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MASTER'S THESIS

FULL DUPLEX DEVICE-TO-DEVICE COMMUNICATION IN CELLULAR NETWORKS

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ABSTRACT

To address the problem of radio spectrum congestion due to increasing demand for wireless communications services, cellular communication systems are going towards small cells with small transmit powers. At the same time, in-band full-duplex (FD) radio design has gained considerable attention due to achievements in signal processing that can make design of full-duplex radios possible for systems with small transmit power. In theory full-duplex radios can double the spectral efficiency of the system. However existing radios still do not provide enough self-interference (SI) cancelation to be used in large transmit power systems. Meanwhile device-to-device communication (D2D) is seen as a promising idea to increase the performance of wireless networks. In D2D, users in vicinity communicate directly without going through base station. So far, very limited work has been carried out to study the applicability of available full-duplex radios in D2D. In this thesis, we investigate full-duplex D2D and amount of self-interference cancelation required in D2D in cellular systems.

While D2D users share the same radio resources with cellular users, both cellular and D2D pair will receive interference. Resource allocation and interference management become crucial in D2D communication. Both uplink and downlink resource sharing are considered. In uplink resource sharing, to handle the interference on the base station power control is used in D2D transmitter. To deal with the interference at D2D receivers from cellular user's uplink transmission, interference-limited-area (ILA) method is used to select users with negligible interference on them. When D2D pair is using downlink resources of cellular users, users receive interference from D2D transmissions. Limiting this interference is also done using ILA method. On the other hand, for the purpose of resource sharing, the user with smallest downlink transmit power is selected to minimize the interference on D2D receivers.

Half-duplex (HD) and full-duplex D2D scenarios are considered in both uplink and downlink resource sharing. Simulations show that how much of self-interference cancelation is required in different scenarios. Effects of the numbers of the selected users for resource sharing, distance between D2D users and also inter-cell interference is studied. It can be concluded that using available full-duplex radios in D2D communication can almost reach the theoretical doubling of throughput in full-duplex mode compared to half-duplex mode.

Keywords: Full-duplex radios, Device-to-Device communication

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FOREWORD

The focus of this thesis was to study the possibility of using full-duplex radios in device-to-device communication. This thesis was carried out in Centre for Wireless Communications (CWC) at university of Oulu and funded partly by CRUCIAL and partly by 5Gto10G projects. I would like to thank my supervisor Docent Premanandana Rajatheva for his great idea and support throughout this thesis. I also would like to thank Dr. Pekka Pirinien and Prof. Matti Latva-aho for giving me the opportunity to work in CWC.

LIST OF ABBREVIATIONS AND SYMBOLS

$R_{T,HD}$	Total system throughput with HD D2D link
R_C	Throughput of cellular users
$R_{Cj,HD}$	Throughput of cellular users that are sharing resources with HD D2D
$R_{D,HD}$	Throughput of HD D2D link
$R_{T,FD}$	Total system throughput with FD D2D link
$R_{Cj,FD}$	Throughput of cellular users that are sharing resources with FD D2D
$R_{D,FD}$	Throughput of FD D2D link
γ_i	SINR of cellular user i
$\gamma_{j,HD}$	SINR of cellular users j in HD D2D mode
$\gamma_{j,FD}$	SINR of cellular users j in FD D2D mode
γ_{Dl}	SINR of D2D user l
$G_{ci,BS}$	Channel gain between base station and cellular user i
$G_{l,BS}$	Channel gain between base station and D2D user i
D_l	D2D user l
CU_i	Cellular user i
CU_j	Cellular user j
P_{RC}	Received signal power level at base station
P_{ci}	Transmit power of cellular user i
P_j	Transmit power of cellular user j
P_{Dz}	Transmit power of D2D user z
P_{cmax}	Maximum transmit power of cellular user
P_{dmax}	Maximum transmit power of D2D user
$I_{Di,cj}$	Interference from D2D user i to cellular user j
I_l	Residual of self interference at D2D user l
$G_{j,BS}$	Channel gain between cellular user j and base station
G_D	Channel gain between D2D users
G_0	Channel gain at the distance of one meter
A_i	Interference limited area of user i
d_i	Radios of interference limited area of user i
β	Self-interference cancelation constant
δ_B	Interference-over-signal threshold at base station
δ_{ILA}	Interference-over-signal threshold at D2D receiver
α	Path loss exponent
S_i	Sub-carrier i
N_0	White Gaussian noise

FD	Full-duplex
HD	Half-duplex
D2D	Device-to-device
FDD	Frequency division duplex
TDD	Time division duplex
TX	Transmitter
RX	Receiver
RF	Radio frequency

SI	Self-interference
ADC	Analog to digital converter
MIMO	Multiple input multiple output
BALUN	Balanced/unbalanced transformer
dB	Decibel
dBm	Decibel-milliwatts
MIDU	Multiple input multiple output full-duplex
CSI	Channel state information
CSIT	Channel state information transmitter
SNR	Signal to noise ratio
SIR	Signal to interference ratio
SINR	Signal to interference plus noise ratio
BS	Base station
UE	User equipment
LTE	Long term evolution
LTE-A	Long term evolution advanced
ISR	Interference-over-signal ratio
ILA	Interference-limited-area
ICI	Inter-cell interference
PFR	Partial frequency reuse

1. INTRODUCTION

Increasing demand for wireless communications services is leading to the congestion of radio spectrum. Since radio spectrum is an expensive and scarce resource, better utilization of radio resources becomes crucial. With limitations on radio spectrum and the need to support very large number of users and rich multimedia services like high quality video delivery, new technologies are required. Technologies like multiple-input multiple-output (MIMO) systems, cognitive radio, large antenna arrays, in-band full-duplex (FD) radios, device-to-device communication (D2D) are among new paradigms that are studied for increasing spectral efficiency of wireless systems.

Full-duplex radio design has gained a lot of interest recently because of its potential to double the spectrum efficiency of the systems. In conventional two way wireless communication systems, one node can not transmit and receive at the same time on the same frequency band. The reason behind is that the node will receive its own transmit signal, which is called self-interference (SI). self-interference can be up to millions of times stronger that the signal of interest, so self-interference will make it impossible to recover the desired signal [1]. Modeling self-interference and solving this problem will lead to doubling the radio spectrum. This has led to several full-duplex radio designs, systems like antenna cancelation [2], balanced-unbalanced transformer (BALUN) [3], two stage antenna cancelation, known as full-duplex MIMO (MIDU) in [4], radio designs at Rice university [5], [6], [7], [8], and most recently single antenna full-duplex radios [9] and full-duplex MIMO [10] are among attempts to build full-duplex radios. So far 110 dB of self-interference cancelation is possible for single antenna and multi antenna systems [9], [10]. Considering these achievements, investigation of possible application areas of available full-duplex radios becomes an interesting topic. Most of the research in this area are focused on full-duplex relaying, or considering ideal full-duplex systems with perfect self-interference cancelation in cellular systems.

Device-to-device communication is also seen as a new technology that can improve the system performance and has wide application areas like cellular offloading, machine-to-machine (M2M) communication, video delivery, relaying, etc. D2D provides spectral and power efficiency and has the potential to improve quality of service in cellular networks [11], [12], [13]. In D2D, users in close proximity communicate directly with each other without going through the base station. Communication between D2D users can be in unlicensed bands such as WiFi or ZigBee, which has the problem of uncontrolled interferences. D2D users can also use licensed cellular bands to communicate, which is more reliable. While using licensed radio resources, D2D users can either have their own dedicated radio resource, or share the radio resource with some other users. The idea of co-sharing the same radio resources between D2D and cellular users leads to higher spectral efficiency. But sharing uplink or downlink resources between cellular and D2D users will result in interference between them. Dealing with this interference is one of the most crucial problems that needs to be addressed in D2D communications. Several interference managements methods to deal with this problem are introduced at [14], [15], [16], [17], [18], [19].

Selecting the user that will be sharing the resources with D2D link is important in interference management. In [20], a new method called interference-limited-area is introduced. In this method, an area in each cell is calculated in a way that interference coming from users on that area to D2D users is negligible. Applying this methods results in controlled interference and less complicated optimization problem.

Since full-duplex radios are available for system with small transmit power, and D2D is for short-range communications with small transmit power, studying the full-duplex requirements to be implemented in D2D communication is necessary. The amount of self-interference cancelation in full-duplex radios that is needed for D2D communication under different scenarios should be studied. The aim of this thesis is to focus on the full-duplex aspect of full-duplex D2D communication and study the possibility of implementing already designed full-duplex radios in D2D communication. Interference effects due to sharing radio resources are investigated and also uplink and downlink resource sharing are considered. Knowing the amount of self-interference cancelation required for D2D communication will make it possible to consider full-duplex radios in future standards of wireless systems.

2. FULL DUPLEX RADIOS

In this chapter we study duplexing schemes and the problem of self-interferene (SI) in wireless radio systems and how it becomes the challenge in in-band full-duplex radio design. Methods to cope with self-interference are introduced and possibility of full-duplex radios is investigated. Availabe full duplex radios and the novel self-interference cancelation mechanisms and technology used in them are explained. Advantages and disadvantages of each of these radios are presented. At the end we look at possible application areas for available full duplex radios and conclusion is made.

2.1. Full-Duplex Radios

2.1.1. Introduction

In wireless communications, transmitted signals attenuate very quickly while traveling in the space. Amount of this attenuation depends on the distance and obstacles in the transmission channel. In two way communication systems, receiver (RX) on one node receives the signal that is transmitted from node's own transmitter (TX). This signal is called self-interference. Since RX and TX on a node are in proximity of each other, self-interferene can be a lot stronger than signal of interest that is coming from another node, which is located far away. If RX and TX of the nodes in two way communication system are operating in the same center frequency at the same time, this self-interferene will make it impossible to recover the signal of interest that can be up to millions of times weaker than self-interferene. To deal with this problem, two way communication systems are using frequency-division-duplex (FDD) or time-division-duplex (TDD). In FDD, RX and TX signals have different center frequencies and a guard band between them, so they don't interfere with each other. In TDD systems, transmission and reception happen in different time slots, with some guard interval between them. Now if one can suppress self-interferene, and make it possible to transmit and receive at the same time on the same frequency band, required spectrum of the system will be half of FDD or TDD. Recently there have been a lot of interest in self-interferene cancelation, and radios that can operate at the same time on the same frequency band are called in-band full-duplex (FD) radios. Figure 1 shows the node model of a full-duplex system.

To make full-duplex communication possible, self-interferene needs to be canceled. The first idea would be that since node knows what is transmitted, it can just subtract it from the received signal and remove self-interferene. But this assumption is not correct since in practice node doesn't know what is transmitted from antenna. Node knows what is transmitted signal in digital domain, but after analog to digital conversion (ADC) and up converting to RF frequency, transmitted signal will have nonlinear distortions plus unknown noise [9]. These nonlinearaties makes it hard to remove the self-interference, so advanced analog and digital signal processing techniqes along with propagation domain interference reduction methods should be applied to reduce the interference.

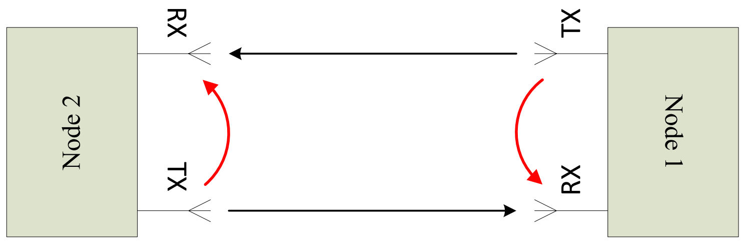

Figure 1: Full-uplex node model with two antennas.

2.1.2. Cancelation Stages

Three different levels of cancelation exists, passive cancelation, active analog and active digital cancelation. Here we explain these three methods.

