Title	Optimal Mixture of Concurrent and Sequential Transmissions for Full-duplex Multihop Wireless Networks
Author(s)	KHUN, Aung Thura Phyo
Citation	
Issue Date	2020-09
Type	Thesis or Dissertation
Text version	author
URL	http://hdl.handle.net/10119/16855
Rights	
Description	Supervisor: リム 勇仁, 先端科学技術研究科, 修士(情報科学)

Master's Thesis

Optimal Mixture of Concurrent and Sequential Transmissions for Full-duplex Multihop Wireless Networks

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Master of Science (Information Science)

September, 2020

OPTIMAL MIXTURE OF CONCURRENT AND SEQUENTIAL TRANSMISSIONS FOR FULL-DUPLEX MULTIHOP WIRELESS NETWORKS

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A thesis submitted to
School of Information Science,
Japan Advanced Institute of Science and Technology,
in partial fulfillment of the requirements
for the degree of
Master of Science

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August 2020

Abstract

Full-duplex (FD) communication has been considered as the potential technology to provide the services for increasing the traffic in the future wireless networks. FD increases the data rate and the spectral efficiency to utilize the capacity of the network. FD performs as an attractive solution to cope with the ever-increasing capacity demand, with the double spectrum efficiency by simultaneous transmission and reception to remarkably enhance the throughput of the transmission than the Half-duplex (HD) communication systems.

One of the key elements of FD is to overcome interference occurred in simultaneous transmissions. Interference is a wireless signal that alters or disrupts the desired wireless signal from transmitting source to a receiver. Since the FD system can transmit and receive simultaneously over a single time/frequency channel, the self-interference (SI) is the main challenge to realize the FD transmission. However, the residual self-interference (SI) can be modelled as additive white Gaussian Noise (AWGN), in the other way, as noise through transmission, according to the existing proposed techniques for self-interference cancellation.

Recent developments towards SI cancellation techniques have allowed to realize the FD communications on low-power transceivers, such as small-cell (SC) base stations. However, with the potential research solution, although SI can be eliminated to Noise level, there is still the interference from other nodes in the network which is called co-channel interference (CCI). Theoretically, although FD brings the potential benefits of doubling capacity if SI can be eliminated, CCI still affects as the potential threat of performance degradation in the dense network. And, the reduction of interference issues in the previous works still need to focus on for advanced wireless communication. Therefore, this research completely takes into consideration the interference issues in transmission in FD networks.

The purposes of the research are to propose a cooperative medium access control (MAC) for high throughput performance in FD multihop wireless network and to propose an optimal transmission scheme for FD wireless network by increasing the achievable capacity while mitigating the interference occurred during simultaneous transmissions. With the motivation of lack

complete research methodology to study the performance of simultaneous transmission in FD network, the system model and the complete methodology of the research is discussed as the first objective of the research. Then, to ensure high achievable capacity by using the mixture of concurrent and sequential transmissions scheme, the second objective is to minimize the interference level from the simultaneous transmissions with power control mechanisms. This research takes into consideration two types of transmission in FD network, i.e., bi-directional FD (BFD) and relay FD (RFD).

By taking advantage of an opportunistic MAC, i.e., spatial reuse in concurrent transmission (CT) for capacity gain and minimum interference in sequential transmission (ST), the mixture of concurrent and sequential transmissions (MCST) scheme is proposed to achieve a better achievable capacity of the transmissions in the FD wireless network. Besides that, to reduce the interference power while maximizing achievable capacity, the power control schemes, minimum transmit power control (MTPC) and minimum interference power control (MIPC), under the constraint of minimum transmit power and minimum interference power of the transmissions are investigated with MCST to manage the CCI.

Since device-to-device (D2D) communication can improve the capacity of the network when the users are close to each other, and FD communication gives an advantage in the small range network with low transmit power, this research focuses on the FD network in a dense environment. Three numerical studies have been done to evaluate the performance of the proposed novel transmission scheme. They are the basic 4-node network topology with fixed transmit power, the dense network topology with different node density, i.e., 20-100 nodes and the 20-node network topology with different transmit power.

According to the theoretical and numerical studies with the assumption of the system model, the achievable capacity of the network can be increased up to 2.5 times of the CT capacity and interference can be mitigated up to about 5% in the basic 4-node FD network with fixed topology. Besides that, the achievable capacity of FD network can be improved with the proposed transmissions scheme up to around 8 times of the achievable capacity with sequential transmissions when the number of wireless node is 100 with BFD transmissions. With RFD transmissions, the achievable capacity gain can be

increased about 5 times of the capacity with sequential transmissions. The interference power can be reduced up to 4% for BFD transmissions whereas up to 17% for RFD transmissions when the number of nodes is 100 in the FD network.

For the mitigation of interference, this research shows that the interference can be mitigated up to 80% in the basic 4-node FD network by applying MCST scheme with MIPC approach power control mechanism. Regardless of the transmit power, the achievable capacity of FD network can be increased about 2.5 times.

Based on the system model and assumptions in this research, the thesis concludes that the MTPC mechanism provides better achievable capacity compared to MIPC algorithm while MIPC reduces more average total interference power than TPC mechanism. Finally, this research concludes that MCST is an optimal transmission scheme for future wireless communication since it always gives a better achievable capacity than the other two simultaneous transmissions, ST and CT.

Keywords: Full-duplex, Device-to-Device Communication, Co-channel interference, Achievable Capacity, Simultaneous transmissions, Transmit Power Control

Acknowledgement

Foremost, I would like to express my deepest appreciation to my supervisor, Associate Professor Yuto LIM for his patient guidance and support for this study. His sincerity and motivation have deeply inspired me a lot and his generosity helped my time in JAIST enjoyable. As my second supervisor, I would also like to extend my deepest gratitude to Professor Yasuo TAN for his support and constant encouragement to continue my study.

I also sincerely thank Professor KURKOSKI, Brian Michael for his patient instruction in my minor research. With his guidance and sharing, I have acquired the concepts and knowledge about the new research area, Information Theory. Besides, I would like to extend my gratefulness to the acting supervisor, Associate Professor Kiyofumi TANAKA, for his kindness and support during temporary lab assignment at the beginning of the study.

I would like to express my deep appreciation to researchers from TAN Laboratory and WiSE Laboratory (LIM Laboratory) for their help and sharing in collaboration meetings. With their friendliness, I enjoyed my student very much during these two years.

What is more, I would like to extend my sincere thanks to Dr Shungo Kawanishi, Research Professor of Global Communication Center, JAIST, for his knowledge sharing, guidance and sincerity the author to be a global leader with intellectual toughness in the social environment in addition to a professional researcher in the area of Information Technology.

Finally, I would like to thank unknown significant others (USO) who help me directly or indirectly to complete my masters' degree. Last but not least, I am always thankful to my family for their love and letting me decorate my brighter future by myself.

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List of Symbols

The following list describes several symbols that are used within the body of this document:

α	Pathloss exponent	
β	Time fraction of concurrent in MCST	
χ	Set of interfering nodes	
η_j	Noise at wireless node j	
ϕ	Time fraction of ST	
B	Channel Bandwidth	[Hz]
C	Achievable Capacity	[bps]
d_0	Reference distance	
d_{ij}	Distance between node i and node j	[m]
G_{ij}	Power ratio between node i and node j	
N	Total number of wireless nodes	
P_i	Transmit power of node i	[dBm]
PL_0	Pathloss under Friis free space model	
PL_{ij}	Channel gain between node i and node j	[dB]
R	Transmission rate of FD transmission	
r'_m	Common rate of concurrent section in MCST scheme	[bps]

r'_{ij}	Transmission rate w/ interference from wireless node i to j	$[bps]$
r^*_m	On-going rate of MCST scheme	$[bps]$
r_{ij}	Transmission rate w/o interference from wireless node i to j	$[bps]$
r^*_{ij}	On-going rate w/ interference in MCST scheme from node i to j	$[bps]$
$SINR_{ij}$	Signal to interference plus noise ratio at node j from node i	
T_{ij}	Transmission from wireless node i to j	
W_{ij}	Wall attenuation from node i to node j	[dB]
X_σ	Gaussian random variable with zero mean, shadowing attenuation caused by flat fading	[dB]

List of Abbreviations

5G 5th generation mobile network

APs Access points

AWGN Additive White Gaussian Noise

BFD Bi-directional Full-duplex

BS Base-station

CCI Co-channel interference

CT Concurrent Transmissions

D2D Device-to-Device Communication

DCF Distributed Coordination Function

EC Effective Capacity

eMBB Enhanced Mobile Broadband

FD Full-duplex

FDD Frequency Division Duplexing

HD Half-duplex

IBFD In-band Full-duplex

IoT Internet of Things

M2M Machine-to-Machine communication

MCST Mixture of Concurrent and Sequential Transmissions

MIMO Multiple-Input Multiple-Output

MIPC Minimum Interference Power Control

mMIMO massive Multiple-Input Multiple-Output

mMTC Massive Machine Type Communications

mmWave millimeter Wave Communication

MTPC Minimum Transmit Power Control

PCS Power Control Scheme

QoS Quality of Service

RFD Relay Full-duplex

SI Self-interference

SINR Signal-to-Interference-plus-Noise Ratio

ST Sequential Transmissions

TDD Time Division Duplexing

TDMA Time-division Multiple Access

UE User Equipment

URLLC Ultra-reliable Low Latency Communications

List of Special Terms

Achievable Capacity is referred to transmit throughput capacity region which is defined as the total number of physically transferred bits per second according to Shannon's capacity theorem

Bi-directional FD (BFD) is a type of communication mode in FD where both of the entities have data to transmit each other

Co-channel interference is the interference signal from other wireless nodes in the range of the transmission, also known as inter-cell or intra-cell interference based on the nature of the network

Concurrent Transmissions is a type of transmission mode where all transmissions are proceeding at the same time

Full-duplex is a type of communication system where both parties can transmit and receive simultaneously

Half-duplex is a point to point communication system where both parties can communicate with each other, but not at the same time or simultaneously

Minimum Interference Power Control is a power control mechanism to minimize the interference of the transmission by adjusting the transmitted power subject to minimum interference power of the receiving node.

Minimum Transmit Power Control is a power control mechanism to minimize the interference of the transmission by adjusting the transmitted power subject to minimum transmit power of the transmitting node.

Mixture of Concurrent and Sequential Transmissions is a type of transmission mode where all transmissions are doing concurrent in the fraction of time, β, and sequentially in the remaining time, $1 - \beta$

Noise is due to effects in receiver electronics, depends on temperature, typical model: an additive Gaussian variable, mean zero, no correlation in time

Power Control Scheme is a control scheme to adjust the transmitted power of the receiver based on minimum transmit power control (MTPC) or minimum interference power control (MIPC) approach

Relay FD (RFD) is a type of communication mode in FD where the relay node can transmit to the third node while receiving from the first node

Self-interference is the interference signal of transmitting antenna to receiving antenna of FD transceiver

Sequential Transmissions is a type of transmission mode where all transmissions are proceeding one after another

Chapter 1

Introduction

Wireless communication is a system of communication that supports the transmission of information (voice, video, data, etc) over large distances using free space as the communication medium. As the latest step in how wireless communications is connecting to the Internet, 5th generation mobile network (5G) is well known to the computer networking era. As a promising technology for 5G and future wireless networks, it has been attractive as an active research field for decades. To cope with the growth of mobile data traffic and devices, the later generation of the wireless system such as 5G or beyond 5G (B5G/6G) is expected to be developed with the standard for the dense environment. Therefore, it is crucial to take into consideration how to improve the technology that brings advanced wireless systems like 5G.

This chapter will introduce the background environment of the research, the research problem that degrades the performance of the wireless network systems. And them, the research motivation with objectives and how the research is going to conduct for solving the research problem will be discussed.

1.1 Research Background

According to the static mobile data traffic forecast by Cisco Visual Networking Index [1], nearly two-thirds of the global population will have Internet access by 2023. It means the number of mobiles devices such as smartphones, tablets, wearable devices and so on, will have great growth. Not only in the number of devices accessed and handheld used by users but also in the embedded devices like sensors in the Internet of Things (IoT) and like connected cars in Machine-to-Machine communication (M2M) applications, the number of connections will grow from 33 percent to 50 percent of the global mobile and connections in 2018 by 2023. At a compound annual growth rate (CAGR) of 8 percent, the global mobile devices and connections were 8.8 billion in 2018 and there will be 13.1 billion by 2023. Therefore, 5G is becoming a major evolution in wireless communication to provide better qualities of service with the growth of the devices and traffic for dense urban areas.

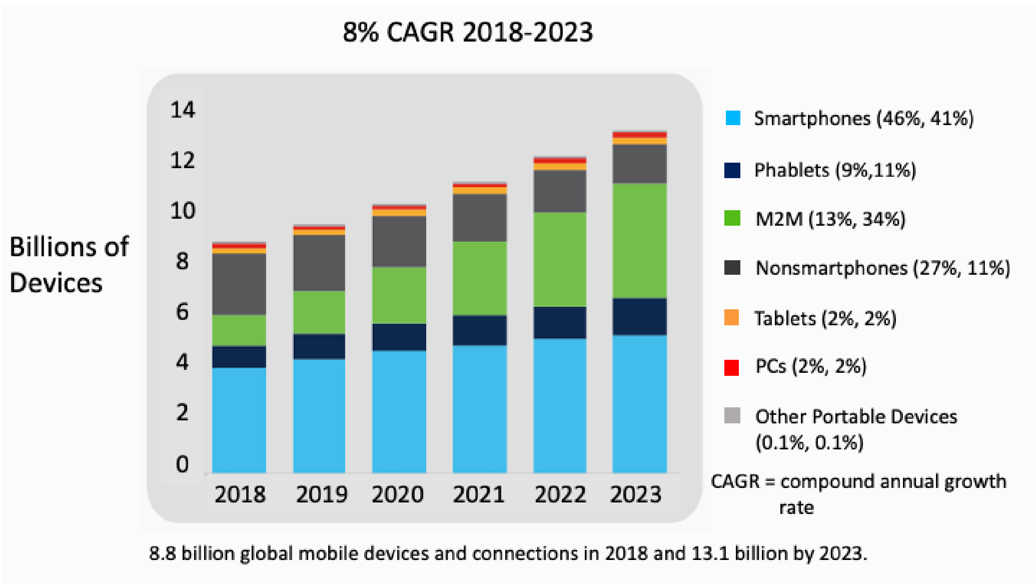

Figure 1.1: Global mobile device and connection growth [1]

5G is trending as the latest generation with the following three main services in today's wireless network systems.

- Enhanced Mobile Broadband (eMBB) for high data rates across a wide area coverage area
- Ultra-reliable Low Latency Communications (URLLC) for strict requirements on latency and reliability for mission-critical communications, such as remote surgery
- Massive Machine Type Communications (mMTC) to support a very

large number of devices in a small area like smart home or smart environment

5G is an attractive research field for providing communication and data services using all possible solutions. Various techniques bring 5G into actions among various perspective. For example, massive Multiple-Input Multiple-Output (mMIMO) for enhanced air interface technology, millimeter Wave Communication (mmWave) and adaptive beamforming are some of the key technologies to achieve key capabilities of 5G. Besides that, with the key features to double the spectral efficiency of a point-to-point radio link with simultaneous transmission and reception [2], Full-duplex (FD) is also one of the main technologies in 5G network.

All we know that the current traditional wireless system is running with Half-duplex (HD) networks which allows the wireless nodes transmitting and receiving but not simultaneously. In the period of transferring from HD types of communication to FD for capacity gain, there are still many problems that degrade the overall network performance. Although FD brings the attractive feature of doubling capacity, without careful planning and addressing the challenges in incorporating FD radios, it is difficult to fully apply FD in the wireless communication instead of HD technology [3]. Some of the challenges include mitigation of residual Self-interference (SI), inter-node or intra-cell interference, inter-cell interference, synchronization and time adjustment issues to establish FD transmissions.

We will briefly introduce and identify some of the problems of the FD wireless communication in this chapter by following the motivation, objectives and approach through the research.

1.2 Problem Statement

Since the 5G network operates in a high-frequency band of the wireless with millimeter wave spectrum, the network will become denser and denser than the previous structure of the network. Although 5G is primarily aimed to achieve a high data rate, low latency and low power consumption with improved transmit capacity, the interference issues cannot be satisfied in the FD wireless networks in a dense environment like a stadium, cinema, classroom and so on, due to the increasing amount of concurrent transmissions. Interference is a signal that alters or disrupts the desired signal as it travels from the transmitting source to receiving source. It occurs when multiple transmitters and receivers share a frequency band (wireless) or medium (wired line). It decreases the coverage and capacity of the network.

There are several types of interference such as narrowband interference, wideband interference, multipath inter symbol interference, adjacent channel interference [4]. Although there are several types of interference, according to types of source, interference in FD networks can be defined into two types: interference from the self-transmitter and interference from the other transmitter. The prior type of interference is also Self-interference (SI), the later one can be defined as Co-channel interference (CCI), inter-node or inter-cell interference or extra-cell interference based on the nature of the network. There are tons of research to handle SI until it is mitigated to noise level [5],[6], [7] [8], [9]. However, there is no co-channel interference or inter-node interference-free medium.

High interference in FD networks raises several questions regarding the potential performance gain of FD technology. This research mainly focuses on the co-channel interference (CCI) as the potential threat of throughput degradation due to the vast occurred interference in dense network environment. Co-channel interference (CCI) is the cross-talk interference that occurs when the channel is used by two or more different devices. CCI is also known as the inter-user interference.

1.3 Research Motivation

Currently, the wireless systems employ half-duplex (HD) with either Frequency Division Duplexing (FDD) in the frequency domain or Time Division Duplexing (TDD) in the time domain for separate transmission and reception. Therefore, the transmitted signal does not interfere with the received signal due to orthogonal use of frequency or time resources. The result is two orthogonal channels are needed for HD systems. It takes twice the time and/or frequency resources compared to FD systems. Since FD is two-way communications and signals travel in both directions simultaneously, it has an advantage of double bandwidth of HD. However, FD can also be defined as the land of interference.

According to the [10], SI cancellation does not affect the capacity gain of the network because strong co-channel interference influences the SI and decreases the capacity improvement. S. Goyal et al. [11] showed that FD radio is not very beneficial to apply in dense outdoor environments due to the high inter-cell interference and proposed scheduling algorithms and advanced interference cancellation techniques are discussed to maximize capacity gain in [3]. However, the physical layer is the lack of considering to focus on interference mitigation. Therefore, instead of SI, the co-channel interference is brought as the main motivation for this research to be mitigated for improving the capacity of the networks.

1.4 Research Objective

The purpose of this research is to propose an opportunistic and cooperative medium access control (MAC) for high throughput performance by introducing a new transmission scheme or a new type of transmission for FD multihop networks. The Mixture of Concurrent and Sequential Transmissions (MCST) is proposed and defined for considering increasing the throughput performance and to guarantee the efficient communication with least interference for future dense wireless networks.

This research focuses on identifying the interference scenario in FD networks, finding and porpoising techniques to address trade-off between capacity gain and high interference occurrence. Therefore, the first object for this research is to model and define a research methodology to revise the existing performance of traditional HD and FD wireless networks in terms of SINR, achievable capacity, interference power [1] and some other factors to define the performance of wireless networks with some relation between transmitting capacity and interference level of the communications.

The second objective is to propose, design and implement a MAC protocol to ensure high achievable capacity and to minimize the Co-channel interference by proposing the MCST scheme which brings the optimal maximum achievable capacity in the dense network environment. And this research

[1] interference power is interference in terms of Watt and interference level is interference in terms of dBm

will open a new additional way to deal with the realization of the FD system in the future dense wireless networks, which contribute to the needs of the Device-to-Device Communication (D2D) communications for IoT society.

1.5 Research Approach

After reviewing the basic study of FD and HD networks, we first evaluate the performance of FD wireless system by comparing with HD wireless system as the first objective to define the research methodology of the research. Then, a new mixture of concurrent and sequential transmissions scheme is proposed to obtain the maximum achievable capacity of the network. In addition, we formulate the optimization problem to minimize the interference power of the transmissions with two power control scheme (PCS). The two PCS are minimum transmit power control scheme (MTPC) and minimum interference power control scheme (MIPC). MTPC tries to reduce the interference by adjusting the minimum transmitted power and MIPC mitigate the interference of the transmissions by controlling the transmitted power to affect the least minimum interference to the transmission. Therefore, our main methodologies for this research are applying the Minimum Transmit Power Control (MTPC) algorithm which subjects to minimum transmit power and Minimum Interference Power Control (MIPC) to adjust the transmit power which subjects to minimum interference power during transmission for equal transmission rate in investigating the Mixture of Concurrent and Sequential Transmissions (MCST). And then, the proposed new type of transmission MCST for FD networks which allow the nodes (transceivers) to transmit and receive simultaneously is evaluated to discuss the capacity gain and variation of interference level.

1.6 Thesis Organization

The thesis of the research is organized with three main sections with a literature review to in-deep understand the background of the research, defining the research methodology to study the trade-off between FD and HD networks, and formulating the research problem. The detail of the thesis is organized by the following:

In chapter 1: as the brief introduction section, the background introduction of the research, some of the challenge problems of FD communication and the focus research problem of the research followed by the research motivation and objectives of the study are described. Besides that, the method or approach to investigate for solving the problem the research are briefly explained.

In chapter 2: the literature review of the fundamental knowledge related to wireless networks and basic theory of FD wireless technologies including some challenges to realize FD communication and the existing research considering reduction techniques of the interference, which is the research problem of the thesis, are explored.

In chapter 3: revisit the performance of the HD and FD wireless networks described in the previous chapter. This chapter mainly discusses the first objective of the research, defining the research methodology to study the trade-off between FD and HD networks with the simultaneous transmission. Besides that, the theoretical proof and numerical studies of the simultaneous transmissions is discussed in details to evaluate the performance evaluations and formulate the research problem.

In chapter 4: the new transmission scheme, the mixture of concurrent and sequential transmissions MCST, is proposed with theoretical proof and numerical study to consider the research problem. The simulation results are discussed in details to show the performance gain of the research in terms of capacity, interference level and some other performance matrices.

