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MAC Protocol for Mixture of Half-duplex and Full-duplex Wireless Network Considering Hidden Terminal Problem

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Master's Thesis

MAC Protocol for Mixture of Half-duplex and Full-duplex Wireless Network Considering Hidden Terminal Problem

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Abstract

Nowadays, one of the future wireless trends is 5G and beyond technology that can be a potential core network of the Internet of Things (IoT) concept as well as its applications, which bring many benefits for society. In addition, the explosive increase in the number of wireless devices and the high demands of communication performance have created a trend of new techniques in wireless networks. In order to catch up with those requirements, the wireless full-duplex technology and network coding technique are attracted by many researchers, because they can significantly improve the throughput of the system. In these research fields, there still exist a few problems that related to challenging for media access control (MAC) protocol, i.e., hidden terminal problem. The hidden terminal problem is a problem in which a node that cannot sense the ongoing transmission but is able to introduce enough interference to corrupt the reception if it transmits. This leads to difficulties in MAC sublayer. The carrier sense multiple access with collision detection (CSMA/CD), which is a MAC method used most notably in early Ethernet technology for local area networking (LAN), does not work effectively. Hence, the collision occurs and directly affects to the performance of the wireless network systems.

To overcome these problems, a lot of research that rated to half-duplex, full-duplex and mixture of half-duplex and full-duplex wireless networks, have already been studied in recent years. Firstly, the half-duplex is a wireless technology in which a wireless transceiver can either transmit or receive signals in a given bandwidth but not both at the same time. Meanwhile, the full-duplex technology can double spectrum efficiency by simultaneous transmission and reception on the same frequency and time resource. In addition, the full-duplex technique also helps to reduce end-to-end packet delay and improve network efficiency, the full-duplex technique is widely considered as one of the promising techniques in the fifth generation (5G) systems. However, the difference in half-duplex technology, the problem already exists on the full-duplex technology as the overwhelming nature called self-interference (SI), which is generated by a transmitter to its own collocated receiver. There are some solutions that related to SI cancellation were studied, such as passive SI suppression, analog cancellation, or digital cancellation. Moreover, there are still some technical obstacles to be overcome before the full-duplex technique is really put into the practice. The current studies mostly focus on theoretical analysis and the experiments based on the simple models. Besides, the mixture of half-duplex and full-duplex wireless networks that is the combination of the half-duplex and full-duplex nodes into the wireless network system, has considered resolving the existing problems as well as enhancing the performance of the wireless network systems.

In detail of the current solutions for solving the hidden terminal problem, there are much research that have presented. Mostly, they concentrated on the carrier sense multiple access with collision avoidance (CSMA/CA) wireless network under the request-to-send/clear-to-send (RTS/CTS) mechanism. In order to evaluate the performance in terms of saturation throughput of the wireless network systems, the two states of the channel, including collision and success have considered. Likewise, the discrete time Markov Chain (DTMC) model was applied to calculate the conditional collision probability that be used to formulate the transmission probability and saturation throughput of the wireless network systems. Additionally, the current solutions that related to full-duplex MAC protocol have been attracted by many researchers in this research field. They have proposed the new frame formats for MAC protocol that can be employed in both half-duplex and full-duplex wireless nodes. A few solutions have described, like shared random backoff, header snooping, virtual contention resolution.

Moreover, in order to improve the performance of wireless networks, network coding is of interest to researchers in recent years. Network coding is essentially a mathematical operation, which is exclusive-OR (XOR) applied to intermediate nodes between the source node and destination node. Instead of simply forwarding data, intermediate nodes may recombine several input packets into one or some output packets. Based on this operation, this can provide the possibility cut down the number of transmissions and maximize the network throughput of the system. A few research have been contributed the full-duplex technology using network coding, specifically physical layer network coding to enhance the performance of the wireless network systems as well as the reliability of the full-duplex technology.

However, today the hidden terminal problem has not completely solved and it still a challenging for MAC protocol. In addition, the performance of the combination of the mixture of half-duplex and full-duplex technology and network coding technique needs to be considered more explicitly. The aim of this proposition is to improve the end-to-end throughput of the wireless network systems. The most important things to achieve this target are related to the solutions for solving the hidden terminal problem and a new MAC protocol design in order to enhance the performance of the wireless network systems.

Therefore, base on the current methods, this research concentrates on analyzing and evaluation in the mixture of half-duplex and full-duplex wireless network considering hidden terminal problem. Likewise, this research revisits the solutions for solving this problem such as shared random backoff, header snooping, virtual contention resolution. The header snooping is the best one for three nodes of the mixture of half-duplex and full-duplex wireless networks and it has been analyzed more explicitly in this research. Additionally, the challenge of MAC protocol design has reconsidered and analyzed to completely resolve the existing problems as well.

The applied method still bases on the RTS/CTS mechanism. Besides, the Markov Chain approach with three states of the channel, like success, collision and freeze has proposed under the three nodes topology considering hidden terminal problem. Based on the system mode, this research extends the scheme of transmission by using the network coding technique. Hence, this research proposes a new MAC protocol called integrated

full-duplex and multiple access (IFDMA) protocol for the combination of the half-duplex, full-duplex, header snooping, and network coding techniques. Especially, the transition models of relay-based XOR and source-based XOR operation have discussed.

In order to evaluate the effectiveness of the proposed IFDMA protocol, the numerical simulation has been determined under the grid topology and the random wireless networks. Besides, the model of the interference influence that is also considered, directly affects the performance of the wireless network system in the real environment. In addition, this research also considered the random wireless networks with the ratio index of the half-duplex and full-duplex wireless nodes that indicates the appearance probability of which topology in combination. Thus, this index alters the throughput of the system. Furthermore, the evaluation results, which were explicitly presented by comparison among various techniques, demonstrated that the wireless networks with the IFDMA protocol operation, give the highest saturation throughput. Likewise, the effectiveness of IFDMA protocol has shown by the recognition the effects of interference model and the combination of all techniques.

In conclusion, the proposed IFDMA protocol has achieved to provide the considerable improvements in the mixture of half-duplex and full-duplex wireless network considering hidden terminal problem. The expected outcome is to show the improvement in the performance in terms of saturation throughput and indicate the comprehensive of the proposed IFDMA protocol as well as the high ability of the full-duplex technique implementation in the real wireless environment. As a result, this research will be an open key to researchers who are interested in full-duplex technology.

Keywords: MAC protocol, half-duplex, full-duplex, network coding, hidden terminal problem, Markov chain.

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Contents

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List of Abbreviations

3GPP	3rd Generation Partnership Project
ACK	Acknowledgment
ARQ	Automatic Repeat-reQuest
AP	Access Point
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
CSMA/CD	Carrier Sense Multiple Access / Collision Detection
DCF	Discounted Cash Flow
DIFS	DCF Interframe Space
EIFS	Extend Interframe Space
FD	Full-duplex
FEC	Forward Error Correction
HD	Half-duplex
IFDMA	Integrated Full Duplex Multiple Access
IoT	Internet of Things
LAN	Local Area Network
MAC	Medium Access Control
MC	Markov Chain Model

MIMO	Multiple-Input Multiple-Output
NC	Network Coding
OSI	Open Systems Interconnection model
PIFS	PCF Interframe Space
RTS/CTS	Request To Send/ Clear To Send
SN	Header Snooping
SNR	Signal-to-Noise Ratio
SIFS	Short Interframe Space
SINR	Signal-to-Interference-plus-Noise Ratio
SISO	Single-Input Single-Output
TDMA	Time Division Multiple Access
WAN	Wide Area Network
WLAN	Wireless Local Area Network
XOR	Exclusive-OR

List of Symbols

$\oplus$	XOR Operation
$\bigcirc$	Half-duplex Wireless Node
$\circledcirc$	Full-duplex Wireless Node
α	Attenuation Constant
σ	Standard Derivation
η	Noise Level
Γ	Modulation Parameter
$\sum_{i=1}^{n}$	Sum of Series from $i = 1$ to n
$\circledast$	Self-wireless Node
$\circ$	Inside of Transmission Range
$-$	Out of Transmission Range
d	Distance
T_s^X	Successful Transmission Time of the X Technique
p	Conditional Collision Probability
p_{xy}	Conditional Collision Probability from Transition State from x to y
L	Length of Successful Period
C	Length of Collision Period

F	Length of Freezing Period
W	Window Size
CW	Contention Window Size
X_A	Discrete Random Variable of A
R	Data Rate
r	Radio Transmission Range
P	Transmit Power
P_T	Transmission Probability
S	Saturation Throughput
C_n^k	Combinatorics Algorithm

Chapter 1

Introduction

Today, the full-duplex (FD) wireless technology has an attractive force to researchers in the wireless communications as well as 5G and beyond technology. Because of its outstanding features such the improvement in terms of throughput and significantly reducing the end-to-end delay. However, there are many problems that related to transfer from half-duplex mode to full-duplex mode as well as the adaptive of the wireless devices in the real environment. In this chapter, we will introduce the research problem that still exists and directly affects the performance of the wireless network system. Additionally, the research motivation, objective and approach of this research will be described explicitly.

1.1 Problem Statement

In the wireless network systems, for instance, MAN networks, mesh networks, ultra-dense networks, there are many wireless nodes. Besides, the high increase in the number of nodes as well as the demands of applications lead to the challenge for MAC protocol. Moreover, due to the wireless and mobility features in IEEE 802.11, we can not expect every station in the WLAN to communicate directly with every other station or to know the whereabouts of every other station. Especially, in the widespread ($>$ 50m radius) WLAN setups with many nodes that use directional antennas and have high upload, the hidden terminal problem in which the nodes are out of range of other nodes or a collection of nodes, can be easily occurred. This leads to difficulties in media access control (MAC) sublayer and considerably reduces the performance of the wireless network systems.

This problem not only exists in the half-duplex (HD) transmission but also affects the FD transmission. In order to overcome this problem, many solutions based on MAC protocol had already been studied. However, the hidden terminal problem still remains unsolved and need to be considered more explicitly. Therefore, this research will revisit, resolve and concentrate on the MAC protocol for mixture of HD and FD wireless networks considering hidden terminal problem.

1.2 Research Motivation

In the communication field, the wireless technique is one of the fastest growing and most vibrant technological areas. In this method, the information is transmitted from one point to other, without using any connection such as wires, cables or any physical medium. The advanced wireless communication systems can support higher data rates. For instance, as compared to 4G wireless networks, 5G wireless networks may provide a thousand-fold (1000×) higher data rate. This increase in data rate is due to network intensification, femtocell deployments, and mmWave communications. In order to catch up this demand, the FD communication is of interest to researchers. This is not a new idea, a continuous wave radar system first used FD communication in 1940 to enhance the network capacity and to efficiently utilize the spectrum resources [1]. While using the existing resources, it was generally believed that a single radio could not send and receive information simultaneously. However, this restriction has been invalidated with the advent of the FD communication. By employing the FD communication, a single radio can send and receive at the same time over the same frequency band. The FD communication, i.e., using a single channel for transmission and reception at the same time, usually demands only half the spectral resources as compared to the HD communication [2]. The FD communication can be achieved by using separate transmitting and receiving antenna pairs, by exploiting a shared transceiver architecture, by employing relaying topologies, and by using multiple spatial streams, such as multiple-input multiple-output (MIMO) and single-input single-output (SISO). In a shared transceiver, the transmitted and received signals are separated using duplexer which routes each of the signals to their respective functions [3]. In addition, in the industry, the FD technique has been attracted to big companies such as Samsung, Nokia or Huawei. Many researchers have investigated the FD MAC protocol to implement the FD communication and also solve the problem for MAC protocol.

The hidden terminal problem that exists in HD communication still happens in FD technology. In recent years, the solutions have proposed to solve completely it in many research. In order to focus on solving the hidden terminal problem, this research revisits the previous study [4], which be used as a preliminary study. Although the main method is concentrated on the hidden terminal problem in a CSMA/CA wireless network under both RTS/CTS and basic access mechanisms, this research only analyzes and extends its system model in case of RTS/CTS mechanism. The main contribution is modeling of the system model for the mixture of HD and FD wireless network considering the hidden terminal problem. The system model that is considered includes three nodes that are applied HD or FD mode in the wireless network system.

In the previous study [4], the theoretical analysis of system model were based on Bianchi's bi-dimensional Markov Chain (MC) modeling [5]. This method is still referred to this research. However, the extension is explicitly considering of three states of the channel around the wireless node, including success, collision, and freeze. The evaluation results of the HD, FD, and mixture of HD and FD wireless network are in terms of saturation throughput, conditional collision probability, and transmission probability. Besides, the solutions that are applied to the mixture of HD and FD to solve the hidden terminal problem have evaluated.

Moreover, network coding is a technique to enhance several aspects of a network such as an efficiency, throughput as well as reliability. Network coding also can be employed in the FD technology. This is simple network coding which only carries out the XOR operation during the encoding and decoding stage. The particular property of network coding is fast and can reduce the number of the data transmission by combining multiple packets into one packet.

Therefore, the motivation of this research is based on the hidden terminal problem still remain unsolved, so this research revisits the previous studies explicitly and investigates the node combination from a network topology between mixture of HD and FD wireless networks and the use of MAC protocol based on the network coding technique.

1.3 Research Objective

The aim of this research is to resolve the hidden terminal problem in the mixture of HD and FD wireless networks. Throughout this thesis, I focus on the MAC protocol for the mixture of HD and FD wireless network considering the hidden terminal problem. The expected outcomes can indicate the effectiveness MAC protocol for the mixture of HD and FD wireless network in the improvement of saturation throughput and also solving the hidden terminal problem.

Therefore, the first objective of this research is to model and define a research methodology (i.e., Markov chain approach) to analyze the existing solutions of the mixture of HD and FD wireless networks.

Furthermore, the final goal is to propose, design and implement a new MAC protocol called Integrated FD and Multiple Access (IFDMA) protocol not only for the HD, FD, mixture of HD and FD wireless networks considering hidden terminal problem but also combination of mixture of the wireless networks with network coding technique in order to enhance the throughput as well as multiple access for the system model. Thus, this research will open a new way to continue to solve the hidden terminal problem completely.

1.4 Research Approach

- This research reviews and evaluates the methods for the HD and FD wireless networks to solve the hidden terminal problem. The header snooping is the best one for the mixture of HD and FD wireless networks. Besides, the Markov Chain model with three states for the channel, including success, collision, and freeze has discussed to analyze the throughput of the wireless network systems. The evaluation results indicate the important role of three states that affect the performance of the wireless network system considering the hidden terminal problem.

- Based on the scheme of system mode, the new MAC protocol has proposed called Integrated Full-duplex and Multiple Access (IFDMA) protocol. The frame format of IFDMA protocol for network combination has presented and also it can be extended in the future.

- Furthermore, the employment of the proposed IFDMA protocol has analyzed by the combination of network topologies for all techniques, HD, FD, header snooping and network coding (XOR operation) in order to improve the performance of the wireless network systems in terms of saturation throughput.

1.5 Thesis Organization

- Chapter 1 mainly explains the research problem, motivation, objective and approach to this research.
- Chapter 2 provides a comprehensive review of the research background in solving the hidden terminal problem for HD, FD, and mixture of HD and FD wireless networks. In addition, the FD MAC protocol in the current studies and network coding are discussed in this part.
- Chapter 3 demonstrates the mixture of HD and FD wireless network with the system model and the theory analysis for calculation saturation throughput of the system's performance. In this chapter, the model with three states of the channel will be discussed.
- Chapter 4 works on the proposed MAC protocol. The IFDMA protocol is described and also the modeling and numerical analysis of system model are presented.
- Chapter 5 draws the conclusion of this thesis and shows some advantage of the algorithm to enhance the performance as well as comprehensive of the proposed IFDMA protocol in the future.

Chapter 2

Background

The comprehensive review of the fundamental knowledge essential for this research is well-revealed in this chapter. This chapter will introduce four separate topics both related to the research conducted in this study.

Firstly, we introduce the general concept of hidden terminal problem and the current methodologies to solving this problem in Section 2.1. Besides, the techniques, as well as the challenges, will be discussed. Secondly, the overview of the mixture of HD and FD wireless network will be presented. Thirdly, the key mechanisms for the design of MAC protocol for FD wireless network are considered explicitly, especially RTS/CTS exchange mechanism in Section 2.3.2. Finally, in Section 2.4, we review the general data communication principle of the network coding on top of the traditional schemes. We also present in the basic theory of network coding and some of the examples of network coding. The advantages of the network coding is also discussed in this section.

2.1 Overview of Hidden Terminal Problem

2.1.1 Definition

The hidden terminal is a node that cannot sense the ongoing transmission but is able to introduce enough interference to corrupt the reception if it transmits [6, 7]. In the hidden terminal problem, packet collision happens at the intended receiver if there is a transmission from a hidden terminal. For example in Fig. 2.1, there are three nodes, like A, B, and C. Node B is within the transmission range of node A and node C, while node C is outside the transmission range of node A, and correspondingly, node A is outside the transmission range of node C. Here, the transmission range of a node is defined as the area inside which other nodes are able to correctly receive its packets. Without loss of generality, we suppose that every node in Fig. 2.1 has the same transmission range (represented by a dashed circle). In this situation, if there is an ongoing transmission from node A to node B, meanwhile, node C will not be able to detect it and may transmit during the ongoing transmission from node A, which leads to collision at node B. Because node C does not know whether node A is transmitting or not, it can occupy the channel

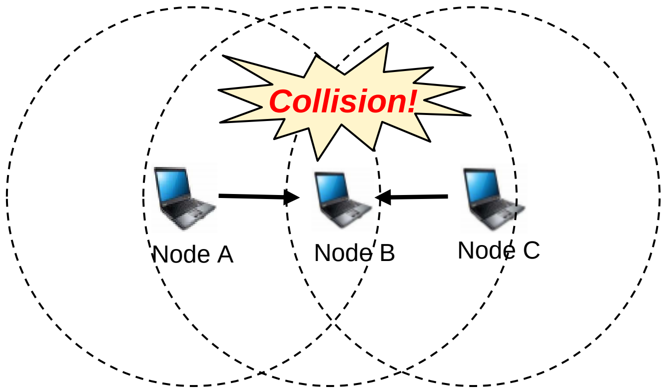


Figure 2.1: The hidden terminal problem.

at any time and the quality of the flow from node A to node B cannot be guaranteed whenever there are any packets from node C to other nodes. Therefore, this degrades the performance of wireless networks systems.

That is, in Fig. 2.1, node A transmits data to node B, while the node B can simultaneously transmit data to node C. Note that node C can successfully receive the data transmitted by node B without collision. This technique requires a new medium access control (MAC) protocols that can exploit the additional capabilities.

2.1.2 Current Solutions for Solving Hidden Terminal Problem

In order to solve the hidden terminal problem, that related to *"conditional collision probability"* of transmission node. Accordingly, firstly we review the Markov Chain model that has been applied to determine the collision probability of transmission. Next, the solutions for solving this problem will be described.

2.1.2.1 Markov Chain Model

Markov chain is based on a principle of memorylessness. In other words the next state of the process only depends on the previous state and not the sequence of states [5].