1. Passive cancelation is done before self-interferene signal is received at RX chain. In the case with one TX and one RX antenna, passive cancelation is the attenuation of signal between the two antennas. Different methods have been proposed to maximize this passive cancelation. Distance between RX and TX, directionality of antenna, material between antennas, or antenna cancelation methods are the factors affecting the amount of passive cancelation [9], [2], [5], [7], [21] . Passive cancelation is not enough to cancel the self-interferene and it should be followed by active analog and digital cancelation.

2. After passive cancelation in done, actively reducing self-interferene in analog domain before the signal reaches the analog-to-digital converter (ADC) is called active analog cancelation. Active analog cancelation can be done either in baseband or carrier frequency.

3. Active digital cancelation is done in digital domain after signal passes through the ADC. Working in digital domain is relatively easier compared to analog domain, but the amount of digital cancellation is limited becuase of the limited dynamic range of the ADC. So for having digital cancelaiton, sufficient amount of reduction should be done before ADC.

2.2. Available Full-Duplex Radios

Several research groups in industry and academia have reported full-duplex radio designs. Different self-interferene cancelation methods have been used and so far up to 110 dB of self-interferene cancelation has been reported. Practical WiFi transceivers are built and tested. In this section we explaine some of these radios and their working principles.

2.2.1. Antenna Cancelation

Antenna cancelation full-duplex design enables full-duplex communication for IEEE 802.15.4 system with 0 dBm TX power and -100 dBm noise floor [2]. Two TX antennas are used as shown in Figure 2, which are located at the distance of d and $d + \lambda/2$ from receiver where λ is the wavelength of the signal. Signals coming from these two antennas are added destructively in receive antenna. Antenna cancelation method can provide up to 30 dB of self-interferene cancelation. Followed by RF analog cancelation and baseband digital cancelation, this method can provide 60 dB of cancelation. Considering 40 dB path loss between TX and RX, this radio can make full-duplex radios possible for IEEE 802.15.4 system. This design has a few drawbacks, first since it uses 3 antennas with a special location requirement, it can't be a part of small devices like mobile phones. Second, it provides maximum -100 dB reduction of self-interference, it can not be used for larger transmit power systems. Third limitation is the bandwidth, antenna cancelation shows a degradation in performance for bandwidth larger than 100 MHz. The main drawback of this system can be that with three antennas, MIMO can deliver three times more throughput, but this full-duplex radio only has 84% rate increase.

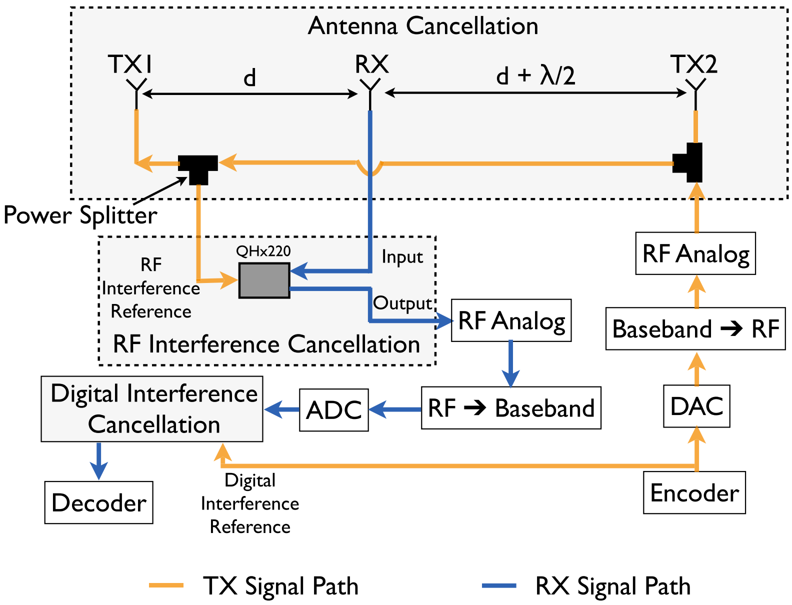

Figure 2: FD Radio with Antenna Cancelation[2]

2.2.2. BALUN Cancelation

In BALUN cancelation design, a balanced/unbalanced transformer (BALUN) has been used to create the inverse of the transmitted signal to be subtracted from received signal in analog domain [3]. Block diagram of the design is presented in Figure 3. BALUN can provide 45 dB of self-interferene cancelation. Combining with digital cancelation can provide up to 73 dB of self-interferene cancelation. With 40 dB of path loss attenuation between TX and RX antenna, this system provides approximately 110 dB isolation to build practical WiFi full-duplex radios. With 20 dBm TX power, residual of self-interference has -93 dBm signal strength. Advantage of BALUN design compared to antenna cancelation is that BALUN radio design does not have any bandwidth limitations.

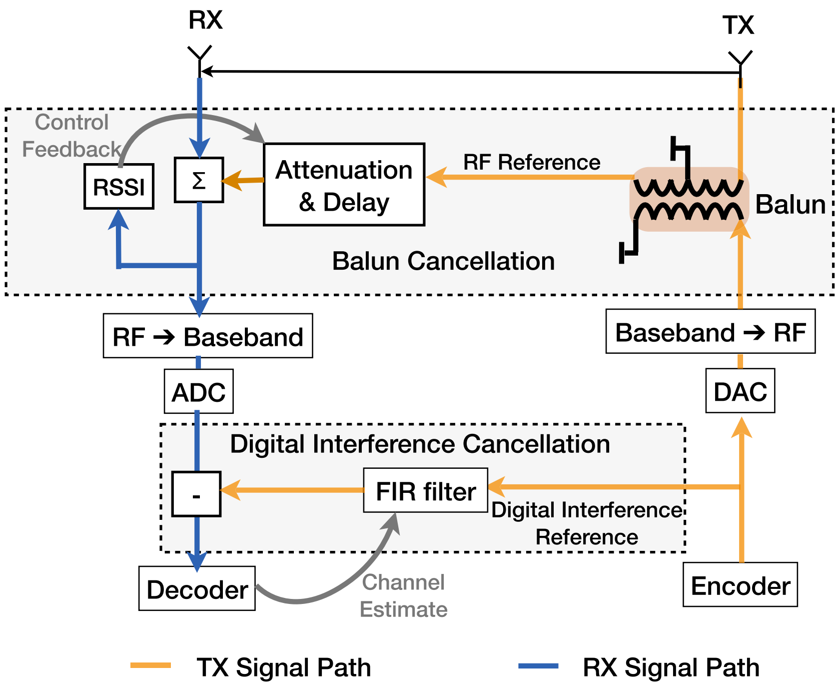

Figure 3: Full-duplex radio with BALUN [3].

2.2.3. *Single Antenna full-duplex Radio*

This radio has only one antenna and uses analog and digital cancelation techniques to cancel the self-interferene to the noise floor [9]. Up to 110 dB cancelation is achieved which is enough for WiFi radios, and reaches the theoretical doubling of throughput. To the best of our knowledge, it is the most recent radio design and has the highest amount of self-interferene cancelation. Figure 4 shows the block diagram of the transceiver. Best advantage of this radio to other full-duplex systems is that it uses almost the same amount of hardware resources as half-duplex radios. Since it is implemented using only one antenna, it can be a part of small devices like mobile phones. It does not have any limitations on the bandwidth and it can be used in all WiFi and LTE bands. A circulator has been used isolate the transmit and receive signals which provides 15 dB of reduction of self-interferene signal. In the next step novel analog cancelation circuit and tuning algorithm cancels 45 dB of self-interference. At the final stage, digital cancelation provides 50 dB reduction.

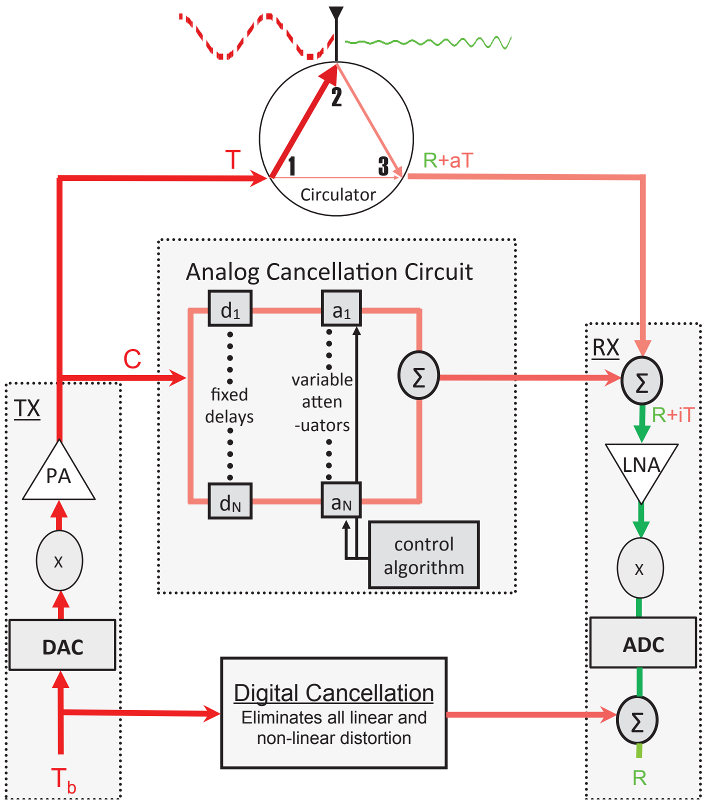

Figure 4: Single antenna full-duplex radio[9].

2.2.4. MIMO full-duplex Radio

Besides self-interference, design of MIMO full-duplex radios has another big challenge, which is the interference coming from node's other transmission antennas. Each antenna in the node will receive the transmitted signal from all of the other antennas in the same node. Since the distance between MIMO antennas in the node is small, this interference is large and needs to be handled. Considering the single antenna full-duplex radios, design of MIMO full-duplex radios is considered in [10]. Considering having a cancelation circuit similar to self-interferene cancelation between all the antennas, will increase the hardware complexity of the design quadratically. But this problem is also addressed in this radio design. Figure 5 shows the structure of the design. The self-interference on each antenna is called self-talk and interference coming from other antennas are called cross-talk. To avoid the quadratic increase of the complexity the so called cascade cancelation is implemented. Also residual of cancelation is also the same as the single antenna radio. This radio can be considered as ideal full-duplex MIMO design for WiFi applications.

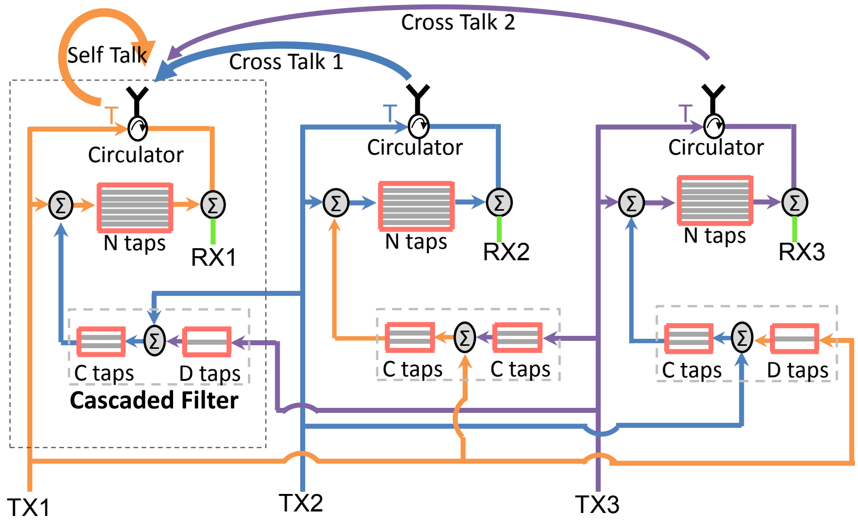

Figure 5: MIMO full-duplex radio [10].