In chapter 5: this chapter is the conclusion of the thesis to summarize the research and is concluded with the advantages of the proposed transmission scheme. And then, the contributions and further works for additional investigation of future wireless communication are discussed in this chapter.

Chapter 2

Background

The reviews of the prerequisites fundamental knowledge for this research are evaluated in this chapter. First, a brief introduction about ad hoc wireless communication system is explored and then traditional HD transmission and FD transmission networks are followed by a detailed review. Besides, the problem of the interference faced in wireless communication is explored and discussed in this chapter. Finally, the previous works related to cancellation and mitigation of the interference in wireless communication are reviewed and discussed.

2.1 Device-to-Device Communication

A wireless network is a network that consists of several nodes that communicate via wireless channels. Depending on the architecture, wireless networks can be divided into two categories. Before the use cases with ad hoc paradigm, the traditional wireless systems in the cellular paradigm is with the static infrastructure with Access points (APs) and Base-station (BS). Two users require to go through the BS for communications in the infrastructure network. However, centralizing at the APs or BS in infrastructure mode cannot fulfil and have some demand to serve the increasing number of devices because of the long-distance communication.

However, in the ad hoc paradigm, all nodes have the same capabilities and responsibilities and two nodes wishing to communicate do so directly or use nodes lying in between them to route their packets with multihop fashion.

As 5G promises more devices to be connected faster in a small cell, direct communication with the infrastructure mode of D2D communication become one of the essential technologies to support 5G wireless networks [12]. D2D communication in ad hoc paradigm is an essential part of the future wireless communication like 5G.

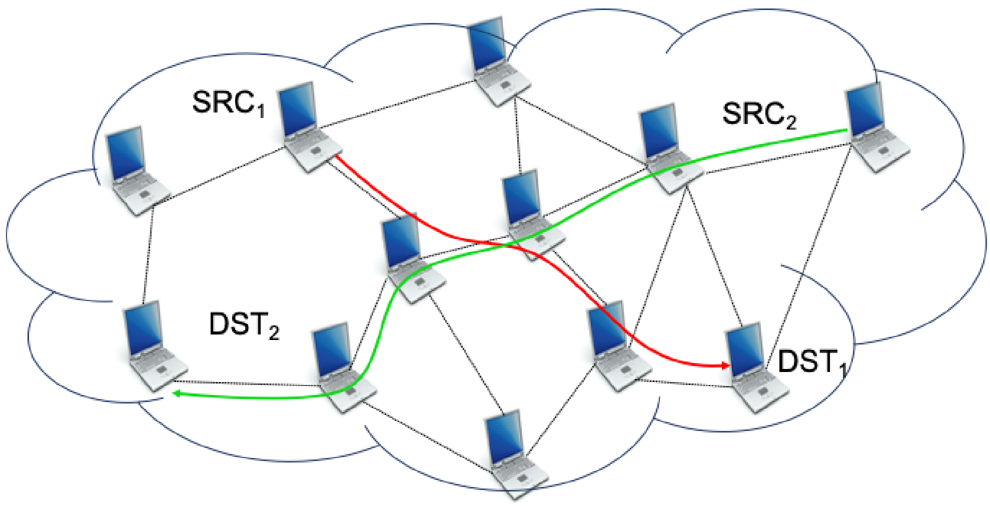

Figure 2.1: Example of a multihop wireless network

D2D communication is a type of wireless communication technology that enable direct communication between the nearest wireless devices rather than through the infrastructure. With D2D communication, the data between a user equipment (UE) pair should not be routed through the main network such as APs or BS as long as they are close. D2D communication is a concept for improving the device performance by allowing direct transmission between very close pairs of users. Therefore, current research trends have shown that D2D will be one of the technologies of the new next-generation mobile network.

D2D communication is also known as the overlay communication scheme that enable users in a close distance to exchange packets in a point-to-point manner. Since D2D communication can improve mobile capacity when the users are close, single-band full-duplex communication that transmits and receives in the same frequency band is a good combination for D2D communication. According to [13], the performance of full-duplex D2D communication is improved as the distance from the user's equipment decreases. At shorter distances, self-interference is reduced with less transmit power, and improves the throughput as the performance of full-duplex is sensitive to the amount of self-interference cancellation. In particular, D2D as well as FD communication have recently attracted interest from academia and industry due to its proximity, reuse and the capacity gains.

Although D2D communication offers many benefits over LTE systems, there are a number of problems in terms of interference mitigation, device discovery and synchronization, mode selection, security, and Quality of Service (QoS). To realize the potential of D2D communication, intensive research has been carried out by both academia and industry to address these issues. In the survey paper, [14], the authors categorize D2D communication based on spectrum reuse and provide the-state-of-art based on the classification in terms of performance metrics studied and conclude with the advantages and disadvantages of the spectrum sharing schemes, common assumptions and the maturity of D2D communication in the real world.

With the motivation of the benefits mentioned, this research is taking into considering D2D communications with the FD wireless transceivers without the help of centralized infrastructure. Therefore, the transmissions can be forwarded via intermediate nodes who have connections with multihop fashion. A multihop wireless network is a network of nodes by wireless communication links where all the nodes process cooperatively to send the packets to the destination in the networks. With the direct communications of the multihop fashion, D2D communication can extend the range of the transmissions.

However, D2D communications with multihop wireless networks have many challenges such as routing protocol for dynamic topology, wireless pathloss, effect of interference which means inter-user or co-channel interference due to small distance and so on. Besides, within each transmission, the transmission of the uplink user will cause an influence on the downlink user depends on the transmit power and mutual distance, etc. Therefore, management of transmit power and transmission is essential to achieve the optimal performance in the network.

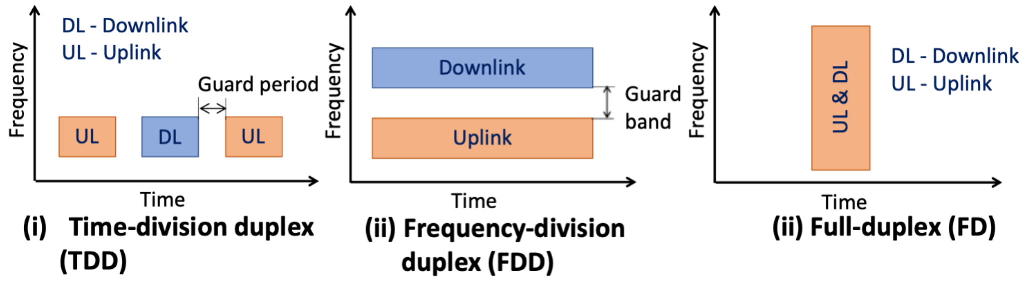

Figure 2.2: Overview of HD and FD techniques

2.2 Half-duplex Technique

From the initial development of the Advanced Mobile Phone system by Bell Labs which is called the first generation (1G), many generations such as 2G, 3G and 4G have resulted with the updates to the wireless communication networks. As the latest trending generation, the standardization of 5G network has been completed and is expected to be commercialized by 2020. Wireless networks have commonly been built on HD radios from the beginning of 1G (first generation) which is an analogue wireless cellular system to allow mobile communications of voices to 5G. Duplexing is the process of achieving two-way communication over a communication channel. HD stands for two way communication with non-overlapping transmission and reception, which means another party has to listen by the time one party is talking.

In 4G-LTE, HD technologies, Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) is widely used. The FDD is a method for establishing a duplex communications link that uses two different radio carrier frequency for transmitting uplink (UL) and receiving downlink (DL). Both the frequency channels are separated by a defined offset frequency, which is also known as a guard band, to stop the interference between UL and DL channel. On the contrary, the TDD is a technique by which UL and DL transmissions are carried over the same frequency by using synchronized time intervals with a guard period between for receiving and transmitting. Figure. 2.2 (i) and (ii) illustrate FDD and TDD in HD technique.

There are some trade-off between FDD and TDD, e.g., FDD offers very low latency since transmit and receive functions operate simultaneously with two different frequency bands whereas TDD incurs some delay from switching from transmitting to receive or receive to transmit and that causes greater latency. However, since TDD uses a single band, no duplexer is needed to separate the transmitter and receiver, whereas this is important in FDD. And again, the longer distance increases the guard period in TDD as the propagation time increases. The increased guard period significantly affects the efficiency. However, there is no problem with small or large distance in FDD. What is more, the data traffic in DL is much higher than in UL in real-life network. It is possible to dynamically adjust the capacity by utilizing more time slots for DL than UL. Since the capacity is normally balanced in both direction with two frequencies in FDD, the unbalanced traffic problem has happened in FDD. There are some pros and cons of FDD and TDD in HD technique to take into considering depends on the requirement, convenience and feasibility.

Because of the performance constraints such as requirement of guard bands and inflexibility bandwidth allocations in FDD and delay in TDD, the performance of HD leads to deficiency of the wireless communications. Therefore, FD with simultaneous transmissions become one of the considerable solutions for future wireless communications.

2.3 Full-duplex Technique

Recently, wireless communication tends to change from one-way-per-time transmission to two-way simultaneous transmission by enabling FD or In-band Full-duplex (IBFD) communication. FD stands for simultaneous communication between two parties with a single frequency band, which means both parties can interact freely as described in Figure. 2.2 (iii). FD is also one of the promising technologies to support the ever-increasing communication traffic and mobile devices. With the potential feature to double spectrum efficiency without requiring new spectrum, FD brings the outstanding performance for future wireless systems.

2.3.1 State-of-the-art of Full-duplex Communications

To enable FD communication, various types of FD radio designs are proposed with shared or separated antenna configuration for the in-band operation of transmitting and receiving radio-frequency. Mayank J. et al. [15] designed an FD system with two antennas as a transmitter and receiver by using a balanced/unbalanced (Balum) transformer for signal inversion and adaptive SI cancellation. Three antennas, which is two for transmitting and one for receiving, FD node is designed and proposed to realize the FD in IEEE 802.11 networks [16]. Besides, because of the space limitation of multiple in the mobile device, single shared antenna FD transceiver is designed and proposed for different perspective [17, 18].

In the FD communication area, there are existing MAC protocols to control the action of the medium through a channel access mechanism to allocation the main resource among wireless nodes. For example, a MAC protocol called Janus, is proposed in infrastructure mode wireless network with the suitable transmissions based on interference levels and showed the achievement in terms of throughput of HD based on CSMA/CA [13]. In the same way, a distributed FD MAC design based on 802.11 DCF is designed for ad hoc and infrastructure mode that adapts to the traffic conditions by considering the inter-node interference, Co-channel interference and contention during transmissions [3].

T. Febrianto et al. [19] proposed an FD MAC protocol for decentralized FD communication network based on CSMA/CA concepts in which several FD transceivers compete for transmission. Besides, in [20], Y. Song et al. provide a MAC protocol for the single-hop network by applying FD features for wireless nodes and cut-through mechanism. The system throughput performance no less than twice of conventional CSMA/CA protocol used in HD networks is achieved.

According to the MAC protocol and traffic conditions of the FD commu-

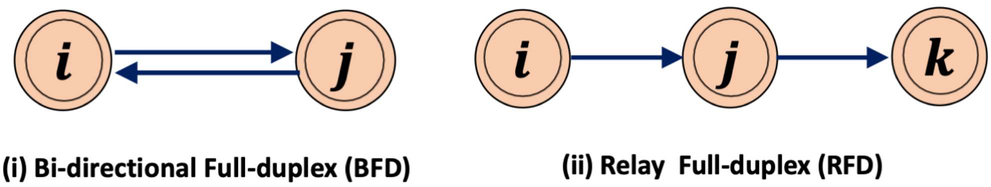

Figure 2.3: FD transmission modes

nication, transmission can be deployed in two different modes. As shown in Figure. 2.3, two FD wireless node i and j in (i) can transmit and receive data simultaneously over a single channel where both have data traffic for each other. This type of transmissions is defined as Bi-directional Full-duplex (BFD) while in (ii), FD wireless node j can forward the data traffic to the other node k while receiving from node i. This type of transmission is also known as Relay Full-duplex (RFD) which is widely considered in infrastructure mode where APs or BS is considered as node j in this example.

For both of the transmission modes, all the wireless nodes get the residual Self-interference (SI) at the receiving process because of simultaneous transmit and receive in the same frequency band. SI is the disturbing signal by its transmitting signal to the receiving process from other wireless node's transmission. Therefore, to realize the simultaneous transmission of FD, the main challenge is the strong SI occurred on the receiving antenna by the node's transmitting antenna [21].

The SI cancellation determines the strength of FD communication. With a limited amount of SI cancellation, less throughput is gained through FD communication. Thus, recent results on FD shows that significant improvements have been made to reduce the SI, and the state of the art of transceiver design may complement that high level of SI cancellation [22, 23]. Thus, the FD technology is getting closer to realize in a new wireless mobile network.

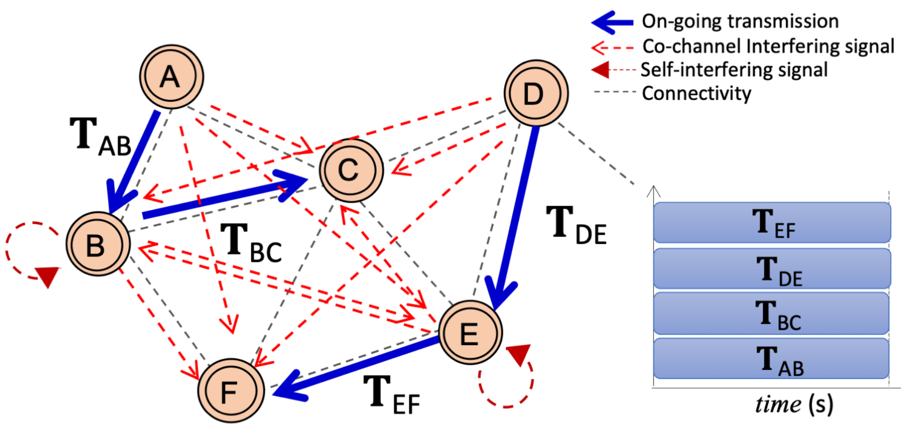

Figure 2.4: Full-duplex multihop wireless network with relay transmissions

The SI of FD communications decreases at a shorter distance because of the lower transmit power. In the other way, FD communication performs better in shorter distances because as long as the transmitted signal power increases, the residual SI will be increased. Since one of the characteristics of D2D is applicable in a close distance, we are interesting the cooperation of FD communication in D2D network for this research.

Figure. 2.4 illustrates an example of FD D2D communication in ad hoc network with RFD transmission mode. There are six wireless nodes with two RFD transmissions. Here, all the wireless nodes are assumed in a single cell network within the same transmission range and interfering range. In this situation, since all the wireless nodes are considered FD nodes, all the transmission and reception are operating concurrently, not only the issues of SI but also the CCI from other transmitters will occur at the nodes. In this case, the performance FD and D2D communication cannot guarantee high performance. Therefore, besides SI cancellation, it is important to schedule and manage the transmissions and to investigate on how to mitigate this interference (CCI) in FD communications to provide better performance for future wireless communications.

2.3.2 Challenges of FD Communications

Since FD communication provides simultaneous transmission and it means that the number of transmitters increases more than HD communication within a certain range. Although the achievable capacity of the transmission is getting improvement, the challenges of interference become serious. The big challenge of FD is self-interference which is caused by the stronger transmit signal of a device's transmissions to the received signal from a remote transmitter. Heavy SI may cause the reduced capacity of the FD system than the HD system. Besides that, CCI is also a big challenge to consider in FD communications. Heavy CCI leads to lower SINR and can result in weaker power of receiving the signal to the wireless nodes of FD. Therefore, although SI may be mitigated with the advanced techniques, as long as the CCI is heavy during transmission, none of the FD techniques can achieve the theoretical gain in term of achievable capacity.

2.3.3 Pros and Cons FD Techniques

This section discusses some of the basic advantages and disadvantages of FD techniques. The advantage of FD is that it can improve the bandwidth efficiency of a cell because FD communication can send and receive the packet on the single frequency band. In the FD networks, two wireless nodes can transmit signals at the same time. Then the system throughput becomes twice as high as the the two nodes operating in the HD mode.

What is more, HD network requires every node to sense the channel before using for transmission by applying carrier sense multiple access with collision avoidance (CSMA/CA) which is also known as listen before talk, whereas FD requires only the initial transmission sense the wireless channel to avoid the collision issues.

Besides that, there is some weakness of FD techniques rather than SI and CCI issues. Since FD have to process twice the number of transmissions due to simultaneous transmit and receive, it leads to higher packet loss rate (PLR) than in the HD network. And then, the increased number of transmission, the huge the CCI and it can result in lower SINR. Therefore, the FD suffers from reduced link reliability compared to HD mode of transmissions. With the motivation to solve these issues and to realize the FD communication, some existing researches considered the interference cancellation and reduction techniques in FD network in different research area.

2.4 Interference and Reduction Techniques

Interference in the communication networks is limiting the benefits desirable from the communication technologies. It poses a major problem, especially in the FD network, since it reduces the quality of service for wireless communication [4]. According to the work presents in [24], the common types of interference in cellular networks are:

- Self-interference (SI)
- Multiple access interference
- Co-channel interference (CCI)
- Adjacent channel interference (ACI)

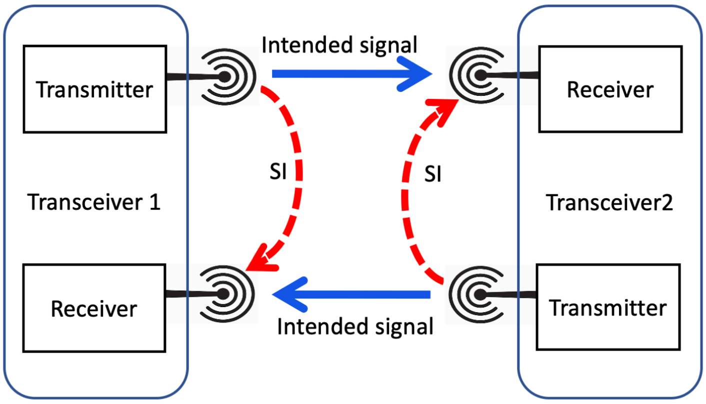

Figure 2.5: SI in FD communication system

Self-interference is caused by signals transmitted on a shared transmitter when the transmission antenna signal interfere with the receiving antenna as shown in Figure. 2.5. Interference between the UL and DL transmissions of a wireless node in an FD system may be also classified as self-interference, as it occurs among signals send on the same two-way communications.

Multiple access interference is induced by transmission from multiple radios using the same frequency resources to a single receiver. An essential method of maintaining orthogonal in multiple access for the matter of multiple access interference is power control.

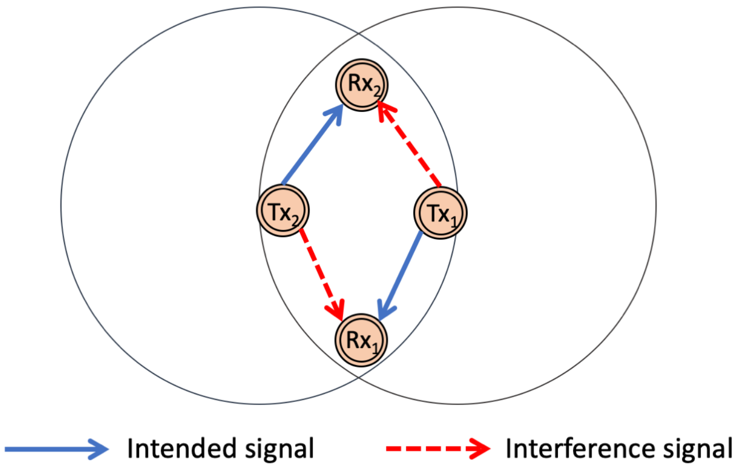

Figure 2.6: Co-channel interference in FD ad hoc network

CCI occurs in the link that reuses the same frequency band or channel as shown in Figure. 2.6. It is also called as inter-cell interference in cellular systems. The effect of CCI may be reduced by using fixed frequency reuse models. Some techniques to consider CCI in mobile network are frequency reuse, MIMO techniques, interference alignment, and adaptation to interference variation. One way to deal with CCI is to consider the cooperation between transmitters. Such practices have been discussed under the name of MIMO in the existing researches. In MIMO, the interference channel is converted into a broadcast channel with the focus of the co-operating transmitters as one transmitter.

ACI is the distortion that occurs between transmissions that communicate in the same space using neighbouring frequency bands. To mitigate and cancellation the various types of interference, there are many techniques that have been proposed. Common methods include power control, effective frequency assignment using intelligent techniques and intermodulation solutions.

Recently, to realize FD communication, many potential types of researches of SI cancellation techniques for FD systems have proposed and significantly suppressed to the receiver's noise floor. There are two main categories of mitigating self-interference: passive suppression, and active cancellation in the analog domain and digital domain [2].

Passive suppression: By increasing the physical separation of antennas to decrease the power of SI and by applying the directional antennas, the issues of SI are suppressed passively [7, 25, 26]. The passive suppression is also known as antenna SI-cancellation techniques. However, the application of passive suppression is very limited since the mobile device is small and does not have enough space to separate the antenna. The cancellation by separating antennas may only be useful in relay systems where isolation could achieve a significant amount of reduction.

Active cancellation: This type of cancellation aims to actively suppress the SI in radio frequency before converting analog-to-digital converter (ADC) in the analog domain. By subtracting an estimated SI from the received signal, this type of cancellation is also known as radio-frequency SI techniques [22, 23]. Besides that, after converting from the analog signal to digital symbol with ADC, the residual SI is reduced by applying various signal processing techniques in the digital domain [27, 28]. This type of SI cancellation in the digital domain has the advantage of lower complexity.

In addition to SI cancellation techniques, since CCI among mesh nodes is a major impairment and result of complicated transmission in FD network, [29] proposed a power allocation solution by considering full-interference to maximize the capacity in ad hoc networks. Besides, unlike the first-in-first-out scheduling, [30] designed and proposed a user scheduling scheme in BS by subjecting to mitigate the inter-user interference or CCI from the UL users to DL users in FD infrastructure network. L. Shi et al. proposed an optimal transmission algorithm for increasing the throughput with successive interference cancellation (SIC) in full-duplex multi-hop wireless networks and achieved a good result with minimum interference [31]. However, the minimum hop count does not guarantee the efficient SINR in the dense network and lack of focusing on the minimum interference is highly considered in the FD network.

