a single user in full-duplex but multiple ones.
- Each node is also provided with a V-BLAST radio with B antennas.
- The ad hoc network is considered to be single-hop. Therefore, all network nodes can directly communicate with each other and overhear any other node.
- All network nodes are synchronized to establish the inter-beacon period properly. For example, nodes can use GPS or an out-of-band solution to acquire such synchronization.
- Each node is granted one of the M available non-overlapping and orthogonal frequency channels (sub-carriers (SANTANA; MORAES, 2022)).
- Accordingly, nodes are provided with a low complex self-cancellation approach that allows them to communicate with multiple users using a narrow band as described in (SHAYOVITZ; KRESTIANTSEV; RAPHAELI, 2022) in the Communication window. In addition, a pre-defined channel is used by all nodes as a control channel during the ATIM window.
- The network is considered to be in a saturated state. Therefore, network nodes always have packets to transmit to neighbors.
- A physical separation between nodes should ensure multi-user detection by differing the transmission signals.

- During the ATIM window, nodes exchange control packets utilizing CSMA/CA in the control channel in a half-duplex way.

To highlight the differences between FD-M2MMAC and its enhanced version, the FD-M2MMAC had two V-BLAST radios that in essence split B antennas into two sets, while the EFD-M2MMAC uses all antennas for reception in a single V-BLAST. That is due to the assumption that the full-duplex reception chain is capable of detecting multiple users. That capability can be achieved by employing NOMA (SINGH et al., 2022) or a radio proposed by Ouyang *et al.* (OUYANG; BAI; SABHARWAL, 2017).

The EFD-M2MMAC aims to allow a multi-user strategy with full-duplex communication in a topology such as presented in Fig. 23 in which two full-duplex cases are illustrated. The first case, is a transmission in the channel that was initially retained to receive data. The second full-duplex case is when a node receives data from another node in the channel that the transmitter has hold. In other words, considering a particular node, C for instance, the first case takes place when this node transmits data to node A in the "yellow" channel, while the second one happens when node C receives data from node B in the "blue" channel which was hold by the later node. In this scenario, each node is also transmitting in distinct frequency to another node. In the C state, the transmission to A also occurs in the "red" transmission, and since there is no reception from C in the "red" channel, this transmission happens in half-duplex manner, or non-full-duplex as adopted in this work. In this figure, the full-duplex transmissions are represented by solid lines while non-full-duplex ones are dashed. The different frequencies that each node reserved during the ATIM Window are displayed in distinct colors. For example, the "blue" color in node B means that in the ATIM Window, this node has reserved the "blue" as the receiving frequency band.

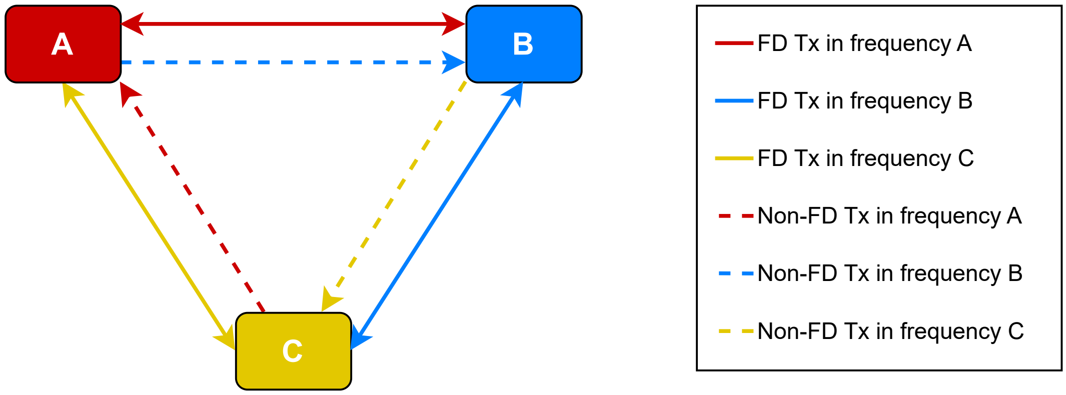

Figure 23 – EFD-M2MMAC example topology. Three nodes communicate in a multi-user approach with full-duplex technology during a communication window slot. (Reprinted from: (SANTANA; MORAES, 2023))

6.2 SIMPLIFIED HARDWARE ARCHITECTURE

Fig. 24 presents a simplified architecture of the transceivers provided in the node in the EFD-M2MMAC. Fig. 24 shows two circuits, the first one at the top of the figure is the Full-Duplex radio along with its transmitter and receiver chains and the bottom one is the MIMO receiver which uses V-BLAST to detect signals from multiple users.