Since the value of the backoff counter of each station depends also on its transmission history (e.g. how many retransmission the head-of-line packet has suffered), the stochastic process $b(t)$ is non-Markovian. However, define for convenience $W = \text{CW}_{min}$. Let m, "maximum backoff stage," be the value such as $\text{CW}_{max} = 2^m W$, and let us adopt the notation $W_i = 2^i W$, where $i \in (0.m)$ is called "backoff stage." Let $s(t)$ be the stochastic process representing the backoff stage $(0, ..., m)$ of the station at time t.

The key approximation in the proposed model is that, at each transmission attempt, and regardless of the number of retransmissions suffered, each packet collides with constant and independent probability p. It is intuitive that this assumption results more accurate

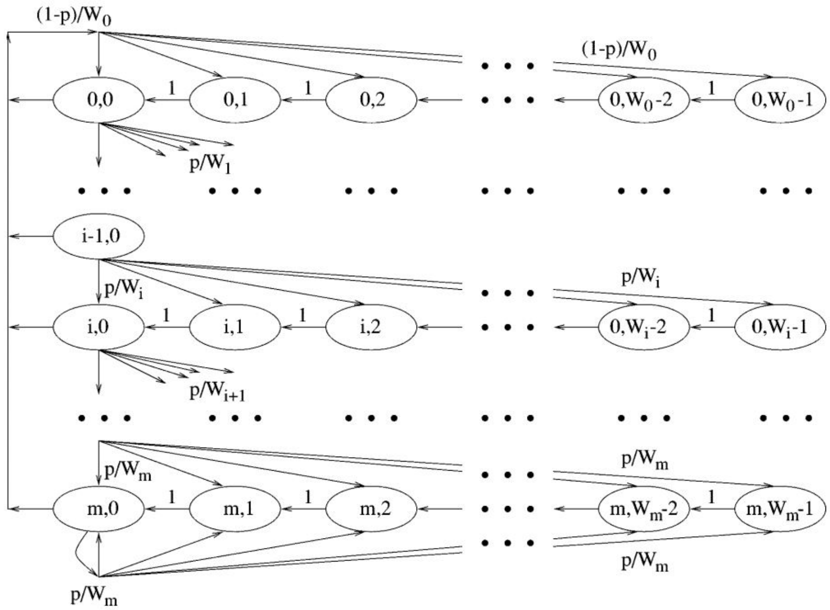


Figure 2.2: Markov Chain model for the backoff window size.

as long as W and n get larger. p will be referred to as *conditional collision probability*, meaning that this is the probability of a collision seen by a packet being transmitted on the channel.

Once independence is assumed, and p is supposed to be a constant value, it is possible to model the bidimensional process $\{s(t), b(t)\}$ with the discrete-time Markov chain [5] was depicted in Fig. 2.2. In this Markov chain, the only non null one-step transition probabilities are:

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

The first equation in Eq. (2.1) accounts for the fact that, at the beginning of each slot time, the backoff time is decremented. The second equation accounts for the fact that a new packet following a successful packet transmission starts with backoff stage 0, and thus the backoff is initially uniformly chosen in the range $(0, W_0 - 1)$. The other cases model the system after an unsuccessful transmission. In particular, as considered in the third equation of Eq. 2.1, when an unsuccessful transmission occurs at backoff stage $i-1$, the backoff stage increases, and the new initial backoff value is uniformly chosen in the range $(0, W_i)$. Finally, the fourth case models the fact that once the backoff stage reaches the value m, it is not increased in subsequent packet transmissions.

Based on this theoretical analysis, the condition collision probability has been determined and applied to other research such as in [4].

2.1.2.2 Current Solutions

In the previous studies, there are a lot of research for solving the hidden terminal problem. Firstly, the solution that related to the directional antennas based on MAC protocol for wireless networks were discussed in [8, 9]. These research indicated that RTS/CTS is not a complete solution and may decrease throughput. CSMA/CA has failed to solve the hidden and exposed terminal problems. In addition, the various directional antennas were demonstrated such as Omnidirectional antenna, sector or panel. The direction of the antenna is rotated in an idle state within some every direction. Whenever it receives antenna beams from its schedule to receive antenna beams from the nearest node, the node wakes up and starts its communication. Moreover, these discussions show that in the directional antennas, the interference of a signal is much reduced in both sender and receiver sides.

Besides, as was mentioned in [10], there are three solutions for solving this problem, including shared random backoff, header snooping and virtual contention resolution. These methods related to the FD MAC protocol, hence they will be explicitly demonstrated in Section 2.3.3.

In order to recognize the effects of the hidden terminal problem in a CSMA/CA wireless network, A. Tsertou *et al.* [4] argued the accurate analysis of the effect of hidden nodes in the performance of wireless systems. In this research, they review the IEEE 802.11 MAC protocol with two cases of transmission scheme, RTS/CTS, and Basic access. However, to achieve the aim, this thesis only referred the RTS/CTS mechanism to evaluate the performance of the wireless system. The scenario of the hidden terminal was referred as Fig. 2.1, with node A, B and C corresponding to node A, R and B. It means that node A and B in [4] are hidden nodes each other. Firstly, this research presented the various states for the channel, including {success, collision, freeze}. However, to formulate and evaluate the performance as well as the effects of hidden terminal problem, this research only considered two states {success, collision}.

According to the analysis in [4], the conditional collision probability p is calculated as follows:

$$p = \frac{2p'}{1+p'} \tag{2.2}$$

where p' is probability that the receiver observes a collision.

Also, the Discrete Time Markov Chain (DTMC) was used for modeling that has only the two states, success (one of A or B is successful) and collision (both A and B face collision) and the transition of state is illustrated in Fig. 2.3.

Here, p_{cc} denotes the collision, conditioned on it seeing a collision in the previous channel state, and p_{sc} argues the collision, conditioned on it observing a successful transmission before.

Hence, the probability p' is formulated as:

$$p' = \gamma_0 = \frac{p_{sc}}{1-p_{cc}+p_{sc}} \tag{2.3}$$

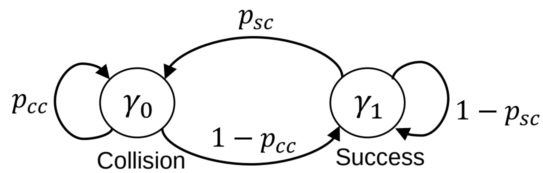


Figure 2.3: The transmitting states of the channel around intermediate transceiver.

In order to obtain the probability, p_{cc} and p_{sc}, this research analyzed the scheme of the transitions between system transmitting states, which is illustrated in Fig. 2.4.

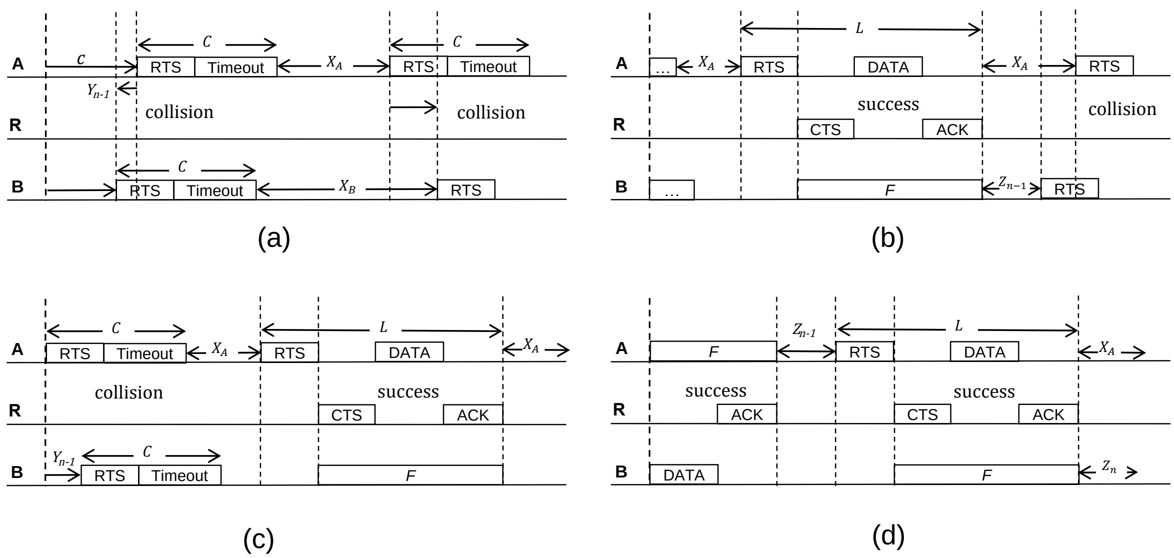


Figure 2.4: Scheme of the transmitting states.

Figure 2.4(a) and 2.4(c) are the changes from collision into collision and success respectively. As an assumption, a starts transmitting RTS and B could not have started transmitting RTS more than c =(RTS+SIFS)/σ slots. They defined $X_A(X_B)$ to be the Discrete Random Variable (DRV) describing the initial backoff counter value of A(B), which follows a uniform distribution in $[0, W-1]$, where W is contention window size. Besides, they denoted Y a DRV representing the time difference of the starting times of the RTS transmissions. The Y_n refers to state "n" and drawn from the interval $[-c, +c]$. The collision probability in these cases as follows:

$$p_{cc} = P\{-c \leq Y_{n-1} + X_B - X_A \leq c\} \tag{2.4}$$

In addition, Fig. 2.4(b) and 2.4(d) indicate the channel state switches from success to collision and success respectively. They defined Z to be the DRV that shows the distribution of the remaining backoff slots of a freezing node after its competitor transmitted successfully and Z_n denotes at the state "n". The collision probability in these cases as follows:

$$p_{sc} = P\{-c \le Z_{n-1} - X_A \le c\} \tag{2.5}$$

Besides, this research explicitly explained how to get these probability and in the end, we can obtain the probability p' in Eq. 2.3 and then get the conditional collision probability p in Eq. 2.2.

Furthermore, to formulate the throughput of system, we revisit the assumption and derivation in this research. Firstly with the model of transmission time in Fig. 2.5, the probability τ', which is an intermediate transmission probability, describes a transmitting slot and $1-\tau'$, correspondingly nontransmitting.

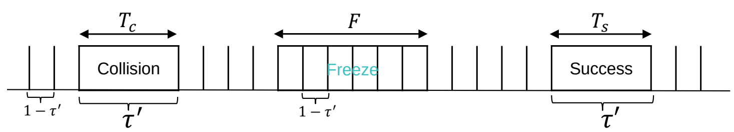


Figure 2.5: The channel model with state transmitting time.

Here, F is denoted as the length of the freezing period in fixed-length slots (an integer multiple of σ), $F = L$ - (RTS+CTS)/σ. In addition, to calculate the τ', they defined π_m, $m \in [0, W-1]$, as the steady-state probability that the backoff counter is equal to m when not frozen. The corresponding states, represented as large circle in Fig. 2.6, are the states of an Markov Chain (MC), as was discussed in Section 2.1.2.1.

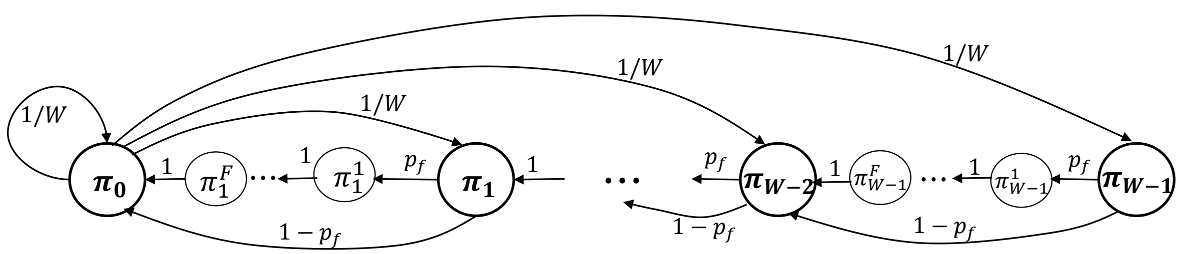


Figure 2.6: Incorporation of the freezing of the backoff counter in the MC.

In there, π_m^i as the steady-state probability that the counter of value m, $m \in [0, W-1]$, is frozen ($i \in [1, F]$ because there are F such states for each m). Also, let p_f be the probability that a node in a state π_m listens to another transmission and freezes its counter, that is, the transition probability from a state π_m to the successive π_m^1. The transition probabilities between two states π_m^i and π_m^{i+1}, $i \in [1, F]$, are equal to 1. From the analysis of the MC, the intermediate transmission probability τ' as

$$\tau' = \pi_0 = \frac{2}{2 + (W-1)[1 + p_f F]} \tag{2.6}$$

where, p_f is formulated as follows:

$$p_f = \frac{2(1-p)}{W-1} \tag{2.7}$$

The transmission probability (P_T) is as follows:

$$P_T = \frac{\tau'}{\tau' + Q(1-\tau')} \tag{2.8}$$

where τ' is given in (2.6) and $Q = \frac{1}{(1-p)L+pC}$, with C is collision period (an integer multiple of σ).

The throughput (S) is defined as the number of packets transmitted during a specific period of time divided by the duration of that period. S (in packets/s) is calculated as follows:

$$S = P_T.\frac{(1-p)L}{(1-p)L+pC}.\frac{1}{L} \tag{2.9}$$

Accordingly, this research is used as a preliminary study. These theoretical analyses are used to analyze and evaluate the effects of hidden terminal to the performance of mixture of HD and FD wireless networks in terms of saturation throughput in this thesis, Section 3.3.2.

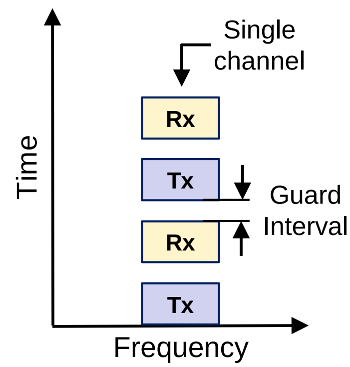
2.2 Half-duplex and Full-duplex Communication

In this part, we review the half-duplex (HD) and full-duplex (FD) communication and also the benefits of FD technique compared to HD technique. Moreover, the operation of FD technique in the practical device, real environment will be discussed.

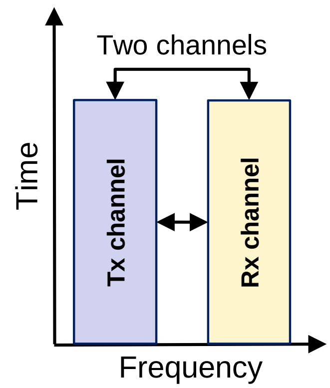
2.2.1 Overview Half-duplex and Full-duplex Techniques

The term "duplex" in a wireless network refers to the ability of two systems to communicate with each other, i.e., both systems are capable of data transmission and reception. However, whether the communication can be done simultaneously or not, depends on the systems data flow capability, i.e., Half-duplex (HD) or Full-duplex (FD). Due to its implementation simplicity, HD is the most commonly used data flow mode in wireless networks. HD enabled systems cannot transmit and receive simultaneously. Figure 2.7 illustrates the basic of HD and FD transmission.

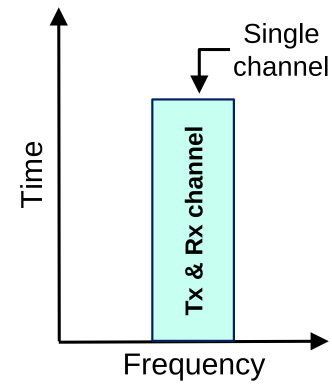
For the long duration of wireless communication networks, the HD technique is used. In the HD system, a wireless transceiver can either transmit or receive wireless signals in a given bandwidth but not both at the same time, where two orthogonal time or frequency channels are allocated for the respective reception and transmission at the relay. Therefore, there is an advantage of HD technology that is no co-channel interference.



(a) Time-division duplex (HD).



(b) Frequency-division duplex (HD).



(c) Full-duplex.

Figure 2.7: Overview HD and FD transmission.

Besides, in the current wireless network, both frequency division duplex (FDD) and time division duplex (TDD) require two separate channels to realize orthogonal transmission and reception, which wastes half of the radio resources. FD can double spectrum efficiency by simultaneous transmission and reception on the same frequency and time resource. In addition, FD also helps to reduce end-to-end packet delay and improve network efficiency, FD is widely considered as one of the promising techniques in 5G systems. Moreover, the FD technology can solve the hidden terminal problem.

The mixture of HD and FD wireless networks is the combination of HD and FD modes into the wireless network systems. The aim of this proposition is to improve the end-to-end throughput of the wireless networks. The requirement of this scheme is related to a new MAC protocol and the hidden terminal problem need to be analyzed and considered because they directly affect to the performance of wireless network system.

2.2.2 Benefits of Employing Full-duplex Techniques

The FD communication does wonders for improvements in throughput and diversity orders of systems communicating over wireless channels. In this subsection, we will review some particular properties of this technique.

Table 2.1 indicates the performance comparison between HD and FD schemes. Based on that, the FD mode has shown several attractive advantages but also exposed weaknesses in contrast to the HD mode. For example, since an FD node has to process twice as many packets as an HD node due to its simultaneous transmission and reception, both the packet loss ratio (PLR), as well as the delay, may become more severe for FD mode than for HD mode. Increasing their buffers queue-length generally benefits FD mode more than HD mode. Nevertheless, striking the most appropriate buffer size versus PLR tradeoff constitutes promising study item. Both advantages and disadvantages of FD techniques have discussed in [10].

Table 2.1: Performance comparison between HD and FD schemes.

Technical Content	**Half-duplex**	**Full-duplex**
Throughput Gain	Lower	Higher
Self-interference	Avoided	Cannot be avoided
Hidden Terminal Collision	Suffered	Mitigated
Congestion	Higher	Lower due to FD MAC scheduling
End-to-end Delay	Higher	Lower
Queue Size Requirement	Smaller	Larger
Packet Loss Ratio	Lower	Higher
Link Reliability	Higher	Lower
Primary User Detection in CR	Challenging	Improved

1. **Advantages of the FD mode**:

   - *Throughput gain*: As compared to the HD mode, the FD mode nearly doubles the throughput of a single-hop wireless link in the physical layer.
   - *Collision avoidance*: In the traditional carrier sense multiple access with collision avoidance (CSMA/CA) protocol, each HD node is required to check the channels quality before using it. The FD mode, however, only requires the first node that initiates transmissions to sense the channel, which is necessary for avoiding collisions at those FD nodes that do not perform carrier sensing.
   - *Solving the hidden terminal problem*: The problem of hidden terminals can be solved using FD techniques. Let us consider a scenario of multiple nodes having data in their buffer for direct transmission to and reception from a common access point (AP). If a node starts transmitting its data to the AP and the AP simultaneously starts transmitting data back to this node, the other nodes will hear the transmissions from the AP and delay their transmissions to avoid collisions. Even if the AP has no data to send back to the first node, it still repeats an ACK for that node so as to prevent the other nodes from transmitting.
   - *Reducing congestion with the aid of MAC scheduling*: The potential throughput loss imposed by congestion can be circumvented by enabling FD operation in congested nodes.
   - *Reducing the end-to-end delay*: An FD node is capable of commencing the forwarding of a hitherto only partially received packet so as to significantly reduce the end-to-end delay of packet delivery through a multihop network, as compared to the conventional store-and-forward technique employed in HD mode, which would make the end-to-end delay a linearly increasing function of the number of hops.
   - *Enhancing the primary users detection quality in cognitive radio (CR) environment*: The reliable detection of the primary user is not an easy task to perform

in CR environments. This would, however, become an even more challenging operation, if the primary receivers were to operate only in a HD mode. As a benefit, the FD mode enables the secondary user to scan for any primary users, while it is actively occupying the spectrum. The primary receivers may transmit at the same time, so as to ease the secondary usersscanning and detection operation.