Besides, by managing the transmission power of the transmitter for maximizing the performance of the network within the transmission area, an interference-aware power management protocol is proposed in [32]. In the power management protocol, each transmitter executes the control algorithm to adjust the carrier sense thresholds by ensuring simultaneous transmissions in FD networks. However, the interference issues still require to take into consideration to fully realize FD communication in the future wireless environment. Therefore, this research tries to apply and evaluates the performance of FD transmission in terms of achievable capacity and mitigation interference by proposing a cooperative MAC with a new type transmission, a mixture of concurrent and sequential transmissions.

2.5 Summary

This chapter has described some of the background knowledge of wireless communication as well as the fundamental studies of device-to-device (D2D), half-duplex (HD) and full-duplex (FD). Besides, the research problem of interference and some of the potential solution in the existing researches are presented.

Chapter 3

Capacity of Half-duplex and Full-duplex Networks

This chapter revisits the existing researches especially for the Full-duplex transmission that is presented in the previous chapter. The objective of the chapter is to review the Achievable Capacity of wireless networks i.e., the HD and FD communication. This chapter mainly focuses on the modeling and designing of a research methodology to revise the existing performance of HD and FD wireless networks in term of Achievable Capacity and total interference power (Co-channel interference) using theoretical and numerical simulations.

3.1 Related Research Works

The performance analysis of wireless network is essential to define the best configuration and transmission mode. In the previous studies to analyze the performance of the wireless network, the Achievable Capacity regions in wireless ad hoc networks are studied by assuming that the transmission range of the wireless node is equal to the interfering range [33]. The author of [34] studies the transmit capacity of wireless networks by using stochastic geometry to measure the multi-user interference in the ad hoc network for Rayleigh and Nakagami fading channel.

Besides, the existing research in [35] applies the layered model of the wireless mesh network to compute the upper capacity bound and investigates the methods to improve the transmit throughput capacity with the scheduling of simultaneous transmissions. [36] applied Markov Model to evaluate the performance of FD network in terms of throughput capacity and drop probability by considering the buffer in the nodes. To consider the medium sharing problem for machine type communication in FD network, [37] proposed the interference cancellation technique with graph-based random access to analyse the throughput and tradeoff of FD network over HD network.

Based on the existing researches to study the capacity of the wireless network, the research methodology is defined and formalized in the following section to study the performance of FD and HD network.

3.2 Research Methodology

The research methodology is defined to revise the performance of HD and FD wireless network as the following workflow shown in the following figure 3.1.

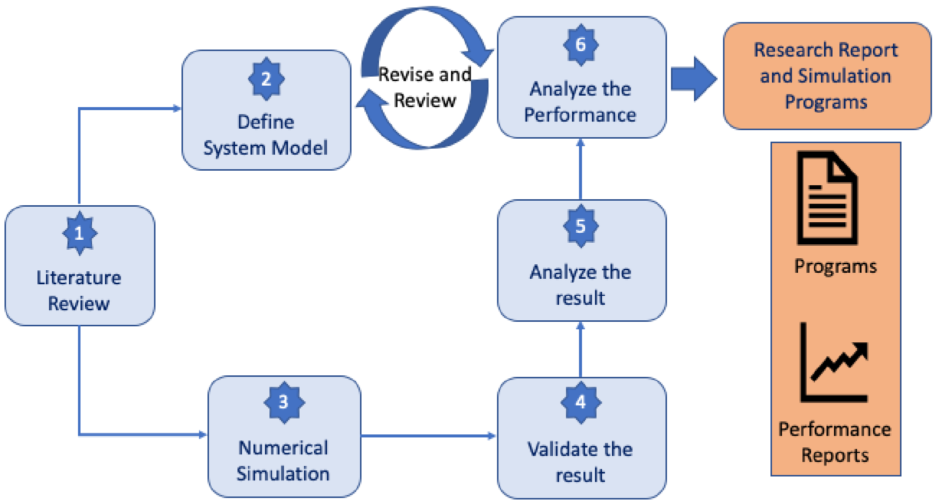

Figure 3.1: 6-step research methodology

After reviewing the related research in the literature reviewing section as the very first step of the methodology, in the system model step, the ad hoc networks with single-hop network model are considered where no hidden terminal problems exist and the wireless nodes are random uniformly distributed in a region of the fixed area in the simulations [33]. For HD network, all the nodes represent HD wireless nodes which can be either transmitter or receiver per-channel use or at a single time. And then, FD nodes who can perform FD functions with simultaneous transmit and receive in FD network. Although Self-interference (SI) plays a crucial challenge to achieve simultaneous transmissions in FD network and the performance of FD communication is sensitive to the amount of SI cancellation, this research assumes that SI can be mitigated up to noise level and omitted SI issues. This research is only focused on the co-channel interference (CCI) instead of SI.

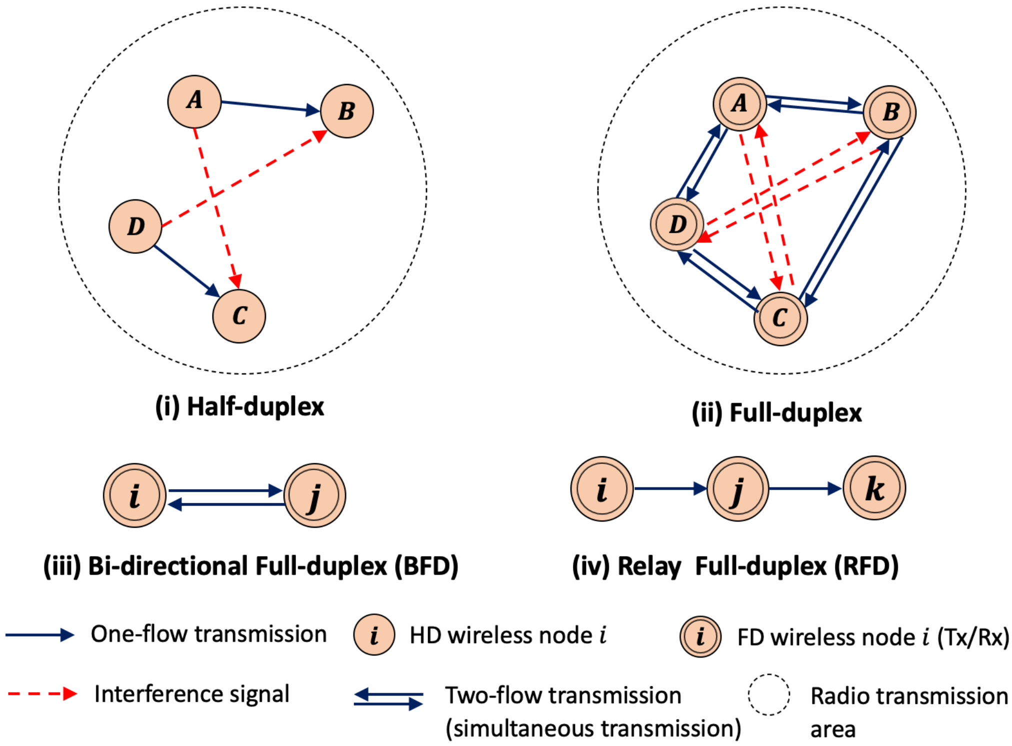

Figure 3.2: A topology of HD and FD networks with four wireless nodes

For simplicity, this research considers both networks are synchronous in which:

- Transmissions are scheduled either uplink or downlink in each time slot
- The time slots are divided equally between transmissions

- Wireless nodes do not wish to multicasting

An example topology in Figure. 3.2 illustrates a single cell network with the total number of nodes, N, is considered for FD and HD networks. Therefore, there can be $N/2$ transmitters and receivers with the equal number of transmitters and receivers in HD network per-channel use. With the feature of simultaneous transmissions of FD network, all the wireless nodes, N, can be transceiver which is transmitter and receiver.

After defining the system model according to the existing research [38], the theoretical and numerical simulation is conducted to evaluate the capacity of simultaneous transmissions in both HD and FD wireless network environment. The capacity means the total number of physically transferred bits per second according to Shannon's capacity. Besides, the interference level is computed and compared among the two networks. The interference level which is the total amount of interference (CCI) caused by simultaneous transmission in the whole network is the main focus to consider in the research. Interference here means the interference affected all other nodes who are not the transmitter of the transmissions. And then, the average total signal-to-interference-plus-noise ratio (SINR) to describe the theoretical upper bound for the transmission on the additive white Gaussian noise (AWGN) channel in the networks. What is more, the simulation output is analyzed and summarized with the motivation to propose a new transmission scheme which is an optimal mixture of concurrent and sequential transmission.

Here in this research, the scheduling fairness and routing protocol were not considered. And we assume that no errors occurred in the frame transmission. The interference cancellation in the physical layer is not discussed. The research methodology is evaluated the trade-off between the transmission capacity and interference level of both networks with spectrum sharing mechanism to improve the overall performance. The following sections will describe the system model of the research to compute the signal attenuation, SINR and transmission rate in the channel layer and data link layer.

3.3 System Model

The system model of the research methodology is described in this section with the following assumptions:

- The transmission range of the wireless node is equal to the interfering range
- An FD node in the wireless network have perfect SI cancellation
- Time-division Multiple Access (TDMA) with perfect time synchronization for simplicity

The capacity of the network is closely linked to the topology. The power threshold is estimated based on the radio propagation of the transmissions and radio propagation varies based on the coverage area and connectivity of the network. Firstly, the wireless nodes are random uniformly distributed in the coverage area and the distance between two wireless nodes $i(x_i, y_i)$ and $j(x_j, y_j)$ is computed for the use of Physical Layer (PHY) model as introduced below.

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{3.1}$$

The channel model determines the received signal of the packet transmitted from wireless node i to node j based on the distance between two nodes and the shadowing result from objections. By consideration, the wall attenuation among two nodes, W_{ij}, the shadowing attenuation from objections, X_σ, and the channel gain between two nodes is considered on the Log-distance Fading model with the following pathloss:

$$PL_{ij} = PL_0 + 10 \cdot \alpha \cdot \log_{10}(\frac{d_{ij}}{d_0}) - W_{ij} + X_\sigma \tag{3.2}$$

where PL_0 is assumed as Friis free space model, $PL_0 = 20 \cdot \log_{10}(d_0)$, α is attenuation constant or pathloss exponent and d_0 is reference distance.

The power ratio at the receiving node j with the signal attenuation between wireless node i and node j according to the pathloss PL_{ij} is

$$G_{ij} = \frac{1}{10^{\left(\frac{PL_{ij}}{10}\right)}} \tag{3.3}$$

After computing the channel gain, the next is the Signal-to-Interference-plus-Noise Ratio (SINR) model to determine whether or not the packet is received error-free in the Physical Layer (PHY) model. SINR is various based on the strength of the received signal and the interference and noise affected during transmission. To receive a successful packet transmission, SINR must exceed the threshold depends on the network.

The Signal-to-Interference-plus-Noise Ratio (SINR) at the receiving node j with the transmit power P_i is

$$SINR_{ij} = \frac{G_{ij} \cdot P_i}{Noise + Interference} \tag{3.4}$$

and

$$Noise = \eta_j \cdot B$$

where η_j is noise at receiving node j and B is the bandwidth of the channel.

Let χ be the set of transmitting nodes and i be the intended transmitting node to receiving node j. Then, the interference power from the transmission T_{ij} is

$$Interference = \sum_{k \in \chi, k \neq i} G_{kj} \cdot P_k$$

where k denotes the interfering nodes and P is the transmit power.

The achievable transmitting rate (bps) which is the physically transmitted bits during a unit of time from wireless node i to node j is computed under the level of SINR with Additive White Gaussian Noise (AWGN) channel model by applying Shannon's capacity theorem.

$$r_{ij} = B \cdot \log_2 \left(1 + \frac{1}{\tau} SINR_{ij}\right) \tag{3.5}$$

The Achievable Capacity is computed based on the individual link rate or transmitting rate of each transmission in the networks. The Achievable Capacity is varied according to the method for improving wireless network capacity, i.e., simultaneous transmissions, Sequential Transmissions (ST), Concurrent Transmissions (CT) and so on.

3.4 Capacity of Simultaneous Transmissions

In this section, we define the achievable capacity of the network with simultaneous transmissions scheme, i.e., sequential transmissions with no spatial use and concurrent transmissions with spatial reuse. The achievable capacity is evaluated as a matrix to define the performance of the network.

3.4.1 Sequential Transmissions (ST)

Sequential Transmissions is a type of transmission in which several transmissions are executed sequentially in a sequential transmission case study. The concept of ST is similar to TDMA. A key concept of TDMA is a way to access method for shared medium networks which allows many users to share the same radio channel by dividing the signal into different time slots. However, the difference between TDMA and ST is that TDMA divides the signal into different time slots for all of the potential transmitting nodes, even some of them not transmit all the time. However, ST is a kind of scheduling method that only support the current transmitting nodes to transmit their data packets sequentially.

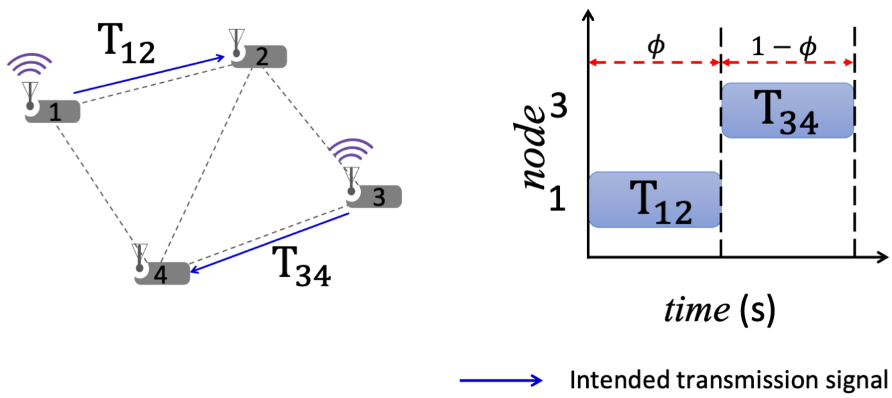

Figure 3.3: Illustration of ST scheme

In this case, the rest nodes other than transmitter who wish to do transmission are keeping silent which means no transmissions. As a result, no interference occurs between wireless nodes because only one transmitter is transmitting data packets to the intended receivers at each time. An example of sequential transmission with two transmissions in the 4-node network is shown in 3.3 where each transmission are in different time slots.

The time fraction, ϕ, plays as an essential role to optimize the Achievable Capacity of the network whether ϕ is equal or not. To formalize and study the Achievable Capacity of ST, two case studies with an equal fraction of time and an unequal fraction of time are discussed in this research.

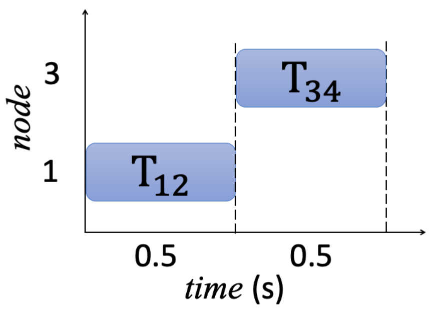

Figure 3.4: Example of sequential transmission with equal ϕ

I. Case study 1

This case study discusses the ST with equal time fraction, $\phi = 0.5$, by assuming the accessing time is 1 second in Figure 3.4. Therefore, the Achievable Capacity (C) of the network with ST is

$$\begin{aligned} C &= 0.5 \cdot r_{12} + 0.5 \cdot r_{34} \\ &= \frac{0.5}{0.5+0.5} \cdot r_{12} + \frac{0.5}{0.5+0.5} \cdot r_{34} \\ &= \frac{1}{2} \cdot r_{12} + \frac{1}{2} \cdot r_{34} \\ &= \frac{r_{12}+r_{34}}{2} \end{aligned}$$

$$\boxed{C = \frac{r_{12}+r_{34}}{2}} \tag{3.6}$$

where r_{ij} is transmission rate for transmission from node i to node j for transmission T_{ij} without interference from other nodes with a unit of bits per second (bps).

II. Case study 2

This case study 2 discusses ST with the different fraction time, ϕ. An alternative example sequential is as the following figure 3.5.

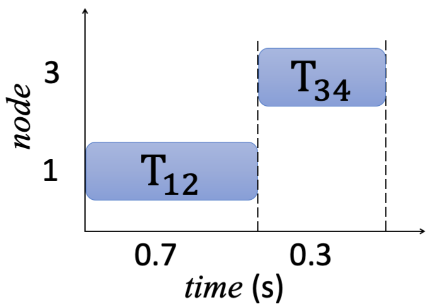

Figure 3.5: Example of sequential transmission with different ϕ

Then, the achievable capacity, C, of the network becomes

$$\begin{aligned} C &= 0.7 \cdot r_{12} + 0.3 \cdot r_{34} \\ &= \frac{0.7}{0.7+0.3} \cdot r_{12} + \frac{0.3}{0.7+0.3} \cdot r_{34} \\ &= \frac{1}{0.7+0.3}(0.7 \cdot r_{12} + 0.3 \cdot r_{34}) \end{aligned}$$

However, the time fraction is computed based on the physical rate of the transmission as the following. Let assume

- first time fraction of the first period, ϕ, for transmission T_{12} is $\frac{r_{12}}{r_{12}+r_{34}}$
- time fraction of the second period, $1-\phi$, for transmission T_{34} is $\frac{r_{34}}{r_{12}+r_{34}}$

Therefore, the Achievable Capacity (C) of the ST is formulated

$$\begin{aligned} C &= \frac{r_{12}}{r_{12}+r_{34}} \cdot r_{12} + \frac{r_{34}}{r_{12}+r_{34}} \cdot r_{34} \\ &= \frac{r_{12}^2}{r_{12}+r_{34}} + \frac{r_{34}^2}{r_{12}+r_{34}} \\ &= \frac{r_{12}^2 + r_{34}^2}{r_{12}+r_{34}} \end{aligned}$$

$$\boxed{C = \frac{r_{12}^2 + r_{34}^2}{r_{12} + r_{34}}} \tag{3.7}$$

where r_{ij} is the transmission rates from wireless node i to node j for transmission T_{ij} without interference from other interfering nodes.

3.4.2 Concurrent Transmissions (CT)

The higher Achievable Capacity is achieved under spatial reuse with the simultaneous transmissions. To improve the Achievable Capacity of the network, CT is one of the examples of spectrum sharing, especially, spectrum efficiency at the same time. CT is a form of transmission in which several transmissions are executed during overlapping periods concurrently instead of sequentially (one completing before the next starts) [39]. Assuming MIMO and FD technologies are used, multiple transmissions would be on transmitting at the same time.

However, since all the transmitters are transmitting in the same frequency band concurrently by sharing the transmission medium, although the higher Achievable Capacity can be achieved, performance degradation due to interference (CCI) issue, collision probability and packet drop probability become more serious. The author Dongjin et al. [40] offers the experimental study of the performance of a wireless sensor network with CT in low-power wireless link communications. Besides, in the ultra-dense network, the interference (CCI) level is rapidly increasing because they are near each other and the transmission is also getting an increase. On the other hand, if the network is sparse, which mean the distance between any two devices is not near, the concurrent communication with the same transmitting power would lead significant Achievable Capacity growth than the short distance between any two devices.

As shown in Figure. 3.6, there are two concurrent transmissions, T_{12} from wireless node 1 to node 2 and T_{34} from wireless node 3 to node 4 at the same time. Since the wireless channel is shared by two transmissions, the interference signal, represented by red dotted arrow, is the issue for this type of CT rather than the intended on-going signal (blue think arrows).

Since all the transmissions are sharing all of the accessing time here in CT, the time fraction, β, is 1 in these types of transmission. Theoretical

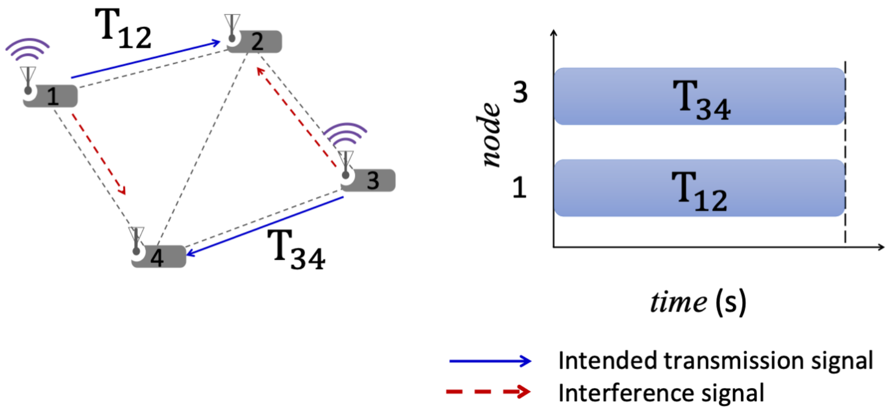

Figure 3.6: Illustration of CT scheme

study of the Achievable Capacity of the transmission in the network is as the following.

$$C = 1 \cdot r'_{12} + 1 \cdot r'_{34}$$

$$\boxed{C = r'_{12} + r'_{34}} \tag{3.8}$$

where r'_{ij} is the transmission rate from wireless node i to node j for transmission T_{ij} with interference from other interfering nodes. The following section will discuss the numerical studies of Achievable Capacity and interference level of FD and HD network with ST and CT with spatial reuse.

3.5 Numerical Simulation

Based on the system model, assumption and theoretical studies mentioned in the previous section, the evaluation result for the comparison of the HD network and FD network is discussed in this section. The numerical simulations are conducted in the random topology for dense networks with the various number of wireless nodes.

3.5.1 Simulation Parameters and Settings

In order to verify the correctness of the simulation, we assume and evaluate and exploit the similar performance study of the previous study [38]. In the previous study, the capacity regions for wireless ad hoc networks is studied under various transmission strategies. With the same simulation scenario and parameters with 5 nodes network, the following Figure.3.7 shows the verification results of the simulation with ad hoc transmissions.