2.2.5. Radios at Rice University

Researchers at Rice university have studied several full-duplex radio implementations. Feasibility of full-duplex radios is studied in [5]. Different cancelation stages and relation between analog and digital cancelation are studied experimentally in [6]. This design studies the characteristics of full duplex wireless systems using of-the-shelf radios. In this experimental work, performance of different combinations of analog and digital cancelation methods have been studied.

Since MIMO is seen as a necessary part of today and future wireless communication systems, possibility of MIMO full-duplex is also an interesting topic, recent work shows that MIMO full-duplex radios are also possible for WiFi systems [8]. Block diagram of this full duplex multi-antenna system is shown in Figure 6.

2.2.6. MIDU : MIMO full-duplex

This system [4] is a combination of MIMO and full-duplex, and this system is the first full duplex MIMO for wireless networks. MIDU employs antenna cancelation with symmetric placement as primary RF cancelation that can achieve 45dB of self-interference cancelation. It can also be used in MIMO systems and hence enables full-duplex MIMO. This symmetric antenna cancelation can use either two TX antennas and one RX antenna (TX antenna cancelation) or two RX antennas and one

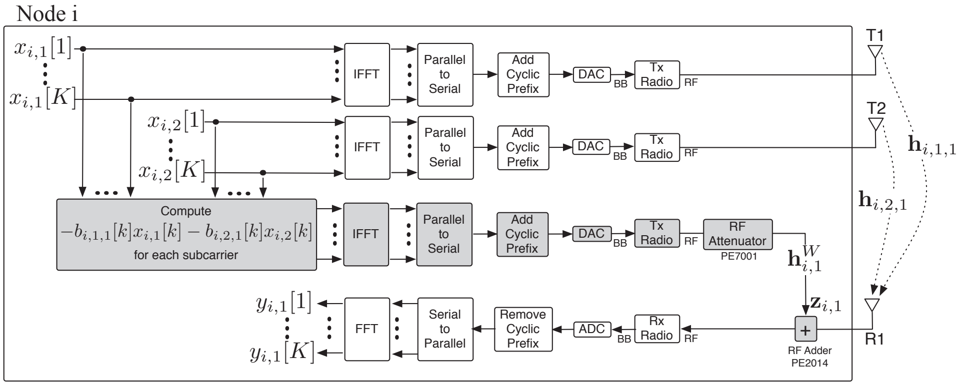

Figure 6: Multi antenna full-duplex [5].

TX antenna (RX antenna cancelation), that enables having a two-level design of TX cancellation followed by RX cancelation which can double the antenna cancelation. full-duplex architecture of MIDU is depicted in Figure 7, and receive cancelation and transmit cancelation are depicted in Figure 8. Results of this design at show that the two level antenna cancelation eliminates the need for variable attenuators and delays, and MIDU has significant potential both in point-to-point and point-to-multipoint half-duplex-MIMO systems.

2.3. Applications of Full Duplex Radios

Full duplex radios in the ideal case can double the system capacity. Improvements in different systems using full-duplex radios have been investigated in several publications. In [22] sum-rate performance of full-duplex radios between two nodes have been studied. Considering channel state information (CSI) at receiver only authors conclude that full-duplex performance depends on the SIR and in low SIR regimes full-duplex radios perform better than half-duplex while in high SIR half-duplex has better results. Considering CSIT the results show that full-duplex is beneficial in low SNR regimes. Authors in [23] have studied full-duplex radio performance compared to MIMO systems. Considering the same number of antennas that are utilized for MIMO or full-duplex, it is shown that full-duplex radios have better gain only in low SNR regimes. Full-duplex multiuser MIMO for small cells is considered in [24]. Joint uplink and downlink rate maximization problem is formulated to find downlink precoders and also uplink power allocation, this problem is not convex, so it has been solved using an iterative algorithm. Full-duplex relaying is a great area of interest and has been studied in several publications [25], [26], [27], [28], [29], [30], [31]. In [25] capacity of a MIMO channel with full-duplex and half-duplex amplify and forward relay has been investigated and full-duplex and half-duplex results are compared. Necessary and sufficient conditions for full-duplex radios to outperform half-duplex radios have been derived. Authors in [26] have considered full-duplex relaying in cognitive radio

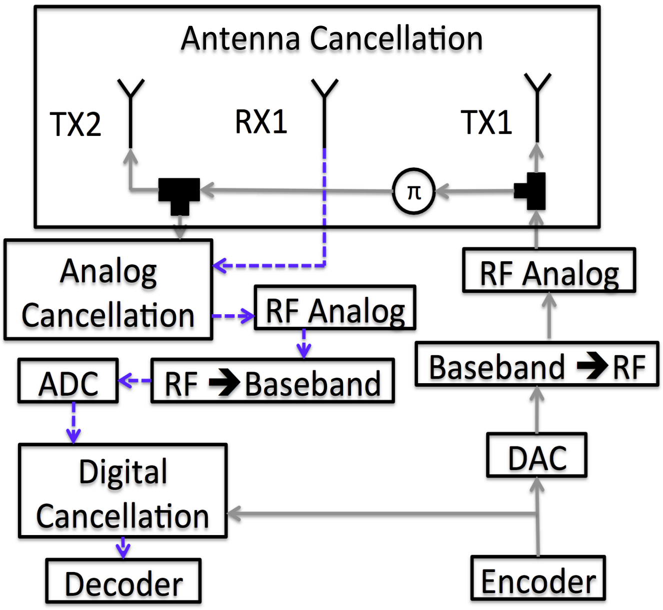

Figure 7: MIMO full-duplex [4].

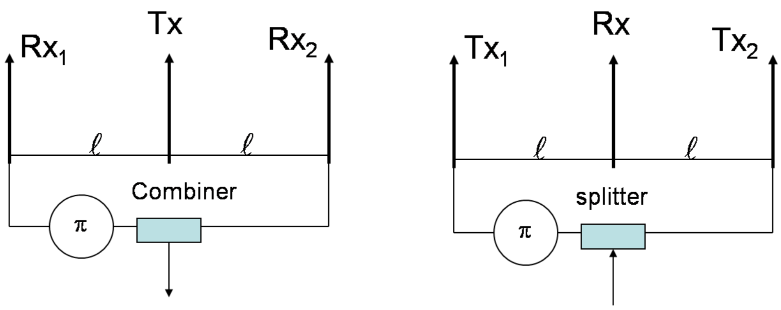

Figure 8: MIDU two stage cancelation [4]

networks and have formulated the optimal power control to minimze the outage probability of users. Mentioned work on applications of full-duplex radios is small review of some of the work. Full-duplex radios are getting more attention and new application areas might be introduced in the future.

2.4. Conclusion

This chapter shows that full-dupex radios are available for wireless systems with small transmit power. Enabling full-duplex radios in wireless systems will provile double radio spectrum in wireles systems, which is a great performance boost. So far all the full-duplex radios are implemented in WiFi systems and studying possible application areas of available full-duplex radios is an open research interest. Device-to-device communication, small cell, machine-to-machine communication, vehicular communications, etc. can be considered as possible areas and be studied. But implementing full-duplex radios had its own challenges. Specially, if these radios are implemented in base stations, interference management between users and also base stations are among the issues that needs to be addressed.

3. DEVICE-TO-DEVICE COMMUNICATION

In this chapter, at first the idea and benefits of device-to-device communication in cellular networks are presented. Different methods of direct communication between users are explained and then the problems of mode selection, resource allocation and interference management are discussed.

3.1. Introduction to D2D

Increasing demand for wireless communication is leading to congestion of radio spectrum, which is an expensive and scarce resource. So better utilizing of radio spectrum becomes more important and new technologies are required for this purpose. Device-to-device communication is seen as a new technology component which can improve the spectral efficiency of the cellular systems. In device-to-device communication, users in close proximity communicate directly with each other instead of going through base station. Since today's users require high data rates specially for local connectivity services like video sharing and gaming, offloading the data transfer from base station and establishing direct communication between users will be highly beneficial for the system. Figure 9 shows the general idea of D2D. Other application areas of D2D can be multicasting, machine-to-machine (M2M) communication and relaying.

D2D is categorized into two groups, *inband* and *outband*. In outband, D2D links use unlicensed band such as WiFi or ZigBee, while in inband, D2D link uses licensed cellular bands. Establishing connection in outband D2D can be done by the base station which is called *controlled outband* or by users themselves which is called *autonomous outband*. Inband D2D also has two categories, D2D users can have either dedicated radio resources, which is called *overlay inband*, or share the same resources as some of the cellular users which is called *underlay inband*. Figure 10 shows the classification of D2D communications. The problem of deciding on whether D2D users should communication through BS (cellular mode) or directly (D2D mode) is an important issue. Also in the case of D2D mode, base station should decide between controlled outband, overlay inband or underlay inband.

3.2. Mode Selection

In this section a review of some of the approaches that have been used in selecting the communication mode of the cellular users in D2D is given. In [32] authors have studied the three different modes, cellular mode, underlay inband and overlay inband and proposed an optimal mode selection for D2D communication in multi-cell systems. Authors in [33] have used system equations to perform the optimal mode selection for all the devices in the network. Join problem of mode selection, resource allocation and power control has been introduced in [34]. Solution to this join problem allows base station to determine if the users should communicate in D2D or cellular mode, and also assign radio resources and perform the power control. Joint problem of mode selection and power control has been solved in [35]. Mode selection of the D2D communication with a relay in the network is studied in [36], authors conclude that introducing relay in

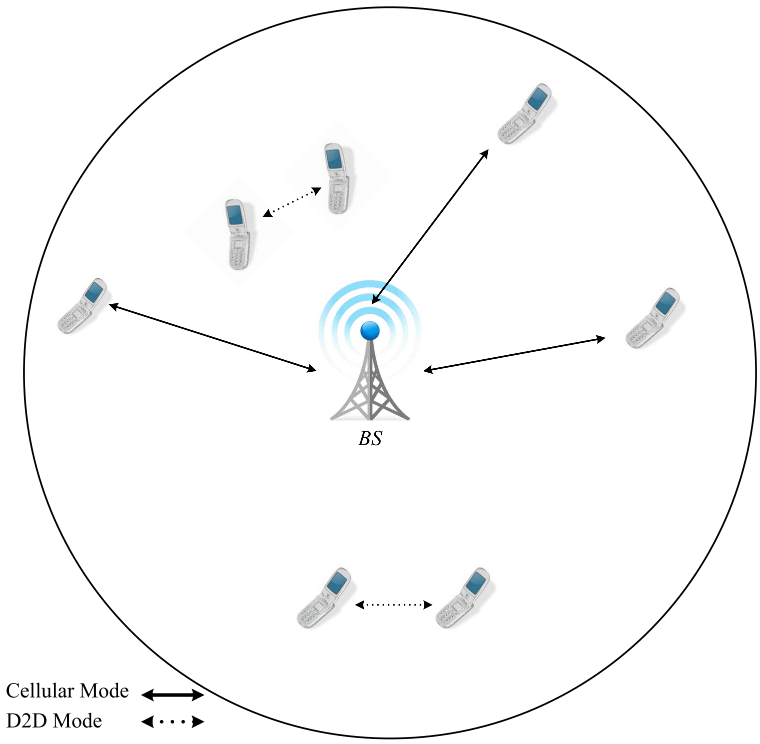

Figure 9: Device-to-device communication concept.