In the Full-Duplex circuit the packets wait to be transmitted in the receivers' frequency. Before they get converted to analog domain the signals are collected to be used in the Digital cancellation circuit. This circuit aims to mitigate the effects of the self-interference signal on the receiver chain in the digital domain. After being converted, the signals are combined to be transmitted. However, the cancellation in the analog domain is required to achieve a full-duplex radio. Therefore, the Circuit Canceller module collects the resulting signal to be subtracted in the analog domain in the receiver chain. It is important to notice that the transmitter and receiver chains are physically isolated by a circulator element connected before the antenna. The circulator is a module that only allows current (signal) to pass in one direction, thus, isolating the receiver from the potent signal employed on the transmitter.

In the full-duplex receiver chain, the transmitted signal must be subtracted before being filtered by the LPF which targets the desired frequency signal. After being converted a digital cancellation is employed before following to a Multi-User detection. The Multi-User detector employs multi-user detection methods, such as Non-Orthogonal Multiple Access (NOMA) to identify the signal from a user of interest. That chain allows the devices to receive in a frequency that is already been used to transmit to other nodes in the network even though multiple users also are transmitting in the same frequency addressing another node.

The Receiver chain is dedicated to detecting signals from different users in the frequency that has been determined to be used while receiving from other nodes. This circuit employs a LPF to filter the target frequency. Finally, a MIMO detector, such as V-BLAST is used to identify the signal from different users.