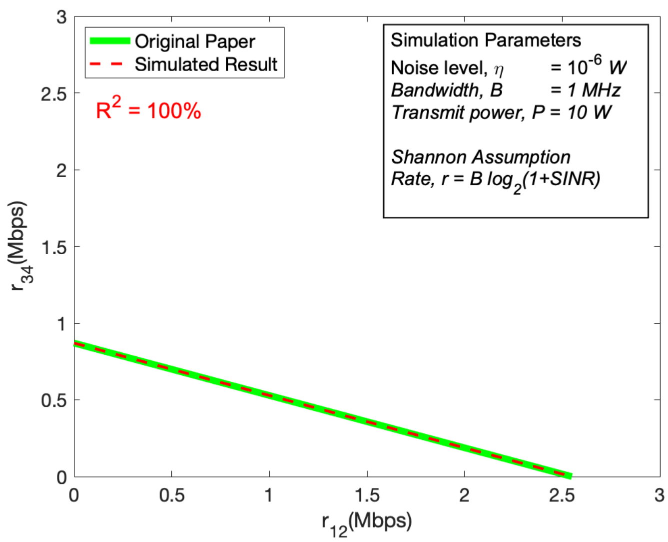

Figure 3.7: The verification of the simulation

Then, the numerical simulation is conducted with the system model defined in the previous section. The parameters of the simulation are listed in the Table. 3.1. The wireless nodes are random uniformly distributed with the network coverage size of 500 m x 500 m. HD nodes are assumed either transmitter or receiver at a time and FD network with RFD transmissions with perfect SI cancellation.

To be simple, 4-nodes with two flows of RFD transmission are grouped logically in FD networks according to the minimum distance. For example, there are 10 groups, two flows in each group with RFD transmissions in 40-node FD network as shown in Figure. 3.8. Both types of network are considered in TDMA approach with D2D communications. And then, the programs are simulated by using MATLAB R2019a.

For evaluation of the performance, the achievable capacity and interference(CCI) power are obtained and discussed by averaging 10,000 times simulation. The capacity in this research is referred to as the achievable capacity which is defined as the total sum-rate of physical transferred bits

Table 3.1: Simulation Parameters and Settings

Parameter	**Value**
Network coverage size	500 m × 500 m
Number of nodes (N)	[40, 80, 120, 160, 200]
Transmit power (P)	23 dBm
Propagation model	Log-distance Fading Model
Attenuation constant (α)	3.5
Wall attenuation (W_{ij})	0 dB
Shadowing parameter (X_σ)	8 dB
Noise level (η)	-120 dBm
Channel bandwidth (B)	10 MHz
Value depends on the choice of coding and modulation parameters, and the BER requirement (Γ)	1
Number of simulations	10,000 times

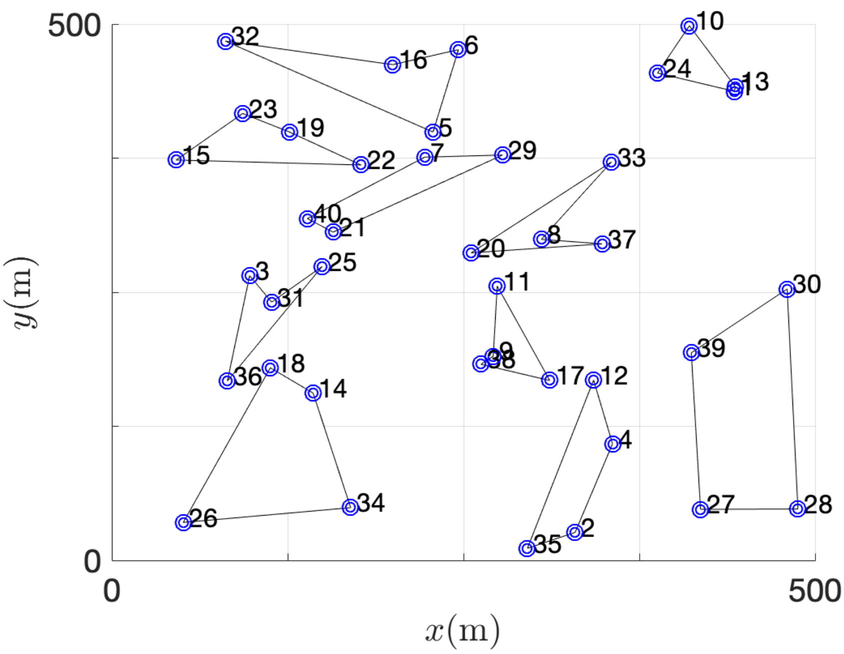

Figure 3.8: An example FD network topology

per second over communication links of the network according to Shannon's capacity theorem. The interference power is the total amount of interference caused in the network by simultaneous transmission. Besides, to consider the pros and cons of FD network which are throughput gain and interference issue, the new matrix, Effective Capacity (EC), is defined by considering the Achievable Capacity in a unit of interference. EC describes the capacity of transmission with the influence of interference.

3.5.2 Simulation Results and Discussion

The simulation results of HD network and FD network with RFD is shown to discuss the performance gain, to identify the research problem and motivation to propose a novel transmission scheme which is the optimal Mixture of Concurrent and Sequential Transmissions (MCST) scheme.

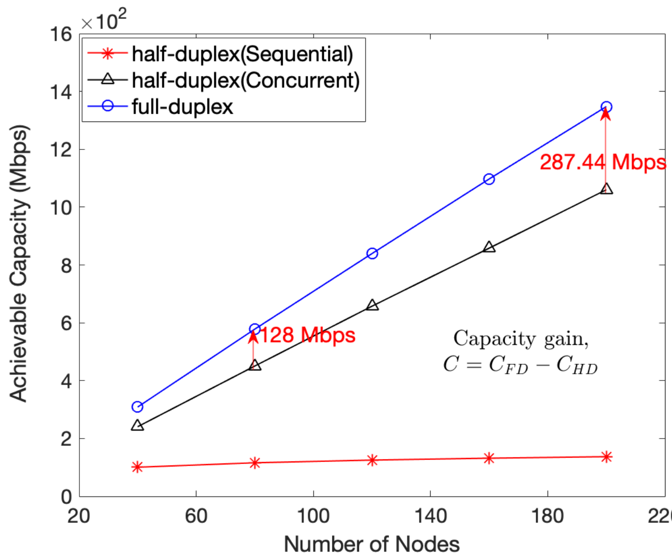

Figure 3.9: Capacity comparison of HD and FD network

Firstly, the Achievable Capacity among HD and FD with RFD is evaluated in Figure. 3.9. The Achievable Capacity of the FD is higher than HD network for both ST and CT with spatial reuse. The capacity difference between FD and HD is getting an increase according to the number of nodes. Figure. 3.9 shows that the Achievable Capacity gain of FD from HD increases

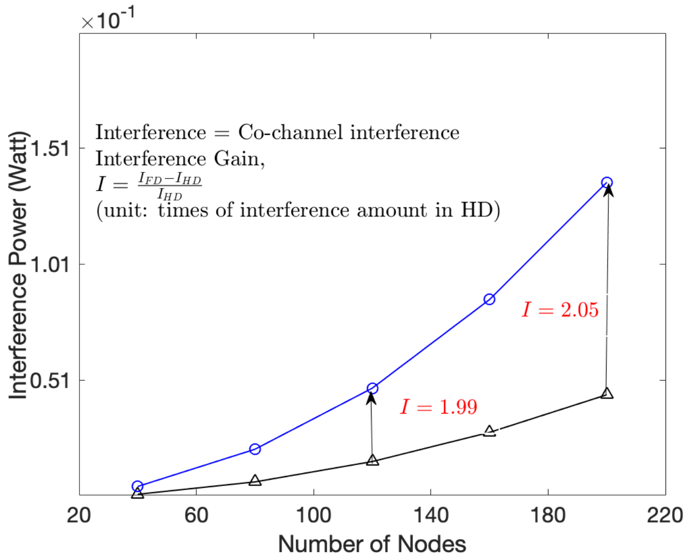

Figure 3.10: Interference level of HD and FD network

from 128 Mbps of 80-node topology to 287.44 Mbps of 200-node topology. The result shows FD is better than HD in terms of Achievable Capacity.

Figure. 3.10 illustrates the increasing amount of interference which means Co-channel interference (CCI) during transmissions for HD and FD networks in term of Watt. According to the assumption in the previous section, CCI is the main focus of the research. The level of interference is getting increase according to the number of nodes in the network. Although FD can bring the better transmit throughput, the level of interference in FD is getting larger than in HD as long as the number of nodes increases.

These results show, in the number of 120 nodes, the increased amount of interference in FD is almost 1.99 time of the amount of interference occurred in HD network. Besides, the increased level of interference affected during transmission in FD becomes over twice of interference occurred during transmission in HD when the nodes are getting increase, i.e., 200 nodes in this example. Based on the result, the amount of interference becomes serious and it is essential to take into considering the Achievable Capacity as well as the interference issues to realize FD communication in the future wireless networks.

Besides, Figure. 3.11 shows the comparison of SINR among HD and FD networks. SINR in this research means the average quantity of Signal-to-

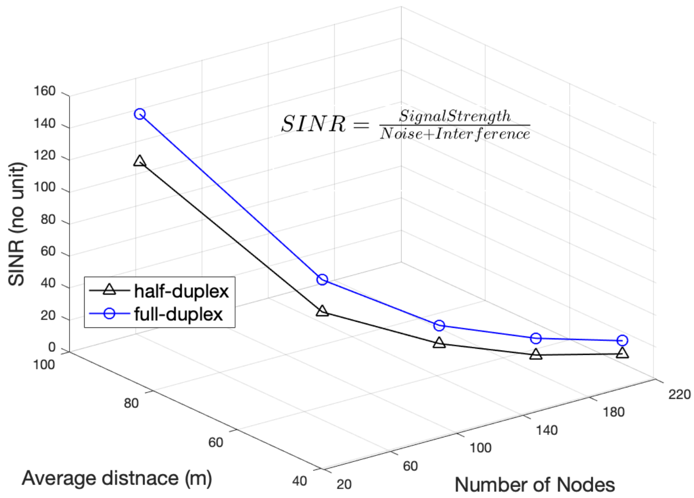

Figure 3.11: Performance comparison in terms of SINR

Interference-plus-Noise Ratio to describe the theoretical upper bound of the transmission on the wireless channel. It can be easily recognized that as long as the number of wireless nodes increases in a specific area, the network becomes denser and each node close to each other. As the effect, the amount of interference is increased and, in both HD and FD network, the average value of SINR for one transmission is tending to be lower. It can be concluded, according to Figure. 3.11, the interference is an important factor for transmission because it can affect SINR and degrade the performance of the communication.

To compare the performance of the HD and FD network in terms of Achievable Capacity in the coverage of the amount of interference, Figure. 3.12 describes the comparisons of capacity change with the performance matrix, effective capacity, EC. Effective capacity is the transmission capacity gain according to the interference. As the result shows, the performance of HD is better than FD in term of EC, since the amount of interference is serious than capacity gain. Although the number of nodes increase, HD still brings better performance than FD in term of EC. Therefore, to realize FD communication, it is essential to take into considering inter-cell interference or co-channel interference as well as SI for capacity improvement and, without careful planning and advanced techniques for interference cancellation,

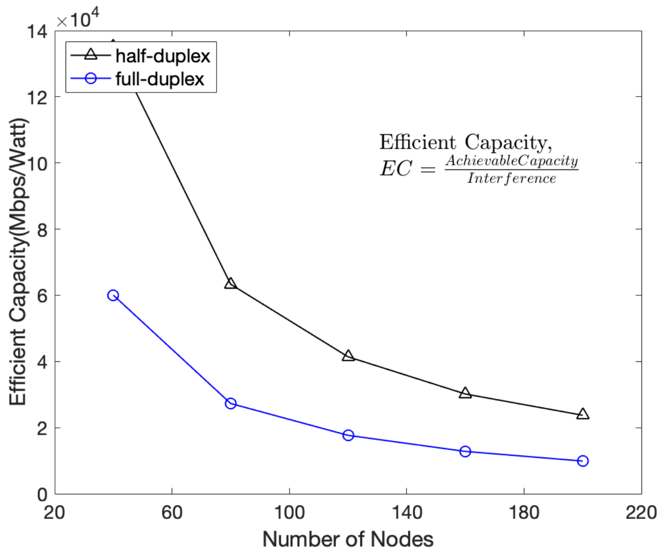

Figure 3.12: Performance comparison in terms of the efficient capacity

it is difficult to replace HD communication with FD for capacity gain [3, 10].

3.5.3 Problem Formulation

The higher performance of the Achievable Capacity can be achieved by applying the concurrent transmission with spatial reuse in the latest communication like 5G. However, the interference level is rapidly increased because of the spatial reused concurrent transmission and increasing the number of communicating devices and traffic. Especially, if the wireless nodes are close to each other in the dense network, the amount of interference leads to significant increases in the concurrent transmissions.

Xiufeng et al. claim that inter-link interference and spatial reuse reduces the capacity of FD gain and disproves the belief that FD can double wireless capacity [41]. Besides, the previous results in the numerical simulation show although the transmission Achievable Capacity of FD can be achieved, HD stills plays as the better communication in terms of EC which is the transmission throughput capacity with the coverage of interference.

Therefore, in this research, we are interested in Achievable Capacity performance with FD network by taking consider the amount of interference that occurred from spatial reuse of the transmission. The following chapter will introduce and propose an opportunistic and cooperative medium access control with a novel transmission to consider throughput performance by taking a considerable amount of interference.

3.6 Summary

This chapter has discussed the research methodology to revisit the performance of HD and FD wireless network with the simultaneous transmissions, i.e., ST and CT. Since there is no complete the existing researches to discuss the performance gain of FD network with the simultaneous transmissions, a complete research methodology to study the performance of the capacity of FD network with the simultaneous transmissions is discussed in this thesis. The theoretical of ST and CT are discussed in details and the numerical simulation is conducted to evaluate the performance of the wireless networks. According to the assumption and simulation setting, the achievable capacity gain of FD over HD networks can be up to around 287 Mbps in the 200-node network. However, the power of interference of FD can reach up to over twice the interference occurred in HD network. Consequently, FD cannot beat HD in terms of efficient capacity since the interference is getting an increase although the capacity is improved. Therefore, the simulation results of the performance study in HD and FD are discussed in this chapter and the research problem of interference is formulated for the future wireless network.

Chapter 4

Mixture of Concurrent and Sequential Transmissions

This chapter introduces a new transmission scheme to improve the Achievable Capacity performance by taking consider the amount of interference occurred from spatial reuse of the transmission in HD and FD wireless networks. The purpose of this chapter is to propose an opportunistic and cooperative medium access control (MAC) with a novel transmission scheme which is an optimal Mixture of Concurrent and Sequential Transmissions (MCST) with the objectives to increase transmission throughput capacity and to mitigate the amount of interference occurred during transmission. Therefore, the detail theoretical study and numerical simulation are conducted to evaluate the performance of the new transmission scheme as the main focus of the research.

4.1 Related Research Works

This research is conducted in wireless communication to focus on two categories of performance. The first one is to improve the Achievable Capacity by mixing concurrent and sequential transmissions, and the second is to mitigate the interference by controlling the transmitted power of the transmitters while keep in achieving higher capacity in the communication. For these purposes, some research had proposed the solutions for both categories for various perspectives.

To increase transmit throughput capacity in the wireless mesh network, [35] investigated the concurrent scheduling of transmissions and showed the improvement and limitation of the capacity with spatial frequency reuse. And then, the author demonstrates that the higher capacity can be achieved with simultaneous packet transmissions rather than no simultaneous transmissions. Besides, as a finding, only a few concurrent transmissions per unit of area are sufficient to maximize the capacity bound and the capacity gain cannot be achieved with multiple concurrent transmissions because of spatial reuse issues such as interference.

Y. Yu et al. [42] introduced the idea of a mixture of concurrent and sequential transmissions with two transmissions in HD ad hoc network and showed the higher capacity can be achieved than other two simultaneous transmissions, ST and CT. Furthermore, with the existing research described in the previous chapter, power control and multi-user communication systems were used to increase the system performance such as data rate, network capacity and coverage area of wireless communication.

As the system-level control of CCI, controlling transmit power, channel allocation and modulation scheme has been attractive as radio resource management for wireless networks [43]. By adjusting the power of every transmitter to meet up the QoS, transmit power control played as the important mechanism to suppress the interference, and then the performance capacity is affected. Based on the nature of the network, there are several control algorithms to adjust the power of transmitter such as distance-based algorithms, SINR based algorithms, interference-based power control algorithms and so on.

4.2 Mix of Con & Seq transmissions MCST

A novel type of transmission, a mixture of concurrent and sequential transmissions, is proposed in the FD wireless network to consider the achievable capacity and the interference level during simultaneous transmission. The proposed MCST framework with a cooperative medium access protocol (MAC) is described in Figure. 4.1. This framework is conceptualized with the cooperative manner in potential network technologies such as D2D, M2M and so on. This framework utilises the network topology and data transmis-

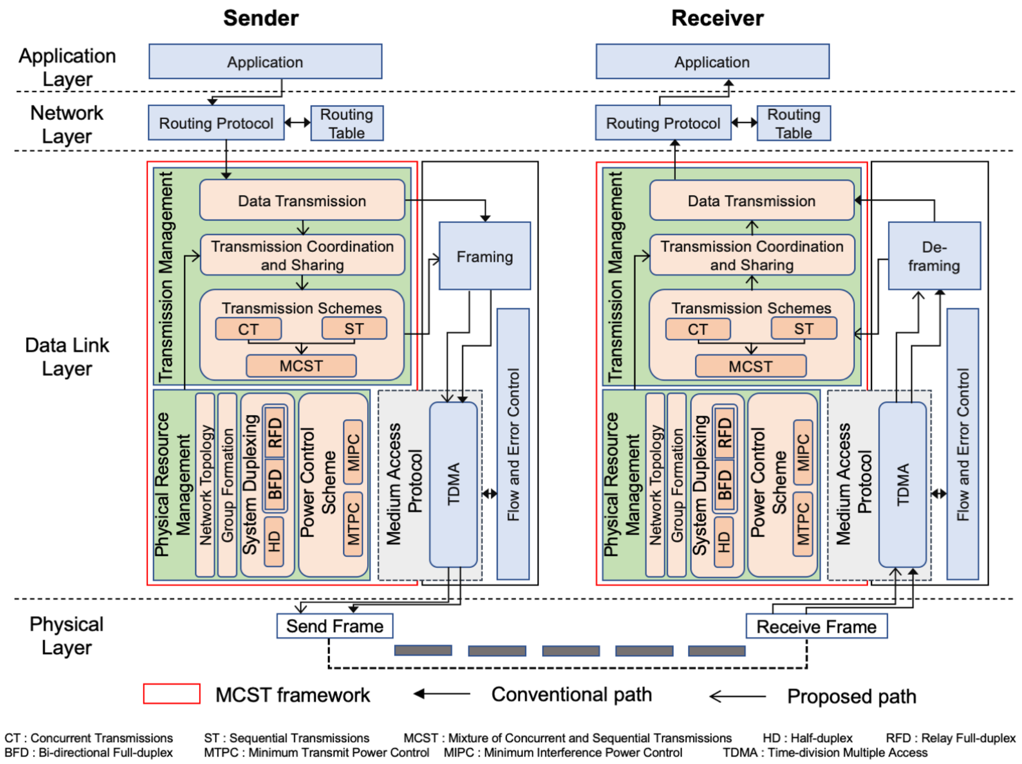

Figure 4.1: Proposed MCST framework

sion in the data link layer with medium access protocol, i.e., TDMA, in this research.

The proposed framework consists of two main components:

1. Transmission management
2. Physical Resource management

The functions and processes of each main component are briefly described as follows:

1. Transmission management: This component mainly controls the transmission schemes with the information detected from the physical resource management component. Three main processes of transmission management component are
    - Data Transmission: Send of the data from transmitting node to receiving node

- Transmission Coordination and Sharing: Collection and sharing the information such as position of the wireless nodes, group of the wireless nodes, transmission modes, transmission rate and so on
- Transmission Schemes: Types of transmissions that define ways to transmit data from sending to receiving nodes. Three transmission schemes: Sequential Transmission (ST), Concurrent Transmission (CT) and proposed mixture of concurrent and sequential transmission (MCST)

2. Physical Resource Management: This component detects the physical resource of the wireless nodes such as network topology, group of the node for the purpose of transmission and duplexing modes, and power control scheme, i.e., minimum transmit power control (MTPC) and minimum interference power control (MIPC). Four main sub-components are

    - Network Topology: Topology that creates the network of the wireless nodes for transmission
    - Group Formation: Formation of logical connection or groups among the participants for transmission. For e.g., 2-node group or 4-node group for data transmission in this research
    - System Duplexing: Detect the duplex and transmission mode of the wireless nodes. For example, half-duplex (HD) transmission in HD network and bi-directional transmission (BFD) or relay transmission (RFD) in FD network
    - Power Control Scheme (PCS): Controlling the transmitted power for mitigating the interference of the transmission, based on minimum transmit power control (MTPC) or minimum interference power control (MIPC) approaches

MTPC is the minimum transmitted power based power control approach to mitigate the interference of the transmissions while MIPC controls the power focusing on minimum interference of each transmission in the network. The detail discussions for MTPC and MIPC power control scheme are discussed in the following subsection.

In the proposed MCST framework, the first component depends on the second component to perform a specific data transfer. Depending on the data transfer process, the wireless nodes detect and share the transmission information with cooperative manner. To evaluate the performance of the proposed MCST framework, ad hoc wireless network, a single-hop network model is considered with no hidden terminal problems [38].

Here in this research, the scheduling fairness and routing protocol were not considered. And we assume that no errors occurred in the frame transmission. Because the performance of FD communication is sensitive to the amount of SI cancellation, we assume the SI can be cancelled up to noise level in this research to bold focus on inter-node interference or co-channel interference (CCI) among multiple transmissions. We are considering there are N nodes in the network that have all FD capability and each node can receive and transmit at the same time simultaneously but cannot receive two or more signals from the others. We did not discuss the interference cancellation in the physical layer but mitigation by controlling transmitted power. The research methodology shows the trade-off between the Achievable Capacity and interference level of FD networks is evaluated.