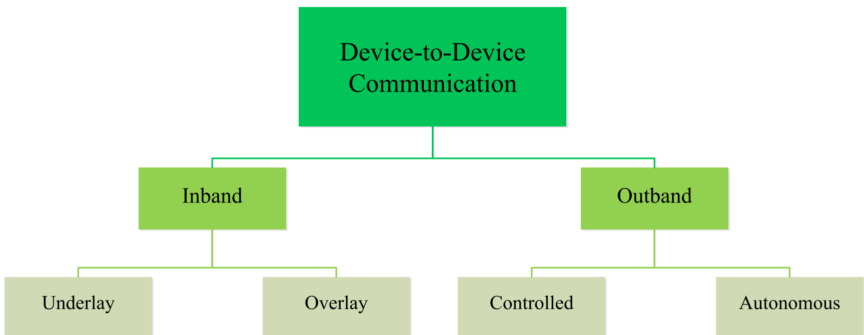

Figure 10: D2D classification.

the system improves the chance of D2D mode possibility. Most of the mode selection problems consider existence of one D2D pair and resource sharing of the cellular users only with one D2D pair, authors in [37] consider an optimization problem in which more than one D2D pair will share the resources with other cellular users. This optimization problem jointly finds the communication mode, radio resource for sharing and transmit power of the users.

3.3. Outband D2D

Conventional D2D communication exploiting unlicensed spectrum like WiFi, ZigBee or Bluetooth already exist, in which users are responsible to establish the D2D connection. This cannot be beneficial to cellular networks since base station does not have control over the connection. On the other hand, in controlled outband, cellular network has control over the D2D connection [38], [39], [40], [41]. The benefit of this scheme is that it does not require licensed spectrum and there is no interference on cellular communications. The major drawback is the interference on D2D connection because of other unlicensed spectrum users. Another limitation is that the device requires the second radio interface such as WiFi. Due to these disadvantages, outband D2D has not gained that much attention in recent research work.

3.4. Inband D2D

Overly inband does not provide so much of spectral efficiency since it requires dedicated radio spectrum, but is can provide energy efficiency [42], or improve the performance of the system [43]. Underlay inband D2D is the most efficient mode in the sense of spectrum utilization [11], [13], [12]. The major problem in this method is that sharing radio resources will cause interference both on D2D and cellular users. If D2D link is sharing radio resources of the uplink transmissions, base station will receive interference from D2D transmissions and also D2D receivers will receive interference from uplink transmissions of other users. When D2D link is sharing the radio resources of downlink communication, cellular users will receive interference from D2D transmission and D2D receiver will receive interference from downlink transmission of the base station. Hence mode selection, radio resource allocation and interference management are the major problems to be addressed in D2D communication. Due to previously mentioned reasons, in this thesis the focus is on underlay inband D2D communication and also underlay inband is implemented in system model.

3.4.1. Underlay Inband Approaches

In this section a review is given on some of the methods that have been introduced in literature for solving the problem of resource allocation and interference management for D2D systems. Interference on cellular users can be on users equipments (UE) or base station (BS) depending on uplink or downlink radio resource sharing. Hence interference coordination becomes critical and needs to be formulated. Several methods exist to limit the interference in D2D systems. In [20] authors have introduced interference-limited-area method to guarantee the quality of service in D2D communication. In this method an area around D2D users will be found in which the interference on D2D users is higher than a predefined threshold and users outside this area are selected for resource sharing. Distance based resource selection method is considered in [44]. Channel allocation is one way to coordinate the mutual interference between D2D and cellular communications. Interference aware resource allocation scheme is introduced in [45]. Cellular communication is considered as primary service and channel allocation problem is solved in a way to guarantee the quality of service for cellular users while trying to maximize number of possible D2D pairs. Problem of mutual interference coordination when D2D users are reusing uplink resources of cellular users is considered in [46]. This paper is using a resource allocation method to handle the interference while trying to maximize the number of D2D links in the system. Authors in [47] have proposed successive interference cancelation (SIC) to limit the interference from D2D users on cellular users while resource allocation is done using a greedy algorithm to maximize the performance of D2D users. In [48] a greedy heuristic algorithm is proposed to solve the resource allocation problem, this algorithm is fast enough to be performed in the scheduling period of LTE and can also lessen the interference caused by resource sharing. Several other studies also have focused on coping with interference in D2D systems [16], [17], [18], [19]. Authors in [16] have proposed to exclude the cellular users with the same resources as D2D users outside the coverage area of D2D users. This is done by a power control algorithm which leads to less interference and a better system performance. A new interference-aware graph has been introduced in [17] to model the interference links in an underlay D2D system. Then a resource allocation scheme based on this graph is implemented that can have close to optimal resource allocation performance. In [18] a scenario with multiple D2D links and one cellular user is considered. Cell throughput maximization problem constrained to SINR of the cellular users is optimized in fast fading and slow fading scenarios. Results of this paper show that several D2D links can exploit the same resources as cellular users without much degradation of its performance. Authors of [19] have considered a cell with multiple antennas in base station and have compared the performance of beamforming and interference cancelation transmit strategies in base station. Scenarios with full channel state information in transmitter (CSIT) and quantized CSIT are considered, authors have proposed an adaptive transmission strategy to achieve the optimum performance.

3.5. Summary and Conclusion

This chapter has introduced the D2D concept and classification in the terms of radio resource allocation. From the discussed topics, it is seen that underlay inband is the best option in terms of spectrum efficiency. Some methods to deal with the interference in underlay inband are presented and it is shown that with proper resource allocation and interference management techniques systems can benefit from D2D communication. A survey on D2D communication and most of the literature in this topic is presented in [49]. In this thesis we will focus on underlay inband D2D and study D2D communication using full-duplex radios.

4. FULL DUPLEX DEVICE-TO-DEVICE COMMUNICATION WITH UPLINK RESOURCE REUSE

In this chapter the idea of employing full-duplex radios in D2D is presented and possibility of full-duplex D2D is investigated. In small cells that are using D2D connection, distance between D2D users should be short and transmit power of the D2D pair will be small. Hence considering the recent work on full-duplex radio design, D2D is a very good candidate to make use of full-duplex radios. With 110 dB of self-interference cancelation and maximum transmit power of 20 dBm for D2D and proper resource allocation scheme, cellular systems can have a good performance gain, either in making a better use of spectrum or increasing the system throughput. Simulations are performed with uplink resource reuse in this chapter and comparison of the performance of half-duplex D2D and full-duplex D2D are given.

4.1. Uplink Resource Reuse

In this section it is considered that D2D users are using the same radios resources as uplink transmissions in the cell. In this case, base station receives interference from D2D transmissions. D2D receivers will also receive interference from uplink transmissions of the cellular users that share the same resources as D2D link. Figure 11 shows the system model. In this figure, A_1 and A_2 are interference limited areas for D2D users D_1 and D_2, and radius of these areas are shown by d_1 and d_2 respectively.

Throughput of the system in the presence of D2D link is increased, the amount of this gain depends on the resource allocation and power control methods. On other hand, while using full-duplex radios, throughput is affected by the residual of self-interference. Total throughput of the system when D2D link is activated is:

For half-duplex (HD) D2D:

$$R_{T,HD} = R_C + R_{Cj,HD} + R_{D,HD}. \tag{1}$$

For full-duplex D2D:

$$R_{T,FD} = R_C + R_{Cj,FD} + R_{D,FD}. \tag{2}$$

In the above equations, R_C is throughput of cellular users that are not sharing resources with D2D users, $R_{Cj,HD}$ and $R_{Cj,FD}$ rate of cellular users that exploit the same resources as D2D users in half-duplex and full-duplex mode respectively. Rate of half-duplex D2D link is $R_{D,HD}$, and for full-duplex D2D we denote the rate by $R_{D,FD}$.

We consider γ_i to be the SNR of CU_i at BS, $\gamma_{j,HD}$ and $\gamma_{j,FD}$ to be the SINR of the cellular users that share the same resources as D2D users while D2D is in half-duplex and full-duplex mode. So the rates for cellular and D2D users are:

$$R_C = \sum_{i=1, i \neq j}^{M} \log_2 (1 + \gamma_i), \tag{3}$$

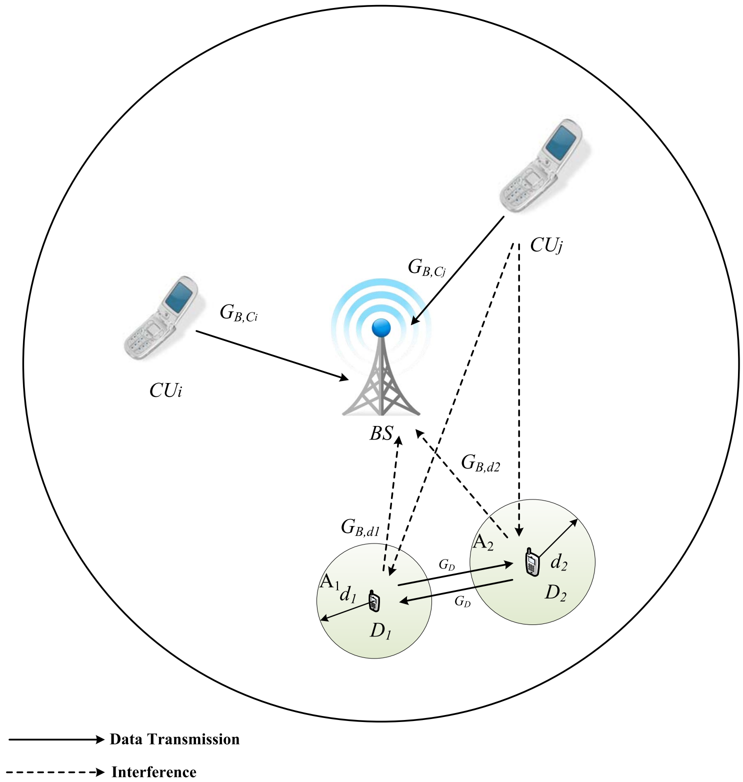

Figure 11: D2D system model

$$R_{Cj,HD} = \sum_{j=1}^{K} \log_2 (1 + \gamma_{j,HD}), \tag{4}$$

$$R_{Cj,FD} = \sum_{j=1}^{K} \log_2 (1 + \gamma_{j,FD}). \tag{5}$$

When D2D users operate in half-duplex mode, D2D user D_2 is transmitting and D2D user D_1 is receiving. We denote the SINR of D2D user D_l as γ_{Dl}. Rate of the D2D link is:

$$R_{D,HD} = \log_2 (1 + \gamma_{D1}). \tag{6}$$

When D2D users use full-duplex radios, both of D2D users transmit and receive at the same time and the D2D link rate is:

$$R_{D,FD} = \sum_{l=1}^{2} \log_2 (1 + \gamma_{Dl}). \tag{7}$$

In SINR equations for cellular transmissions, we consider P_{ci} to be the transmit power of CU_i and $G_{ci,BS}$ channel gain between CU_i and BS. P_j is the transmit power of cellular user that is using the same resources as D2D users and $G_{j,BS}$ is the channel gain between CU_j and BS, and $I_{Di,cj}$ is interference from D2D transmissions to CU_j.

$$\gamma_i = \frac{P_{ci}.G_{ci,BS}}{N_0}. \tag{8}$$

SINR for half-duplex mode is:

$$\gamma_{j,HD} = \frac{P_{cj}.G_{cj,BS}}{N_0 + I_{D2,cj}}. \tag{9}$$

SINR for full-duplex mode is:

$$\gamma_{j,FD} = \frac{P_{cj}.G_{cj,BS}}{N_0 + I_{D1,cj} + I_{D2,cj}}. \tag{10}$$

In the equation for SINR of D2D users, we consider that P_{Dl} and G_D are transmit powers of D2D users and channel gain between them respectively. I_l is the residual of self-interference at node l which can be written as $I_l = C(0, \sigma_l^2)$ [6], $\sigma_l^2 = \beta P_l$ where β depends on the amount of self-interference cancelation in the node l . $I_{cj,l}$ is the interference coming from CU_j to D2D user l.