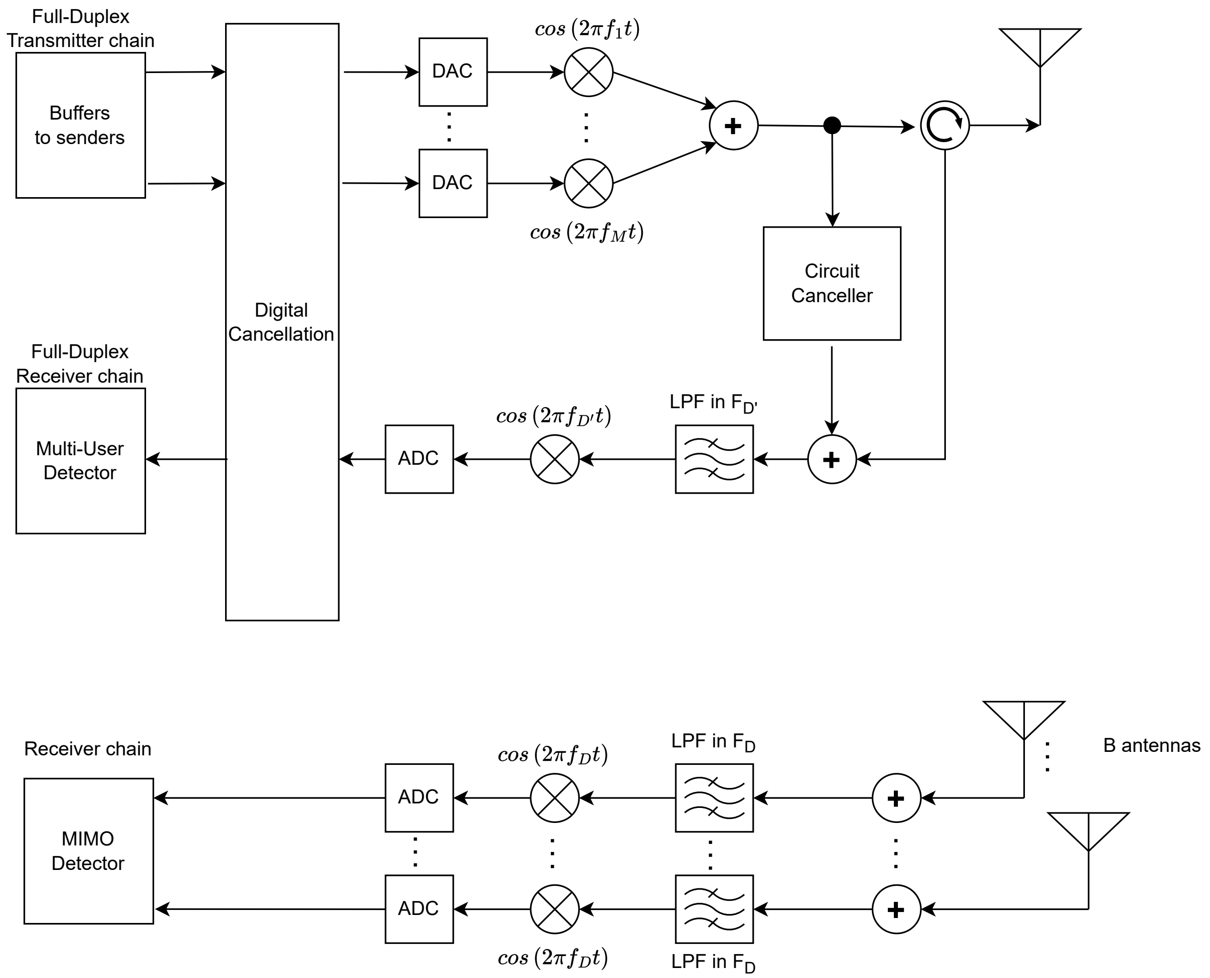

Figure 24 – Simplified transceivers hardware architecture in EFD-M2MMAC.

6.3 PROTOCOL DESCRIPTION

In the ATIM window, presented on the left side of Fig. 25, nodes contend to acquire the channel to establish a configuration with their targets in the next phase.

Similar to M2MMAC and FD-M2MMAC, each node must hold a channel to receive from multiple other users. Therefore, before any communication in the ATIM window, a node that has a packet to transmit must ensure that it has already retained to be used as a receiving channel. In the scenario that it is the first communication that a particular node takes place, it must select a receiving channel among those available and reserve it by sending an ATIM control packet with the indication of the selected channel along with the destination node. It is important to notice that nodes are awakened and overhearing the default channel. Due to that, they also know the channels that are no longer available by overhearing ATIM and ATIM-ACK packets. Since each control packet exchange establishes a bi-directional communication, the nodes that are transmitting the ATIM packet must also verify if it has an available stream to receive data.

Whenever a node receives an ATIM packet with its address, it verifies if it has already reserved a channel during the current ATIM window yet it randomly selects a channel between those possible and holds it by broadcasting an ATIM-ACK in response. Despite that, if the node already acquired a receiving channel, the node certifies that the new incoming stream can be included. If all the verification succeeds, the receiving node responds with an ATIM-ACK packet.

If any verification described fails, the destination node broadcasts an ATIM-NACK packet to the neighbor nodes to indicate that it is no longer applicable for receiving data and, therefore, transmitting nodes should give up to address it.

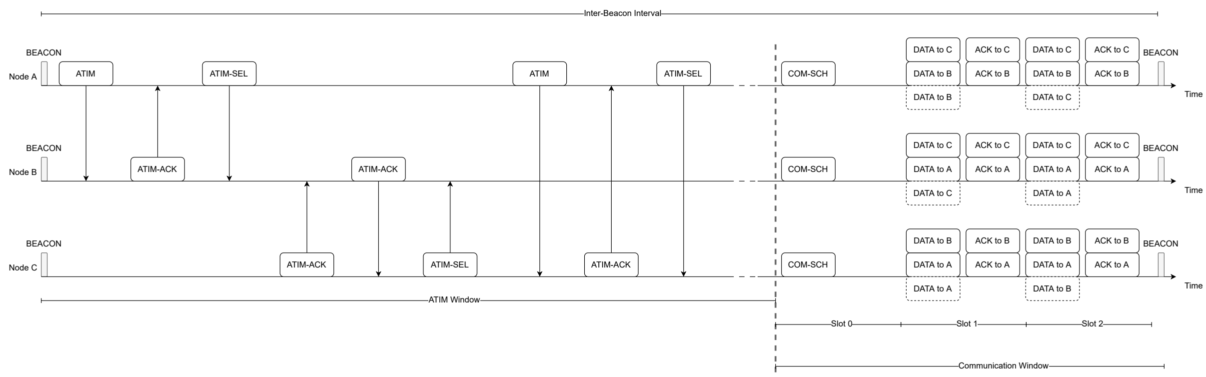

Figure 25 – EFD-M2MMAC Communication sequence in an inter-beacon interval. (Reprinted from: (SANTANA; MORAES, 2023))

In the EFD-M2MMAC, the control packets, *i.e.* ATIM, ATIM-ACK, and ATIM-RES are modified to include the schedule of the node's full-duplex reception. In other words, the device that is transmitting any control packet during the ATIM Window also broadcasts a mapping of the slots in the communication window that it can receive in full-duplex manner.