Figure. 4.2 illustrates the flowchart of the proposed MCST scheme as the workflow of the research. By considering in the homogeneous network of in HD mode or FD mode with BFD or RFD, the signal strength, SINR is measured to calculate the achievable rates of the transmissions. The achievable capacity of MCST is evaluated and compared with two other simultaneous transmissions, i.e., ST and CT. Figure. 4.3 describes the details operation of the MCST scheme in the proposed framework with and without PCS to adjust the transmit power for capacity and mitigation the interference during simultaneous transmissions.

Two distributed power control algorithms are considered into the MCST scheme. Firstly, MTPC based on the minimum transmit power is applied to reduce the range of the transmission for mitigating CCI during transmissions with the respective idea from transmitting power control algorithm [44]. And then, the power of the transmitter is adjusted subject to minimum interference of the receiver of the transmissions and it is defined as MIPC.

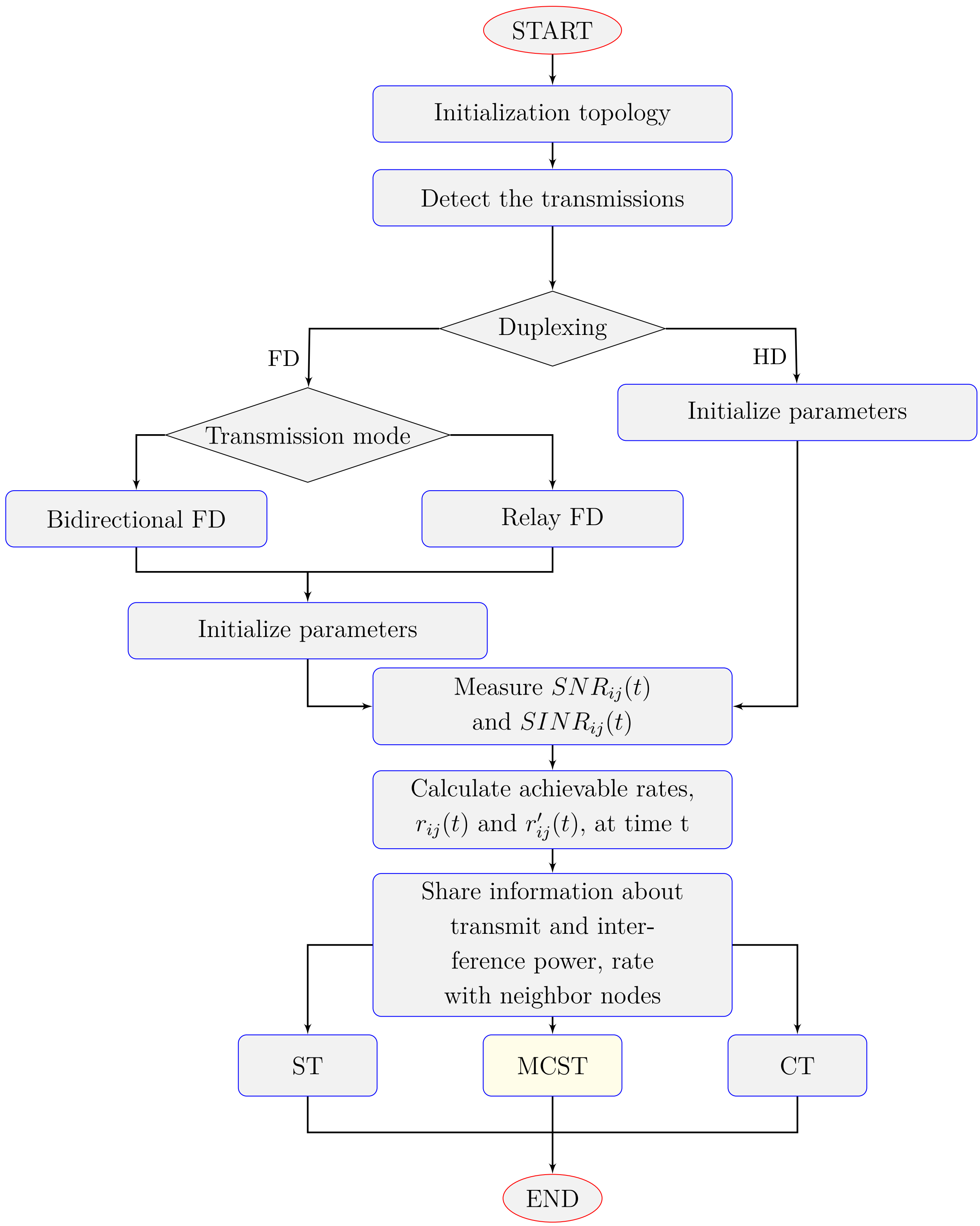

Figure 4.2: Flowchart of the proposed MCST framework

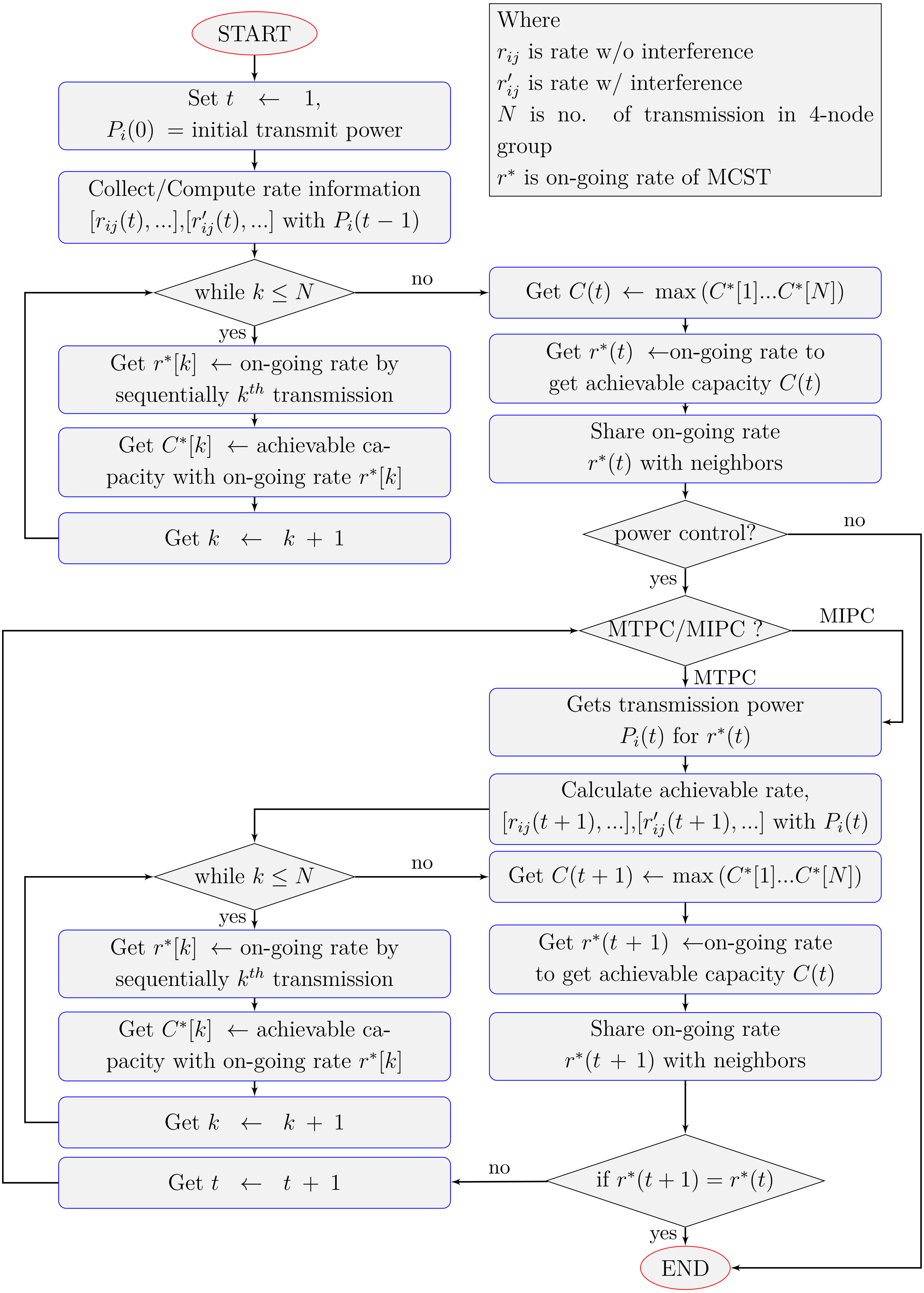

Figure 4.3: Flowchart of the proposed MCST scheme

4.2.1 Minimum Transmit Power Control

The amount of interference influence the physical rate of the transmission with the minimum SINR. Therefore, the interference should be reduced to achieve high transmit capacity. The power control scheme is proposed to mitigate interference by reducing transmitted power. The minimum transmit power control (MTPC) tries to minimize the interference by focusing on minimum transmit power. The objective of MTPC mechanism is to obtain the minimum transmit power, P, of the transmitting nodes that minimize the interference for the purpose of maximizing the achievable capacity, C. Alternatively, MTPC subjects to minimum transmit power for achieving higher achievable capacity with proposed MCST scheme.

Maximize:

$$\max_{P} \ C$$

Subject to:

$$P = \min\left(P_1, P_2, ..., P_N\right), \text{ where } 0 \leq P_i \leq P_{max}$$

where i = transmitter, and N is the number of transmitting nodes.

4.2.2 Minimum Interference Power Control

As the second mechanism of the power control scheme, minimum interference power control tries to reduce the interference of the transmission by adjusting the transmitted power with the subject of least interference to the transmission. The objective of MIPC mechanism is to obtain the transmit power of each transmitting node that gives the least amount of interference, I, to the network. On the other way, MIC subjects to minimum interference to give the higher achievable capacity, C.

Maximize:

$$\max_{I} \ C$$

Subject to:

$$I = \min\left(I_1, I_2, ..., I_N\right)$$
$$I_j = \sum_{k \in \chi, k \neq i} G_{kj}.P_k \text{ where } \chi \text{ is set of interfering nodes}$$

where j = receiver, G = channel gain and P_i = transmit power of node i, and N is the number of receiving nodes.

Algorithm 1 discusses the proposed MCST scheme with the power control scheme which operates based on the time slot with iterations to obtain the transmitted power of the specific mechanisms, i.e., MTPC or MIPC.

Algorithm 1 Mixture of Concurrent and Sequential Transmissions

Definition: t is timeslots, N is no. of transmission in 4-node group

Input: $P_i(0)$ = initial transmit power

Output: C, r^* ▷ Achievable capacity and on-going rate

1: **function** MCST($P_i(0)$)
2:     Measure $SINR_{ij}(t)$
3:     Calculate $r_{ij}(t)$ and $r'_{ij}(t)$
4:     $N \leftarrow$ no. of transmission in a 4-node group
5:     **for** $k \leftarrow 1$ to N **do**
6:         $r^*[k] \leftarrow$ on-going rate by sequentially k^{th} transmission
7:         $C^*[k] \leftarrow$ achievable capacity with on-going rate $r^*[k]$
8:     **end for**
9:     $C(t) \leftarrow \max(C^*(1), \ldots, C^*(N))$
10:     $r^*(t) \leftarrow$ on-going rate to get capacity C
11:     **if** $PowerControl = True$ **then**
12:         Calculate $P_i(t)$ from $r^*(t)$ by MTPC or MIPC
13:         Calculate $[r_{ij}(t+1), \ldots]$ and $[r'_{ij}(t+1), \ldots]$ with $P_i(t)$
14:         go to step 18
15:     **else**
16:         go to step 31
17:     **end if**
18:     **for** $k \leftarrow 1$ to N **do**
19:         $r^*[k] \leftarrow$ on-going rate by sequentially k^{th} transmission
20:         $C^*[k] \leftarrow$ achievable capacity with on-going rate $r^*[k]$
21:     **end for**
22:     $C(t+1) \leftarrow \max(C^*(1), \ldots, C^*(N))$
23:     $r^*(t+1) \leftarrow$ on-going rate to get capacity C
24:     **if** $r^*_{ij}(t+1) = r^*_{ij}(t)$ **then**
25:         Set $t \leftarrow t+1$
26:         Go to step 31
27:     **else**
28:         Set $t \leftarrow t+1$
29:         Go to step 11
30:     **end if**
31:     **return** $C(t), r^*(t)$
32: **end function**

The power control scheme applied in algorithm 1 iterates as the time slot approach according to the constraints defined in transmit power-based MTPC mechanism and interference-based MIPC scheme, as the following steps.

1. All the transmitters are set the initial transmit power

2. The transmitting node i initializes the transmission with the power decided for time t to the receiving node i

3. The receiving nodes j measure $SINR_{ij}$ and share the information back to the transmitter i

4. The achievable rates with and without interference, $r'_{ij}(t)$ and $r_{ij}(t)$, respectively, are calculated and distributes the information with other transmitting nodes. We assume that overhearing techniques can be considered for sharing.

5. Based on the received information, the on-going rate $r^*(t)$ and achievable capacity $C(t)$ is calculated as follows:

$$C(t) = \max\left(C^*[k]\right) \tag{4.1}$$

   where $k = 1 \ldots N$ and N is the number of transmission in the 4-node group in FD network.

6. If the power control is applied to minimize the transmit power and to reduce the interference power, the next step is getting the power, $P_i(t+1)$ of MCST scheme according to the control algorithm described in Section 4.2.1 and 4.2.2.

7. With the updated transmit power, $P_i(t+1)$, the achievable rates, $r_{ij}(t+1)$ and $r'_{ij}(t+1)$ including the on-going rate, $r^*(t+1)$ of each transmitter is calculated from (2) to (5).

8. If the ongoing rate $r^*(t+1)$ is equal to $r^*(t)$, the transmit power $P_i(t+1)$ is decided as the final transmit power of the iteration. Otherwise, the new transmit power is updated according to (6) and the achievable rates and capacity will be calculated attractively from (2) to (5).

4.3 Theoretical Study

This section evaluates the theoretical studies of MCST. The wireless network with 4 wireless nodes (1, 2, 3 and 4) with two transmissions from node 1 to 2 and node 3 to 4 is considered as an example. In this example, nodes operate in HD mode where each node can be either transmitting node or receiving node.

Sequential Transmissions (ST) have an advantage of interference-free transmissions and Concurrent Transmissions (CT) can achieve a better Achievable Capacity with spatial reuse and spectrum sharing mechanism. By combining both types of ST and CT, there is a different type of transmissions which is Mixture of Concurrent and Sequential Transmissions (MCST) to maximize the Achievable Capacity of the network in a given time slot.

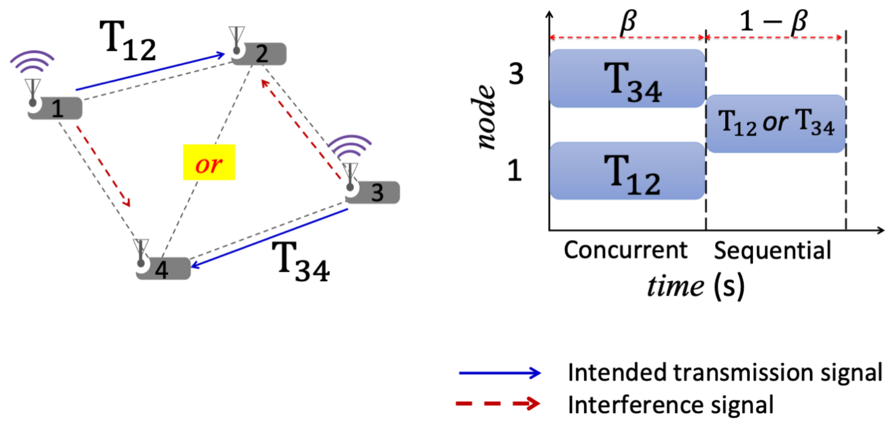

Figure 4.4: Illustration of MCST scheme

Figure 4.4 shows an alternative example of the MCST scheme of the wireless network by applying the advantages of the previous transmissions. As an assumption, all of the transmitters concurrently transmit with the on-going rate, $r_m^* = \beta \cdot r'_m$ where r'_m is the transmission rate calculated from all transmission rates in concurrent section by applying root mean square (RMS) function and β is the time fraction of concurrent transmission in MCST scheme. Therefore, the on-going rate for transmission T_{12} and T_{34} in MCST scheme are r_{12}^* and r_{34}^*, respectively. To achieve the optimal achievable capacity of the network with MCST is a type of optimization problem with the time fraction, β and the optimal selecting for the transmissions in concurrent section and for sequentially as the following.

$$\boxed{C = \max \begin{cases} \beta \cdot (r_{12}^* + r_{34}^*) + (1-\beta) \cdot r_{12} \\ \beta \cdot (r_{12}^* + r_{34}^*) + (1-\beta) \cdot r_{34} \end{cases}} \tag{4.2}$$

where r_{ij}^* is the on-going rate from wireless node i to node j in MCST scheme and r_{ij} is the transmission rate from wireless node i to node j without interference or the sequential transmission in the MCST scheme.

By referencing eq.3.8 for CT for first time fraction and eq.3.7 for ST, the transmit capacity of MCST scheme is

$$\boxed{C = \max \begin{cases} \frac{(r_{12}^* + r_{34}^*)^2 + r_{12}^2}{(r_{12}^* + r_{34}^*) + r_{12}} \\ \frac{(r_{12}^* + r_{34}^*)^2 + r_{34}^2}{(r_{12}^* + r_{34}^*) + r_{34}} \end{cases}} \tag{4.3}$$

By assuming successful time synchronization with synchronization techniques like Primary Synchronization Signal (PSS) or time alignment, and by sharing the prior transmission information among nodes, the on-going rate of the transmitting nodes which follows as sequential transmission in addition to concurrent transmission is T_{12} with the ongoing transmission rate.

$$\begin{aligned} r_{12}^* &= r_m^* \\ \beta \cdot r_{12}' + (1-\beta) \cdot r_{12} &= \beta \cdot r_m' \\ \beta &= \frac{r_{12}}{r_m' - r_{12}' + r_{12}} \end{aligned}$$

Then, based on the time fraction of the concurrent transmission, β, by considering T_{12} will follow sequentially, the transmission rate, r_{12}^* for transmission T_{12} is

$$\begin{aligned} r_{12}^* &= \beta \cdot r_{12}' + (1-\beta) \cdot r_{12} \\ &= \frac{r_{12}}{r_m' - r_{12} + r_{12}} \cdot r_{12}' + (1 - \frac{r_{12}}{r_m' - r_{12}' + r_{12}}) \cdot r_{12} \\ &= \frac{r_{12} \cdot (r_{12}' - r_{12})}{r_m' - r_{12}' + r_{12}} + r_{12} \end{aligned}$$

And, the transmission rate, r_{34}^* for transmission T_{34} is

$$\begin{aligned} r_{34}^* &= \beta \cdot r_m' \\ &= (\frac{r_{12}}{r_m' - r_{12}' + r_{12}}) \cdot r_m' \end{aligned}$$

By this way, the two on-going rates in the concurrent session of the MCST scheme is shown to be equal as the following since the nodes concurrently transmit with the on-going rate of the scheme.

$$r^*_{12} = r^*_{34}$$

Then, the achievable capacity, C of the network with MCST scheme become

$$C = \frac{(r^*_{12} + r^*_{34})^2 + r^2_{12}}{(r^*_{12} + r^*_{34}) + r^2_{12}}$$

4.4 Numerical Study

Based on the system models and theoretical analysis with the three types of simultaneous transmissions ST, CT and proposed MCST, the achievable capacity of FD network with the fixed location of the wireless nodes is evaluated in the following 4-node FD network with relay FD transmissions as shown in Figure. 4.5.

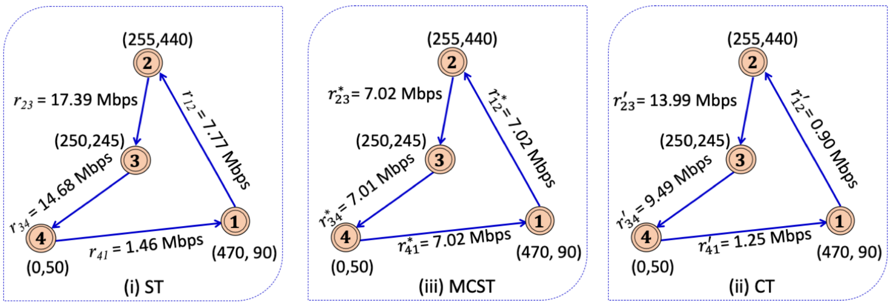

Figure 4.5: An example topology for the 4-node FD network

We consider a homogeneous network consisting of a macro cell and all nodes operate in the FD mode and serve simultaneous transmissions with perfect SI cancellation. In this research, we consider the first RFD transmission is $1 \rightarrow 2 \rightarrow 3$ and $3 \rightarrow 4 \rightarrow 1$ as the second RFD transmission. Therefore, with the functionalities of simultaneous transmit and receive in FD network, the transmission rate of the first RFD and second transmission is $R_1 = r_{12} + r_{23}$ and $R_2 = r_{34} + r_{41}$, respectively.

As shown in the figure. 4.5, the achievable rate without interference are $r_{12} = 7.77$ Mbps, $r_{23} = 17.39$ Mbps, $r_{34} = 14.68$ Mbps and $r_{41} = 1.46$ Mbps in sequential transmissions. With concurrent transmissions, the achievable rates are $r'_{12} = 0.90$ Mbps, $r'_{23} = 13.99$ Mbps, $r'_{34} = 9.49$ Mbps and $r'_{41} = 1.25$ Mbps respectively.