2. **Disadvantages of the FD mode**:

    - *Performance constrained by SI*: In an FD device, the receive antenna (RA)'s input signal of interest is usually several orders of magnitude lower in power than the received SI signal imposed by the devices transmit antenna (TA) output. Hence, the interference imposed by the TA upon the RA will consequently drown out the weak input signal and degrade the FD gains.
    - *Degraded link reliability*: The FD mode suffers from a reduced link reliability, regardless of the SNR. As indicated in [11], a state-of-the-art off the-shelf radio is capable of achieving 88% of the link reliability compared to its HD mode counterpart.
    - *Suffers from higher PLR*: As compared to the HD devices, an FD node has to process twice the number of packets due to its simultaneous transmission and reception, thus leading to a higher PLR than the HD mode.
    - *A higher buffer size requirement*: To reduce the PLR of the FD mode, a sufficiently large buffer is required for enabling the packets to be forwarded (that would otherwise have been discarded due to queue overflow). Since the effects of packet-loss level are more severe in the FD mode, a larger buffer size is required than for the HD mode.

In order to implement the FD mode or the HD mode in the real environment, they depend on several particular factors, such as the required throughput of network systems, the SI cancellation capability, and the affordable hardware or software complexity.

2.2.3 Full-duplex Operations

In the full-duplex (FD) communication, there are two types of links, including the bidirectional link and the unidirectional link, as shown in Fig. 2.8. Here, Tx and Rx denote the transmitter and receiver at the wireless FD node, and SI denotes the self-interference from the transmitter to the receiver. In the wireless communication, interference is a combination of two or more propagated signals to generate composite waves, where these waves propagated at the same time and occupy some common frequency bans, which will lead to constructive or destructive interference. Hence, self-interference is a phenomenon that occurs inside of the transceiver in the FD wireless communication.

Figure 2.8(a) illustrates the bidirectional link between two nodes, node A and B. These nodes which are the FD nodes, can transmit and receive simultaneously. In this figure,

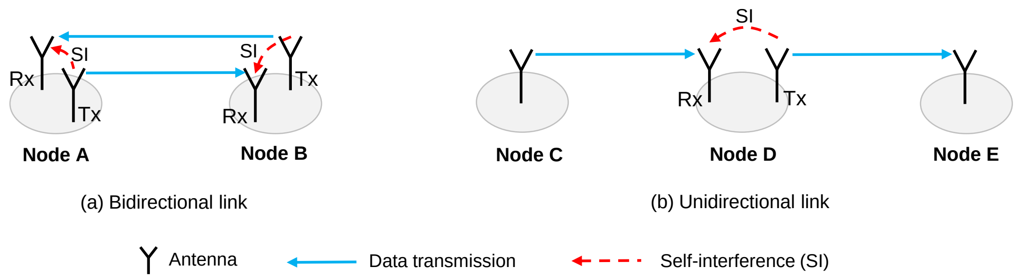


Figure 2.8: The basic model of full-duplex communication.

the antennae are separated to distinguish Tx and Rx, also to recognize the effect of self-interference (SI) from the transmitter to receiver. However, in the practical devices, they can design only one antenna in which there are two functions transmit and receive by using the circulator equipment. Besides, in the Fig. 2.8(b) demonstrates the unidirectional link with three nodes, node C, D and E. The direction of data transmission is from node C to node D or from D to node E. In this case, node D has function of the FD nodes, it can receive the data from node C, and also at that time, already has data to send to node E. Meanwhile, node C and D may be HD or FD nodes, it depends on the scenario of wireless networks. In this type of FD transmission, the SI effect happens at the node D. This research focuses on analyzing the FD uni-direction scenario to consider and solve the hidden terminal problem in wireless networks.

However, in order to achieve the goal of FD communication is to simultaneously transmit and receive within the same frequency, the self-interference problem needs to be suppressed. In recent years, the technique that related to SI cancellation is of interest to many researchers in this field. In [12], there mentioned a few solutions for solving this problem, including passive SI cancellation, active SI cancellation with analog and digital mechanism. In addition, the active and passive SI cancellation has explicitly discussed for 5G technology in [13].

Besides, the SI cancellation for multiple antennae was discussed in [14]. D. Bliss *et al.* proposed a multiple antenna inputs and multiple antenna output (MIMO) extension for FD, tested different MIMO beam forming and nulling techniques for improving self-interference suppression, and reported improvements for 0.1 MHz bandwidth four transmitters and three receiver antenna (4×3) MIMO communication at 370 MHz frequency center. Moreover, J. Choi *et al.* [11] proposed antenna cancellation using three antennas to create a beamforming null that cancels self-interference at the receiver antenna. This design created null zones in numerous locations in the far field. In order to void this problem and allow cancellation for more than three antennas per device, that design was modified in [15]. However, this change is practically challenging due to the complexity of the required antenna placement and to analog circuitry requirements which increase as a function of the number of transmitting and receiving antenna. Also, the distance between communicating devices was no more than three meters in the experiments report. Therefore, the SI cancellation still is an open topic that requires the researchers in this field to continue to solve thoroughly.

Moreover, the FD technique has discussed in much research in order to enhance the performance of wireless network systems. It has applied in cellular networks that were mentioned in [16]. Besides, the FD communication in cognitive radio network has been discussed in [17]. Wireless networks with their ubiquitous applications have become an indispensable part of our daily lives. Wireless networks demand more and more spectral resources to support the ever-increasing numbers of users. According to network engineers, the current spectrum crunch can be addressed with the introduction of cognitive radio networks (CRNs). In HD-CRNs, the secondary users (SUs) can either only sense the spectrum or transmit at a given time. This HD operation limits the SU throughput, because the SUs can not transmit during the spectrum sensing. However, with the advances in self-interference suppression (SIS), FD-CRNs allow for simultaneous spectrum sensing and transmission on a given channel. This FD operation increases the throughput and reduces collisions as compared with HD-CRNs. In addition, in this research, M. Amjad *et. al.* discussed a comprehensive survey of FD-CRN communications. They covered the supporting network architectures and the various transmit and receive antenna designs. Also, this research investigated the spectrum sensing approaches and security requirements for FD-CRNs and the major advances in FD MAC protocols as well as open issues, challenges, and future research directions to support the FD operation in CRNs.

Furthermore, FD technique also has attracted a considerable attention in industry [18, 19] by SAMSUNG source. These discussions have published on the 3rd Generation Partnership Project (3GPP), focused on the feasibility of FD configuration with techniques, such as SI cancellation, isolation between transmitter and receiver. Also, the impact on RF and baseband front-end. In addition, the design of FD chip has been discussed in [20, 21].

2.3 Basic MAC Protocol

The media access control (MAC) is a sub-layer in the Data Link layer, the second layer in the seven-layer OSI model. The MAC layer in 802.11 is unique to WLANs. The main function of the MAC protocol is to regulate the usage of the medium through a channel access mechanism. This mechanism is a way to divide the main resource between nodes, i.e., regulate the use of the radio channel which is the shared wireless medium. The channel access mechanism is the core of the MAC protocol. In addition to medium access, this layer is also responsible for calculating the CRC checksum, encryption, packet fragmentation (for transmitting), reassembling fragments (for receiving), and rendering these processes transparent to higher level protocols. The MAC layer management is also responsible for synchronization and power management.

The MAC layer used by the 802.11 family of standards. There are three main classes of channel access mechanisms for radio access:

- TDMA (Time Division Multiple Access);
- CSMA/CA-based access, termed Distributed Coordination Function (DCF);

- polling-based access, termed Point Coordination Function (PCF).

The CSMA/CA protocol is by far the most used in 802.11 networks. CSMA/CA is related to the CSMA/CD protocol used in 802.2 Ethernet. CSMA/CA is a listen before talk (LBT) access scheme. In CSMA/CA, a station that has something to send listens to the medium, and when there is no station active (and that is the difference with respect to CSMA/CD), waits a random time before sending its data, while still monitoring the medium. CSMA/CA is, like all Ethernet protocols, peer-to-peer, hence there is no requirement for a master station. The detail steps of a wireless node that wants to transmit as follows:

1. Listen on the desired channel;
2. If the channel is idle (i.e., there are no active transmitters) send the packet;
3. If the channel is busy (i.e., there is an active transmitter), wait until transmission stops, then a further contention period. The contention period is a random waiting period after every transmit operation, and statistically allows nodes to have equal access to the media.
4. If the channel is still idle at the end of the contention period, transmit the packet; if the channel became busy during the waiting, the waiting is stopped and the process is repeated from step 3 above until a free channel is present. Note that each time this happens, only the remaining contention period is taken into account while waiting. In the event that the waiting time becomes 0 without having transmitted the packet, a new random contention period is generated at step 3 with an exponentially increasing rang.

2.3.1 Frame Formats

This subsection shows the basic struture of the frame and general information of data and control frames.

2.3.1.1 Data Frames

Figure 2.9 illustrates the basic frame structure of IEEE 802.11 packets passed to PHY layer from MAC layer with the following components:

Frame control (2B)	Duration (2B)	Address1 (6B)	Address2 (6B)	Address3 (6B)	Seq. control (2B)	Address4 (6B)	Payload (0-2312B)	CRC (4B)

Figure 2.9: The IEEE 802.11 Frame Format

- *Frame Control:*
  Frame control including many subfields may affect the interpretation of other fields in the MAC header. For instance, some bits used to distinguish the association, RTS, CTS, ACK and data frames.

- *Duration:*
  It contains the value of network allocation vector (NAV) and represents the time period in which medium will not be free. (NAV is a timer that indicates the amount of time the medium will be reserved, in milliseconds)

- *Address Fields:*
  Address1 is used for MAC address of the receiver, Address2 is the MAC address of the transmitter, and Address3 contains the MAC address of the router interface that connects basic service set (BSS) subnet to other subnets.

- *Sequence Control:*
  This field is used for discarding duplicate frames and for defragmentation.

- *Payload:*
  Payload or Data field moves the higher-layer payload from source to destination.

- *CRS:*
  Cyclic Redundancy Check (CRC) or Frame Check Sequence (FCS) allows stations to check the reliability of received frames.

2.3.1.2 Control Frames

Control frames provide reliability functions of the data transmissions over MAC layer and administrator access to the wireless medium. Control frames are all header. No data transmitted in the body, and frame check sequence (FCS) follows the header. The impacts of control frames on the throughput of the different 802.11 standards. The most notably control frames are: RTS, CTS and ACK.

- *Request to Send (RTS)*
  RTS frame is used to reserve the medium for the transmission of unicast frames. A control packet used by a station to indicate that it has data to send. Figure 2.10 illustrates the components of RTS frame.

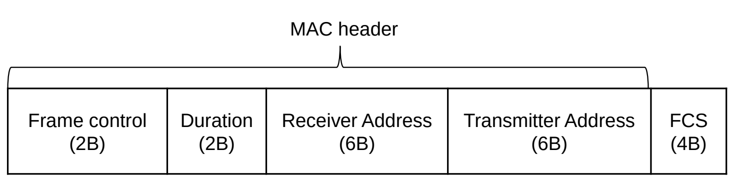


Figure 2.10: RTS Frame Format.

- *Clear to Send (CTS)*
  CTS frames were used as a response for RTS. In this case, it always follows the RTS. The new function of CTS frame is for protection purposes in 802.11b and 802.11g mixed mode. Figure 2.11 illustrates the components of CTS frame.

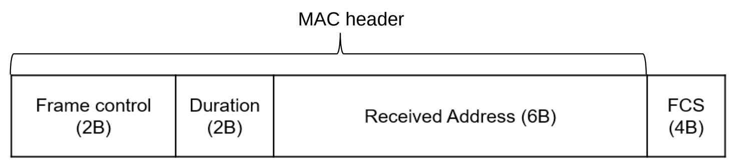


Figure 2.11: CTS Frame Format.

- *Acknowledgment (ACK)*
  ACK frame is used to send the positive acknowledgment required by the MAC. Figure 2.12 illustrates the components of ACK frame.

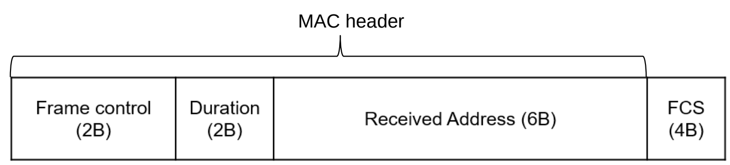


Figure 2.12: ACK Frame Format.

2.3.2 RTS/CTS Mechanism

In order to prevent the stations send out a request to send (RTS) and clear to send (CTS) frames to signal that a transmission is about to happen and find out if the media is busy or not. The source sends the RTS frame to its destination which returns a CTS frame back to the source. The RTS and CTS frames serve to announce to all stations in the neighbourhood of both source and receiver the upcoming frame transmission. The information received via these two frames tells the stations receiving them how long the transmission will occur and to delay any transmissions of their own.

The model of data transmission of RTS/CTS mechanism is as follows in Fig. 2.13. In this mechanism, the timing intervals which are mentioned followed by IEEE 802.11 standard.

- *Short interframe space (SIFS)*
  This is the shortest interval and used for high-priority transmissions such as RTS/CTS frames and positive acknowledgment. High-priority traffic can begin once the SIFS has elapsed and the medium becomes busy.

- *DCF interframe space (DIFS)*
  The DIFS is the minimum medium idle time for contention-based services. STAs may transmit if it has been free for a period longer then DIFS.

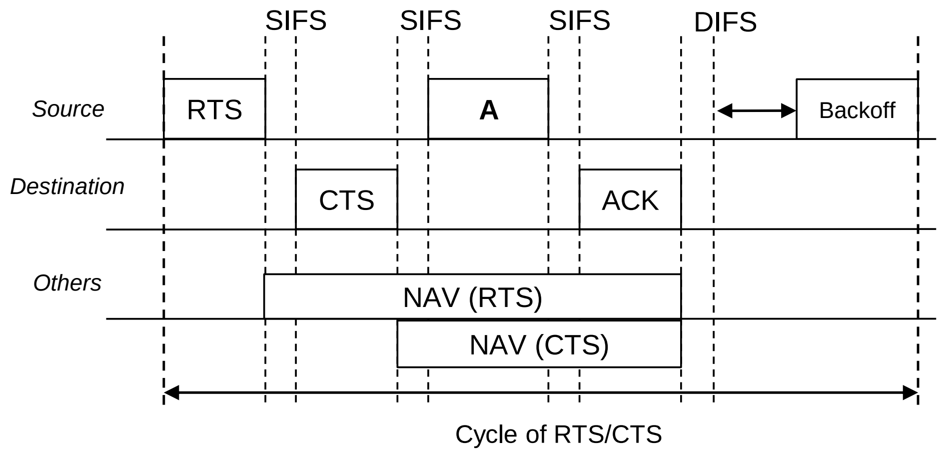


Figure 2.13: Successful data transmission of RTS/CTS mechanism.

Besides, there are two other frames for control protocol in IEEE 802.11 standard.

- *PCF interframe space (PIFS)*
  This interval is used by the PCF during contention-free operation. STAs with data to transmit in the contention-free period can transmit after the PIFS has elapsed.

- *Extended interframe space (EIFS)*
  This interval is only used when an error has occurred in the frame transmission.

2.3.3 Full-duplex MAC Protocol

As was mentioned in [22], there are three main challenges in MAC design. The first, challenge in designing full-duplex (FD) MAC is an identification of the nodes which can engage in a full-duplex mode. The second challenge is imposed by the physical layer. Any MAC design has to expect this constraint in its design. The third challenge is shared by any MAC protocol (full or half-duplex) and is to provide an opportunity to all nodes to access the medium. In other words, the MAC protocol needs to bring an adaptive network for all nodes inside the wireless network system.

Based on the IEEE 802.11 packet structure, the structure of FD MAC frame was proposed for three mechanisms like shared random backoff (SRB), header snooping (SN) and virtual contention resolution (VCR). The FD-MAC was described for the more popular use case of infrastructure mode of 802.11 which does not use RTS/CTS. Figure 2.14 illustrates the format of proposed MAC frame. The function of each field inside of the FD MAC frame as follows:

- DUPMODE: To distinguish the HD or FD mode

- HOL: Head-of-Line, indicating the next packet in the buffer is for the destination of the current packet

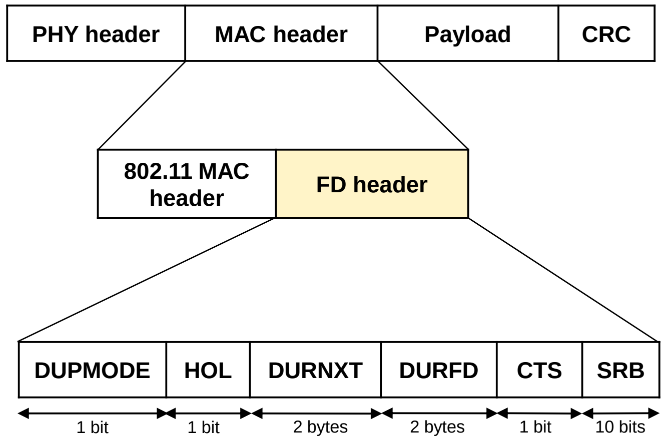


Figure 2.14: Structure of MAC frame.

- DURNXT: Duration of next packet, and is useful when HOL = 1
- DURFD: Duration time for FD transmission
- CTS: Clear-to-Send, indicating that destination of the current packet can send a packet to source of the current packet
- SRB: Shared Random Backoff

This proposed FD MAC protocol has been applied to three mechanisms, including shared random backoff (SRB), header snooping (SN) and virtual contention resolution (VCR). Also, these mechanisms are solutions for solving the hidden terminal problem, which was discussed in [10].

Firstly, the SRB mechanism temporarily couples the backoff counter of a pair of nodes, which have discovered that they have a packet destined for each other. Figure 2.15 shows the pair of source node AP and node M. The AP has packet lined up in the buffer for M, it sets HOL=1 in the DATA packet. Here $SRB_{AP} = 0$ and the DUPMODE = HD. Thus, the first packet in a two-way exchange is half-duplex. If M receives the DATA successfully and has a packet for AP, it sends an ACK packet with HOL = 1 and DURNXT set to the length of the head of the buffered packet. Also, SRB = 0, CTS = 1. After receiving the ACK, both nodes know that they can initiate a full-duplex. The PHY needs AP to train its self-interference channel, and thus AP sends an ACK packet, with HOL = 1, and also reveals DURNXT, and set SRB = 0, CTS = 1. Now the two nodes are set to be in full-duplex. They wait for $\max(SRB_{\mathrm{DATA}}; SRB_{\mathrm{ACK}})$ (which is = 0 at this stage) and then send their respective DATA packets with the DUPMODE = FD, and DURFD = $\max(DURNXT_{\mathrm{AP}}; DURNXT_{\mathrm{M}})$. Each node sends an ACK only at the end of DURFD duration. Also, AP always sends the ACK after the M in full-duplex mode, which allows hidden nodes to contend in the medium at the end of the ACK from AP.