For half-duplex mode we only write the γ_1 :

$$\gamma_1 = \frac{P_{D2}.G_D}{N_0 + \sum_{j=1}^{K} I_{cj,1}}. \tag{11}$$

For full-duplex mode:

$$\gamma_l = \frac{P_{Dz}.G_D}{N_0 + I_l + \sum_{j=1}^{K} I_{cj,l}} \quad l, z \in \{1, 2\}, l \neq z. \tag{12}$$

N_0 is additive white Gaussian noise in all the equations.

4.1.1. D2D Power Control

It is considered that received signal power from cellular users at BS is kept at a constant level P_{RC}, i.e. users have a power control mechanism that depends on their channel gain to the BS. D2D transmissions cause interference on the BS since D2D link is sharing resources with other cellular users. To suppress this interference transmit power of D2D users should be controlled. We propose that D2D users should transmit with a power that interference over signal ratio (ISR) for users that share resources with D2D link at BS should to be smaller than a defined threshold δ_B. ISR at the BS is expressed as

$$ISR = \frac{P_{Dl}.G_{l,BS}}{P_{RC}} \leq \delta_B. \tag{13}$$

Where P_{Dl} is the transmit power of D2D user l, $G_{l,BS}$ is channel gain between lth D2D user and BS, and P_{RC} is received power level of cellular users at BS. From (1) we use the following power for D2D transmitter:

$$P_{Dl} \leq \frac{P_{RC}.\delta_B}{G_{l,BS}}. \tag{14}$$

This maximum transmit power for D2D link will guarantee that the SINR of BS does not fall below a defined threshold.

4.1.2. Interference Limited Area

While D2D users share the same frequency bands with other cellular users in uplink, D2D receivers receive interference from uplink transmissions of cellular users. In this section we present the interference limited area (ILA) method for selecting a group of users which their sub-channels can be used in D2D link, so that the interference on D2D receivers will not be harmful. In this method, an area around D2D receivers is calculated in which the interference coming from cellular communications will be large. In this work, this area is considered to be a circle with the radios d_i for D2D user D_i. Users outside this area are selected for resource sharing with D2D users. Area in which the ISR for D2D user D_l is larger than δ_{ILA} can be calculated as:

$$ISR_l = \frac{P_{cmax}.G_{ci,Dl}}{P_{Dl}.G_D} > \delta_{ILA}, \tag{15}$$

$$G_{ci,Dl} > \frac{P_{Dl}.G_D.\delta_{ILA}}{P_{cmax}}. \tag{16}$$

Channel gain between CU_i and D_l can be written as $G_0.(d_l)^{-\alpha}$, so

$$G_0.(d_l)^{-\alpha} > \frac{P_{Dl}.G_D.\delta_{ILA}}{P_{cmax}}. \tag{17}$$

The minimum distance to limit the interference to D2D is:

$$d_l < (\frac{P_{cmax}.G_0}{P_{Dl}.G_D.\delta_{ILA}})^{1/\alpha}. \tag{18}$$

In these equations, P_{cmax} is the maximum transmit power of cellular users and α is the path loss exponent. d_l is the distance to D2D user D_l in meters and G_0 is the gain when distance is equal to 1 meter. Now we have found areas around D2D users A_1 and A_2. All the users that are outside these areas are selected to share the same resources with D2D users.

4.1.3. Resource Allocation

Two resource allocation scenarios are considered in this chapter. At first, only one of the cellular users is selected for resource sharing. It is considered that from sub-channels of users shown by S_i that are outside ILA , one of them that maximizes the total throughput R_T of the system is selected, this is shown by S^*

$$S^* = \max_{S_i} R_T. \tag{19}$$

In the second scenario, all the sub-channels of users outside ILA are selected for resource sharing.

4.2. Simulation Results

This section presents the simulation results to show with how much of self-interference cancelation full-duplex radios improve the performance of a D2D link in a practical cellular system. LTE systems employ orthogonal frequency division multiple access (OFDMA) in downlink communication, and single carrier frequency division multiple access (SC-FDMA) in uplink. The bandwidth in LTE is divided into resource blocks (RB). Each resource blocks occupies 180 kHz in frequency domain (equal to 0.5 ms in time domain). Since the minimum uplink scheduling interval in LTE is 1 ms, the smallest resource in frequency domain is two resource blocks, i.e. 360 kHz. Here we consider a single cell scenario where 30 users are randomly dropped in the cell, two users with less than 25 meters distance are selected as D2D pair. It is assumed that each user has two LTE resource blocks to communicate in uplink and D2D users have to use sub-channels of other cellular users. Table 1 shows the simulation parameters.

Table 1: Simulation parameters.

Parameter	Value
Cell Radios	500 m
Maximum D2D Distance	25 m
CUs Per Cell (M)	30
δ_B	0.01
δ_{ILA}	0.01
α	4
Maximum CU transmit power	23 dBm
Noise Figure at BS	2 dB
Noise Figure at CU	9 dB
D2D Path Loss Model	148 + 40log(d[km])
BS to CU Path Loss Model	128.1 + 36.7log(d[km])
Noise spectral density	-174 dBm/Hz

Figure 12 shows the throughput of the system when only one CU_j is sharing resources with D2D and Figure 13 when K out of M users are sharing resources. Throughput of the system with full-duplex D2D will increase as the amount of self-interference cancelation increases, it can be seen that for less 78 dB of self-interference cancelation half-duplex D2D has better performance due to large residual of self-interference. However as amount of self-interference cancelation increases, residual of self-interference will be small and SINR of D2D receivers will increase and full-duplex will outperform half-duplex. At 110 dB cancelation, full-duplex D2D link has almost double throughput of half-duplex D2D.

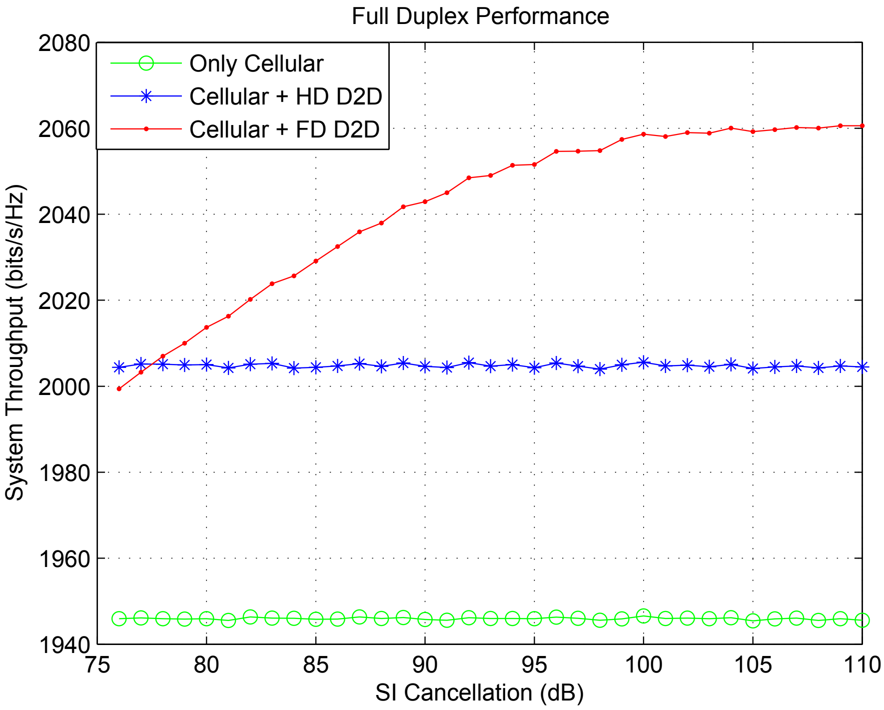

Figure 12: Throughput of system for one user resource sharing for minimum SNR at BS of 10 dB

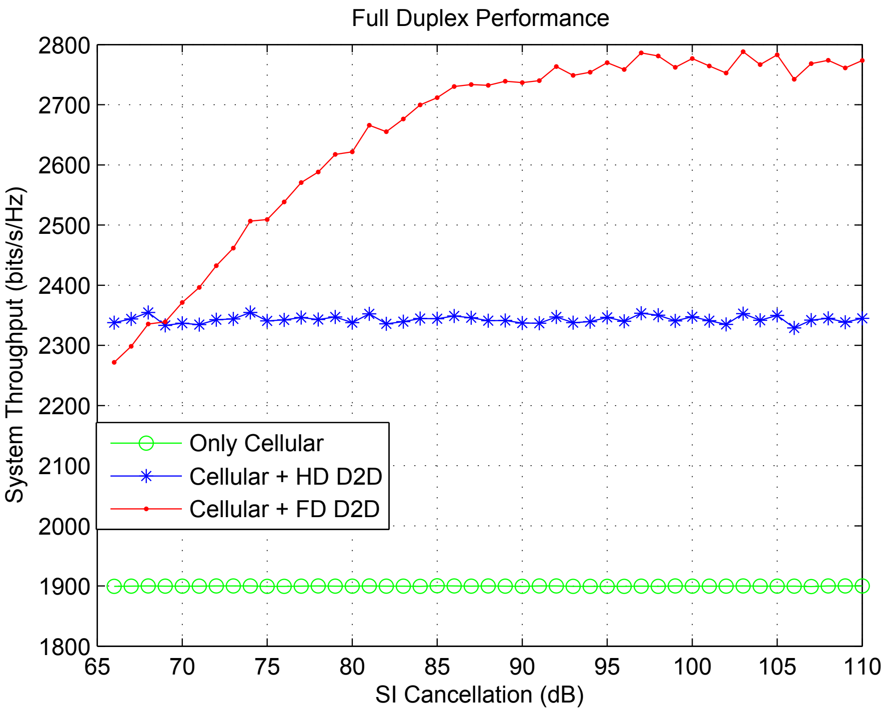

Figure 13: Throughput of system for K user resource sharing for minimum SNR at BS of 10 dB.

Figure 14 we present the ratio of full-duplex D2D link rate over half-duplex D2D link rate for two scenarios, fisrt when D2D is sharing resources with only one cellular user and second when resources of K users are being shared. In second case , full-duplex outperforms half-duplex with lower amount of self-interference isolation (69 dB). The reason is that when the number of users that share resources with D2D link is increased, D2D receivers receive more interference and interference plus noise level increases. This makes the effect of residual of self-interference on SINR of D2D to be less than the case where only one user shares the resources.

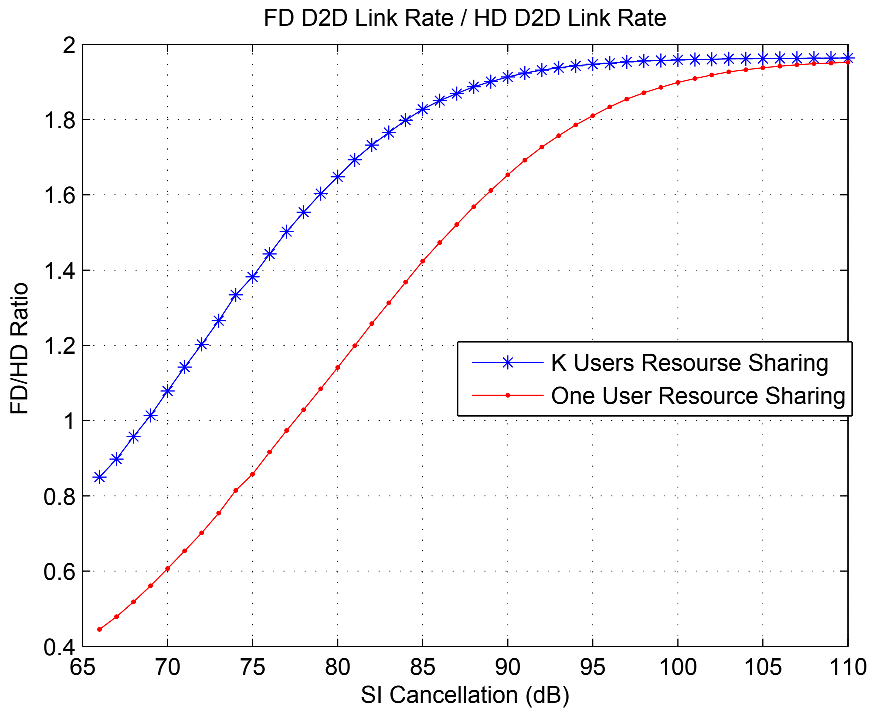

Figure 14: Full-duplex/half-duplex link rate comparison.