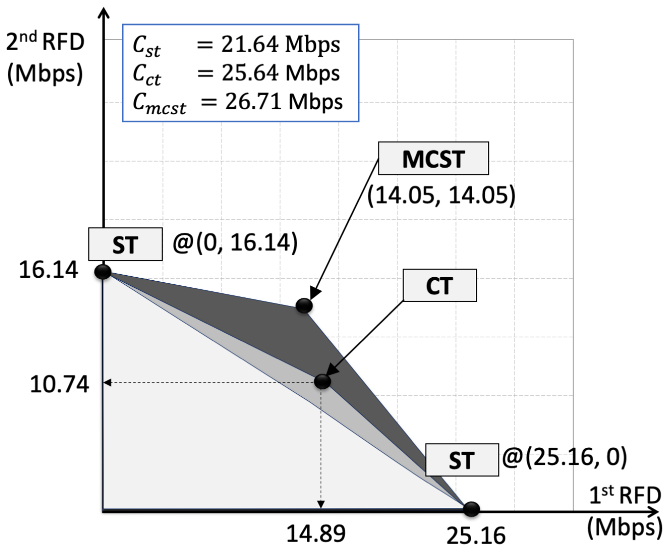

Figure 4.6: Achievable capacity of simultaneous transmissions in the 4-node FD network with RFD transmissions

The achievable capacity of simultaneous relay full-duplex (RFD) transmissions of 4-node FD network is illustrated in Figure. 4.6. Under sequential transmissions, according to (3.7), the achievable capacity can be achieved up to 21.64 Mbps with the rate of first RFD transmission 25.16 Mbps with the link from node 1 to node 2 and node 2 to 3, and second RFD transmission rate 16.14 Mbps with the link from node 3 to 4 and node 4 to 1.

Under concurrent transmission with spatial reuse, the network capacity can be achieved to 25.64 Mbps by (3.8). Besides, by considering the equal link rate with the mixture of concurrent and sequential transmission, the achievable capacity of the network can be achieved up to 26.71 Mbps. As shown in Figure. 4.7, the best value of time fraction, β, is 0.5276 from the following equation.

$$\begin{aligned} \beta(R_1^* + R_2^*) + (1-\beta)(R_1) &= \beta(28.10) + (1-\beta)(25.16) \\ &= 26.71\text{Mbps} \end{aligned}$$

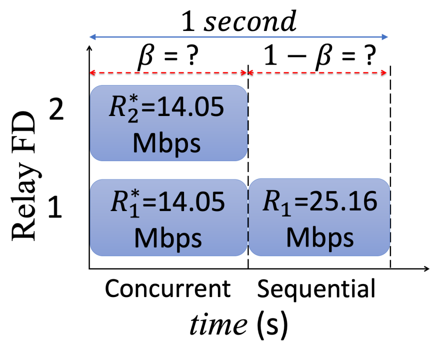

Figure 4.7: Mixture of concurrent and sequential transmission in 4-node FD network

where R_i^* is the on-going rate of RFD transmission i and R_i is the sequential transmission rate without the interference of RFD transmission i.

The results in Figure. 4.6 that presents the achievable capacity of simultaneous transmissions if 4-node FD network with two RFD transmissions describes that MCST scheme can achieve a better capacity than the other two simultaneous transmissions.

In the 4-node network with bi-directional FD transmission in Figure. 4.8, the capacity comparison for two BFD transmissions $1 \longleftrightarrow 2$ and $3 \longleftrightarrow 4$ is evaluated. In this case, the transmission rate of first FD transmission, R_1 is $r_{12} + r_{21}$ and $R_2 = r_{34} + r_{43}$ for the second BFD transmission.

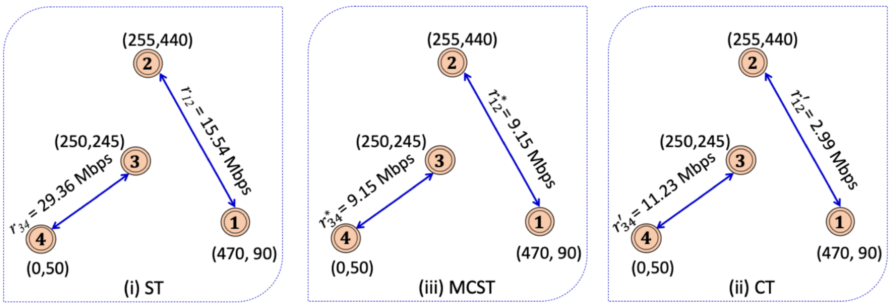

Figure 4.8: An example topology for 4-node FD network with BFD transmissions

Figure. 4.9 shows the achievable capacity of bi-directional transmissions FD network with 4 wireless nodes. It shows that the FD networks with two BFD transmission can achieve 14.21 Mbps with CT and the high transmit

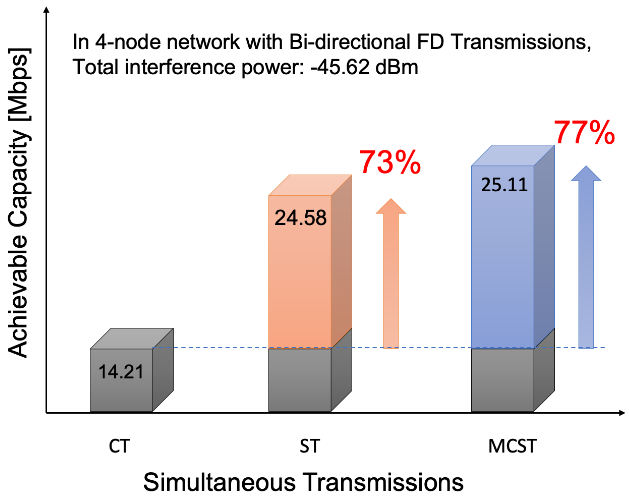

Figure 4.9: Comparison results for the achievable capacity of simultaneous transmissions in a 4-node FD network with two BFD transmissions

capacity can be achieved up to 24.58 Mbps with the simultaneous transmission. Consequently, the MCST scheme can bring the higher transmission capacity up to 25.11 Mbps which is 77% higher than capacity achieved in CT.

Table 4.1: Simulation Results of 4-node Fixed Topology

Transmission Mode	Average Total Interference Power [dBm]	Average Achievable Capacity [Mbps]			Average Transmit Power
		CT	ST	MCST	
HD	-49.95	12.48	12.28	18.56	0.2
BFD	-45.62	14.21	24.58	25.11	0.2
RFD	-47.04	25.63	21.64	26.71	0.2

Under the same location of the wireless node with the same system model and setting, the capacity of the HD network two transmissions, the first transmission from node 1 to node 2 and second from node 3 to 4, can be achieved 12.48 Mbps under CT and 12.28 Mbps by ST. However, under MCST, the capacity of the HD network with two transmissions can be achieved up to

12.56 Mbps. Table. 4.1 summarizes the simulation result of three types of transmissions in HD and FD network with RFD and BFD transmission mode for fixed topology in the 4-node network.

4.4.1 Simulation Scenarios and Settings

The quantitative comparison of simultaneous transmissions of 4-node FD network under the parameter settings in Table. 4.2 is evaluated. The random topology of 4 wireless nodes is obtained by uniformly and identically distributed within the network coverage of 500 m × 500 m.

Table 4.2: Simulation Parameters and Settings of FD network

Parameter	**Value**
Network coverage size	500 m × 500 m
Number of nodes (N)	4
Transmit power (P)	23 dBm
Propagation model	Log-distance Fading Model
Attenuation constant (α)	3.5
Wall attenuation (W_{ij})	0 dB
Shadowing parameter (X_σ)	8 dB
Noise level (η)	-120 dBm
Channel bandwidth (B)	10 MHz
Value depends on the choice of coding and modulation parameters, and the BER requirement (Γ)	1
Number of simulations	10,000 times

4.4.2 Simulation Results and Discussion

In the simulation scenario, a 4-node wireless network with D2D communications performs three possible types of transmissions, i.e, ST, CT and MCST. Figure. 4.10 illustrates the average capacity according to the interference level in term of dBm by running 10,000 times simulations. In 4-node FD network with 2 RFD transmissions, the average achievable capacity can be achieved up to 47.57 Mbps with CT and up to 60.93 Mbps of ST. As a result, the MCST can give the achievable capacity of 68.84 Mbps by around 45% of CT and 13% of ST.

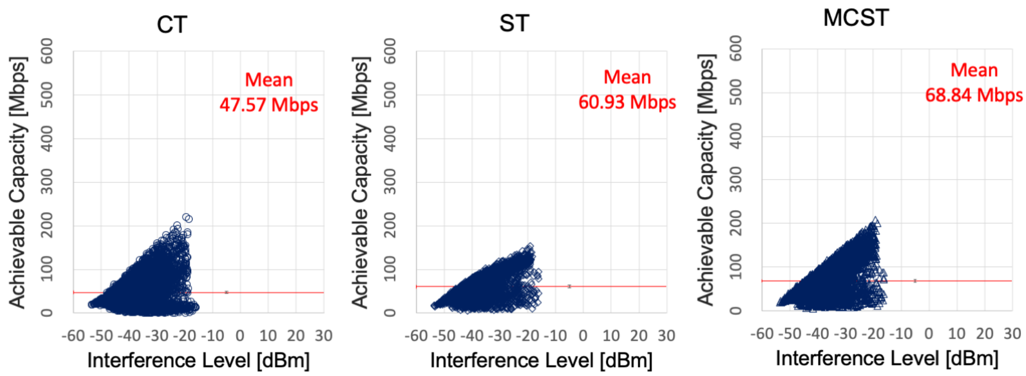

Figure 4.10: Quantitative comparison results of simultaneous transmission in the 4-node FD network with RFD transmissions

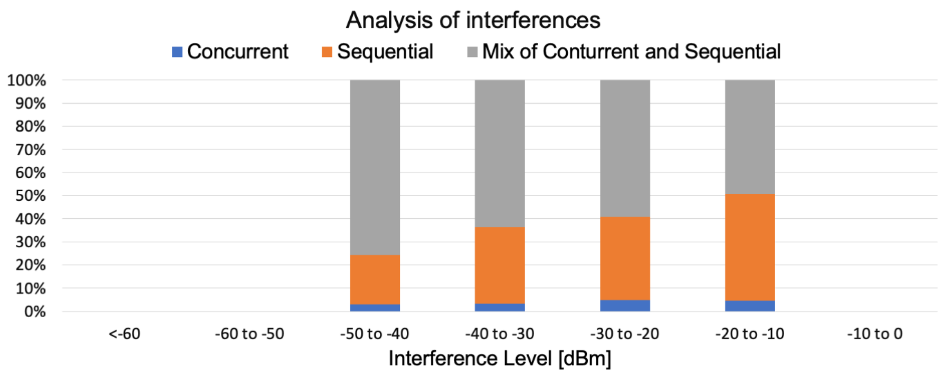

Figure 4.11: Effect of total interference power in a 4-node FD network with RFD transmissions

Figure. 4.11 describes the effect of the interference level of the transmissions in the 4-node FD network by performing 10,000 simulations under the same settings. The result shows that the average interference level of the transmissions can be among -50 dBm to -10 dBm and by applying the new transmission scheme, MCST, the network has high possibility to achieve the better transmission capacity than the other two simultaneous transmissions, ST and CT, for any network topology with any amount of interference.

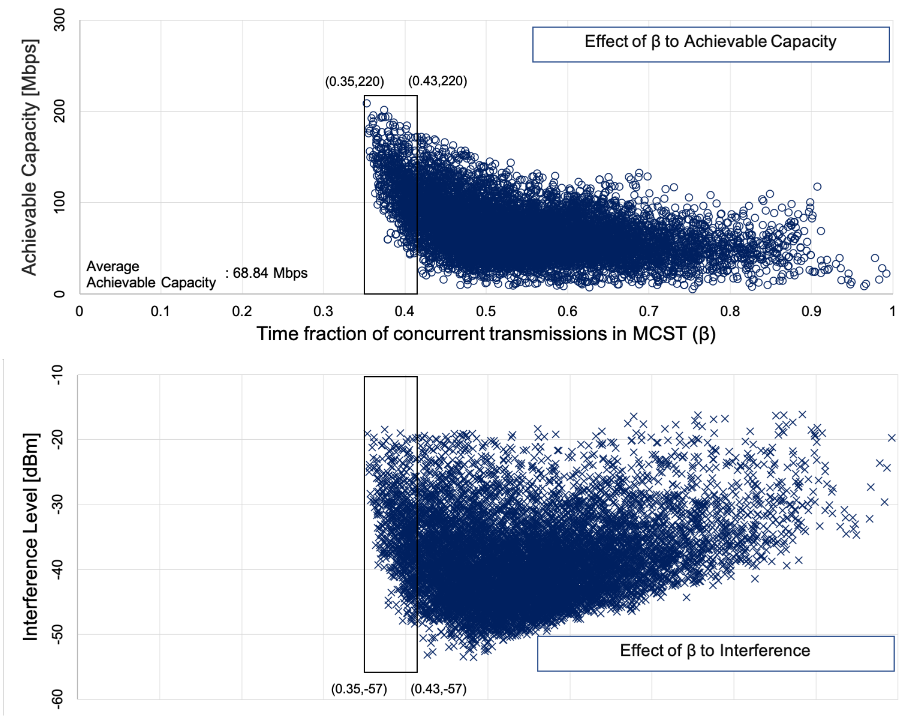

Figure 4.12: Time fraction of concurrent transmission in MCST in the RFD network

The achievable capacity and interference level with the unit of dBm regarding to the time fraction of concurrent transmission in MCST is illustrated in Figure. 4.12 for FD network with RFD transmissions. According to the assumption and system model, the minimum value of β in MCST is around 0.35, which is 35 % of the time. If β is getting increase and it means the period of concurrent transmissions increase. Consequently, the interference is increased and it reduces the capacity of the transmission. As we can see in the figure, the achievable capacity is high with the lower interference around 10 percent of β. Therefore, we can conclude that β should be around 0.35 to 0.52 for optimizing the achievable capacity with least interference in MCST scheme.

The simulation results in Figure. 4.13 show the average achievable capacity of 4-node FD network with two BFD transmission. Under CT, the network can achieve 46.85 Mbps whereas ST can achieve 77.77 Mbps. Under the mixture of concurrent and sequential transmissions, the network capacity

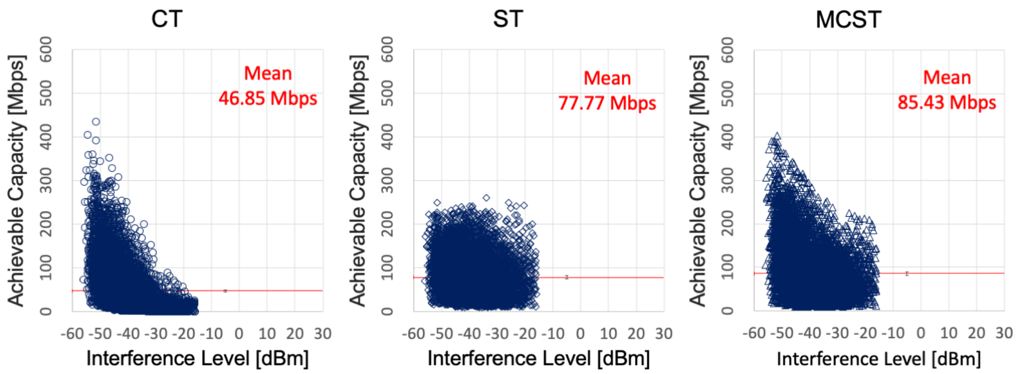

Figure 4.13: Quantitative comparison results of simultaneous transmission in a 4-node FD network with BFD transmissions

can achieve up to 85.43 Mbps and the achievable capacity is better than the other type of transmissions over 80% of CT and around 10% of ST.

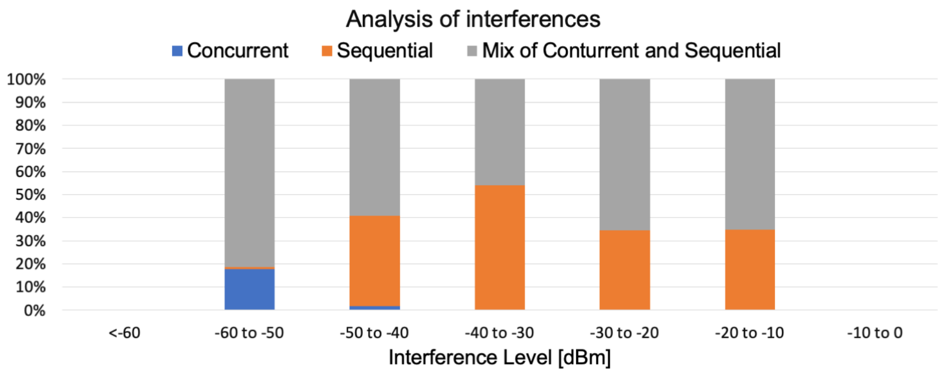

Figure 4.14: Effect of total interference power in a 4-node FD network with BFD transmissions

The effect of the interference level of BFD transmissions to the network capacity is illustrated in Figure. 4.14. As we can see, to achieve a higher network capacity, MCST has a higher possibility than the other two simultaneous transmissions. By this way, based on the result of the numerical studies with 4-node FD network, MCST can be defined the optimal transmission scheme since it always brings the better network capacity than the other two simultaneous transmissions.

Figure. 4.15 discusses the effect of time fraction of concurrent transmission

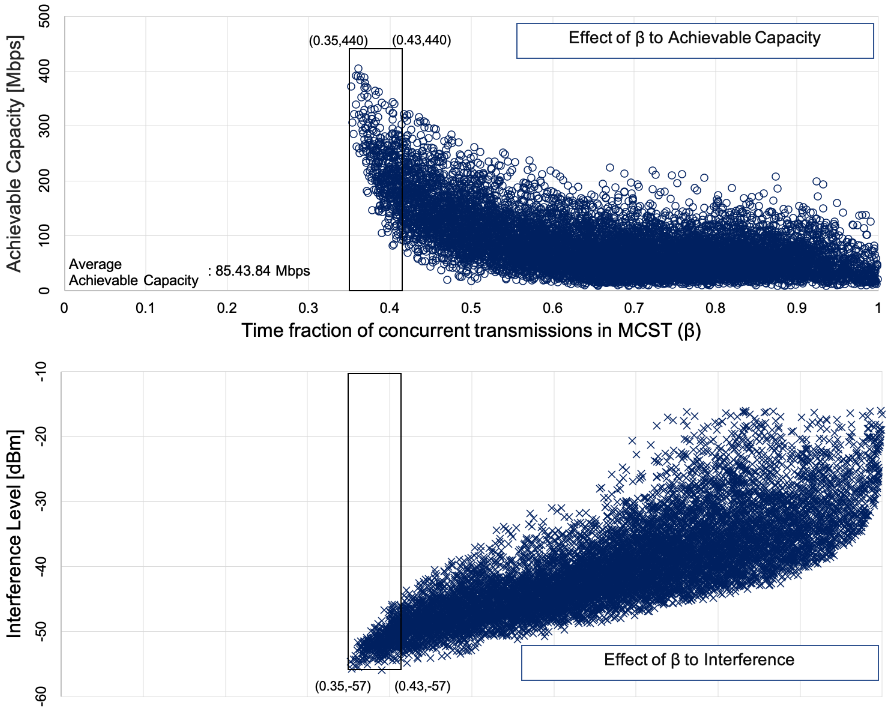

Figure 4.15: Time fraction of concurrent transmission in MCST in BFD network

to achievable capacity and interference in term of dBm in MCST scheme. As we can see that, similar to FD network with RFD transmissions, the achievable capacity reduces with high interference when β close to 1. The interference is very low and achievable capacity is better in the first 10 percent of β as shown in the figure with the square box. Therefore, β should be around 0.35 to obtain the optimal achievable capacity of the transmission in the FD networks.

The Table. 4.3 summarizes the simulation results of the 4-node network with random topology for comparisons between HD network and FD networks with RFD transmissions and BFD transmissions. Under the same setting with 10,000-time simulation, as we can see that the capacity of the FD network is greater than HD for any type of transmissions. Besides, for both of the network, HD and FD with RFD and BFD transmissions, MCST always brings the better network capacity than other two transmissions. However, the interference power in the FD network is still higher than the one in the

Table 4.3: Simulation Results of Three Different Transmission Schemes for Random Topology

Transmission Mode	Average Total Interference Power [dBm]	Average Achievable Capacity [Mbps]			Average Transmit Power
		CT	ST	MCST	
HD	-45.94	30.62	38.89	47.65	0.2
BFD	-40.11	46.85	77.77	85.43	0.2
RFD	-38.39	47.57	60.93	68.84	0.2

HD network.

The next sections will apply and investigate the power control algorithm described in the previous section 4.2 to mitigate interference power while fulfilling the higher network capacity.

4.4.3 Minimum Transmit Power Control for Minimizing Interference

This section evaluates the MCST scheme with the power control scheme (PCS) to minimize the interference for the purpose of increasing higher achievable capacity. Firstly, the minimum transmit power control (MTPC) mechanism is evaluated with the same simulation settings. According to [45, 46], one of the useful mechanisms to manage inter-node interference or co-channel interference is controlling the total transmit power constraint. Therefore, this research aims to maximize the achievable capacity through power control under the constraints of minimum transmit power to reduce the interference.

The iterative process to control the power of the transmitter is operated by Algorithm 1 with the optimization constraint described in section 4.2.1. By considering the same simulation setting and parameters in Table. 4.2, the following Table. 4.4 demonstrates that the interference power can be mitigated for each of the transmission mode or network by reducing the transmitted power of the nodes of the specified network topology in Figure. 4.5.

For the fixed location of the 4-node network in Figure. 4.5, the power control scheme with MTPC mechanism can bring down the interference level of the transmission from -45.62 dBm to -45.67 dBm in FD network with BFD transmissions. Besides then, interference level from -47.04 dBm in FD network with RFD transmission is reduced to -47.51 dBm whereas MTPC can bring down from -49.95 dBm to -50.12 dBm in HD network.