Secondly, in the SN mechanism, even when the nodes have frozen their counter, this mechanism still requires the nodes to observe the headers of all ongoing transmissions

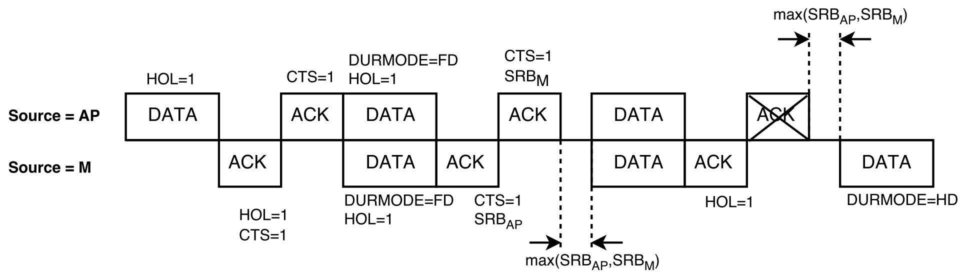


Figure 2.15: Shared random backoff.

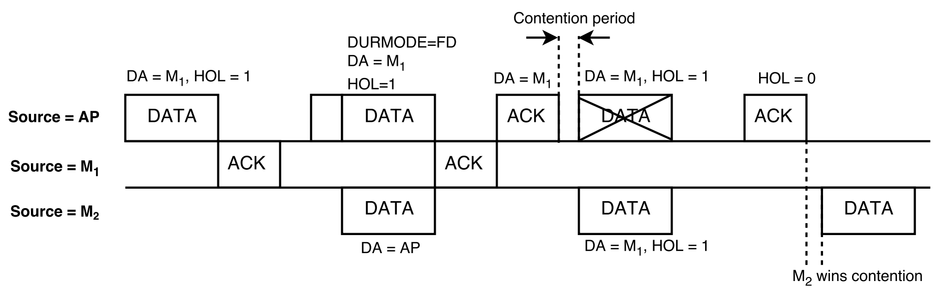


Figure 2.16: Header snooping.

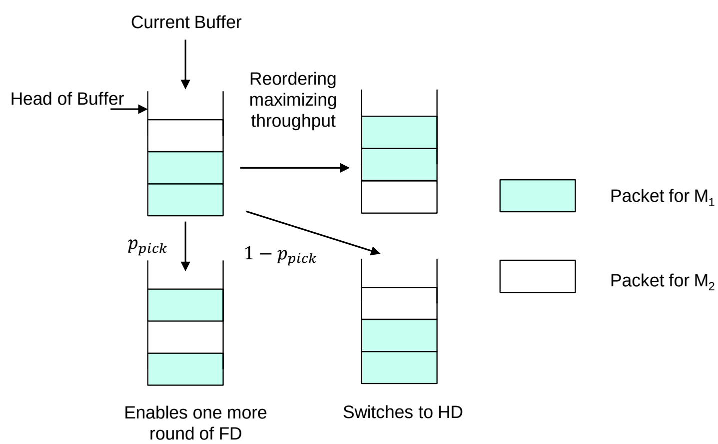


Figure 2.17: Virtual contention resolution.

within the transmission range. In order to elaborate a little further, the packet snooping mechanism allows nodes to estimate their local topology. Figure 2.16 illustrates the scheme of SN mechanism with three nodes, node AP, M_1 and M_2, where M_1 and M_2 are hidden nodes each other. The scheme is $\{AP \rightarrow M_1, M_2 \rightarrow AP\}$.

The third is VCR mechanism, when the AP is capable of observing multiple packets in its buffer, it statistically decides, which of the packets it will serve first. The AP may also opt for using FD mode by inspecting multiple packets in the queue. Figure 2.17 shows the principle of this mechanism with three nodes, node AP, M_1 and M_2.

The experimental results have shown that FD MAC protocol achieves a throughput gain of up to 70% over its comparable HD counterpart [22].

Furthermore, there are a lot of research that have proposed an FD MAC protocol to analyze and evaluate the feasibility of FD technique in wireless networks. The efficient asymmetric transmission in WLAN of FD MAC protocol has described in [23]. The notable point is the discussion about the transmission opportunities to balance the amount of traffic in both uplink and downlink direction. In addition, the energy efficiency of FD MAC protocol in distributed wireless networks is discussed in [24]. Moreover, the complexity of multi-user (MU) in the FD MAC protocol design for the next generation wireless networks has discussed in [25]. The simulation results show that the proposed FD MAC protocol significantly improved the saturation throughput up to 200% compared with IEEE 802.11 DCF.

However, according to the goal of this thesis, I propose a new MAC protocol for the mixture of HD and FD wireless network considering the hidden terminal problem. Therefore, the above research that related to FD MAC design for wireless network systems will be referred to analyze and design a new FD MAC protocol in Section 4.3, especially the original design [22] will be mainly focused on.

2.4 Overview of Network Coding

The network coding is firstly described in [26]. Ahlswede *et al.* investigated the concept of information flow that the received data can be mixed and then exchanged. This alternative method to the traditional principles of data transmission is known as network coding whereby it consists of encoding and decoding schemes to be applied at the intermediate nodes to improve the network performance by combining the transmitted information.

Besides, this technique is essentially a mathematical operation, which is exclusive-OR (XOR) applied to intermediate nodes between a source node and destination node. Instead of simply forwarding data, intermediate nodes may recombine several input packets into one or several output packets. In recent years, this is of interest to researchers because of its benefits in the potential throughput improvements.

Network coding was originally an absolute theoretical technique that involving several requirements such that the existing flows have to be known in advanced and the coding schemes have to be centralized [27]. The fundamental of network coding is the integration of mathematical computation, network topology, and algorithms. In order to perform the feature of distributed, network coding has evolved to enabling the utilisation of random parameters and hence the applications can be practical.

Wireless networks have been constructed based on the design of wired networks. In spite of that, the characteristics of wireless communication have diverged from the properties of wired communication. Fundamentally, wired networks have been established with physical links surrounded by static nodes which are predictable and dependable. Moreover, wired transmission is mostly unicast and the transmissions by wired are free from interference among themselves. On the other hands, wireless networks have been set up with dynamic nodes in encouraging mobility as well as flexibility. The preponderance of wireless communications is based on broadcast links which have the unexceptional situations like interference in the medium. Accordingly, transmissions in the wireless medium are facing high bit error rate [28]. It is obvious that the features of contemporary wireless networks are conflicting with the layout of the wired network, that resulting in low throughput, incompetent portability infrastructure as well as dead spots.

The ability of wireless networks to give away data redundancy also worthy of attention that it can be made use of data compression to improve the data flow in each transmission for better network throughput. This can be done via the simple network coding mechanism of exclusive-OR that is mentioned in Section 2.4.1. Both of the advantages from the characteristics that have been discussed can be accomplished in advanced design paradigm of wireless networks by engaging the principle of network coding [29]. As was concluded in [28], network coding can be utilized to assist wireless networks in order to achieve higher efficiency, more reliable and adequate scalable.

2.4.1 XOR Operation of Network Coding

Traditionally, the original message will be duplicated only at the intermediate nodes and send to the destination without any computational combination. In the new paradigm with network coding, the relay nodes have the ability to combine the packets from the transmitting nodes with Exclusive-OR (XOR) operation and create new packets to be transferred to the receiving nodes [30]. By doing this, the operation can provide the possibility cut down the number of transmissions and maximize the network throughput.

XOR operation can also be known as a bitwise operation by using the exclusive disjunction. The fundamental of the XOR operation can be described as below. The XOR operation can be represented by the symbol $\oplus$ in Table 2.2.

Table 2.2: Basic XOR operation.

$\oplus$	**0**	**1**
0	0	1
1	1	0

- For example: $1010 \oplus 0110 = 1100$

2.4.2 Network Coding Schemes

The network coding is beneficial in the network that consists of more than two nodes with the goals to ameliorate the network performance in respect to the throughput and the efficiency of data transmission in term of robustness in the entire network. In order to achieve the objectives above, the intermediate nodes are designated as the relay nodes to recruit the encoding and decoding schemes. The simple network coding is considered as rapid encoding as well as decoding system with XOR operation, also denoted as bitwise addition [31]. Another common network coding protocol is linear network coding with more complicated encoding and decoding scheme. The important information is included in a coefficient matrix to be interpreted at decoding nodes.

The initial concept of network coding is to decrease the transmission number of a message to be sent from a transmitter A to a receiver B across an intermediate node R. The conventional store-and-forward approach is illustrated in Figure 2.18 in which node A and node B are transmitting a message to each other via the intermediate node R.

In the first time slot, message {a} is transmitted from node A to node R. In time slot 2, node R forwards message {a} to node B. Similarly, in time slot 3, node B sends message {b} to node R. In time slot 4, node R forwards the remaining message {b} to node A. According to Figure 2.18, there are four transmissions taken in place throughout the four-time slots to complete the data transmission between node A and node B [32].

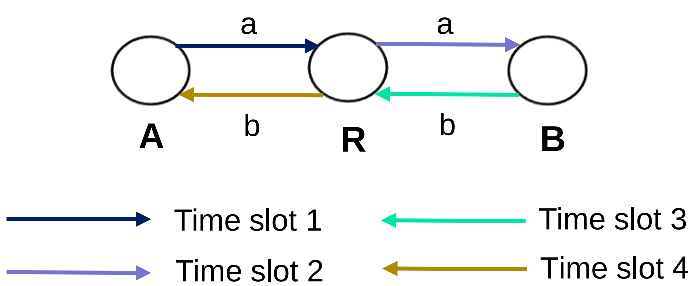


Figure 2.18: Model of traditional data transmission without network coding.

Figure 2.19 shows the basic of network coding method or XOR operation for three nodes with the assumption that the NC scheme is applied at node R. During the time slot 1 and time slot 2, the message {a} and {b} are sent from node A and B respectively. When node R has received the packets from both the nodes A and node B, it will combine them together with XOR operation {a⊕b} and broadcasts it as one message towards node A and node B.

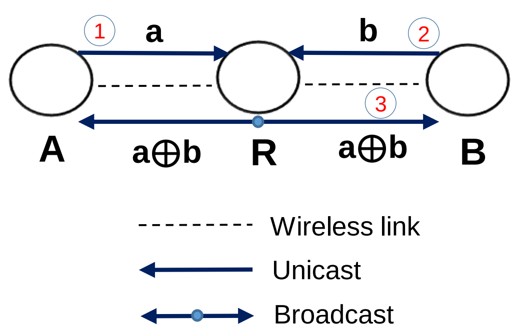


Figure 2.19: Model of data transmission with network coding.

Besides, Fig. 2.20 illustrates the scheme of data transmission with network coding under XOR operation. Based on the RTS/CTS mechanism, total time of successful transmission is $T_s{}^{XOR}$.

$$T_s{}^{XOR} = 3\text{RTS} + 4\text{CTS} + 3\text{DATA} + 4\text{ACK} + 11\text{SIFS} + 3\text{DIFS} \tag{2.10}$$

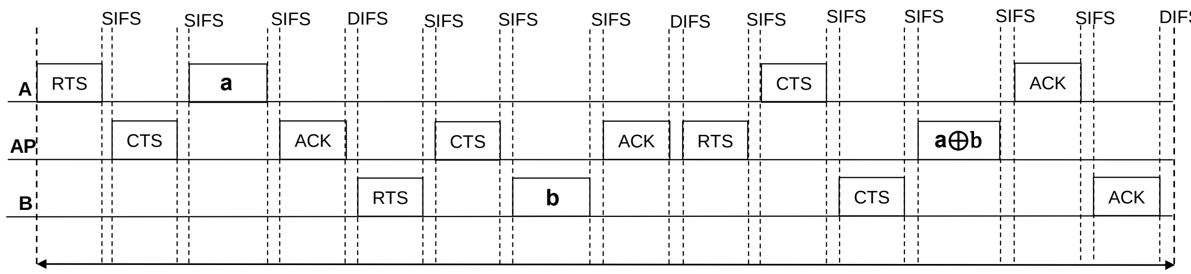


Figure 2.20: Scheme of data transmission with network coding.

Moreover, Physical Layer Network Coding (PNC) has described in [33]. It presented a scheme in which the number of time slots to be reduced. For instance, in Fig. 2.19, there are three nodes and that needs three-time slots to complete a successful transmission. However, with the scheme of PNC, it allows nodes A and B to transmit together and exploits the XOR operation performed by nature in the superimposed electromagnetic waves. By doing so, it further reduces the number of time slots to two and hence improves the performance of transmission system. Figure 2.21 illustrates two-time slots for the scheme of PNC. This PNC scheme is used to refer to modeling XOR operation of system model in this research.

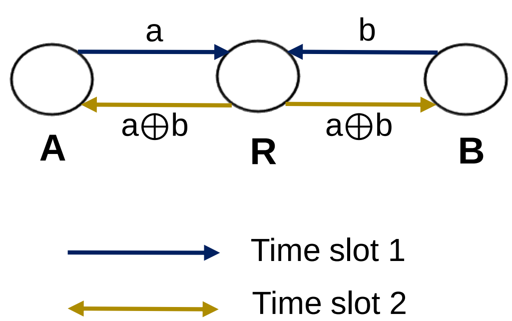


Figure 2.21: Model of physical layer network coding.

2.4.3 Advantages and Opportunity of Network Coding

This subsection introduces the potential strengths of the network coding technique in the wireless environment. This technique does wonders for throughput, reliability, mobility, and monitoring.

2.4.3.1 Throughput

Nowadays, the throughput of wireless networks is rather unpleasant due to its indeterminable properties. The idea of network coding technique is to increase the wireless network's throughput by granting the intermediate node to compress the relayed information regarding to the known information at different nodes [34]. Based on the knowledge of the information owned and desired among the neighbor nodes, the relay node is able to broadcast one message which contains multiple packets to be acquired at different neighboring nodes.

2.4.3.2 Reliability

The reliability of the current network communication paradigm can be maintained by the retransmission of the dropped packet. The concept of retransmission might be useful for wired network with the low bit error rate whereas the error prone wireless medium is impotent to this mechanism [35]. The authors in [36] have considered four types of reliability mechanisms such as End-to-End ARQ, End-to-End FEC, Link-by-Link ARQ and Link-by-Link FEC (NC). Those techniques are investigated based on the access point model for the reliable multicast over a tree topology. In conventional data transmission, the source node has to be aware of the specific packet lost from the destination nodes to proceed the retransmission stage with ease. Network coding is an alternative strategy to enhance reliability more efficiently by mixing the informations from multiple packets. By doing this, every message will be standardised to eliminate the identifiable packets.

2.4.3.3 Mobility

The wireless network is well-known with its dynamic in the communication architecture, and the updating of the routing from time to time is necessary and its very costly. The mobility can be improved by exploiting network coding in the wireless communication. This can be described with the scenario of one moving node as transmitter surrounded by a few of receiving nodes. In this case, the mobile transmitter node has no knowledge about the neighbor nodes. in the conventional way, the transmitter node has to first undergoes neighbor nodes discovery which involved several packets exchange. Due to the mobility features of the transmitter node, the connection may on and off depending whether both the transmitting node and receiving node are within the transmission range. Hence, they have to trace the previous information during the last transmission before the new transmission is begun [29].

2.4.3.4 Monitoring

The unreliable characteristic of wireless environment has caused frequent unpredictable link loss. Network coding has the advantages to provide a better monitoring over the state of link loss in the wireless network [29].

2.4.4 Network Coding for Full-duplex Networks

As was presented in previous sections, the full-duplex (FD) and network coding (NC) techniques have many benefits for the performance of the wireless network systems. Therefore, how to apply NC technique into the FD networks is a challenge also requires researchers need to evaluate the efficiency and robustness of these techniques in practical devices. In recent years, there is a few research that have contributed to that. In most of them, the physical layer network coding (PNC) operation that is presented in Section 2.4.2, is considered to achieve this proposition.

The practical network code for the wireless two-way relay channel where all nodes communicate in full-duplex mode has described in [37]. In addition, the performance analysis of multiband cognitive radio (CR) full duplex relay system is analyzed in terms of outage probability, as was discussed in [38]. Moreover, in [39], the authors presented a two-way relay channel using a lattice-based physical layer network coding scheme, a massive MIMO array, and in-band full-duplex, taking into account the residual self-interference that results after applying recently developed cancellation techniques for the loopback interference.

Besides, the network coding scheme for the multiple access full-duplex relay networks was described in [40]. Z. Li *et al.* proposed this scheme that uses XOR operation at the relay and iterative decoding at the destination. Also, the authors described in detail the iterative decoding algorithm which can obtain the substantial spatial diversity contained in the XOR operation. The results have evaluated for AWGN and Rayleigh fading channels.

This combination is still a challenge and an open key for researchers in the future. This thesis tries to apply and evaluates the effectiveness of FD MAC protocol for the combination of FD and NC techniques.

2.5 Summary

This chapter has presented background knowledge of the research with the particular definitions and related works. In this chapter, the hidden terminal problem and the solutions for solving the hidden terminal problem as well as the formulas to evaluate the saturation throughput of the wireless network system are described. Besides, the half-duplex and full-duplex communication are discussed. Especially, the comparison between the half-duplex and full-duplex technique has described. Also, the benefits of FD technique show that it can be highly potent in the future networks. In addition, the MAC protocol with the basic scheme and the FD MAC protocol have discussed. Moreover, the network coding and the network coding for FD networks have also described.

Chapter 3

Revisit Mixture of HD and FD Wireless Network

3.1 Objectives

This part will revisit the existing research that not only solve the hidden terminal problem, but also propose a new MAC protocol for full-duplex technology.

The mixture of HD and FD wireless networks is the combination of HD and FD nodes into the wireless network system. Therefore, the objective of this research is to propose a new scheme for MAC protocol that can operate both HD and FD mode and the hidden terminal problem will be resolved. In addition, this section will analyze the performance of HD, mixture of HD and FD, and FD wireless network. Also, the verification of simulation results will be described.

3.2 System Model

In this section, we introduce the system model with three nodes for HD transmission, the mixture of HD and FD transmission and the ideal case of FD transmission in the wireless network.

As was illustrated in Fig. 3.1, there are three nodes under the chain topology and among them, we assume the HD node and FD node with transmission Tx and reception Rx simultaneously. In this figure, node AP is within the transmission range of node A and node B, while node B is outside the transmission range of A and vice versa. In other words, node A and node B are hidden nodes each other. Node AP has applied the FD-MAC protocol in [22].

Figure 3.1(a) illustrates the three HD nodes. The RTS/CTS mechanism is applied to analyze and evaluate the throughput of the system.