Figure 15 shows the full-duplex D2D over half-duplex D2D ratio versus the SNR target at BS for uplink signals for different self-interference cancelation amounts. As this SNR target increases, cellular users can transmit with larger power, this will result in larger transmit power for D2D users also. This will lead to increase in residual of self-interference as the SNR target increases and full-duplex performance will worsen. In this case, only one cellular user's resources are shared.

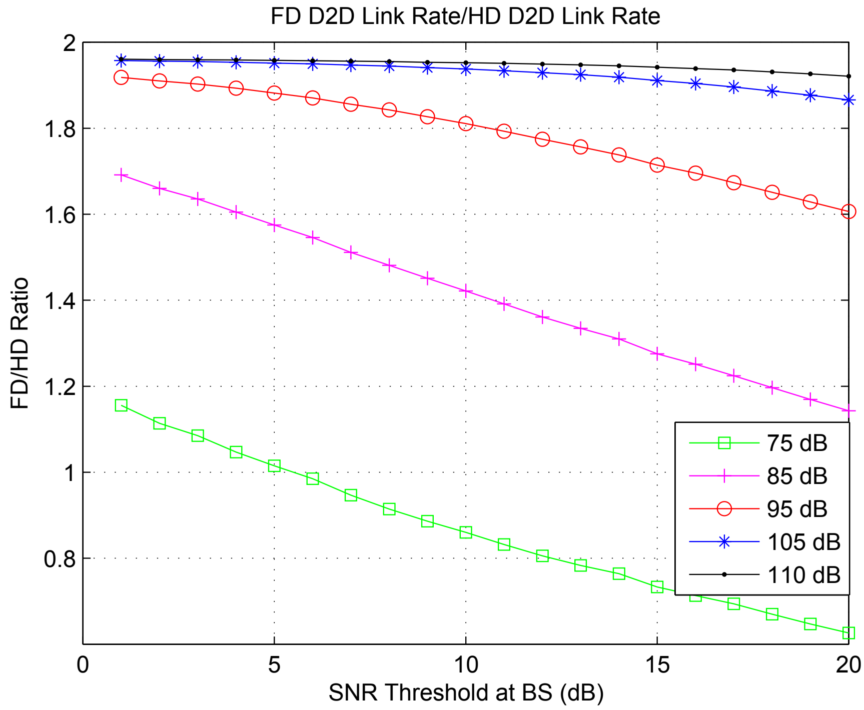

Figure 15: Full-duplex/half-duplex link rate comparison for different SINR Target.

4.3. Summary and Conclusion

This chapter presented a system model for uplink radio reuse for D2D link which is using full-duplex radios. Uplink power control and interference-limited-area method are presented for interference management. Simulations show the performance gain that can be achieved by using full-duplex radios in D2D and the amount of self-interference cancelation required for full-duplex radios so they can be used in D2D. Results show that available full-duplex systems can be considered as ideal for D2D communications since D2D is for short distances with small transmit powers.

5. FULL DUPLEX DEVICE-TO-DEVICE COMMUNICATION WITH DOWNLINK RESOURCE REUSE

In this chapter, underlay D2D with downlink resource sharing is considered and the effect of residual of self-interference on performance of full-duplex D2D is studied. Multi-cell scenario and the effect of inter-cell interference is also investigated.

5.1. Downlink Resource Reuse

This chapter presents the scenario in which downlink transmission resources are being shared with D2D users. In this case, D2D receivers will receive interference coming from base station. Cellular users, which share the same resources as D2D users, will also have interference because of D2D transmissions. Selecting the cellular users for resource sharing is important because of these interferences. Since cellular communications is the primary service, quality of service in cellular downlink transmissions needs to be guaranteed. For this purpose interference limited area method is used to select a group of users for resource sharing that would not face harmful interference from D2D transmissions. To minimize the interference on D2D link, we select the user with minimum transmit power from the group of users selected in ILA method. System model of D2D communication with downlink resource resource reuse is shown in Figure 16. In the system model, A_1 and A_2 are interference limited areas for D2D users D_1 and D_2, and radius of these areas are presented by d_1 and d_2 respectively.

5.1.1. Downlink Formulation

An OFDMA based cellular network is considered with M cellular users randomly dropped in the cell. Each user has its own dedicated radio resource and users do not interfere with each other. Base station transmits signals to users in a way the SINR requirements of the users are met.

Like the uplink scenario that is discussed in the previous chapter, the rates in the system can be written as:

$$R_C = \sum_{i=1,i\neq j}^{M} \log_2{(1+\gamma_i)}, \tag{20}$$

$$R_{Cj,HD} = \sum_{j=1}^{K} \log_2{(1+\gamma_{j,HD})}, \tag{21}$$

$$R_{Cj,FD} = \sum_{j=1}^{K} \log_2{(1+\gamma_{j,FD})}. \tag{22}$$

As seen from 16, when D2D users operate in half-duplex mode, D2D user D_2 is transmitting and D2D user D_1 is receiving. SINR of D2D user D_l is denoted as γ_{Dl}. Rate of the D2D link is:

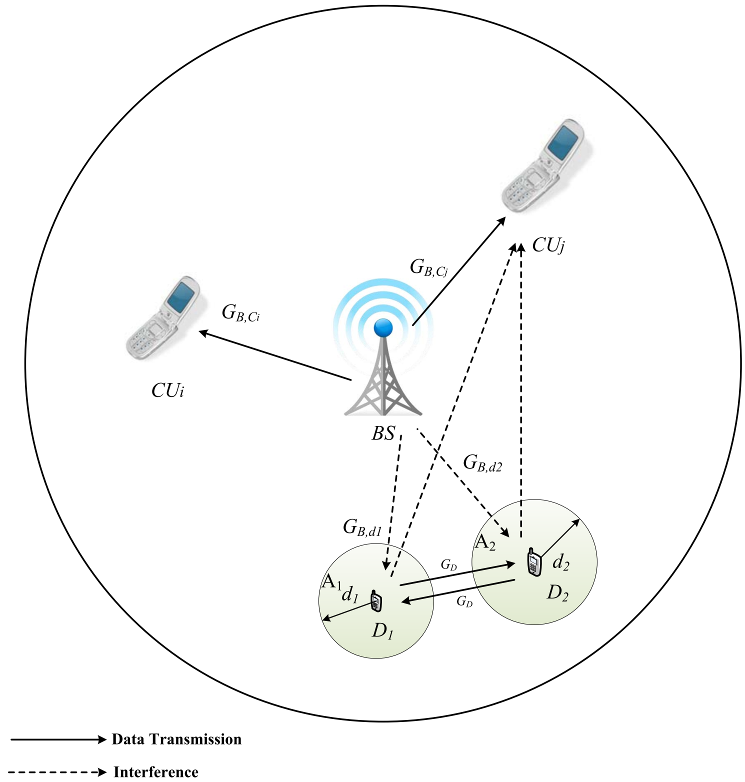

Figure 16: D2D system model.

$$R_{D,HD} = \log_2 (1 + \gamma_{D1}). \tag{23}$$

When D2D users use full-duplex radios, both of D2D users transmit and receive at the same time and the D2D link rate is:

$$R_{D,FD} = \sum_{l=1}^{2} \log_2 (1 + \gamma_{Dl}). \tag{24}$$

In SINR equations for cellular transmissions, we consider P_{ci} to be the transmit power of CU_i and $G_{BS,ci}$ channel gain between BS and CU_i. P_j is the transmit power of cellular user that is using the same resources as D2D users and $G_{BS.j}$ is the channel gain between BS and CU_j, and $I_{Di,cj}$ is interference from D2D transmissions to CU_j. SINR for the cellular users ind downlink without interference from D2D is

$$\gamma_i = \frac{P_{ci}.G_{ci,BS}}{N0 + ICI}. \tag{25}$$

SINR for cellular users with half-duplex D2D resource sharing is

$$\gamma_{j,HD} = \frac{P_{cj}.G_{cj,BS}}{N_0 + I_{D2,cj} + ICI}. \tag{26}$$

SINR for cellular users with full-duplex D2D resource sharing is

$$\gamma_{j,FD} = \frac{P_{cj}.G_{cj,BS}}{N_0 + I_{D1,cj} + I_{D2,cj} + ICI}. \tag{27}$$

In the following equations for SINR of D2D users, we consider that P_{Dl} and G_D are transmit powers of D2D users and channel gain between them respectively. I_l is the residual of self-interference at node l which can be written as $I_l = C(0, \sigma_l^2)$, $\sigma_l^2 = \beta P_l$ where β depends on the amount of self-interference cancelation in the node l . $I_{cj,l}$ is the interference coming from CU_j to D2D user l.

For half-duplex mode we only write the γ_1 :

$$\gamma_1 = \frac{P_{D2}.G_D}{N_0 + \sum_{j=1}^{K} I_{cj,1} + ICI}. \tag{28}$$

For full-duplex mode:

$$\gamma_l = \frac{P_{Dz}.G_D}{N_0 + I_l + \sum_{j=1}^{K} I_{cj,l} + ICI} \quad l, z \in \{1, 2\}, l \neq z. \tag{29}$$

5.1.2. Interference Limited Area

In this section, interference limited area is applied to coordinate the interference on cellular users from D2D transmissions. Considering the minimum SINR requirements for cellular users, we calculate the interference-over-signal ratio for cellular users considering the maximum D2D transmit power. This interference-over-signal ratio should be smaller than a predefined threshold. The following shows the calculation of interference limited area:

$$ISR_l = \frac{P_{dmax}.G_{Dl,ci}}{P_{ci}.G_{BS,ci}} > \delta_{ILA}, \tag{30}$$

$$G_{Dl,ci} > \frac{P_{ci}.G_{BS,ci}.\delta_{ILA}}{P_{dmax}}. \tag{31}$$

Channel gain between CU_i and D_l can be written as $G_0.(d_l)^{-\alpha}$, so:

$$G_0.(d_l)^{-\alpha} > \frac{P_{ci}.G_{BS,ci}.\delta_{ILA}}{P_{dmax}}. \tag{32}$$

The minimum distance to limit the interference to D2D is:

$$d_l < (\frac{P_{dmax}.G_0}{P_{ci}.G_{BS,ci}.\delta_{ILA}})^{1/\alpha}. \tag{33}$$

5.1.3. Resource allocation

Selection of the user for resource sharing with D2D users in this section is done in a way to minimize the interference on D2D users. Since all the users outside the ILA that is calculated in previous section can be used for resource sharing without any harmful interference on cellular users, user with minimum transmit power is selected to utilize the same resources as D2D link.

5.2. Simulation Results

Simulation results show how much self-interference cancelation is required for downlink resource reuse of cellular communications. In this section, at first the single cell results are presented. Then results of multi-cell scenario are shown to study the effect of inter-cell interference. Table 2 shows the simulation parameters used in downlink system model.

Table 2: Simulation parameters.