Table 4.4: Simulation Results of 4-node Fixed Topology with Minimum Transmit Power Control Mechanism

Transmission Mode	Average Total Interference Power [dBm]	Average Achievable Capacity [Mbps]			Average Transmit Power
		CT	ST	MCST	
HD	-50.13	2.58	6.68	6.48	0.11
BFD	-45.67	12.66	21.98	22.05	0.18
RFD	-47.51	24.64	29.61	31.20	0.18

The following Figure. 4.16 concludes the achievable capacity of the 4-node networks with MTPC as the quantitative comparison of the transmissions. The simulation results of Figure. 4.16(i) shows that the capacity of the HD network is 20.91 Mbps under CT while ST can provide 26.12 Mbps. Besides, the network can achieve up to 29.03 Mbps capacity through MCST with MTPC mechanism under the constraints of the minimum transmitted power.

Under CT, the FD network with BFD transmissions can give 46.19 Mbps while 76.38 Mbps by ST in Figure.4.16(ii). By controlling the power of the transmitting nodes, the network capacity can be maximized up to 84.18 Mbps with MCST scheme. Besides that, with simultaneous transmissions schemes, the achievable capacity of CT is 39.12 Mbps and ST is 52.91 Mbps in FD network with RFD transmissions. By taking the advantages of both concurrent and sequential transmissions, MCST achieves 55.57 Mbps with MTPC mechanism as shown in Figure. 4.16(iii).

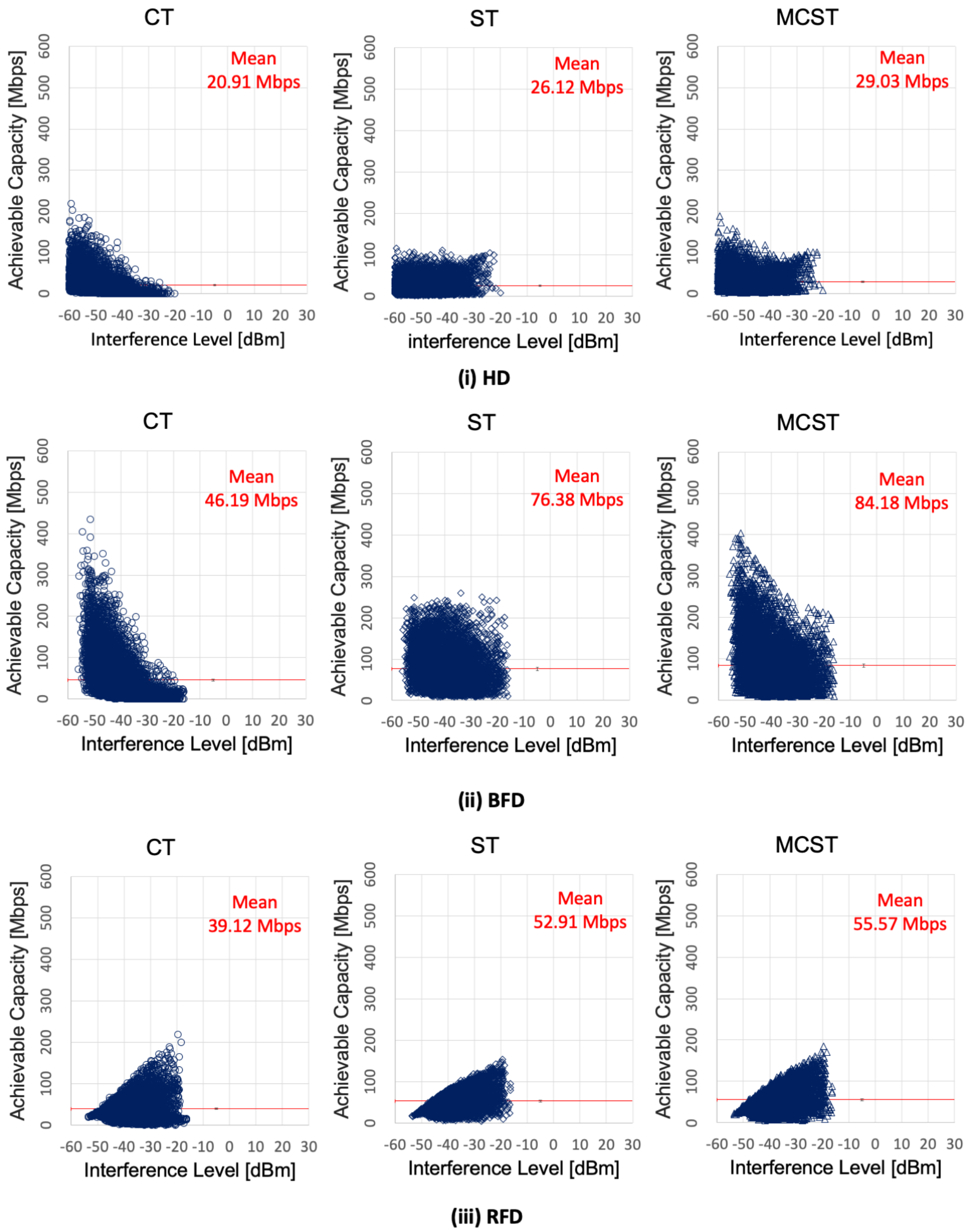

Figure 4.16: Simulation results of three transmission schemes in 4-node networks with MTPC mechanism

Table 4.5: Simulation Results of 4-node Random Network with Minimum Transmit Power Control Mechanism

Transmission Mode	Average Total Interference Power [dBm]	Average Achievable Capacity [Mbps]			Average Transmit Power
		CT	ST	MCST	
HD	-49.83	20.91	26.11	29.03	0.13
BFD	-40.37	46.18	76.38	84.18	0.19
RFD	-38.57	39.12	52.91	55.57	0.18

Table. 4.5 summarizes the MCST scheme with MTPC mechanism under the constraints of the minimum transmitted power to manage the co-channel interference. By comparing with Table. 4.4, we can see that the interference level can be reduced by controlling the transmit power. Since the transmit power is adjusted with the constraints of 4.2.1, it reduces the coverage of the transmission as well as the interference power and affects the achievable capacity of the network. However, MCST with MTPC mechanism still provides a better achievable capacity than the other two transmissions, ST and CT, for HD network and FD network with BFD and RFD transmissions.

The effect of interference in the HD and FD networks is analyzed as the level with the unit of dBm in Figure. 4.17. According to the assumption and system model in the 4-node networks, although the MCST can achieve the higher achievable capacity than the other two transmissions in HD network, if the level of interference is very low, the spatial reuse with the CT may bring the better achievable capacity. However, in the topology with high interference level, MCST provides a better capacity in HD network. Therefore, we can conclude that, in HD network, the capacity of MCST depends on the position of the wireless nodes. It means that the interference is high in the dense environment and MCST is better to apply for achievable capacity gain.

Even in the FD network, MCST most likely to provide the higher achievable capacity with BFD transmissions, it depends on the density of the network to achieve the higher capacity for RFD transmissions. Because RFD acts as the primary receiver from the primary transmission and forwards to the second receiver as the secondary transmitter, the level of interference becomes the considerable factor in the dense environment. Therefore, we can

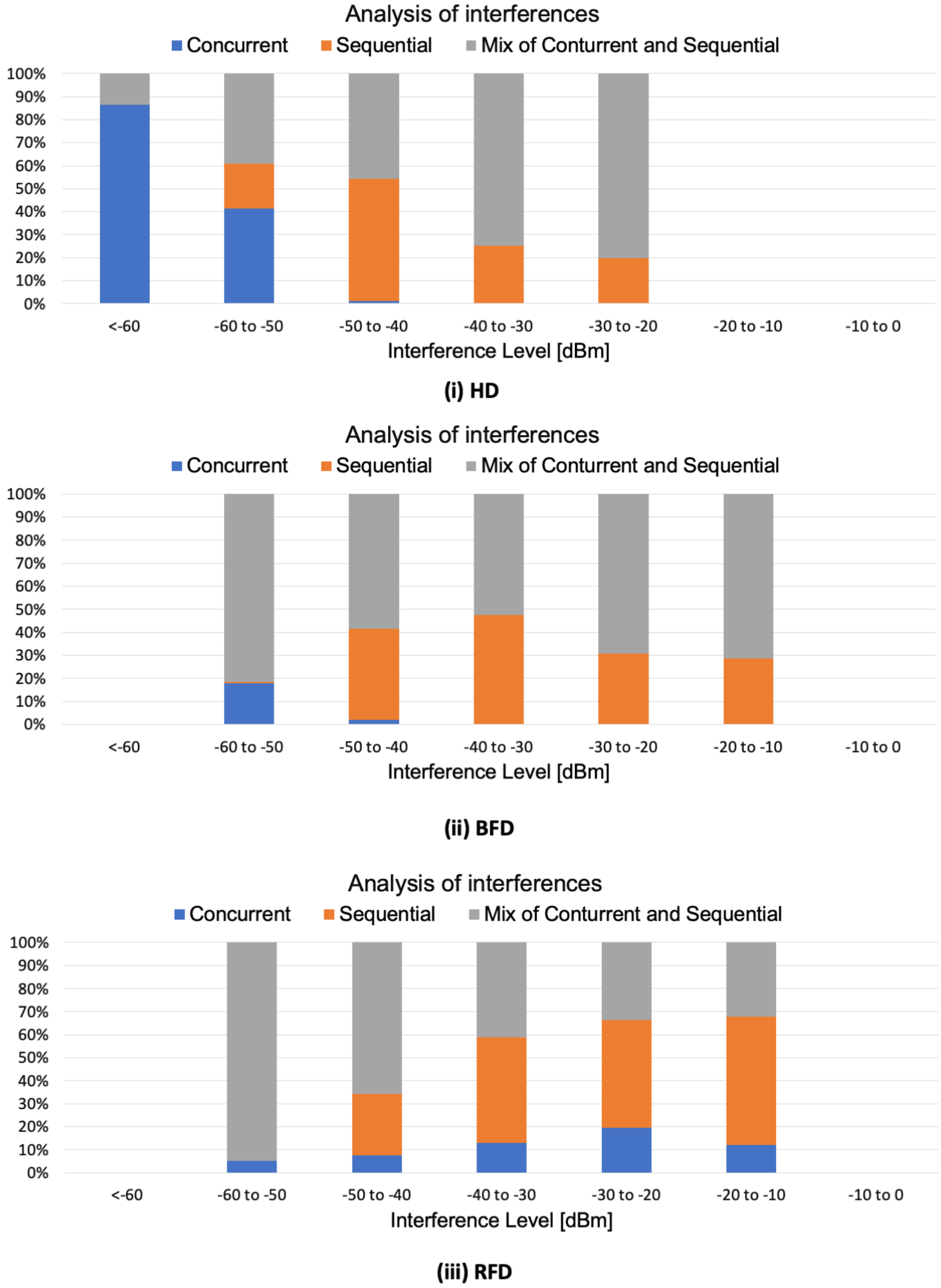

Figure 4.17: Effect of total interference power in 4-node networks with MTPC mechanism

conclude that the MCST scheme with MTPC mechanism should be applied in the FD network with RFD transmission by the time the interference level is low.

4.4.4 Minimum Interference Power Control for Minimizing Interference

As the second transmitted power control mechanism, the control function of the transmitted power based on minimum interference during transmissions, MIPC, is investigated to MCST scheme. To obtain the maximum achievable capacity with the least amount of interference, the power of the transmitting node is adjusted iteratively as discussed in section 4.2.2 with MIPC mechanism.

For the sake of numerical study with fixed topology in Figure. 4.5, with the same simulation setting and system model described in the previous section, Table. 4.6 shows the achievable capacity that is achieved by ST, CT and MCST schemes for HD and FD in the 4-node wireless network.

Table 4.6: Simulation Results of 4-node Fixed Topology with Minimum Interference Power Control Function

Transmission Mode	Average Total Interference Power [dBm]	Average Achievable Capacity [Mbps]			Average Transmit Power
		CT	ST	MCST	
HD	-50.13	1.87	7.03	6.63	0.10
BFD	-47.11	36.52	41.37	50.24	0.42
RFD	-49.46	8.55	6.23	11.42	0.18

As we can see that the interference power of the FD network can be reduced 3.3% of interference level with BFD transmissions by applying the MCST with the MIPC and 5% of interference with RFD transmissions in the 4-node FD fixed network. The difference between MTPC and MIPC is that MTPC controls the power of the transmitting node based on the minimum transmit power constraint whereas MIPC adjusts the power by focusing on minimum interference power. Consequently, the transmit power in MTPC function is always lower than the constraints of maximum transmit power while there is no power constraint in MIPC but minimum interference power.

Table 4.7: Simulation Results of Three Transmission Schemes for the 4-node Network with Fixed Topology

Transmission Mode	Power Control Scheme	Average Total Interference Power [dBm]	Average Achievable Capacity [Mbps]			Average Transmit Power
			CT	ST	MCST	
HD	w/o	-49.95	12.48	12.28	18.56	0.2
	MTPC	-50.13	2.58	6.68	6.48	0.1
	MIPC	-50.14	1.87	7.03	6.63	0.1
BFD	w/o	-45.62	14.21	24.58	25.11	0.2
	MTPC	-45.67	12.66	21.98	22.05	0.18
	MIPC	**-47.11**	36.52	41.37	50.24	0.42
RFD	w/o	-47.04	25.63	21.64	26.71	0.2
	MTPC	-47.51	24.64	29.61	**31.20**	0.18
	MIPC	**-49.46**	8.55	6.23	11.42	0.18

Table. 4.7 summarizes the simulation results of three simultaneous transmissions in three transmission mode, HD, BFD and RFD transmission, with and without power control scheme. As we can see that, in the fixed topology 4-node network, MCST the power control scheme always give the better network capacity in all of the three transmission modes as well as mitigate the interference by MTPC and MIPC mechanisms.

The numerical simulations to evaluate the MCST with MIPC is discussed in the following figures with the same setting and model by running 10,000 times simulations. It will show the achievement of capacity and how much the interference can be reduced with three modes of transmissions. Figure. 4.18 describes the simulation results of three different transmission schemes in HD and FD networks. We can see that MCST with MIPC mechanism reduces the interference and provides a better achievable capacity compared to the other two transmissions.

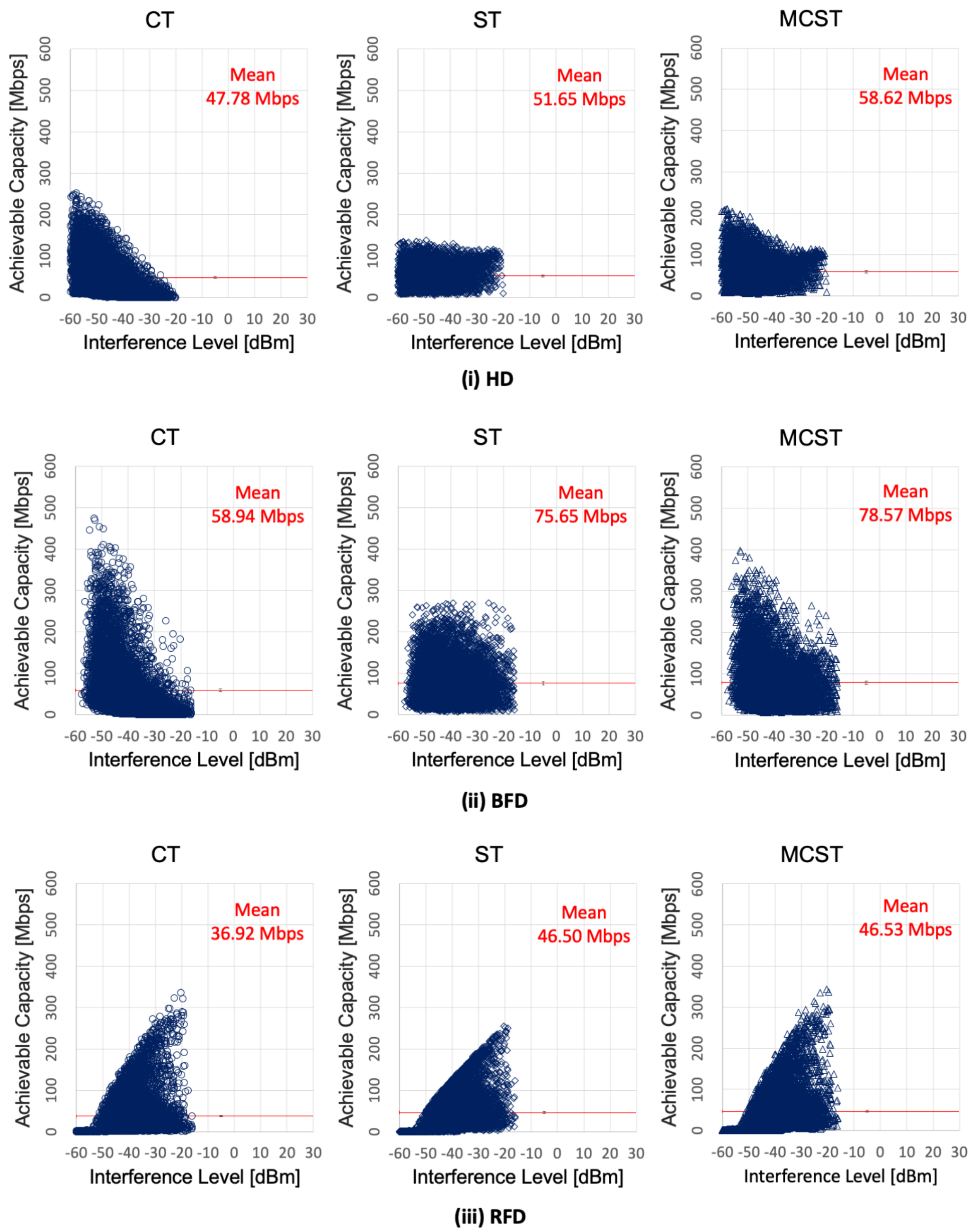

Figure 4.18: Simulation results of three transmission schemes in 4-node networks with MIPC mechanism

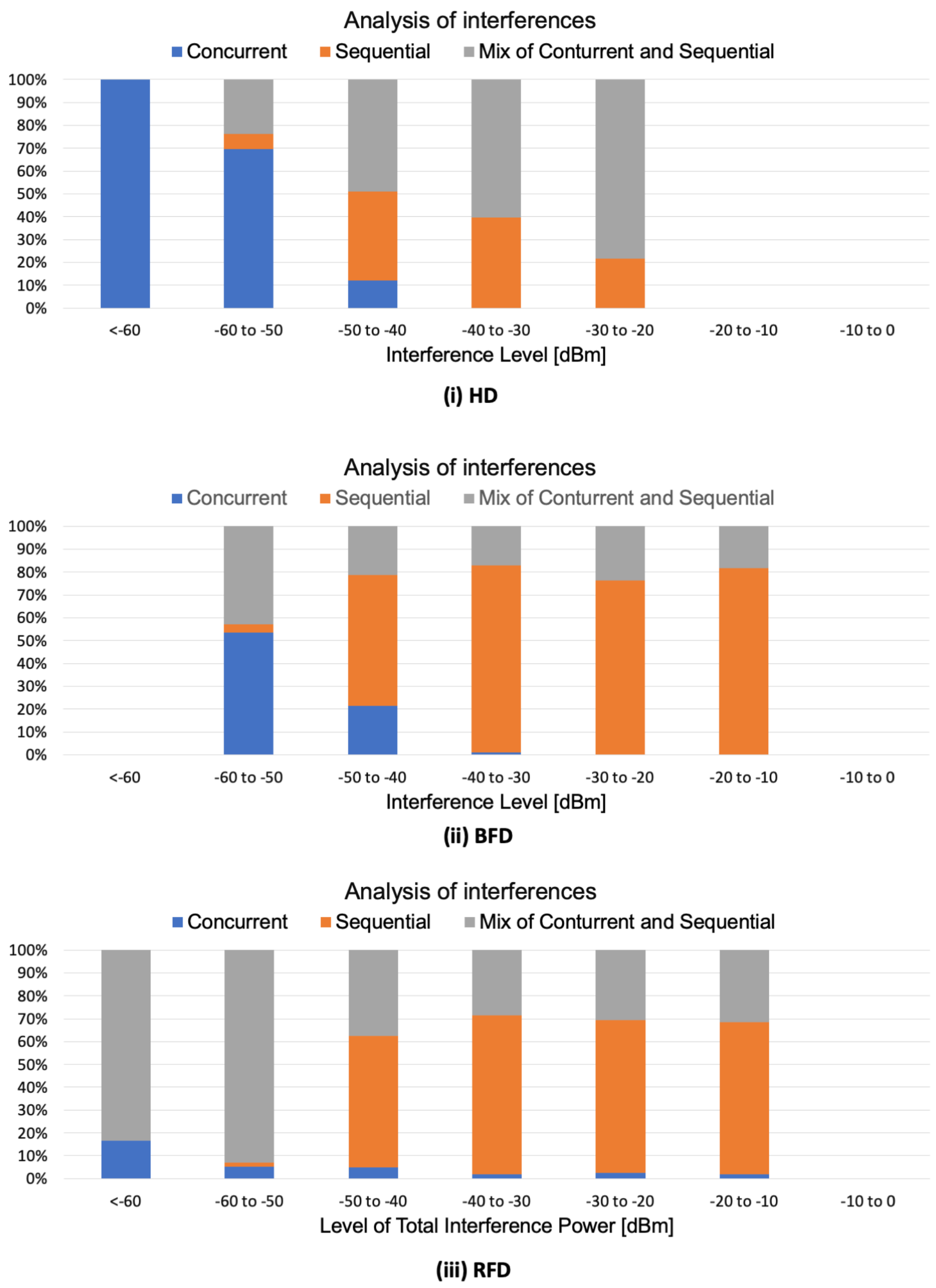

Figure 4.19: Effect of total interference power in 4-node networks with MIPC mechanism

Figure. 4.19 shows the effects of interference power for achieving a higher capacity of the networks. The results show MCST can give a better capacity in high interference HD network. However, in the FD network, by controlling the transmitted power with least interference, MCST with MIPC scheme gives a better achievable capacity of the network.