Figure 3.1(b) illustrates the mixture of HD and FD wireless network. The FD transmission is at node AP. There are two potential actions for FD node. Firstly, node AP starts a new reception session, while transmitting. Let us assume that node AP is transmitting to node A when node B initiates the transmission of the packet. Then node AP has to

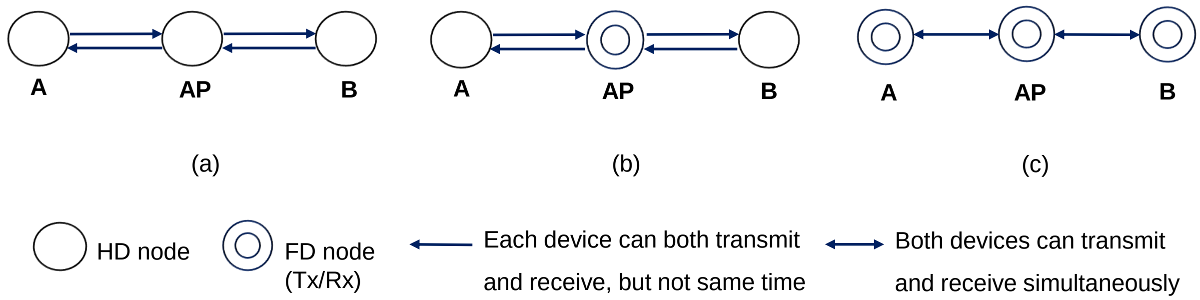


Figure 3.1: The chain topologies: (a) HD, (b) Mixture of HD and FD, (c) FD.

estimate the channel between node B and itself so as to decode node B's packet. Secondly, node AP starts a new transmission session, while receiving. When node AP has already commenced receiving a packet from node A and intends to send a packet to node B.

Figure 3.1(c) illustrates the ideal case with all nodes are FD mode. This model can be called as bidirectional full-duplexing. All transmission and reception are simultaneous at the same time and frequency. However, the transmission is made a pair of nodes, node A and node AP or node AP and node B. Node A and node B are hidden node each other.

3.3 Theoretical Analysis

3.3.1 Objective

In order to derive and evaluate the performance of the wireless network systems, this part will present the formulas to calculate the saturation throughput.

3.3.2 Saturation Throughput

Firstly, in order to analyze the saturation throughput of this wireless network system. This part will formulate the formulas to calculate the conditional collision probability and to this end is saturation throughput.

As was described in Subsection 2.1.2.2 and referred in [4], to calculate the conditional collision probability, transmission probability, and saturation throughput. First, this research revisits the definition of the time slot, which is of variable length depending on the state of the channel. For RTS/CTS mechanism, the time of successful transmission T_s is defined in Fig. 3.2 with five cases, T_s^{HD} for HD transmission, T_s^{FD} for of FD transmission, T_s^m for mixture of HD and FD transmission. The time of transmission is operated based on MAC protocol that was described in the previous section.

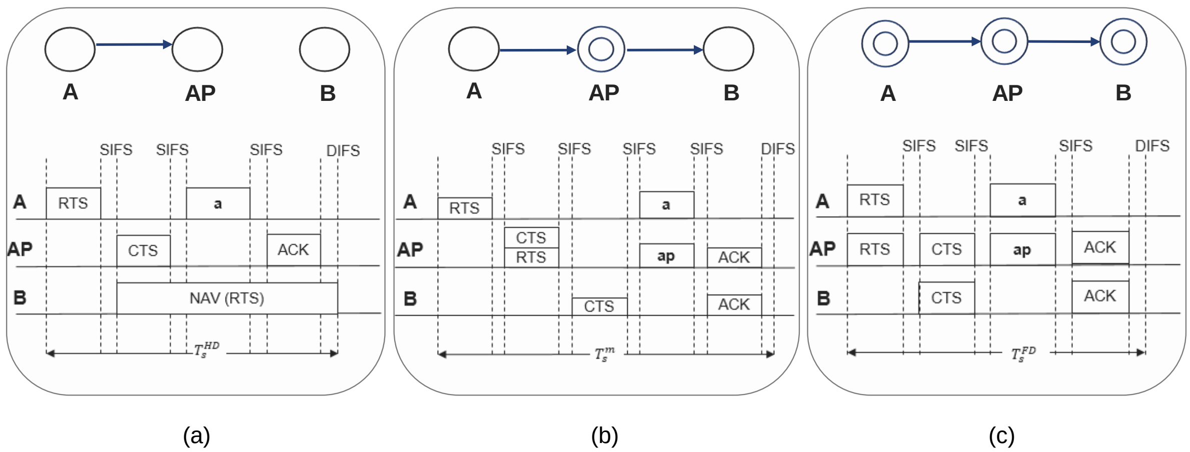


Figure 3.2: The frame exchange in the time of successful transmission: a) HD, (b) Mixture of HD and FD, (c) FD.

Here,

$$
\begin{aligned}
{T_s}^{HD} &= \text{RTS} + \text{CTS} + \text{DATA} + \text{ACK} + 3\text{SIFS} + \text{DIFS} \\
{T_s}^{FD} &= \text{RTS} + \text{CTS} + \text{DATA} + \text{ACK} + 3\text{SIFS} + \text{DIFS} \\
{T_s}^{m} &= 2\text{RTS} + \text{CTS} + \text{DATA} + \text{ACK} + 4\text{SIFS} + \text{DIFS}
\end{aligned}
\tag{3.1}
$$

Besides, the slot has the length of a collided transmission, T_c = RTS + DIFS, for all stations. When the node is in backoff time, it has slot time length σ, is $20\mu s$.

According to the analysis in [4] with the states of collision and success that were considered, the conditional collision probability p is calculated as follows:

$$
p = \frac{2p'}{1 + p'} \tag{3.2}
$$

where p' is probability that the receiver observes a collision.

In order to facilitate the analysis, this research uses an intermediate step that can incorporate and accurately describe the joint behavior of the senders. The conditions are the same conditions as were analyzed in [4]. Therefore, this research still use (3.2) to calculate the conditional collision probability p.

Moreover, the Discrete Time Markov Chain (DTMC) was used for modeling that has only the two states, success and collision [4]. We extend this scheme by adding the freeze state (shown in Fig. 3.3). There are nine transition probabilities, correspondingly with three states. Here, collision (C) state, $p_{cc}+p_{cf}+p_{cs} = 1$; success (S) state, $p_{ss}+p_{sc}+p_{sf} = 1$ and freeze (F) state, $p_{ff}+p_{fs}+p_{fc} = 1$ (all outgoing probabilities from one state equal to 1).

The purpose of this part is to verify the probability p' to calculate the conditional collision probability p in (3.2). The equation is as follows:

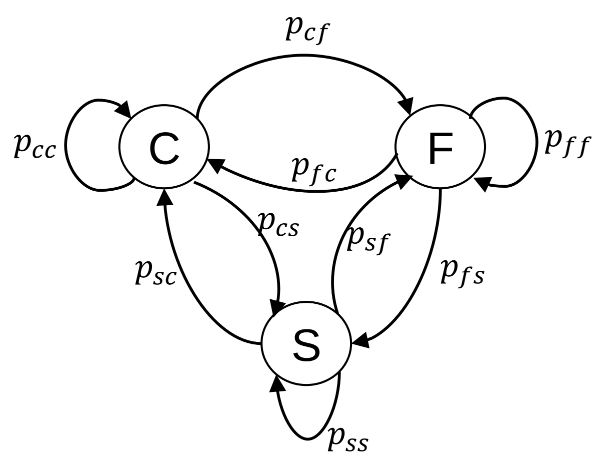


Figure 3.3: The proposed transmitting states.

$$p' = \frac{p_{sc} + p_{fc}}{1 - p_{cc} + p_{sc} + p_{fc}} \tag{3.3}$$

where p_{cc} and p_{sc} were explicitly discussed in the schematic analysis of the transitions between system transmitting states [4]. We need to concentrate on the derivation of the transition probability p_{fc} that related to freeze state.

As was presented in [4], the formulas to calculate probability of p_{cc} and p_{sc} are Eq. 2.4 and Eq. 2.5, respectively. In order to formulate the probability p_{fc}, let see Fig. 3.4 that illustrates the scheme of the state transition from feeze to collision state.

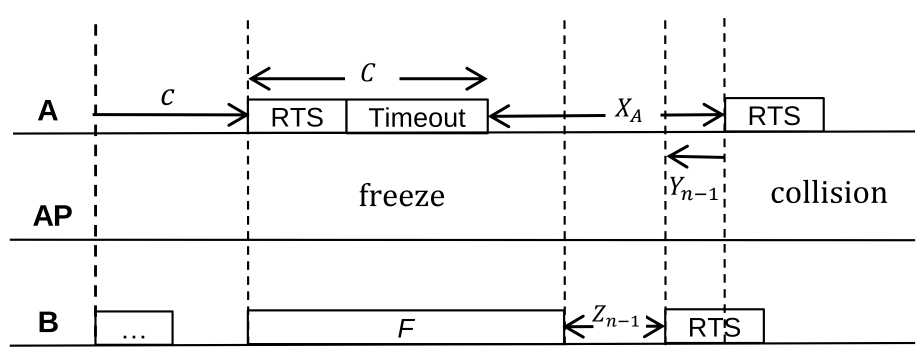


Figure 3.4: Scheme analysis of the state transition from freeze to collision state.

In there, as was described in [4], c =(RTS+SIFS)/σ slots, X_A is the Discrete Random Variable (DRV) describing the initial backoff counter value of A, which follows a uniform distribution in $[0, W-1]$, where W is contention window size and Z is the DRV that shows the distribution of the remaining backoff slots of a freezing node after its competitor transmitted successfully. Hence, the state transition probability from freeze to collision as follows:

$$p_{fc} = P\{-c \leq Y_{n-1} + Z_{n-1} - X_A \leq c\} \tag{3.4}$$

Similarly, the previous research [4] defined the probability τ' as an intermediate transmission probability, as follows:

$$\tau' = \frac{2}{2 + (W-1)[1 + p_f F]} \tag{3.5}$$

Here, W is window size; F is the length of the freezing period in fixed-length slots, $F = L - (\text{RTS} + \text{SIFS})/\sigma$, where L is successful period (an integer multiple of σ) and p_f is the frequency with which the counter freezes divided by the average number of backoff slots, as follows:

$$p_f = \frac{2(1-p)}{W-1} \tag{3.6}$$

The transmission probability (P_T) is as follows:

$$P_T = \frac{\tau'}{\tau' + Q(1-\tau')} \tag{3.7}$$

where τ' is given in (3.5) and $Q = \frac{1}{(1-p)L+pC}$, with C is collision period (an integer multiple of σ).

The throughput (S) is defined as the number of packets transmitted during a specific period of time divided by the duration of that period. S (in packets/s) is calculated as follows:

$$S = P_T . \frac{(1-p)L}{(1-p)L + pC} . \frac{1}{L} \tag{3.8}$$

These analyses will be determined to evaluate the performance of the wireless network system considering the hidden terminal problem.

3.4 Simulation Analysis and Verification

3.4.1 Objective

Before doing the simulation, we need to make the simulation scenario and also set up the value for all particular parameters in the simulation. However, how to recognize the simulation results are correct or incorrect. We have to verify them and the simple way is the comparison of the theoretical results with the previous study, which has published or accepted by the committee in the research field.

3.4.2 Simulation Setting

In this thesis, in order to verify the correctness of simulation parameter and setting, firstly we assume the simulation scenario and parameters like in previous study [4]. Table 3.1 shows the parameters for simulation as mentioned in [4], followed the IEEE 802.11b.

In the previous study, the simulation results are the average of the measured quantity over 10 different runs of the traffic scenario for 200 seconds of simulation time. Another important thing, they made the simulation on the NS2 simulator. In order to verify the simulation, I built the same scenario and set the same parameters for simulation on the MATLAB R2016b. Also, the number of simulation times are 10 times. Although the NS2 and MATLAB are two different software for simulation, I think that in this case, the simulator model is not too complicated, so the results will not be much different. Therefore, the verification results will show the simulation is reliable or not.

Table 3.1: Simulation parameter and setting.

Parameter	**Value**
Packet length (bytes)	[256, 512, 1024, 1536, 2048, 2294]
Contention window	[32, 64, 128, 256, 512, 1024]
Basic rate (Mbps)	[1, 2]
Data rate (Mbps)	[1, 2, 11]
PLCP header (bits)	192
MAC header (bits)	272
PHY header (bits)	128
RTS size (bits)	160
CTS size (bits)	112
ACK size (bits)	112
SIFS length (μs)	10
DIFS length (μs)	50
Slot time length (μs)	20

3.4.3 Simulation Result and Verification

Figure 3.5 illustrates the verification of the simulation with half-duplex transmission under the conditions with data rate $R = 2$ (Mbps), window size $W = 32$, and packet length is 256 (bytes).

This figure shows the saturation throughput of the original result in [4] and my simulations results. I also add the proposed simulation result with three states compared with two states of the channel in the previous research. This result is less than the result with two states, 94.25 (packets/s) compared with 98.12 (packets/s). This can be explained in a simple way, by considering three states that would cost more time, so in the same time transmission, the number of successfully transmitted data will reduce.

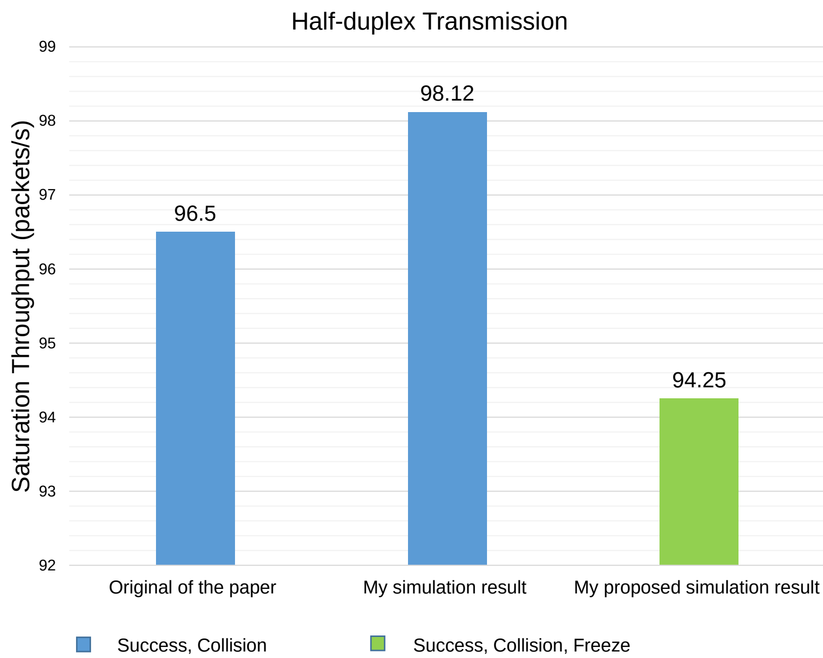


Figure 3.5: The verification of the simulation.

With the two-state conditions, the saturation throughput of HD transmission in the original paper and my result are 96.5 (packets/s) and 98.12 (packets/s) respectively. These results are averaged of all simulation times. Likewise, as was mentioned in previous Section 3.3.2, the saturation throughput depends on the conditional collision probability, which depends on the discrete random variable and other random values. Besides, the simulation results have made at the different time and it is impossible to accurately require the values in my study and previous one. The results are acceptable if they are not so much different. In this case, the difference is only 1.62 (packets/s) corresponding to 1.68%, which can be reliable. Hence, my simulation for this research is acceptable.

In addition, Figure 3.6 shows the comparison of saturation throughput with other schemes, under the condition of the data rate $R = 2$ (Mbps), window size $W = 32$, and packet length is 256 (bytes). The saturation throughput has reduced for all schemes, including HD, the mixture of HD and FD, and FD transmission. The largest decrease is in FD case, which had dropped 12.5%, followed by the mixture of HD and FD with 10.1% and 4.8% for HD transmission.

Moreover, in order to analyze the effect of the hidden terminal problem to the throughput of the wireless network systems. We will evaluate in all cases, including HD, FD, and mixture of HD and FD wireless networks. Figure 3.7 demonstrates the effect of hidden terminal problem to saturation throughput of the wireless networks, under the conditions of the data rate $R = 2$ (Mbps), packet length is 256 (bytes). We can easily see that the hidden terminal problem reduced the saturation throughput to 1.1 times, 1.2 times and 1.4 times corresponding to the HD, mixture of HD and FD, and FD transmission.

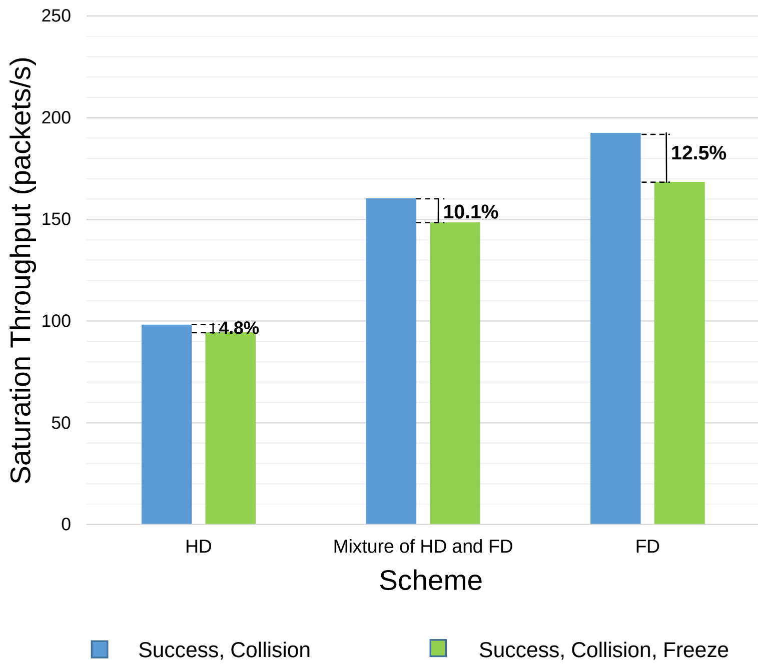


Figure 3.6: The comparison of saturation throughput with other schemes.

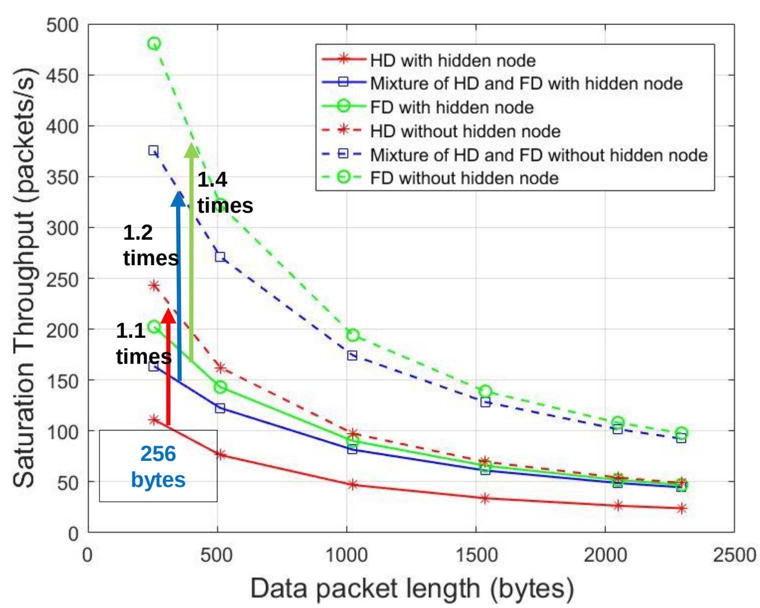


Figure 3.7: The effect of hidden terminal problem.