In a saturation scenario, ensuring fairness involves giving the same opportunity to each node. Therefore, the EFD-M2MMAC limits the request of full-duplex slots in proportion to the maximum number of concurrent incoming streams which is given by $B-1$ factor. After successfully receiving an ATIM-ACK, the initiating node transmits the ATIM-RES to confirm the agreed-upon configuration.

As in the prior protocols, the communication window in EFD-M2MMAC is also a collision-free phase. The data exchanged in this window is a result of the successful negotiations in the previous phase. As shown in the right part of Fig. 18, nodes start by broadcasting a communication schedule packet (COM-SCH) in its reserved receiving channel to reinforce its transmission scheduling and, in this way, avoiding a collision from unaware devices in essence, the COM-SCH packet does the CTS packet role in the EFD-M2MMAC. After the COM-SCH transmission, devices start the data packets (DATA) transmission. At the end of each slot, nodes send ACK packets to acknowledge their received data packets.

6.4 MATHEMATICAL MODEL

We evaluate the aggregated (*i.e.*, from all stream flows) throughput performance by developing a mathematical model that enforces the protocol constraints similar to the related predecessor protocols (SANTANA; MORAES, 2022), (GHOBAD; MORAES, 2017). The analysis considers the maximum data sent in the Communication window. Since the EFD-M2MMAC employs a split-phase mechanism, the nodes only transmit data in the communication phase. Also, we partitioned the non-full-duplex and full-duplex components for simplicity.

Following the M2MMAC, the first constraint to be analyzed is the number of data packets each node transmits in an inter-beacon interval. To calculate that, we must obtain the time period that the protocol spends on the ATIM phase and extract the maximum number of slots that is suitable in a Communication window, *i.e.*, the remaining inter-beacon duration, can fit. Accordingly, we have in Eq. 2.14 that

$$NCOM_{max} = \left\lfloor \frac{l_{beacon} - l_{atim}}{l_{slot}} \right\rfloor - 1,$$

where l_{beacon} is the beacon interval, l_{atim} is the ATIM window duration, and l_{slot} is the minimum time slot required to transmit a packet with the maximum possible length. The minus one factor appears due to the COM-SCH packet transmission in the first slot of the Communication window.

Furthermore, the number of network devices is an essential aspect of the throughput evaluation. Considering that n node composes the single-hop network, even if the physical layer provides more data stream capability, each node can only communicate with the other $n-1$ nodes. Therefore, the network is limited to $n(n-1)$ potential connections.

Another constraint is the number of concurrent transmissions that are possible to occur during the Communication window. Again, the physical layer capacities determine the concurrent transmissions that network nodes are capable of. In our protocol, the number of signals the receiving chain can detect specifies the number of simultaneous transmissions; hence, each successful negotiation in the ATIM window establishes two streams, one per direction. To successfully detect multiple concurrent users, the devices can accept up to $B-1$ incoming streams, where B is the number of receiving antennas on the V-BLAST radio. In summary, each node can transmit up to other $B-1$ devices (KIM; LEE, 2015).

The number of connections successfully established during the ATIM window also limits the throughput. It is important to notice that like the IEEE 802.11 PSM, nodes not entangled are arranged to doze mode to save power. Since in the ATIM window, the EFD-M2MMAC protocol follows the CSMA/CA channel access mechanism employed by IEEE 802.11 (IEEE Computer Society LAN MAN Standards Committee, 1997), we use the analytical model described by (TINNIRELLO; BIANCHI; XIAO, 2009) to evaluate the maximum amount of streams that could be successfully negotiated in the ATIM window. Accordingly, the duration of a successful negotiation is given by

$$\begin{aligned} T_s = &\tfrac{ATIM-H_P}{R} + \tfrac{H_P}{R_{basic}} + SIFS + \delta + \tfrac{ATIMACK-H_P}{R} + \tfrac{H_P}{R_{basic}} + SIFS + \delta \\ &+ \tfrac{ATIMRES-H_P}{R} + \tfrac{H_P}{R_{basic}} + \delta + DIFS, \end{aligned} \tag{6.1}$$

where $ATIM$, $ATIMACK$, and $ATIMRES$ are the ATIM, ATIM-ACK, and ATIM-RES packet lengths, respectively. R is the data transmission rate, δ is the channel propagation delay, $SIFS$ is the time duration of Short Inter-frame Space, and $DIFS$ is the time duration of DCF Inter-frame Space.