Table 4.8: Simulation Results of Three Transmission Schemes for 4-node Network

Transmission Mode	Power Control Scheme	Average Total Interference Power [dBm]	Average Achievable Capacity [Mbps]			Average Transmit Power
			CT	ST	MCST	
HD	w/o	-45.94	30.62	38.89	47.65	0.20
	MTPC	-49.83	20.91	26.12	29.03	0.13
	MIPC	-46.78	47.78	51.65	58.62	0.61
BFD	w/o	-40.11	46.85	77.77	85.43	0.2
	MTPC	-40.37	46.19	76.38	**84.18**	0.19
	MIPC	**-40.41**	58.94	75.65	78.57	0.52
RFD	w/o	-38.38	47.57	60.93	68.84	0.2
	MTPC	-38.57	39.12	52.91	**55.57**	0.18
	MIPC	**-41.42**	36.92	46.50	46.53	0.22

Table. 4.8 summarizes the simulation results of three simultaneous transmissions in three transmission mode, HD, BFD and RFD, with and without PCS. With a power control scheme, the transmission schemes with MTPC mechanism for mitigating interference by controlling the transmit power of each transmission is firstly evaluated. By choosing the minimum transmit power with the aid interference management, the total interference power is reduced as well as keeping high achievable capacity by MCST scheme. Besides that, transmission schemes with MIPC mechanism that optimizes the rate of transmissions by choosing the minimum total interference power of each transmission is evaluated.

Through the simulations with the 4-node topology, the total interference mitigation can be achieved up to about 8.5% in HD network and about 8% in FD network. Although both MTPC and MIPC are mechanisms of the power control scheme, we can see that MIPC can mitigate the interference than MTPC whereas MTPC brings a better achievable capacity as well as low interference. We can see that MCST always provides a better achievable throughput compared to the other two transmissions. Therefore, we can conclude that MCST is an optimal transmission scheme for wireless networks.

4.5 Performance Evaluations

To evaluate the performance of the MCST scheme, the following simulations and discussions with different node density, i.e., 20, 40, 60, 80 and 100 in the 500 m × 500 m network with the same parameters is conducted as the second scenario.

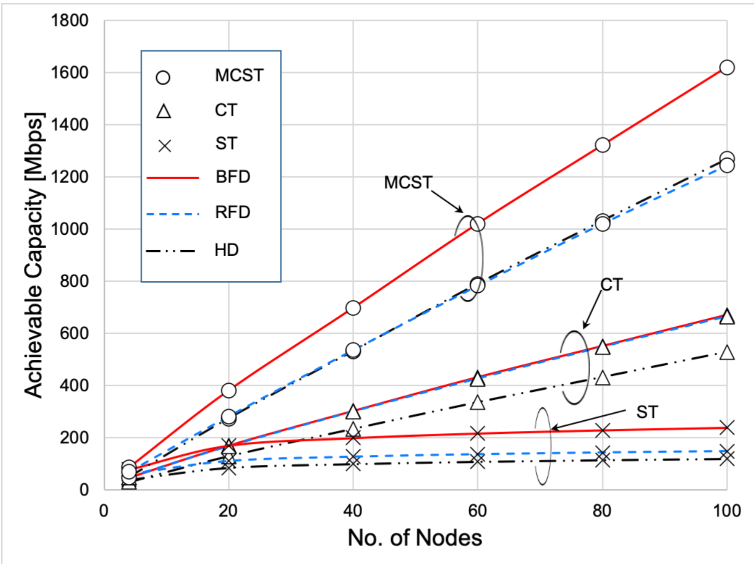

Figure 4.20: Achievable capacity with different transmission scheme and transmission mode

By averaging the 10,000 times simulations, Figure. 4.20 shows the achievable capacity of the simultaneous transmissions in HD and FD networks without the power control scheme, i.e., MTPC and MIPC. With the same simulation setting and parameters, we can see that the proposed MCST scheme always give a better achievable capacity than the other two transmissions. In the FD network, BFD and RFD can achieve about 8 times and

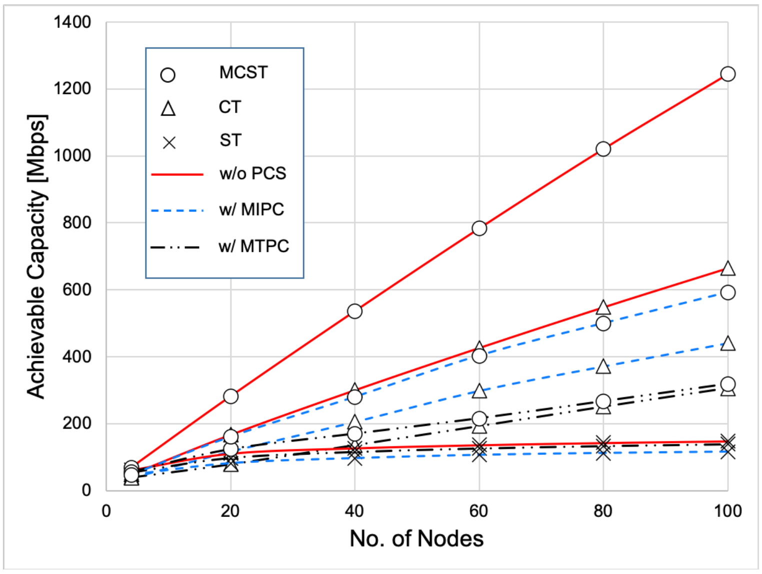

Figure 4.21: Achievable capacity with different transmission scheme and power control scheme in FD with RFD wireless networks

5 times capacity achievement compared to ST, respectively when the number of nodes is 100. FD with BFD gives advantage than RFD for applying MCST scheme. In the RFD transmission, the relay nodes receive from the primary transmission and forward to the secondary receiver. Consequently, the interference of the transmission is getting increase when the nodes become denser in the network.

Figure. 4.21 discusses the achievable capacity of the FD network with RFD transmission regarding the power control schemes. We can see that the power control scheme with MIPC approach gives the advantage to achieve higher achievable capacity than MTPC approach. The twice number of FD transmissions affects the mesh interference in the dense network. Therefore, mitigation the interference gives an advantage to the achievable capacity in the dense network.

Besides, the effect of the interference of the dense network is discussed. Figure. 4.22 shows that the interference is getting an increase in the dense network and the gap between FD and HD networks in term of interference power with a unit of Watt. Since the interference is the negative effect to the communication, the lower is the better in the Figure. 4.22. It shows that interference power can be reduced by MIPC in FD network with RFD trans-

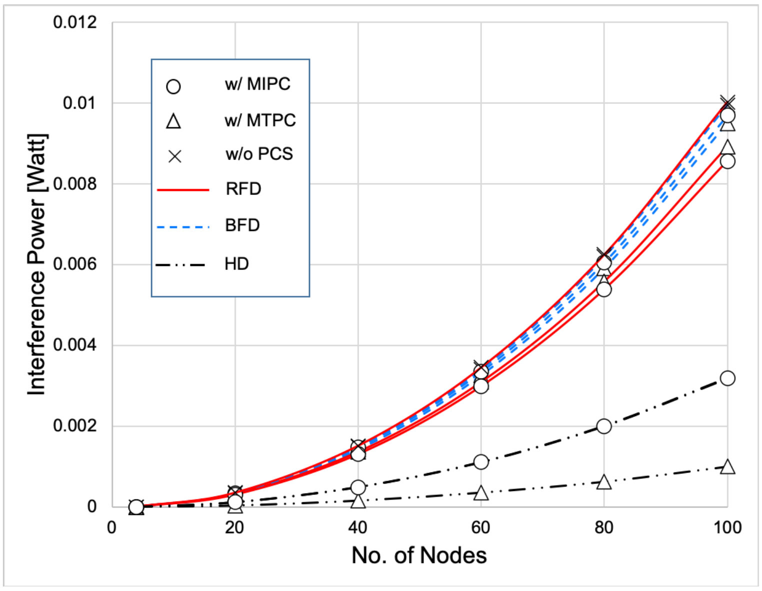

Figure 4.22: Interference power with different transmission scheme and transmission mode

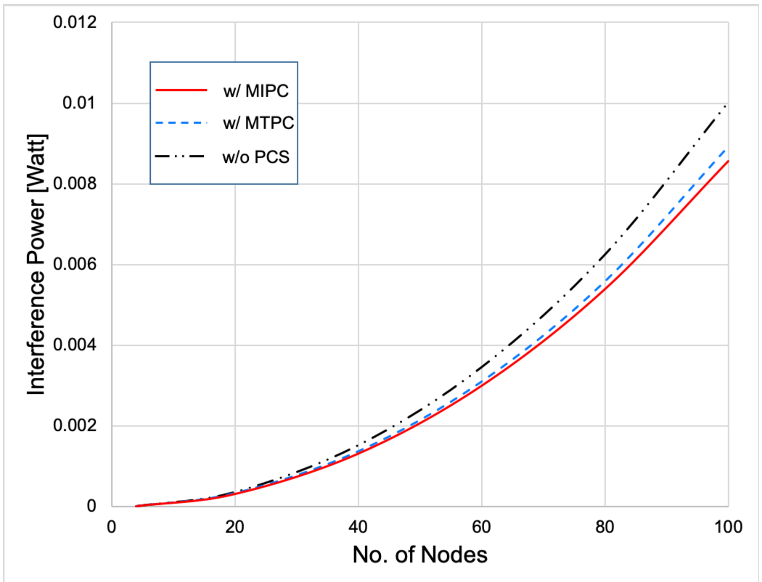

Figure 4.23: Interference power with different power control scheme in FD with RFD wireless nodes

missions whereas MTPC brings an advantage to minimize the interference in BFD transmission when the network becomes denser. Regardless of the interference power, RFD gives more advantage than BFD when MCST is applied, i.e., interference power can be reduced up to 4% in BFD transmissions FD network whereas up to 17% for RFD when the number of nodes is 100.

Figure. 4.23 discusses the interference power with the different power control scheme in the FD network with RFD transmissions. Under FD network with RFD, MCST that uses MIPC approach always gives less interference power than MTPC. According to the assumption and simulation settings, MIPC and MTPC can reduce 17% and 12% of the interference, respectively compared to the MCST without PCS when the number of nodes is 100 in the FD network with RFD transmissions.

What is more, as the third simulation scenario, the 20-node network topology with different transmit power is discussed, i.e., 13 to 33 dBm or 0.002 to 0.2 Watt.

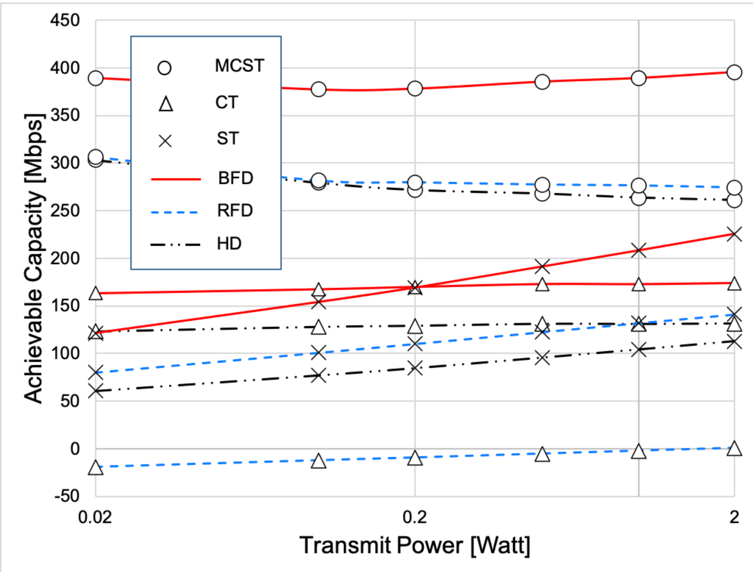

Figure 4.24: Achievable capacity with different transmission scheme and transmission mode

Figure. 4.24 describes the influence of transmitted power to the achievable capacity by considering 20-nodes networks. We can see that MCST always gives the better achievable capacity to either in the network with low transmitted power nodes or higher transmitted power. However, this numerical simulation study concludes that, regardless of the transmit power, the achievable capacity of the wireless network does not depend on the transmission scheme, i.e., ST, CT and MCST. It does depend on the transmission modes, i.e., HD, BFD and RFD. According to the assumption with different transmit power, BFD transmissions always guarantees to achieve high capacity in FD network. From this fact, we can conclude that implementing and considering the transmission mode is very important for future wireless communication.

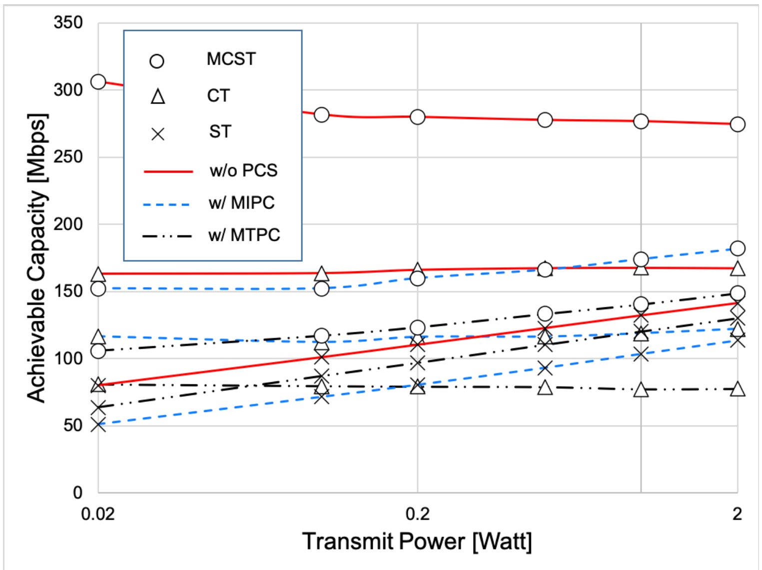

Figure 4.25: Achievable capacity with different transmission scheme and transmission mode in FD network with RFD transmissions

And the application of PCS in the FD network with RFD transmissions is described in Figure. 4.25 and shows the benefits of MIPC to increase the achievable capacity of the 20-node networks with RFD transmissions. We can see that MCST brings a better achievable capacity with either PCS or not. With PCS, MIPC is better than MTPC because MIPC can reduce interference than MTPC. The effect of interference power in terms of watt due to the transmitted power is illustrated in Figure. 4.26. MIPC reduces the interference power of the RFD to be lower than BFD in FD network. Therefore, based on the finding, we can conclude that MCST with MIPC mechanism may give the lower interference power in the FD network with high transmitted power wireless nodes. Therefore, we can conclude that MTPC mechanism provides high achievable capacity and MIPC mechanism

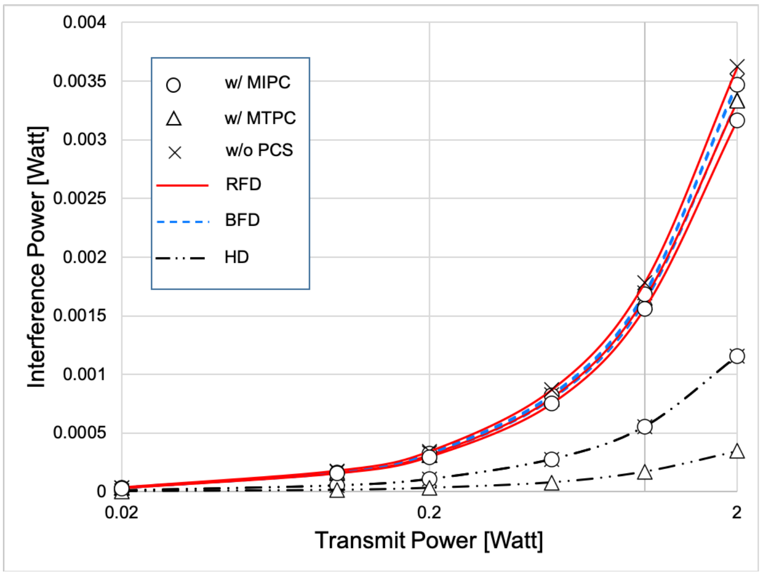

Figure 4.26: Interference power with different transmission mode and power control scheme

bring keep high achievable capacity as well as reduces more average total interference power compared to MTPC algorithm.

4.6 Summary

This chapter has presented a novel transmission scheme with a mixture of concurrent and sequential transmissions in the wireless networks. To maximize the achieving capacity and reduce interference power, the power control scheme under the constraints of minimum transmitted power (MTPC) and minimum interference power (MIPC) has cooperated with the proposed MCST scheme. Three scenarios with numerical simulations are conducted to evaluate the proposed transmission scheme. As the first scenario, the basic 4-node network topology with fixed transmit power, the network coverage with different node density for the second scenario and the 20-node network topology with different transmit power is conducted as the third scenario.

The simulations are evaluated, discussed and compared to evaluate the performance of the network in terms of achievable capacity and interference power. According to the assumption and simulation settings, the achievable capacity of the FD network can be improved with the proposed transmission scheme up to around 8 times of the capacity with the sequential transmission when the number of nodes is 100 with BFD transmissions and over 5 times of the capacity improvement in FD network with RFD transmissions. And then, the interference power can be reduced up to 4% for BFD whereas up to 17% for RFD when the number of nodes is 100 in the FD network. Besides that, regardless of the transmit power, the achievable capacity of the network depends on the transmission modes and the FD network can achieve the improvement about 2.5 times of the achievable capacity with BFD transmissions. Besides that, this thesis showed the mitigation of the interference can be achieved up to 80% in FD network by applying the proposed MCST scheme with MIPC approach power control mechanism. Regardless of the implementation, the time fraction of the proposed MCST is suggested to be around 3.5 to 4.5 to achieve a higher achievable capacity with the minimum interference.

Chapter 5

Conclusion

5.1 Concluding Remarks

This research has focused on the interference issues of wireless communication, especially, in FD communication. With the motivation of the increasing interference in FD transmission and with the objective of to ensure high achievable capacity, a cooperative MAC with a novel transmissions scheme, a mixture of concurrent and sequential transmissions (MCST), is proposed.

Firstly, the performance of HD and FD network with simultaneous transmission, sequential transmission and concurrent transmission, is revised and discussed the pros and cons of the network. With the motivation of lack complete research methodology to study the performance of simultaneous transmission in FD network, the system model and the complete methodology of the research are discussed in detail as the first objective of the research. Then, the research problem of co-channel interference is formulated by discussing the performance of HD and FD network with the performance of achievable capacity, interference power and efficient capacity (EC) which is the capacity of the network with the coverage of interference. According to the assumption and simulation settings, the achievable capacity gain of the FD network can improve around 287 Mbps than HD network in 200-node topology. However, the power of interference occurred in FD network can reach up to over twice of the interference occurred in the HD network.

To achieve better performance with high achievable capacity and least interference of the transmissions in FD network, MCST is proposed for better achievable capacity for simultaneous transmissions and for mitigating the average total interference power of the transmissions by applying power control schemes. The theoretical and numerical studies of the proposed transmissions are discussed and described to evaluate the performance of the wireless network. What is more, the performance of the proposed transmission scheme is evaluated in the dense network with multiple wireless nodes and discuss the findings. The effect of the transmitted power to the achievable capacity and the interference power is also discussed and showed the benefits of the proposed transmission scheme.

According to the numerical study, the achievable capacity of the FD network can be improved with the proposed transmissions scheme up to around 8 times of the achievable capacity with sequential transmissions when the number of wireless nodes is 100 with BFD transmissions and in RFD transmissions network, the achievable capacity gain can be increased about 5 times of the capacity with sequential transmissions. And then, the interference power can be reduced up to 4% for BFD transmission whereas up to 17% for RFD transmission when the number of nodes is 100 in the FD network. Besides, the achievable capacity of the FD network can increase about 2.5 times regardless of the transmit power. For the mitigation of the interference, this thesis shows that the mitigation of the interference can be achieved up to 80% in FD network with 4-node topology by applying the proposed MCST scheme with MIPC approach power control mechanism. And then, regardless of the implementation of the proposed transmission scheme, the time fraction is suggested to be around 3.5 to 4.5 for achieving the higher achievable capacity with the minimum interference. As a result, this thesis shows the achievement of MCST in terms of capacity and reduction of interference and concludes that MCST with MIPC reduces more average total interference power while MCST with MTPC provides a better capacity to the wireless transmission in FD wireless networks.

5.2 Contributions

For capacity achievement in FD network, the previous research mainly focuses on self-interference (SI) cancellation and have investigated the scheduling techniques, power controlling techniques to mitigates the interference and cancelling the interference of the transmitting with successive interference cancellation (SIC) in the receiver side. Although controlling the transmit power is one of the useful methods to mitigate the interference, the transmitting capacity of the intended signal such as SINR, received signal strength indication (RSSI) can be affected because of the low transmit power. Since there is no interference-free medium for wireless communication, it is important to consider to reduce the interference power during transmission. However, it is also essential to keep higher transmit capacity to cope with ever-increasing capacity demand for wireless communications.

In this thesis, we defined the complete research methodology to study the performance of HD and FD network and proposed a new transmissions scheme with two power control scheme to minimize the interference of the transmission. They are minimum transmit power control (MTPC) mainly focus on minimum transmit power and minimum interference power control (MIPC) mainly focus on minimum interference power of the transmission. By applying the proposed power control scheme to the cooperative MAC, this research not only improves the achievable capacity of the network but also mitigates the total interference level.

5.3 Future Works

The future directions of the research can be extended as the following:

- the medium access control (MAC) performance of the proposed MCST scheme is further investigated by considering the packet collision and packet loss by using the Markov Chain model.
- the feasibility of the proposed MCST scheme is examined when the mixture of HD and FD nodes in the environments of dense wireless networks or multihop wireless networks.
- the adaptive implementing transmissions of the FD network by combination the transmission mode and the proposed scheme is considered for capacity improvement.

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List of Publications

1. Khun Aung Thura Phyo, LIM Yuto, and TAN Yasuo. Study of Temporally Coupled Framed Access Scheme in Slotted ALOHA. In *2019 International Conference on Advanced Information Technologies (ICAIT)*, pages 1–6. IEEE, 2019.

2. Khun Aung Thura Phyo, LIM Yuto, and TAN Yasuo. On the Capacity of Full-Duplex Wireless Networks with Mixture of Concurrent and Sequential Transmissions. In *23rd International Symposium on Wireless Personal Multimedia Communications (WPMC2020)*, Okayama, October 2020. **(Submitted)**.