Therefore, based on the parameters set and the above simulation results that have verified, we will set up the scenario and particular parameters for simulation in this thesis. The outcomes of the simulation will show the improvements of this research.

3.5 Summary

In this paper, we revisited the hidden terminal problem in HD wireless network (CSMA/CA) and extended the system model not only the mixture of HD and FD, but also the FD wireless network. In addition, we also discussed the solutions that are used to solve the hidden terminal problem in the mixture of HD and FD wireless network. Moreover, in order to evaluate the effectiveness of the proposed scheme, this chapter derived the formulas to calculate the saturation throughput and also the influence of interference. Especially, the states of the channel have extended with three states, including success, collision, and freeze. Based on the simulation results which have been verified, in order to extend the system model, we still use the derivation of saturation throughput to obtain the new improved results which will be reliable.

Chapter 4

Proposed IFDMA Protocol

4.1 Objectives

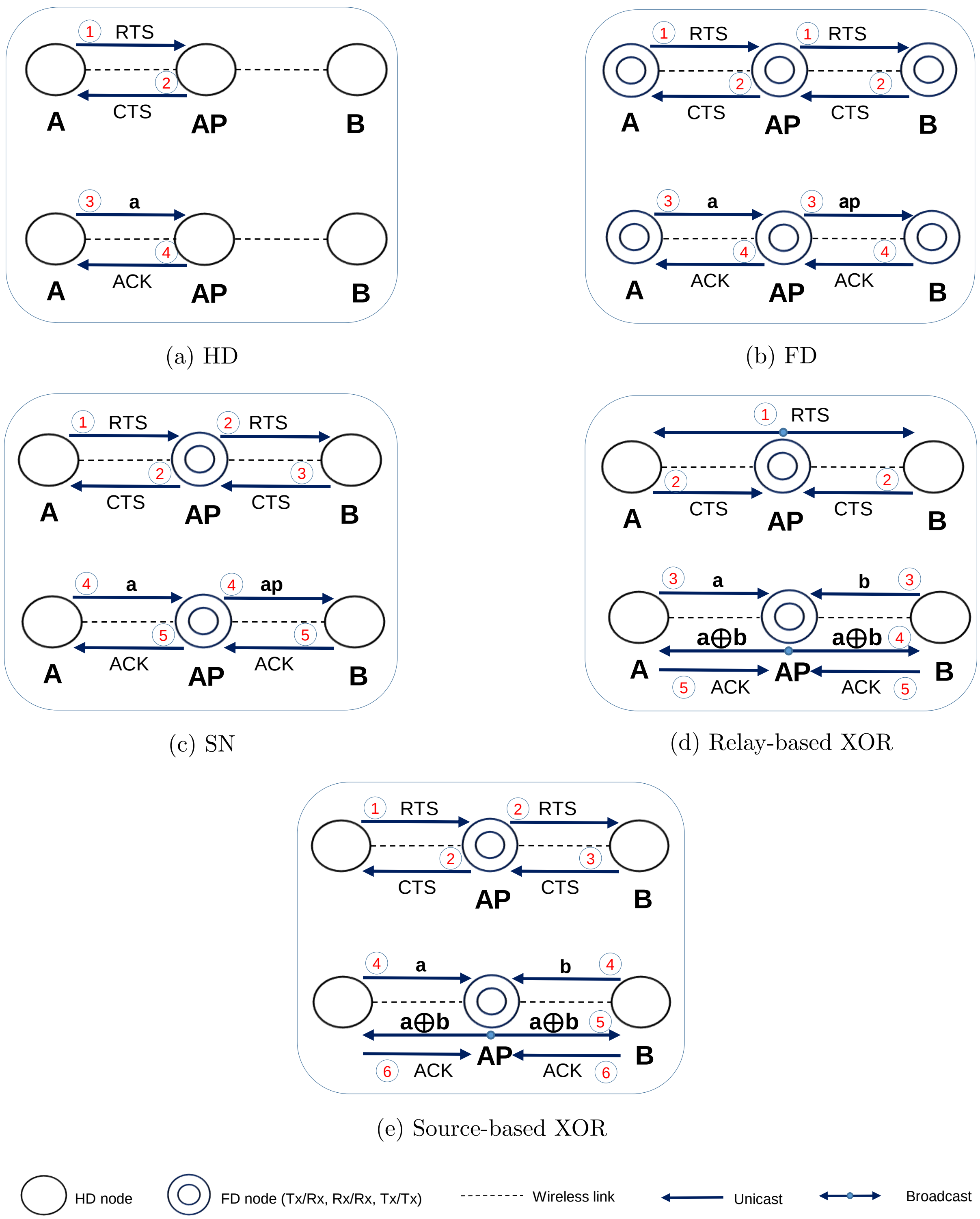
In order to improve the scheme for the mixture of HD and FD wireless network and also enhance the performance of the system, this chapter will extend the scheme and propose a new methodology for multiple access (MA) in the wireless network system. Likewise, the dealing with HD and FD wireless nodes and taking the advantages of solutions for solving the hidden terminal problem have discussed. Besides, the FD MAC protocol using network coding technique to improve the throughput of wireless network system was discussed in much research.

Therefore, the objective of this chapter is to propose a new scheme for MAC protocol for the mixture of HD and FD wireless network considering the hidden terminal problem. Thus, this chapter presents a new design of MAC frame called integrated full-duplex and multiple access (IFDMA) protocol to enhance the performance of the wireless network systems. Furthermore, to evaluate the performance as well as the effectiveness of these methods, this chapter will present the new protocol to operate the MA methods for IFDMA protocol and the numerical analysis of saturation throughput, influence of interference for evaluations.

4.2 Frame Exchange and Topology

Figure 4.1 demonstrates the system model for scheme of the transmission mode of multiple access (MA) for mixture of HD and FD wireless networks in five topology cases.. There are three nodes by the combination of HD node and FD node, where FD node can be transmission Tx, reception Rx simultaneously. In this figure, node AP is within the transmission range of node A and node B, while node B is outside the transmission range of A and vice versa. In other words, node A and node B are hidden nodes each other. Node AP has applied the FD-MAC protocol except the HD transmission case.

Figure 4.1a illustrates the three HD nodes. The RTS/CTS mechanism is applied to analyze and evaluate the throughput of the system. In this scheme, the only transmission happens between node A and AP.



(a) HD

(b) FD

(c) SN

(d) Relay-based XOR

(e) Source-based XOR

Figure 4.1: Transmission mode of MA methods.

Figure 4.1b illustrates the ideal FD case with all nodes that are FD mode. This model can be called as bidirectional or unidirectional full-duplexing. In this scheme, we consider the unidirectional transmission from {A → AP, AP → B}, where node A and node B are hidden nodes each other. All transmission and reception are simultaneous at the same time and frequency.

Figure 4.1c shows the header snooping (SN) mechanism. The FD transmission is at node AP. There are two potential actions for FD node. First, node AP starts a new reception session, while transmitting. Let us assume that node AP is transmitting to node A, when node B initiates the transmission of the packet. Then node AP has to estimate the channel between node B and itself so as to decode node B's packet. Second, node AP starts a new transmission session, while receiving. When node AP has already commenced receiving a packet from node A and intends to send a packet to node B.

Figure 4.1d demonstrates the XOR based on relay node AP. Firstly, node AP sends the RTS frame to node A and B. After that, node A and node B send the CTS frame to node AP to realize that the channel is free and already for transmission. Also, node A and node B have a packet for transmission to node AP. By assumption, node AP can receive two packets at the same time. After node AP receive two packets from node A and node B, it will combine them together by XOR calculation and then broadcasts the encoded packet to both node A and node B. At node A and node B, they receive that packet and decode to get the expected packet.

Figure 4.1e indicates the XOR based on the source node, i.e., node A. Firstly, the RTS frames are to be sent from node A to node AP and node AP to node B. After that, node AP and node B send the CTS frame to node A and node AP respectively to realize that the channel is free and already for transmission. Also, node A and node B have a packet for transmission to node AP. Similar with relay-based XOR, the XOR operation or encoding and decoding to obtain the expected packets like in the relay-based XOR.

The difference between SN and XOR operation is the exchange of data. In the XOR scheme, node A and node B can send and receive each other, although they are hidden nodes. Meanwhile, the other schemes of frame exchange are {A → AP, AP → B}. If node B wants to send a packet to node A, it would cost one more time. Therefore, this is a novel point in IFDMA protocol for multiple access to the wireless communication.

Moreover, in order to facilitate the analysis as well as evaluation, this research proposes a definition for HD and FD node and the topology as in Table 4.1a. In addition, the definition for topology with three nodes as in Table 4.1b.

(a) Assumption of mode.

Mode	Encode (bit)
FD	**1**
HD	**0**

(b) Definition of topology.

Method	Topology		
HD	**0**	**0**	**0**
FD	**1**	**1**	**1**
SN	**0**	**1**	**0**
XOR	**0**	**1**	**0**

Table 4.1: Assumption of topology model.

4.3 IFDMA Protocol

As was illustrated in Section 2.3.3 and in [22], based on IEEE 802.11 packet structure, the structure of FD MAC frame was proposed for three mechanisms, including shared random backoff (SRB), header snooping (SN) and virtual contention resolution (VCR). The FD-MAC was described for the more popular use case of infrastructure mode of IEEE 802.11 which does not use RTS/CTS. In order to improve that, based on RTS/CTS mechanism, this research analyzes and applies for the combination of multiple access both HD, FD, SN and XOR operation. Especially, the multiple access (MA) control protocol will be determined in this MAC protocol.

The proposed MAC protocol is called Integrated FD and Multiple Access (IFDMA) control protocol in order to improve the capacity of data transmission in the wireless networks.

Figure 4.2 demonstrates the structure of proposed MAC frame format with integrated FD and multiple access (IFDMA) control protocol.

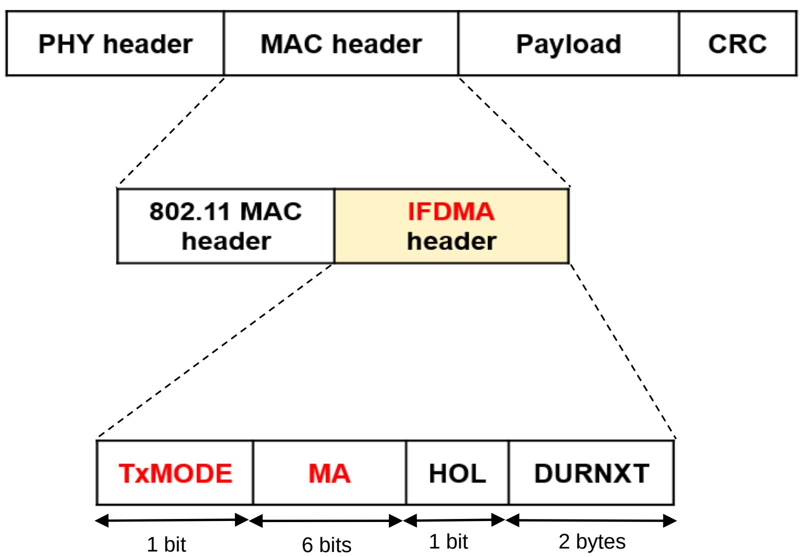


Figure 4.2: Frame of proposed MAC protocol.

- TxMODE: Mode to consider the HD or FD mode
- MA: Multiple Access, considering HD, FD, XOR or SN procedure
- HOL: Head-of-Line, indicating the next packet in the buffer is for the destination of the current packet
- DURNXT: Duration of next packet, and is useful when HOL = 1

The HOL field is used to snooping for next packet with the destination (DA) determined. The MA is to indicate the packet which is transmitted for processing of HD, FD, XOR or SN, especially usefulness for XOR and SN mechanisms. They help to distinguish the function of HD, FD node. The DURNXT is useful for estimating the time for FD exchange. For instance, in Fig. 4.1c, node A has a packet to transmit to node AP and at that time node AP also have a packet to transmit to node B and hence, DURFD $= max\{\mathrm{DURNXT_A}, \mathrm{DURNXT_{AP}}\}$.

4.4 Theoretical Analysis

The objective is to evaluate the throughput of the wireless network system and also determines the effects of interference to the performance of the system. Hence, this part investigates the saturation throughput and the influence of interference in two subsections.

4.4.1 Saturation Throughput

First, this part revisits the definition of time slot, which is of variable length depending on the state of the channel. For RTS/CTS mechanism, the time of successful transmission T_s is defined in Fig. 4.3 with five cases, T_s^{HD} for HD transmission, T_s^{FD} for of FD transmission, T_s^{SN} for mixture of HD and FD transmission and T_s^{XOR} for XOR operation with $T_s^{XOR\_r}$ and $T_s^{XOR\_s}$ corresponding to the relay-based XOR and source-based XOR. The time of transmission is operated based on MAC protocol that was described in previous section.

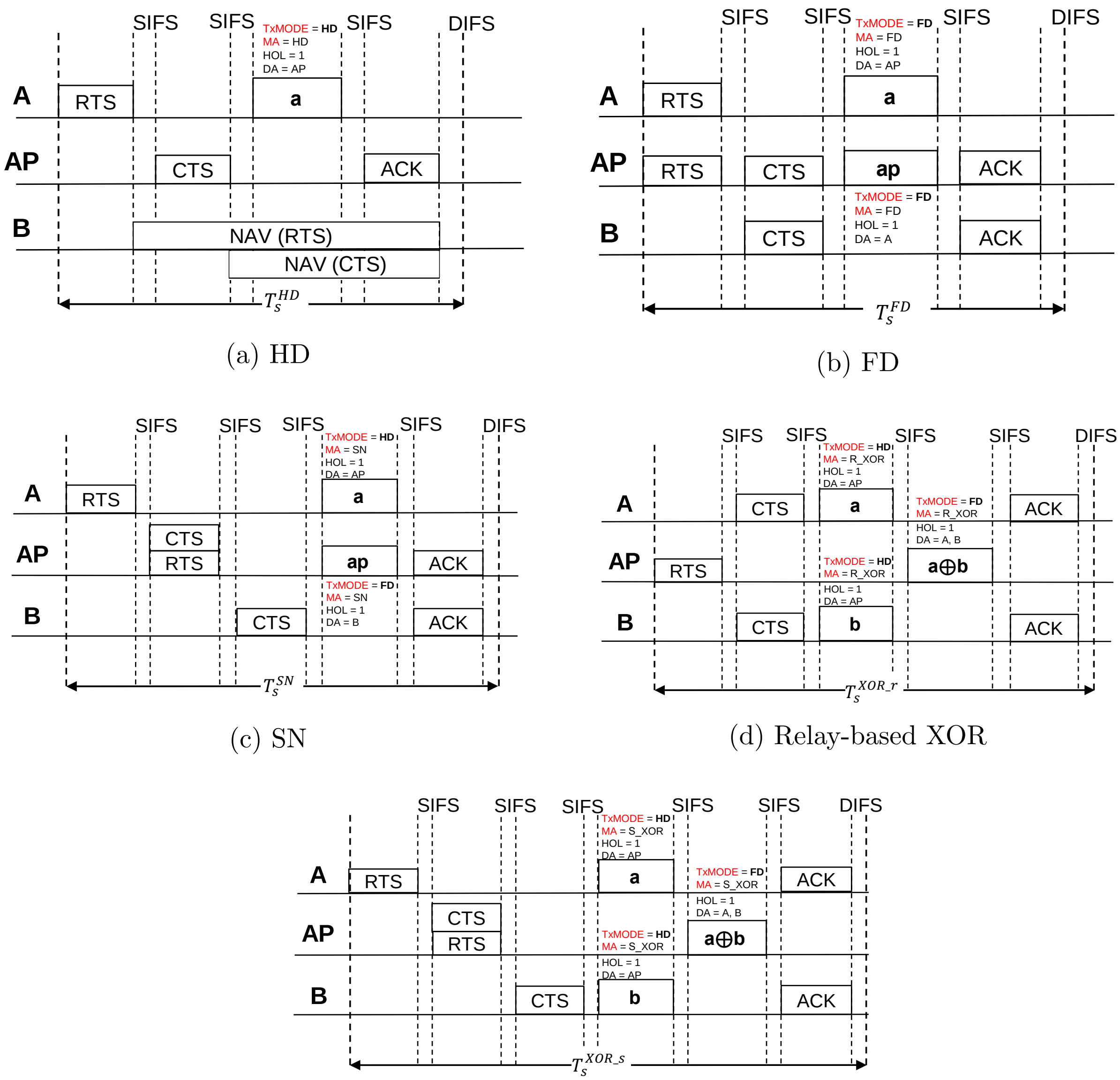
$$
\begin{aligned}
{T_s}^{HD} &= \mathrm{RTS + CTS + DATA + ACK + 3SIFS + DIFS} \\
{T_s}^{FD} &= \mathrm{RTS + CTS + DATA + ACK + 3SIFS + DIFS} \\
{T_s}^{SN} &= \mathrm{2RTS + CTS + DATA + ACK + 4SIFS + DIFS} \\
{T_s}^{XOR\_r} &= \mathrm{RTS + CTS + 2DATA + ACK + 4SIFS + DIFS} \\
{T_s}^{XOR\_s} &= \mathrm{2RTS + CTS + 2DATA + ACK + 5SIFS + DIFS}
\end{aligned}
\tag{4.1}
$$

Similarly in Section 2.4.3.1, the Markov Chain model has applied to calculate the conditional collision probability for three states of the channel, including success, collision, freeze.

The throughput (S) is defined as the number of packets transmitted during a specific period of time divided by the duration of that period. S (in packets/s) is calculated as follows:

$$
S = P_T . \frac{(1-p)L}{(1-p)L + pC} . \frac{1}{L} \tag{4.2}
$$

Moreover, in order to quantify the amount of variation of throughput, we calculate the standard deviation as follows:



(a) HD

(b) FD

(c) SN

(d) Relay-based XOR

(e) Source-based XOR

Figure 4.3: The frame exchange in the time of successful transmission.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N} \left(S_i - \bar{S}\right)^2}{N-1}} \tag{4.3}$$

where σ is standard deviation, N is number of data, S_i is i-th throughput and $\bar{S}$ is mean of throughput.

This evaluation shows that a low standard deviation indicates that the throughput points tend to be close to the average one, while a high standard deviation indicates that the throughput points are spread out over a wider range of values.

4.4.2 Influence of Interference

In the wireless communication, the effects of the environment such as rain, restoration, ISI directly affect the performance of wireless network systems. Especially, the inference phenomenon is too difficult to control and manage. They always exit in every wireless communication. Therefore, this research considers the influence of interference in the wireless environment. Figure 4.4 illustrates the effect model of interference to receiver wireless node j.