On the other hand, the collision duration is given by

$$T_c = \tfrac{ATIM-H_P}{R} + \tfrac{H_P}{R_{basic}} + DIFS + \delta. \tag{6.2}$$

According to Bianchi (BIANCHI, 2000), the probability of finding the channel in a busy state P_{busy} and the probability of a successful transmission P_{succ} is, respectively, obtained by

$$P_{busy} = 1 - (1 - \tau)^n, \tag{6.3}$$

$$P_{succ} = n\tau(1 - \tau)^{n-1}, \tag{6.4}$$

where n is the number of nodes and τ is the probability of transmission to occur in a time slot, which can be obtained from (BIANCHI, 2000).

Therefore, the successful number of agreements per time that can occur during the entire ATIM window is given by

$$N_{succ} = \frac{P_{succ}}{(1-P_{busy})\delta + P_{succ}T_s + (P_{busy} - P_{succ})T_c}. \tag{6.5}$$

The successful negotiation in the ATIM phase establishes two stream flows in the Communication phase, *i.e.*, the communication in the transmitter-receiver direction and the receiver-transmitter direction. Thus, the maximum number of stream flows negotiated in an ATIM window is

$$NATIM = 2N_{succ}l_{atim}. \tag{6.6}$$

Therefore, the throughput evaluation for the non-full-duplex component is given by

$$S_{non\_full\_duplex} = \frac{min\{M(M-1), B-1, NATIM\}NCOM_{max} \times DATA}{l_{beacon}}, \tag{6.7}$$

where $DATA$ is the data packet length.

Considering that each full-duplex radio is capable of a single self-interference signal cancellation, each node eligible to accept an additional stream is in a full-duplex fashion.

Since each node is only capable of a single full-duplex connection, the full-duplex component is limited to the number (n) of network nodes. Hence, it follows that

$$S_{full\_duplex} = \frac{min\{M(M-1), n, NATIM\}NCOM_{max} \times DATA}{l_{beacon}}. \tag{6.8}$$

Finally, the aggregated throughput is the combination of non-full-duplex and full-duplex components from (6.7) and (6.8), respectively. Therefore, we have that

$$S_{aggregated} = S_{non\_full\_duplex} + S_{full\_duplex}. \tag{6.9}$$

6.5 RESULTS

As in the FD-M2MMAC the numerical results were evaluated on the MATLAB platform and the protocol parameters were detailed in Table 2. For simplicity in the comparison between the new protocol and M2MMAC and FD-M2MMAC, we excluded the initial slot dedicated to broadcasting COM-SCH in EFD-M2MMAC protocol.

First, we evaluated the throughput as a function of the ATIM window duration, when the network is provided with only 3 channels. Fig. 26 shows that EFD-M2MMAC increases the throughput by 33% when compared with M2MMAC, similar to the results achieved by FD-M2MMAC protocol which has overlapping curves with EFD-M2MMAC results, except for the scenario that FD-M2MMAC is provided with 4 antennas in each node.