Parameter	Value
Cell Radios	500 m
Number of cells	19
Maximum D2D Distance	25 m
CUs Per Cell (M)	30
δ_{ILA}	0.01
α	4
Noise Figure at BS	2 dB
Noise Figure at CU	9 dB
D2D Path Loss Model	148 + 40log(d[km])
BS to CU Path Loss Model	128.1 + 36.7log(d[km])
Noise spectral density	-174 dBm/Hz

5.2.1. Single Cell

Figure 17 shows the throughput of the system in the presence of half-duplex D2D and full-duplex D2D based on different amount of self-interference cancelation. Throughput is constant for only cellular case and half-duplex D2D case. full-duplex D2D rate increases as amount of self-interference cancelation increases. For small number of self-interference cancelation, half-duplex performs better than full-duplex since the residual of self-interference is too large and it deteriorates the SINR of the D2D receivers. While with around 100 dB self-interference suppression, full-duplex can almost achieve the theoretical doubling of throughput.

To have a better presentation of the rate performance of full-duplex over half-duplex, Figure 18 depicts the ratio of full-duplex D2D link rate over half-duplex D2D link rate. This figure shows that with 110 dB self-interference cancelation, full-duplex has double throughput compared tho half-duplex, with is an ideal full-duplex scenario for D2D systems.

One of the most important aspects of D2D communication is small distance between D2D users. So studying the effect of the distance of D2D users from each other on performance of full-duplex radios is important. In Figure 19, ratio of full-duplex

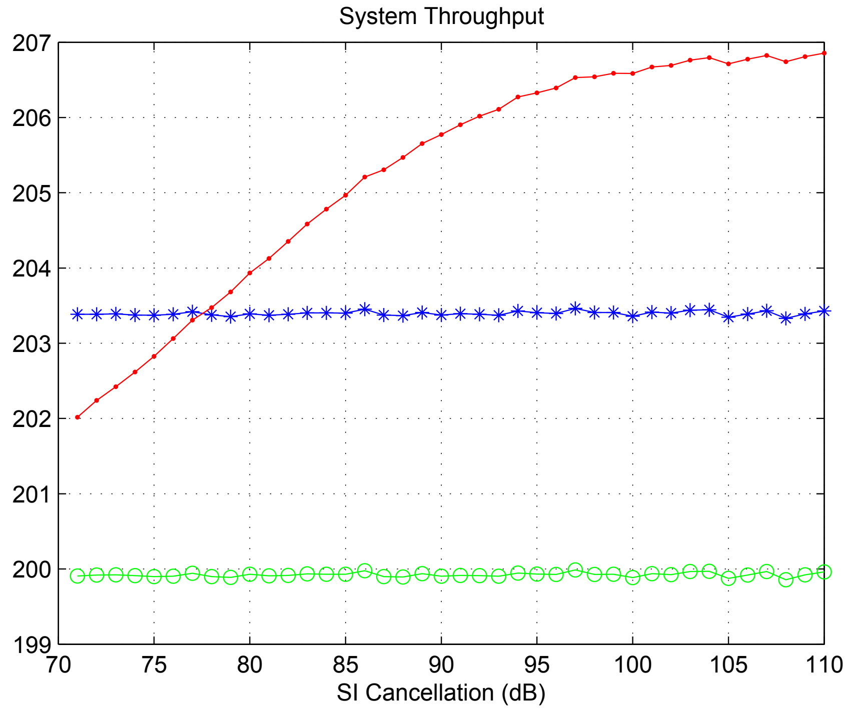

Figure 17: Throughput of system for downlink resource reuse - single cell

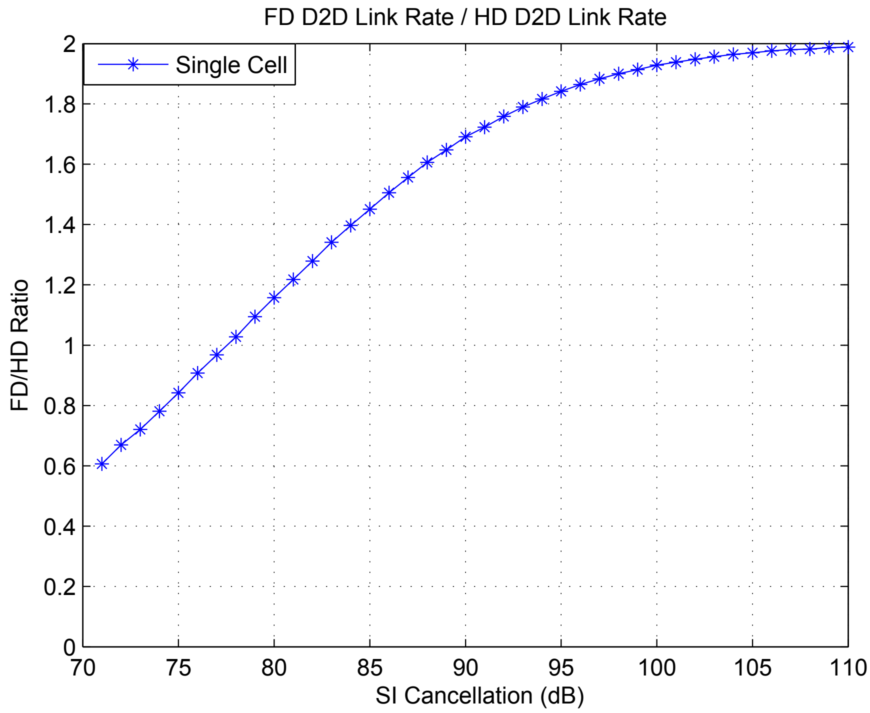

Figure 18: FD/HD ratio for downlink resource reuse - single cell

throughput over half-duplex throughput is presented for 5 different amounts of self-interference cancelation, based on the distance of D2D users. This figure shows that distance of the D2D users, has a huge effect on performance of full-duplex radios. Smaller distance lead to smaller transmit powers, which makes it easier to reduce the self-interference to noise floor, and have almost perfect full-duplex radios. As seen in the figure, for example even 85 dB self-interference cancelation provide almost double throughput for full-duplex radios. Most important point of this figure is that with more than 100 dB self-interference cancelation, full-duplex link has double throughput even for large distances of D2D users.

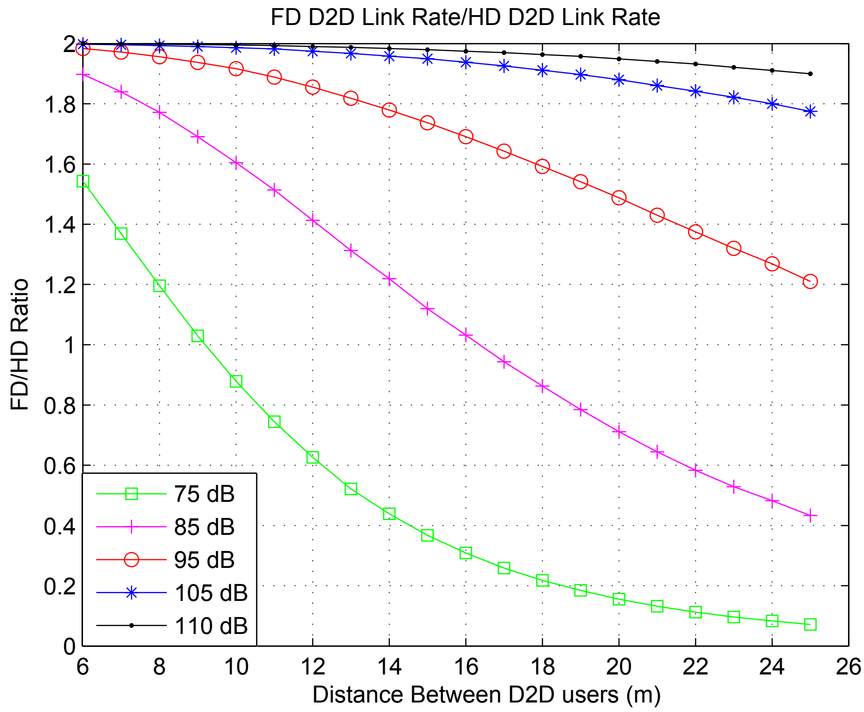

Figure 19: FD/HD ratio based on distance

5.2.2. Multi-cell

In cellular systems inter-cell interference management is a critical issue. In previous cellular systems, adjacent cells had different frequencies. New wireless systems utilize frequency reuse of one, it means that all the cells use the same frequency band. In this case, dealing with inter-cell interference becomes more challenging. Different methods exist to deal with the inter-cell interference [50]. In this thesis it is considered that each cell is divided to center and edge areas. Frequency reuse factor in center of the cell is one and in the edge of the cell frequency reuse of three is used. This is called Partial Frequency Reuse (PFR) as shown in Figure 20. PRF has been studied, e.g. in [51], [52], [53]. This section studies the performance of full-duplex radios in the presence of inter-cell interference. PRF is with edge reuse factor of 3 is implemented.

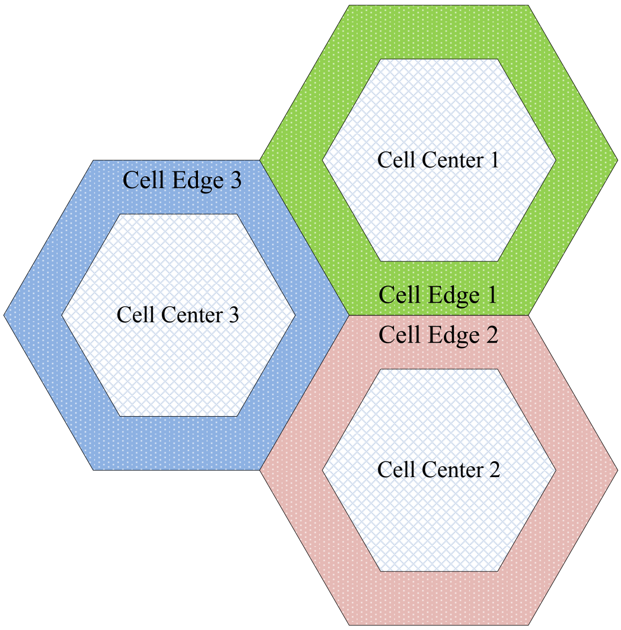

Figure 20: Partial frequency reuse

The simulation results are presented in the following figures. Figure 21 shows the throughput of the system for three modes, only cellular, half-duplex and full-duplex D2D. Similar to previous section, we see that full-duplex radios have poor performance when the self-interference cancelation is small. But will larger number of self-interference reduction, full-duplex radios can provide double throughput.

In Figure 22, full-duplex over half-duplex rate ratio is depicted. Comparing this figure to Figure 18 for single cell scenario, we see that full-duplex radios in multi-cell case have better performance. As seen, in single cell scenario, at 78 dB self-interference reduction full-duplex and half-duplex have equal rate, but in multi-cell, this amount is at around 68 dB. Reason is that in multi-cell, intercell-interference increases the noise-plus-interference level. Higher level of noise-plus-interference means that less self-interference cancelation is required for full-duplex radios. Figure 21 shows that with 110 dB self-interference cancelation, full-duplex radios can be considered as ideal for D2D communication.

In Figure 23, results of the full-duplex over half-duplex rate ratio for different amount of self-interference cancelation are plotted over the distance of D2D users. Results of this figure also show that for small distances between D2D users, even 75 dB self-interference cancelation can provide around 85% increase in the throughput. With 100 and 110 dB reduction on the level of self-interference, full-duplex doubles the rate of the link.