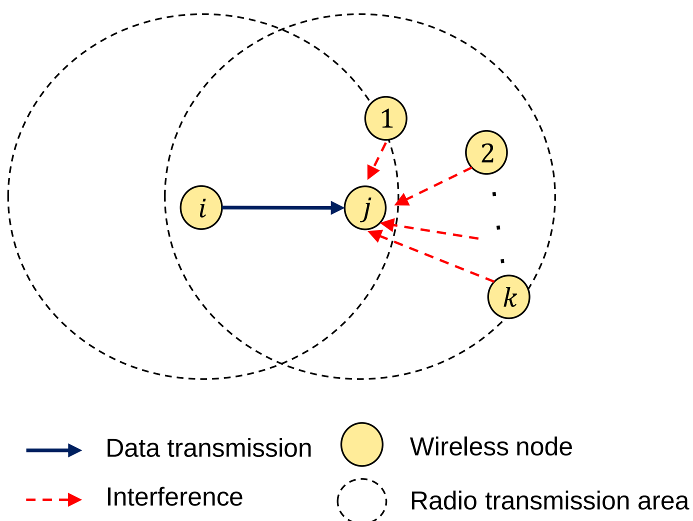


Figure 4.4: Interference model.

In this section, the system model and assumption issues are described with the influence of interference as follow:

- Channel gain (in decibels) between node i and node j is depend on the Log-distance pathloss model, PL_0 is assumed as Friis free space model

$$PL_{ij} = PL_o + 10 \cdot \alpha \cdot \log_{10}\left(\frac{d_{ij}}{d_o}\right) - W_{ij} + X_\sigma \tag{4.4}$$

  where $PL_o = 20 \cdot \log_{10}(d_o)$

- Power ratio (no unit) between node i and node j is

$$G_{ij} = \frac{1}{10^{\left(\frac{PL_{ij}}{10}\right)}} \tag{4.5}$$

- Signal to interference and noise ratio (no unit) at node j is

$$SINR_{ij} = \frac{G_{ij}P_i}{\eta_j B + \sum_{k\in\mathcal{X},k\neq i} G_{kj}P_k} \tag{4.6}$$

- Rate of transmission (bit/s) from node i and node j is

$$R_{ij} = B\log_2\Big(1 + \frac{1}{\Gamma} SINR_{ij}\Big) \tag{4.7}$$

where

- P_i: transmit power of node i
- d_{ij}: distance between node i and node j
- W_{ij}: wall attenuation from node i to node j
- X_σ: shadowing attenuation
- G_{ij}: channel gain from node i to node j
- η_j: noise of node j
- $SINR_{ij}$: SINR from node i to node j
- R_{ij}: achievable rate from node i to node j
- B: channel bandwidth

This achieved rate of transmission or channel rate is to evaluate the capacity or performance that related to the physical layer of the network system. Meanwhile, this research focuses on the MAC protocol. Therefore, it needs to be converted to the data rate of MAC rate for calculating the throughput of MAC system as following the standard IEEE 802.11g in Table 4.2.

Table 4.2: Standard for data rate of IEEE 802.11g.

Channel Rate (Mbps)	**Data Rate** (Mbps)
≥ 54	54
≥ 48	48
≥ 36	36
≥ 24	24
≥ 18	18
≥ 12	12
≥ 9	9
≥ 6	6
≥ 5.5	5.5
≥ 2	2
≥ 1	1
Others	1

4.5 Simulation Analysis

4.5.1 Objectives

Based on the proposed system models and the modeling, analysis of system model with the conditional collision probability and saturation throughput have described in the previous chapter, this chapter shows the simulation setting and the evaluation results in comparison of saturation throughput for the combination of all techniques, including HD, FD, SN, and XOR operation. In order to evaluate the performance of the network systems as well as the possibility to apply to the real environment with the actual devices or techniques, I made the simulation based on MATLAB R2016b. Moreover, the calculation based on the equations of conditional collision probability, SINR and saturation throughput.

4.5.2 Simulation Theory

The aim of the simulation to determine the performance of the proposed system models in terms of saturation throughput and evaluate the effectiveness of the proposed scheme. Therefore, the simulation theory is to operate the proposed IFDMA protocol and in order to calculate the saturation throughput as well as considering the effects of interference.

Figure 4.5 illustrates the principle of simulation to calculate the saturation throughput and evaluate the performance of wireless network system.

Firstly, the topology will be initialized. Secondly is checking the mode of wireless node under the TxMODE field inside of IFDMA frame. Likewise, the condition of hidden node in topology which includes three nodes is checked. Next, which is the function of node access for that topology. This is determined in MA field inside of IFDMA frame. After that, the topology and its operation is indicated. Now the steps are for calculation of the conditional collision probability, SINR and throughput. Finally, based on the simulation results, we can make the evaluation of the effectiveness as well as comprehensive of proposed MAC protocol.

Without loss of generality, the algorithm for synchronization transmission has been based on time-division multiple access (TDMA). The time slot is fixed and assumed all nodes have packets to send.

In addition, this research focuses on the combination of all five techniques, including HD, FD, SN, R_XOR and S_XOR operation to evaluate the integration of FD and multiple access of the proposed IFDMA protocol. In order to determine the multiple access as well as the comprehensive of IFDMA protocol, the maximum of all combinations has defined as follows:

$$\text{IFDMA} = max \begin{Bmatrix} \text{HD, FD, SN, R\_XOR, S\_XOR} \\ \text{(HD, FD), (HD, SN), (HD, R\_XOR), (HD, S\_XOR)} \\ \text{(FD, SN), (FD, R\_XOR), (FD, S\_XOR)} \\ \text{(SN, R\_XOR), (SN, S\_XOR)} \\ \text{(R\_XOR, S\_XOR)} \end{Bmatrix} \tag{4.8}$$

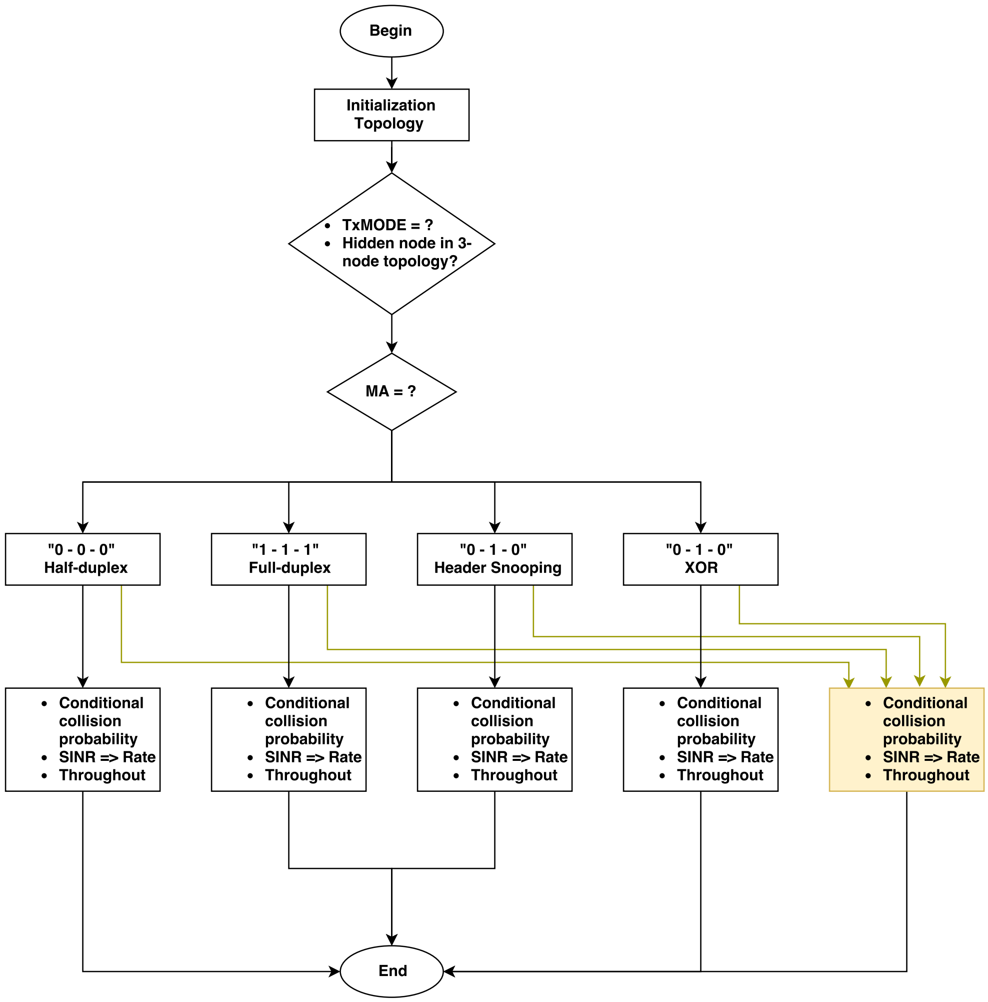


Figure 4.5: Flowchart of simulation theory.

Furthermore, in order to formulate the all available combinations, the combinatorics algorithm is considered with the number of available combinations as follows:

$$\mathrm{N} = \sum_{k=1}^{m} \mathrm{C}_n^k \tag{4.9}$$

where

- m: Maximum of number combination (this case, $m = 2$)
- n: Number of techniques (this case, $n = 5$)
- k: Available value of combination

Therefore, this methodology can easily extend to the larger number of techniques or combinations by considering these particular factors.

4.5.3 Simulation Parameter and Setting

In order to achieve the saturation throughput, as well as the evaluation results in the performance of the wireless network systems. The initialization for scenarios and parameters for simulation are really necessary. Besides, the particular parameters that have described in the previous section, we have to consider other parameters in the influence of interference.

Table 4.3 shows the simulation parameters and value setting for system model. The parameters are described in previous chapters. Also, the values for parameters setting refer to IEEE 802.11 standard [41, 42].

Table 4.3: Simulation parameters and setting.

Parameter	**Value**
Scenario size	350 m × 350 m
Transmission range	200 m
Minimum distance between nodes (d_o)	10 m
Maximum transmit power (P_{max})	0.2 Watt
Attenuation constant (α)	3.5
Wall attenuation (W_{ij})	0 dB
Shadowing parameter (X_σ)	8 dB
Noise level (η)	– 174 dBm
Channel bandwidth (B)	10 MHz
Value depends on the choice of coding and modulation parameters, and the BER requirement (Γ)	1
Packet length (bytes)	[256, 512, 1024, 1500, 2048, 2294]
Contention window	[32, 64, 128, 256, 512, 1024]
Basic rate (Mbps)	[1, 2]
Data rate (Mbps)	[1, 2, 5.5, 11, 6, 9, 12, 18, 24, 36, 48, 54]
PLCP header (bits)	192
MAC header (bits)	272
PHY header (bits)	128
RTS size (bits)	160
CTS size (bits)	112
ACK size (bits)	112
SIFS length (μs)	10
DIFS length (μs)	50
Slot time length (μs)	20

4.5.4 Numerical Simulation

4.5.4.1 Grid Topology

In order to evaluate the effectiveness of proposed scheme in the real environment with many outside effects as well as properties of wireless communication, firstly we make the grid topology with the small number of nodes and set their situation in a scenario.

The scenario for simulation is illustrated in Fig. 4.6 with $N = 9$ nodes and the place for each node is controlled inside the area (350m $\times$ 350m). The hidden terminal problem is determined by considering the transmission range of each wireless node. In this case, it equals 200m and same for all nodes.

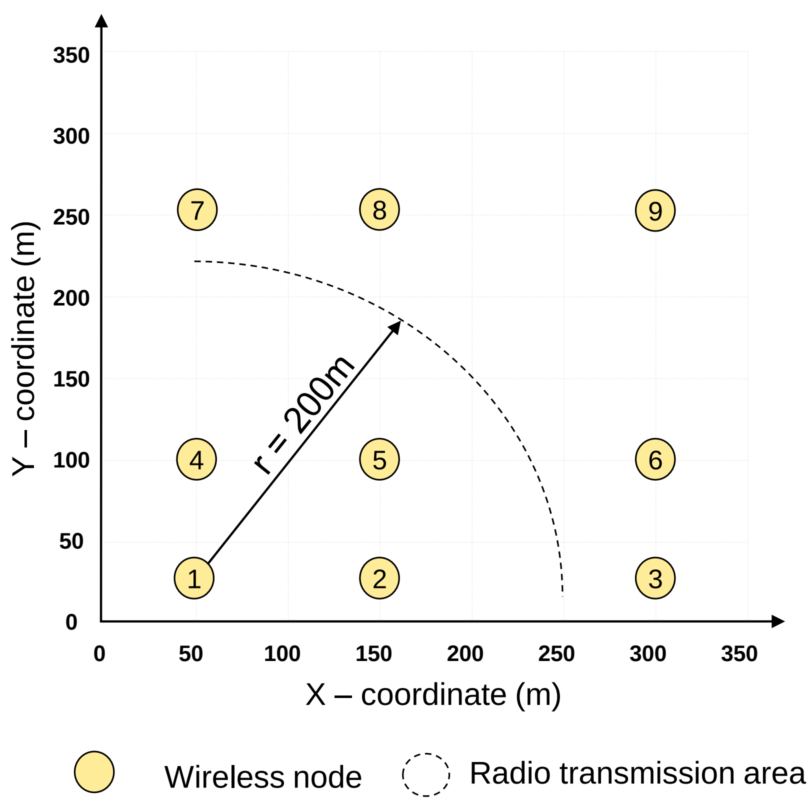


Figure 4.6: Simulation scenario with grid topology.

In addition, Table 4.4 shows the status of node and its neighbor nodes. Where, the symbol ($\circledast$) is by itself, ($\circ$) is in of transmission range, and (-) is out of transmission range.

The objective of this scenario is to find out the effective topology for combination of wireless networks with XOR operation. Therefore, with $N = 9$ nodes in Fig. 4.6 for mixture of HD and FD nodes, there are 512 topology cases which we need to evaluate.

Table 4.4: Status of node and neighbor nodes.

Node	1	2	3	4	5	6	7	8	9
1	⊛	○	-	○	○	-	-	-	-
2	○	⊛	○	○	○	○	-	-	-
3	-	○	⊛	-	○	○	-	-	-
4	○	○	-	⊛	○	-	○	○	-
5	○	○	○	○	⊛	○	○	○	-
6	-	○	○	-	○	⊛	-	-	○
7	-	-	-	○	○	-	⊛	○	-
8	-	-	-	○	○	-	○	⊛	○
9	-	-	-	-	-	○	-	○	⊛

4.5.4.2 Random Wireless Networks

After we have the first evaluation results for the grid scenario, we need to consider the random wireless networks and also increase the number of wireless nodes.

The scenario for simulation is illustrated in Fig. 4.7 with the various number of wireless nodes inside of the area (350m × 350m). The hidden terminal problem is also determined by transmission range of each wireless node. In this case, it still equals 200m and same for all nodes. Figure 4.7 illustrates in more detail of this scenario.

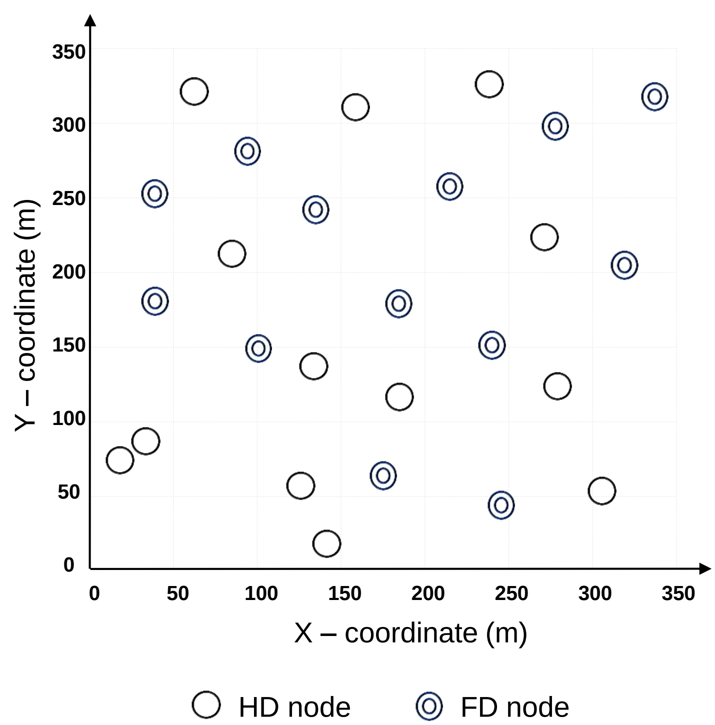


Figure 4.7: Simulation scenario with random networks.

The objective of this scenario is to evaluate the performance of the random wireless networks system in terms of saturation throughput. For this scenario, we will investigate based on the probability of HD and FD mode, as well as the difference of the number of wireless nodes.

4.5.5 Simulation Result and Discussion

This part will show the simulation results and evaluate them. Following the simulation scenarios, the are two subsections respectively.

4.5.5.1 Grid Topology

Firstly, in order to compare the saturation throughput among HD, FD, SN, relay-based XOR (R_XOR) and source-based XOR (S_XOR) operation, I considered the three-node topology without the interference. Figure 4.8 illustrates these results under the data rate equals 12 Mbps. We can easily recognize that the FD technique obtains the highest throughput, followed by SN, XOR and finally the HD technique gets the smallest one. Especially in XOR operation, the results of R_XOR are better than S_XOR operation.