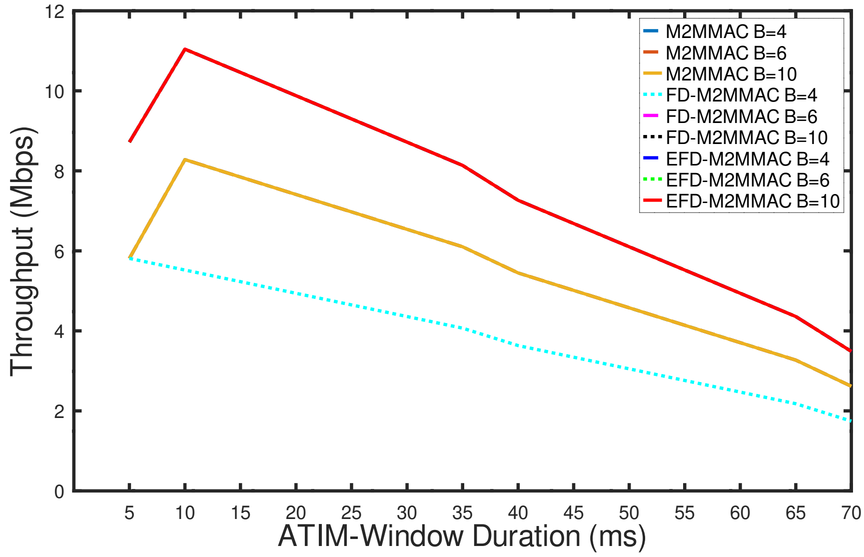

Figure 26 – EFD-M2MMAC aggregated throughput over different ATIM Window duration with three channels available ($M = 3$). The M2MMAC curves are overlapped, and the FD-M2MMAC overlaps with EFD-M2MMAC curves in most scenarios. (Reprinted from: (SANTANA; MORAES, 2023))

Then, we evaluate the scenario where 12 channels are available. Fig. 27 shows that EFD-M2MMAC increases the throughput by 33% when compared with M2MMAC, similar to the results achieved by FD-M2MMAC protocols.

Another scenario is when the ATIM window is fixed in $20\,ms$ and the channels available in the network vary, or in the FD-M2MMAC case the number of sub-carries is varied. Fig.28 shows that in a scenario where there are 6 antennas and 9 channels available, the EFD-M2MMAC increases the throughput by 50% when compared with FD-M2MMAC. and 8% when 10 antennas are provided. EFD-M2MMAC increases the throughput by 50% when compared with M2MMAC, similar to the results achieved by FD-M2MMAC protocols as shown in Fig. 28. Once again, the results in FD-M2MMAC overlaps with the ones obtained by EFD-M2MMAC protocol while the M2MMAC has the scenario with 6 and 10 antennas overlapped.

In Fig. 29, comparing FD-M2MMAC and EFD-M2MMAC while using twice the ATIM window duration (*i.e.*, 40 ms) with 6 antennas the EFD-M2MMAC increases up to 54%

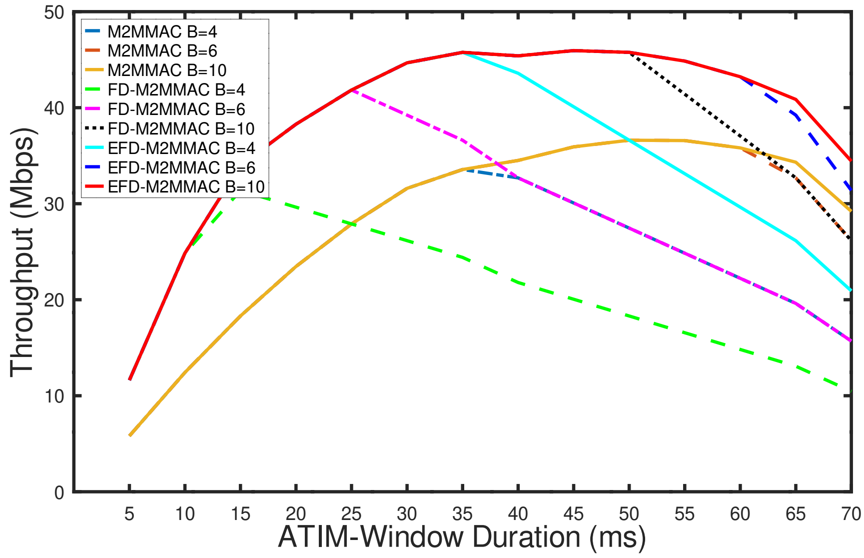

Figure 27 – EFD-M2MMAC aggregated throughput over different ATIM Window duration with twelve channels available ($M = 12$). (Reprinted from: (SANTANA; MORAES, 2023))