5.3. Summary and Conclusion

This chapter studies the downlink radio reuse of cellular users for D2D communication. It is considered that D2D users have self-interference cancelation systems and can

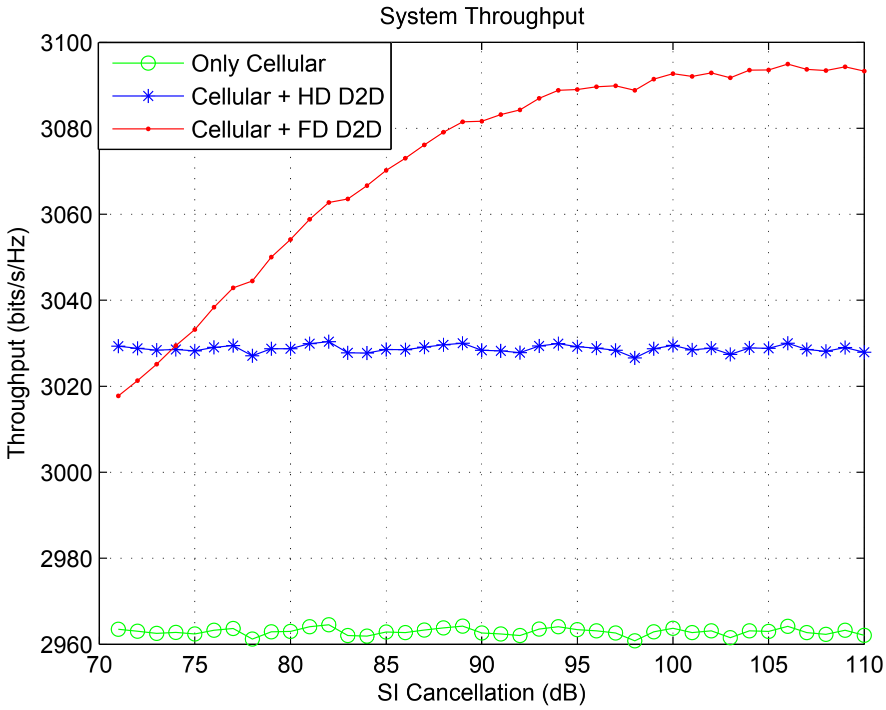

Figure 21: Throughput of system for downlink resource reuse - multi cell

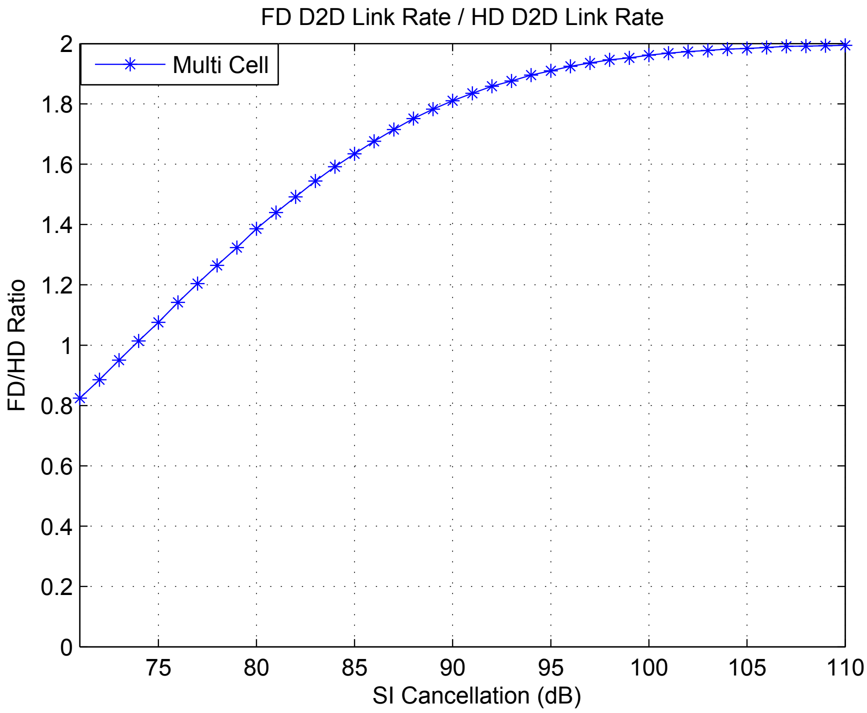

Figure 22: FD/HD Ratio For Downlink Resource Reuse - Multi Cell

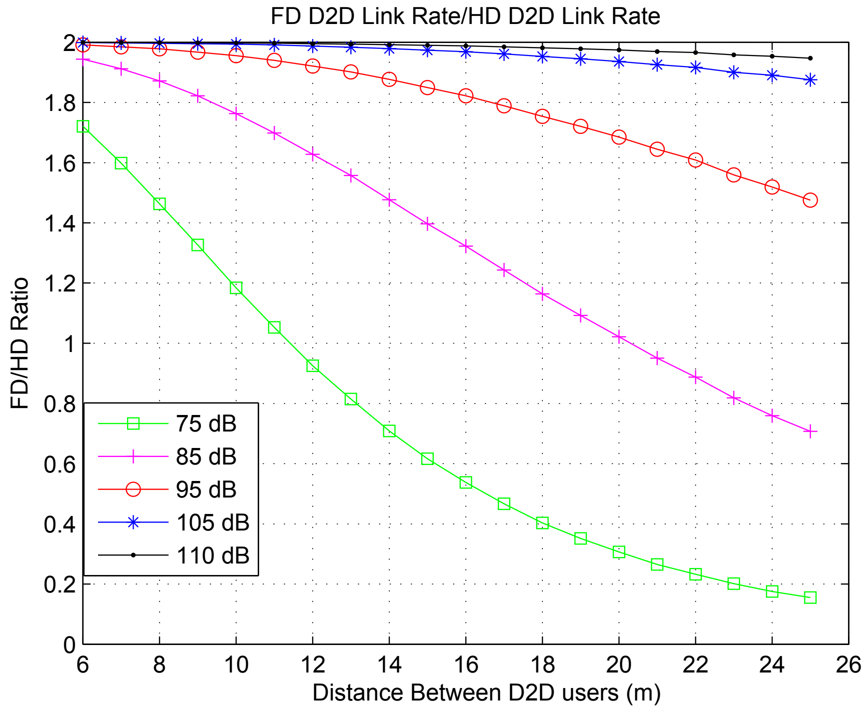

Figure 23: FD/HD Ratio Based On Distance

operate in both half-duplex and full-duplex modes. Interference-limited-area is used for interference management on cellular users. Full-duplex performance is compared to that of half-duplex for single cell and multi cell scenarios. In multi cell scenario, PFR with edge frequency reuse factor of 3 is implemented to limit the intercell interference. Simulations show that intercell interference effect the self-interference cancelation requirements for full-duplex radios since it increases the signal-plus-noise radio in D2D receivers. Results show that full-duplex is possible for D2D communication and can be considered in future wireless systems.

6. DISCUSSION

The focus of this thesis is to study the requirements for full-duplex radios to be used in device-to-device communications. Full-duplex radios can provide almost double spectral efficiency for wireless communications systems. The problem nowadays is that full-duplex radios are only available for systems with small transmit power. It was well known that if a radio can reduce the interference coming from its own transmitter to noise floor, it can simultaneously transmit and receive on the same frequency band and there will be no need to have time-division-duplex or frequency-division-duplex for two way communications. Until recently, radio engineering and signal processing technologies were not able to cancel the so called self-interference and the use of FDD or TDD was necessary. Recently full-duplex radio design has gained a lot of interest since wireless communication systems are going towards small cells and small transmit power systems, which makes it easier to eliminate the self-interference. Recent works on full-duplex radio design show the possibility of this technology for WiFi systems [2], [3], [9], [7], [21], [5], [6]. Research groups have been able to reduce the self-interference to the noise floor and double the throughput of the wireless systems. Radio design in [9] uses only one antenna and provides 110 dB self-interference cancelation. Implementation of full-duplex radios for multiple antenna systems also have gained a lot of interest [8], [4], [10]. Full-duplex MIMO radio in [10] can provide 110 dB self-interference reduction, also it provides the reduction of interference coming from other antennas in the node, while the complexity of the design is increased linearly with the number of antennas. This is almost an ideal full-duplex MIMO radio for WiFi systems. Investigating the possible application areas of full-duplex radios specially in cellular systems seems to be necessary. Most of the work in this area has considered ideal full-duplex radios without any residual of self-interference for all transmit power systems. This assumption is not realistic and it does not give a proper view at the problems in cellular systems. Also most of the work in this area have considered using separate transmit and receive antennas, which is not possible in hand held devices like mobile phones.

Device-to-device communication is considered to be one of the key technologies in future wireless systems to increase the spectral efficiency. Providing direct communication between devices will decrease latency and also offload data from base station. Underlay D2D which is co-sharing the spectrum between cellular and D2D users provides higher spectral efficiency but also causes mutual interference between cellular and D2D users. Since D2D is for devices in close proximity, transmit powers are small and thus possible to use full-duplex radios. Since in full-duplex D2D both of the users are transmitting at the same time on the same frequency band which is also being used by one or more cellular users, studying the interference and also the resource allocation becomes crucial. Also considering the effect of residual of self-interference and how much self-interference cancelation is required for full-duplex D2D needs to be investigated. Co-sharing cellular bands with D2D users can be done in uplink or downlink period. Each of them has advantages and disadvantages. But since future cellular systems may employ dynamic TDD for uplink and downlink communications, here both uplink and downlink resource sharing are studied.

In uplink resource sharing, the interference on base station from D2D transmitter is limited by the power control done at D2D transmitter. Base on acceptable interference-over-signal ratio in base station, D2D transmitter adjusts its transmit power to keep the interference less than a predefined ratio. To deal with the interference on D2D receivers coming from transmission of cellular users, the so called interference-limited-area method [20] is used. In this method an area around each D2D receiver is calculated in a way that interference coming to D2D receiver from cellular users would be high, then the users outside this area are considered for recourse sharing. This will guarantee that D2D users will not receive harmful interference and also makes the problem of resource allocation in base station more simple.

In chapter 5, allocating downlink resources for D2D communication is considered. When D2D users use the same resources as downlink communications, D2D users will receive the signal from base station which is sent to cellular users. On the other hand, transmission of D2D users causes interference to cellular users. Similar to the uplink resource sharing, to limit the interference on cellular users, interference-limited-area method is implemented. An area around D2D users is calculated based on the maximum D2D transmit power and interference-to-signal ratio in cellular users. Only the users outside this area are to be considered for resource sharing. To have the minimum interference on D2D receivers, cellular user with minimum transmit power will be selected to share the resources with D2D. Effect of inter-cell interference on amount of required self-interference cancelation is also studied in chapter 5. Distance of D2D users has a great impact on the performance of the full-duplex radios in D2D.

The main contribution of this thesis is that the results show that available full-duplex radios can be implemented in D2D communication. Throughout system level simulations, realistic results make it clear that full-duplex D2D should be a part of future wireless systems. The studies in this thesis have been limited to single antenna systems. While future cellular systems are going to employ multiple antennas, so further study of full-duplex D2D for systems with multiple antennas in base station and also mobile users is necessary.

7. SUMMARY

This thesis studied full-duplex device-to-device communication. Self-interference cancelation requirements for full-duplex radios to be implemented in device-to-device communication are investigated and it is shown by results that currently available full-duplex radios can be used in device-to-device communication. In the simulations, underlay D2D both in uplink and downlink are considered. Power control, resource allocation and interference-limited-are are used to deal with the interference that is the result of resource sharing. Since no work has been done prior to this thesis in full-duplex D2D, this thesis bridges the gap between full-duplex radios and D2D communication. Results show that with 110 dB self-interference cancelation, full-duplex D2D link can deliver double the throughput of traditional half-duplex scheme. Methods of resource allocation and also interference management effect the performance of full-duplex radios. In scenarios with high interference level, full-duplex radios easily outperform half-duplex even with less self-interference cancelation. In downlink resource sharing, inter-cell interference is also considered, simulations show that increase in noise-plus-interference level due to inter-cell interference leads to a better condition for full-duplex radios to be used.

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