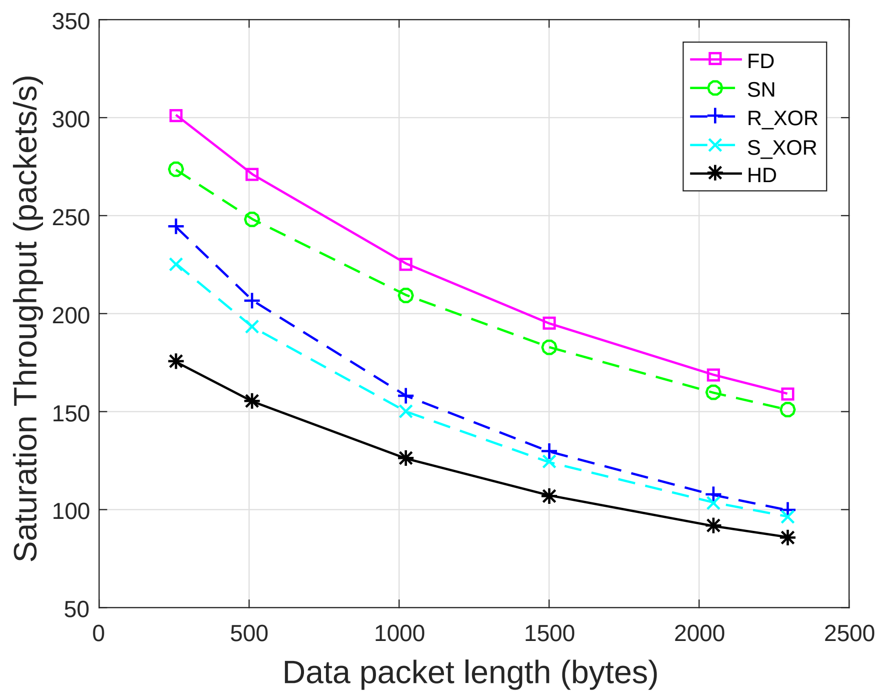
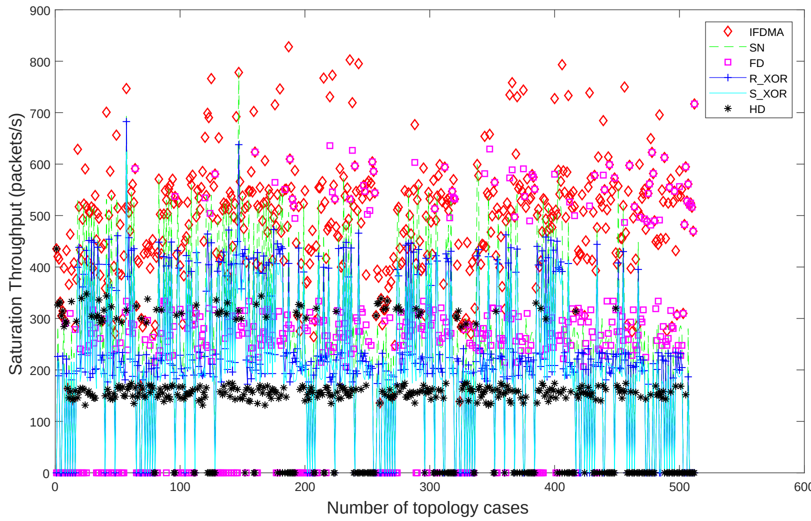
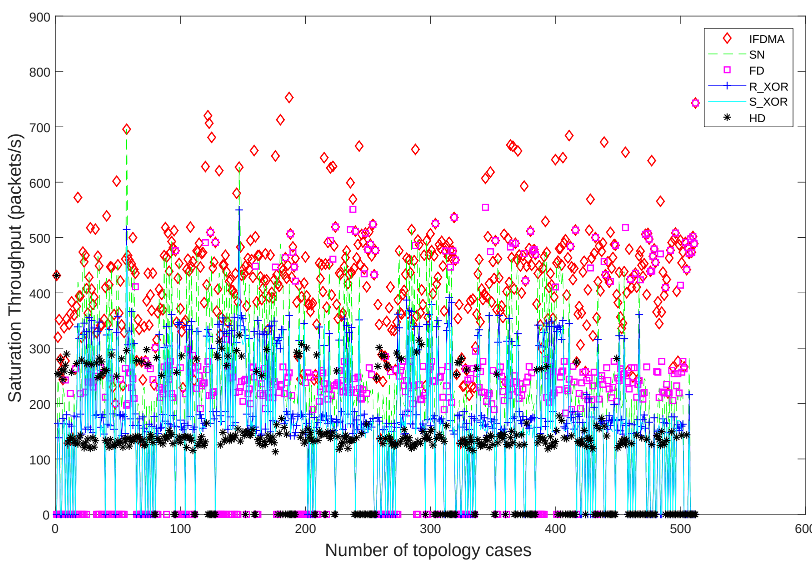


Figure 4.8: Comparison of saturation throughput with data rate 12 Mbps.

Figure 4.9a and Figure 4.9b show the comparison results without and with interference respectively under the 512 topology cases for $N = 9$ nodes. Besides, the packet length is 512 bytes, window size $W = 32$ and the data rate for without interference is 12 Mbps.



(a) Without interference.

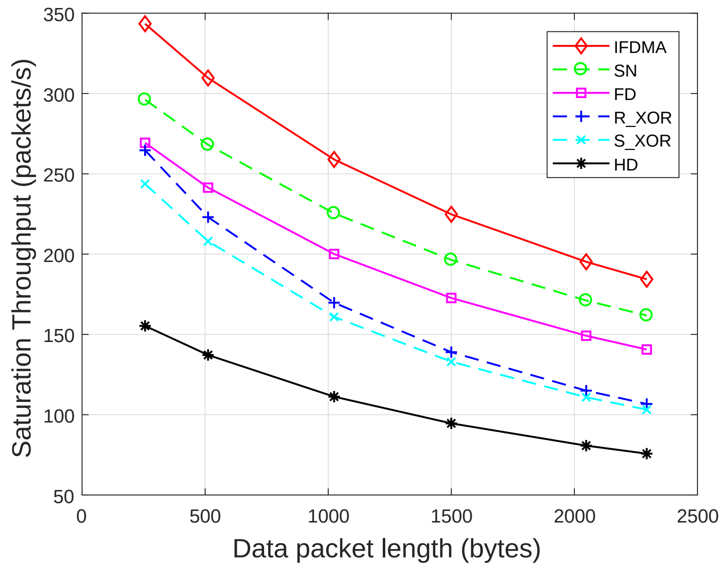


(b) With interference.

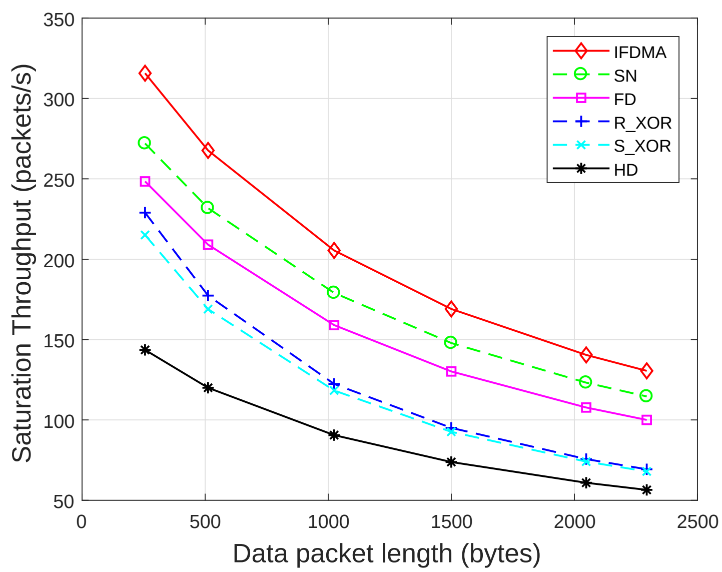
Figure 4.9: Comparison of saturation throughput in different topology cases.

These results show that the IFDMA operation which is higher appearance probability achieves the highest throughput for both cases with and without the effect of interference.

Besides, Fig. 4.10a and Fig. 4.10b show the comparison of saturation throughput with and without the effect of interference, respectively. Each simulation point in the graphs corresponds to the average of throughput with $W = 32$. With the effects of interference, the saturation throughputs are reduced for all techniques and the IFDMA operation gives the highest throughput, followed by SN operation.



(a) Without interference.



(b) With interference.

Figure 4.10: Saturation throughput of grid topology.

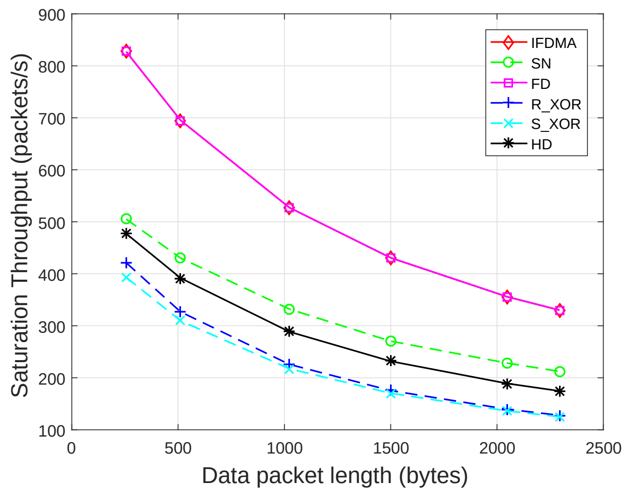
In addition, Table 4.5 shows the details of the throughput for all topology cases with packet length equals 512 (bytes). The maximum, average and standard deviation with and without the interference effect have described for all techniques as well as the combinations for implementation of IFDMA protocol. These results also indicate which combination gets the highest saturation throughput for operation of IFDMA protocol. The method to achieve the IFDMA result as described in Eq. 4.8.

Table 4.5: In more detail of comparison of throughput.

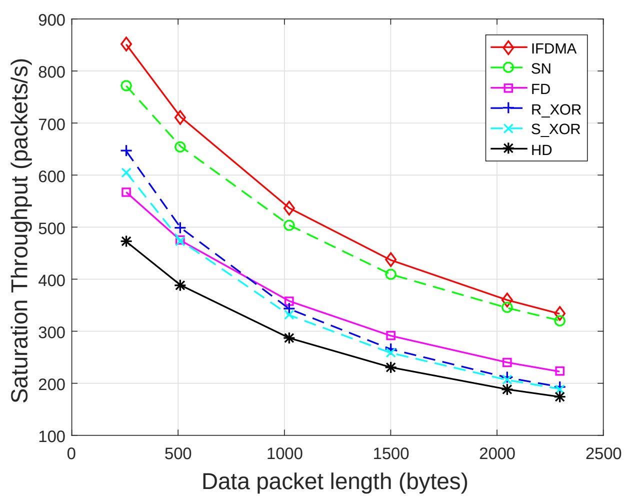
Technique	**Maximum** (Mbps)		**Average** (Mbps)		**Standard Deviation** (Mbps)	
	Without Inter.	With Inter.	Without Inter.	With Inter.	Without Inter.	With Inter.
HD	1.902	1.699	0.561	0.492	0.419	0.369
FD	3.331	2.957	0.998	0.855	0.752	0.642
R_XOR	2.732	2.141	0.913	0.728	0.572	0.460
S_XOR	2.544	1.916	0.858	0.690	0.538	0.434
SN	3.110	2.790	1.106	0.957	0.693	0.596
HD+FD	3.094	2.758	1.123	0.976	0.795	0.693
HD+SN	2.763	2.544	1.033	0.896	0.585	0.512
HD+R_XOR	2.501	1.982	0.882	0.716	0.521	0.432
HD+S_XOR	2.348	1.893	0.840	0.688	0.501	0.420
FD+SN	3.561	3.170	1.262	1.095	0.831	0.715
FD+R_XOR	3.131	2.524	1.121	0.915	0.770	0.646
FD+S_XOR	3.002	2.416	1.073	0.881	0.758	0.629
SN+R_XOR	2.870	2.531	1.056	0.898	0.630	0.531
SN+S_XOR	2.927	2.657	1.047	0.892	0.617	0.519
R_XOR+S_XOR	2.418	2.271	0.873	0.729	0.560	0.462

4.5.5.2 Random Wireless Networks

This part will show the simulation results of the random wireless networks which have mentioned in the previous section. Firstly, the results are for $N = 20$ nodes in the scenario size (350m $\times$ 350m). Figure 4.11 shows the comparison of saturation throughput with the effects of interference. Each simulation point in the graphs corresponds to the average of throughput with $W = 32$. Besides, the ratios of HD:FD mode in two cases are 50% : 50% and 60% : 40%. We can easily see that the difference between two figures which technique gives the highest throughput. In Fig. 4.11a, the IFDMA and FD technique obtain the highest throughput. Meanwhile, in Fig. 4.11b, the best one is IFDMA method, followed by SN operation. The HD transmission gives the smallest saturation throughput.



(a) Ratio HD:FD is **50:50**.



(b) Ratio HD:FD is **60:40**.

Figure 4.11: Saturation throughput of random topology with interference.

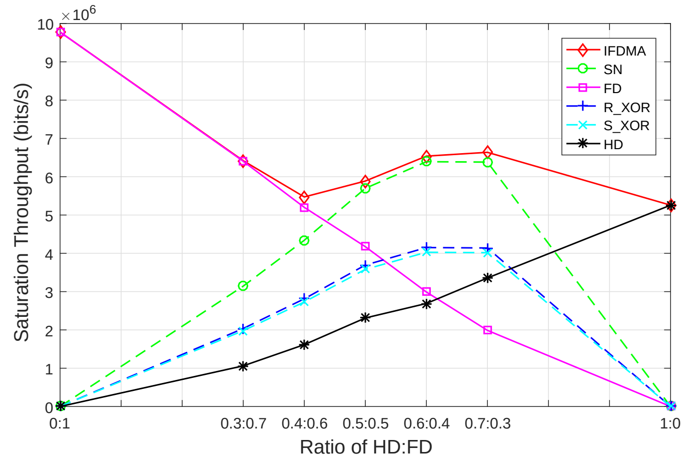
Therefore, the appearance probability of topology or ratio of HD and FD mode in the scenario directly affect the throughput of the wireless network systems. In order to explicitly evaluate the saturation throughput and compare among the various techniques, we have to analyze the performance base on this factor.

Table 4.6 shows the particular parameters to simulate the random wireless networks. In the same scenario size (350m $\times$ 350m), the number of wireless nodes will be increased and were made randomly, specifically in the three cases for $N = 20, 40, 100$ random nodes. Besides, the window size $W = 32$, packet length is 1500 (bytes) and the processing time is 100 times. The influence of interference is also considered in these simulations.

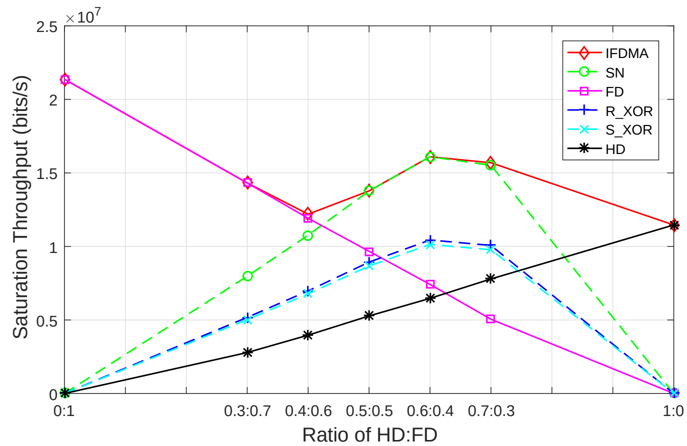
Table 4.6: Simulation setting for random wireless networks.

Parameter	**Value**
Scenario size	350 m $\times$ 350 m
Number of nodes	20, 40, 100
Packet length (bytes)	1500
Contention window	32
Basic rate (Mbps)	1
Number of simulation (times)	100

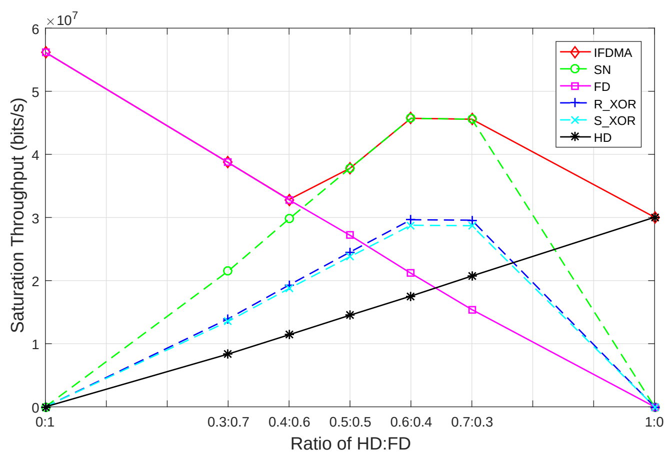
Figure 4.12 shows the comparison of saturation throughput with the ration of HD:FD mode. Each simulation point in the graphs corresponds to the average of throughput. The ideal case with FD communication gives the highest output, we concentrate on the mixture of HD and FD wireless nodes. The IFDMA method gives the better throughput in two cases of HD:FD ratios, 60% : 40% and 70% : 30% for all three simulations, $20, 40$ and 100 random nodes. These propositions can be explained that depend on the appearance probability of SN and XOR topology which give the better throughput. Because of in the three nodes of these topologies, there are two HD nodes and only one FD node. Thus, the ratio of HD nodes is higher than FD nodes.



(a) 20 random nodes.



(b) 40 random nodes.



(c) 100 random nodes.

Figure 4.12: Saturation throughput with ration of HD:FD modes.

4.6 Summary

This chapter proposed the schemes of the system model for HD, FD, SN and XOR techniques. The system model includes three nodes and the condition of the hidden terminal problem has considered. In addition, the IFDMA protocol has proposed for multiple access by a combination of the mixture of HD and FD technique with XOR operation in network coding.

In addition, this chapter also presented the simulation and results of the thesis. Firstly, the simulation results have verified and then make the simulation setting with the grid, random scenario and also the parameters for simulation have described.

Besides, the evaluation results have discussed for not only grid topology, but also the random wireless networks. Also, the ratio of half-duplex and full-duplex mode has considered and evaluated.

As a result, we can say that the mixture of half-duplex and full-duplex wireless network using XOR operation by proposed IFDMA protocol is more effective in the improvement in saturation throughput of wireless network system. This is really an advantage of full-duplex wireless networks using network coding.

Chapter 5

Conclusion

5.1 Concluding Remark

- This research has concentrated on analyzing the mixture of half-duplex and full-duplex wireless networks considering the hidden terminal problem. This research revisited the solutions for solving this problem such as shared random backoff, header snooping, virtual contention resolution. Likewise, the states of the channel have been described by applying the Markov chain model to calculate the conditional collision probability and saturation throughput. Hence, the evaluation results indicated the performance of the wireless network system will be dropped under considering three states, including success, collision, and freeze. Besides, the challenge of MAC protocol has discussed in order to implement the full-duplex technique and resolve the hidden terminal problem.

- Besides, this research also proposed the new MAC protocol called integrated full-duplex and multiple access (IFDMA) protocol for the combination of the half-duplex, full-duplex, header snooping and network coding technique with XOR operation. Especially, the scheme of XOR operation under relay-based XOR and source-based XOR have described explicitly. In addition, the influence of interference which was considered directly affects the performance of wireless network system.

- Furthermore, the simulation scenarios have been described in not only grid topology, but also random wireless networks. The evaluation results which were explicitly presented by comparison among various techniques and showed that the wireless networks with the operation of IFDMA protocol give the highest saturation throughput. In addition, this research also considered the random wireless networks with the ratio of half-duplex and full-duplex wireless nodes that directly affect the throughput of the wireless network systems.

5.2 Contribution

- Based on the current solutions for solving the hidden terminal problem, this research proposed a new scheme for three states of the channel, including success, collision and freeze under the three nodes topology considering the hidden terminal problem. The Markov Chain approach has been applied to calculate the conditional collision probability, saturation throughput of the wireless network system.

- In addition, this research proposed a new IFDMA protocol for a combination of multiple access to the half-duplex, full-duplex, header snooping and network coding technique with XOR operation. Especially, the transition models of relay-based XOR and source-based XOR operation have discussed.

- Moreover, the wireless random networks with the effects of interference, SINR are considered. The evaluation results show the effectiveness of the proposed IFDMA protocol in order to improve the ability of full-duplex implementation in the real environment.

5.3 Future Work

- In order to evaluate the comprehensive of the IFDMA control protocol for wireless networks, the function of each field inside of MAC frame needs to be analyzed more explicitly. Especially, the multiple access control protocol should be discussed in more detail.

- Besides, based on the effective topology with 9-node combination, we can extend this research by grouping in the dense networks with the large number of nodes. Also the algorithms for optimization of wireless networks such as topology control management, transmit power control (TPC) should be considered.

- In addition, the synchronization, fairness and traffic model of the wireless network systems should be considered more explicitly. Although, the assumption is all nodes have packets to send, but how to make fairness for all nodes still is a challenge in the full-duplex communication.

- Furthermore, the management and control of the data transmission between up-link and down-link of FD technology should be evaluated.

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