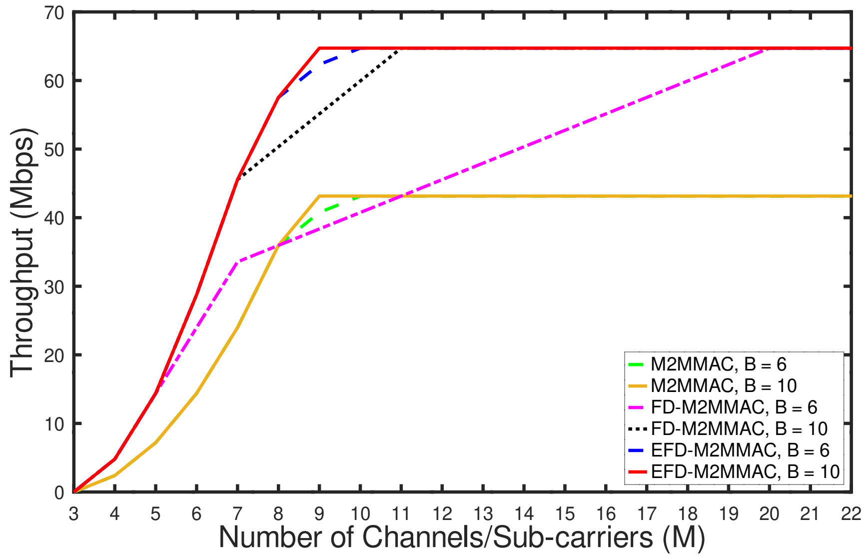

Figure 28 – EFD-M2MMAC aggregated throughput versus number of available channels for ATIM window fixed in 20 ms. (Reprinted from: (SANTANA; MORAES, 2023))

the network throughput, while with 10 antennas the increase is 37% for 11 channels. Also, when 17 channels are available, the EFD-M2MMAC was able to increase the throughput up to 56% with 6 antennas, and 5.7% with 10 antennas, before reaching the saturation point. Additionally, the same 50% increase is obtained when analyzing with the double ATIM window (40 ms) in Fig. 29. Both FD-M2MMAC and EFD-M2MMAC achieved $96.76\,Mbps$ aggregated throughput while the M2MMAC attains $64.50\,Mbps$.

Note that the aggregated throughput reaches saturation as M grows on Figs. 28 and 29 due to the fixed duration of the ATIM window which limits the number of negotiated streams.

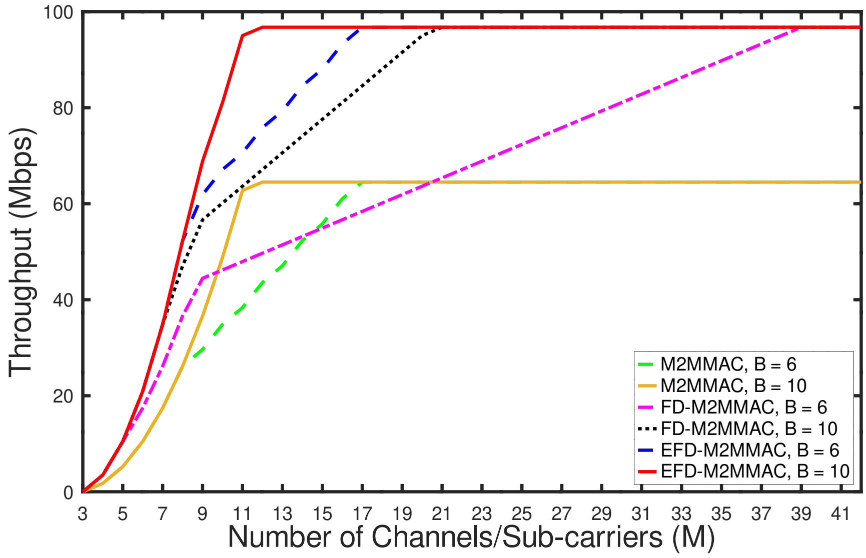

Figure 29 – EFD-M2MMAC aggregated throughput versus number of available channels for ATIM window fixed in 40 ms. (Reprinted from: (SANTANA; MORAES, 2023))

Besides the usage of a simple radio compared to FD-M2MMAC which uses two, the EFD-M2MMAC uses a single V-BLAST combined with a full-duplex radio and was able to obtain similar results when compared with FD-M2MMAC which uses two radios. In scenarios where the radio is provided with a small number of reception antennas, such as 6 antennas in Fig. 28, the EFD-M2MMAC was capable of better use of the radio resources. Also, the EFD-M2MMAC has presented a better aggregated throughput when the ATIM duration increases.

6.6 CHAPTER SUMMARY

In this chapter, we presented an enhanced version of FD-M2MMAC, the EFD-M2MMAC. The new protocol considers the full-duplex radio to decode signals from more than one user. That premise allowed the protocol to avoid using two V-BLAST radios. Additionally, we presented the modifications that were required in the mathematical model when this assumption is considered. Also, we compared the two protocols in the scenarios described for FD-M2MMAC.

We expected that the throughput would increase since all reception antennas were dedicated to additional streams. However, the other limiting factor overcomes the number of maximum streams which results in a similar saturation throughput when the number of available channels increases.

Despite that, the enhanced protocol has increased the throughput when the number of available channels is limited between 5 to 10 channels/sub-carries.

7 CONCLUSION

We presented the fundamental concepts in the MAC protocol analysis in which Tinnirello, Bianchi, and Xiao (TINNIRELLO; BIANCHI; XIAO, 2009) work stands out. The many-to-many mechanism was introduced along with the M2MMAC that inspired this work. The elemental ideas regarding full-duplex radios were presented in this work so that the challenges and opportunities in full-duplex MAC design can be transparent. The brand-new topology raised in full-duplex technology usage and its device roles terminology in the MAC layer were introduced.

We introduced the main protocols in the MAC full-duplex area, highlighting those using a multi-user approach. A table with a summary of those protocols was also presented to make the information concise.

Our work presented two full-duplex protocols, the FD-M2MMAC and EFD-M2MMAC, that combine full-duplex technology and the many-to-many (M2MMAC) communication approach. We created a mathematical model based on (GHOBAD; MORAES, 2017; ADAUTO; MORAES, 2018) and we compared it with the original M2MMAC, the prior and half-duplex version, showing that full-duplex technology improved throughput and bandwidth utilization. The ATIM window limits the aggregated throughput since it defines the number of successful connections that can be established.

Our protocol demonstrated enhanced efficiency in utilizing the communication medium, yielding higher saturation throughput in the assessed scenarios. Specifically, the FD-M2MMAC protocol achieved aa aggregated throughput of $96.76Mbps$ with a $40ms$ ATIM duration that represents a 50% increase compared to the M2MMAC. Furthermore, the Enhanced FD-M2MMAC (EFD-M2MMAC) displayed a 56% increase in aggregated throughput compared to FD-M2MMAC under the conditions of a $40ms$ ATIM window duration and six antennas.

7.1 FUTURE WORKS

A network simulation should be considered to evaluate the protocol models in future work. Besides that, a network simulation would bring the physical layer impairments that the protocol should consider. The ATIM Window presents a limitation in the split-phase proposed protocols because its duration directly influences the number of packets that can be transmitted in the communication window. Since the network is considered saturated, the protocol can benefit from employing a control channel mechanism instead of a split-phase.

The mathematical model consider that nodes are overhearing the communication exchanged during the ATIM window. Therefore, senders should be able to choose recipient properly and avoid being refused. Despite that, the mathematical mode might consider the cases in which the communication is denied by recipient due to lack of available stream or channel.

The protocols can benefit from using full-duplex communication during the ATIM window, increasing the number of transmissions that can fit this phase. A full-duplex multi-user detection can be considered in this approach since, without it, overhearing nodes cannot detect the exchanged control packets, therefore the protocol of advertising the other network nodes.

The protocols described should be evaluated in a nonsaturated network scenario. Additionally, other metrics must be considered, such as latency, bandwidth utilization, and energy efficiency. Furthermore, the protocol should be adjusted to multi-hop networks, which are close to sensor wireless networks' actual use cases. Employing full-duplex with a beamforming technique can improve multi-user detection in the receiving chain.

The future works previous mentioned can be summarized as following:

- Simulate the protocol;
- Consider scenarios where nodes might deny communication in ATIM window by transmitting ATIM-NACK;
- Evaluate the usage of a control channel instead of ATIM window;
- Adopt full-duplex communication in the ATIM window;
- Evaluate nonsaturated network scenario;
- Evaluate latency, bandwidth utilization, and energy efficiency metrics;
- Adjust the protocol for multi-hop networks;
- Employing full-duplex associated with a beamforming technique.

7.2 PUBLICATIONS

Two research papers were published from the results presented in this work, enumerated below in the following chronological order:

- SANTANA, W. P. S.; MORAES, R. M. de. FD-M2MMAC: A full-duplex many-to-many mac protocol for wireless ad hoc networks. In: IEEE 95th Vehicular Technology Conference: (VTC2022-Spring). Helsinki, Finlad, June 2022.
- SANTANA, W. P. S.; MORAES, R. M. de. EFD-M2MMAC: An enhanced full-duplex many-to-many mac protocol for single-hop wireless ad hoc networks. In: IEEE 97th Vehicular Technology Conference (VTC2023-Spring). Florence, Italy, June 2023.

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