



COGNITIVE SUBCARRIER SHARING SCHEMES FOR COOPERATIVE D2D COMMUNICATION FRAMEWORKS

by

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D2D COMMUNICATION FRAMEWORKS**

by

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Certificate

This is to certify that the thesis titled **Cognitive Subcarrier Sharing Schemes for Cooperative D2D Communication Frameworks** being submitted by **Naveen Gupta** to the Indraprastha Institute of Information Technology-Delhi, for the award of the degree of **Doctor of Philosophy**, is an original research work carried out by him under my supervision. In my opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree.

The results contained in this thesis have not been submitted in part or full to any other university or institute for the award of any degree/diploma.

September, 2017

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Abstract

Past few decades have seen a phenomenal growth in wireless multimedia and data applications. Recent forecast (via Cisco) suggested that the overall mobile data traffic could reach 24.3 exabytes per month by 2019. As a consequence, there is a perpetual need for novel spectrum access techniques to alleviate the problem of spectrum scarcity. This dissertation investigates two solutions to enhance the capacity of the wireless/cellular networks: cooperative spectrum sharing (CSS) and device-to-device (D2D) communication.

In a conventional CSS protocol, the secondary system (a cognitive user) acts as an amplify-and-forward (AF) or decode-and-forward (DF) relay for the primary system to achieve the target quality-of-services (QoS) of the primary system in exchange for spectrum access by the secondary system. However, most of the existing CSS protocols are interference limited and performance of the system may degrade due to interference from one system to another. To mitigate the interference, we propose orthogonal frequency division multiplexing (OFDM) based opportunistic spectrum sharing (OSS) for cooperative cognitive radios. According to the scheme, secondary system helps the primary system via two phase DF relaying in exchange of OSS. Both primary and secondary systems employ OFDM modulator and demodulator at transmitter and receiver, respectively. If the primary system

is unable to achieve its target rate, then the secondary transmitter (ST) forwards a few subcarriers to the primary receiver (PR) to fulfill the quality-of-services (QoS) requirement of the primary system and the remaining subcarriers can be used by the secondary system for its own data transmission. Thus, OSS can be achieved by the secondary system without interfering to the primary system, since primary and secondary subcarriers are orthogonal to each other.

To further boost the performance of both primary and secondary systems, we propose an adaptive subcarrier sharing scheme for OFDM-based cooperative cognitive radios. According to the scheme, ST uses adaptive mode of transmission to relay the primary signal with higher throughput while maintaining the bit-error-rate (BER) constraint of the primary system. At PR, a BER based selection combining (BER-SC) scheme is employed to combine the signals received in two phases. Closed-form analytical expressions for BER and outage probability of primary and secondary system for a Rayleigh flat fading channel have been derived. Results show that the outage probability with the proposed scheme (for dissimilar modulation) outperforms direct transmission and conventional maximal ratio combining scheme (for similar modulation).

Recently, D2D communication has been incorporated as a part of long-term-evolution advanced (LTE-A) Release 12 and 13 to avail the high capacity benefits to the cellular users with minimal constraints on infrastructure maintenance. In a generic D2D framework, two cellular users living in proximity can form a direct link for data transmission without routing it through the evolved node B (eNB) / base station (BS). Utilization of available resource allocation frameworks to facilitate D2D communication while maximizing the throughput of both cellular and D2D users is an open issue. In this dissertation, we propose the rate and outage trade-offs for orthogonal frequency division multiple access (OFDMA) based

D2D communication frameworks where multiple D2D users coexist with the cellular users in the same cell. Analytical expressions of outage probability for three D2D frameworks namely underlay, overlay and cooperative D2D (C-D2D) have been derived. Specifically, for underlay framework, a minimum value of the angle (an angle between a cellular link and D2D interference link) is derived for which the target rate and outage probability constraint of both cellular and D2D users are satisfied. For overlay and C-D2D frameworks, an optimal subcarrier sharing scheme is proposed which not only helps the cellular users to achieve the target QoS, but also helps the D2D users to communicate with each other. In addition to above, benefits involved in employing one framework over other have also been investigated. Our results show that for a higher outage probability constraint of the cellular user, the C-D2D framework outperforms the underlay and overlay frameworks.

We augment the development of C-D2D framework by incorporating the best D2D user selection scheme. As per the proposed scheme, among M available D2D pairs, a D2D transmitter (DT) that can achieve the largest QoS improvement for uplink cellular transmission is selected to serve as a user relay for the cellular transmission. In addition, a novel round robin process with priority cube method is proposed to facilitate the fair distribution of available resources among M DTs. In particular, closed-form expressions of the outage probability for two different cases: with and without direct cellular link are derived. Results show that the proposed best D2D user selection improves the QoS of the cellular user as compared to the conventional C-D2D framework.

Another issue related to D2D communication is the lack of measurement results for proof of concept demonstration and performance assessment in a realistic scenario. We try to resolve this issue by designing and developing a software defined

radio (SDR) based test-bed implemented on National Instruments (NI) Universal Software Radio Peripheral (USRP) platform. The performance of the testbed has been validated by obtaining received signal to noise ratio (SNR) and symbol error rate (SER) for both cellular and D2D users. The measurement results show that the proposed frameworks significantly improves the performance of cellular network in both line of sight (LOS) and non-line of sight (N-LOS) scenarios.

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List of Abbreviations

ADC	analog-to-digital converter
AF	amplify-and-forward
AM	amplitude modulation
AMC	adaptive modulation and coding
AWGN	additive white Gaussian noise
BPSK	binary phase shift keying
BER	bit error rate
BER-SC	bit error rate based selection combining
BS	base station
CCTH	cooperative clear-to-help
CCTS	cooperative clear-to-send
CCR	convolutional code rate
C-D2D	cooperative device to device communication
CR	cognitive radio
CRTS	cooperative right-to-send
CSI	channel state information

CSS	cooperative spectrum sharing
CU	cellular user
D2D	device to device communication
DAC	digital to analog converter
DF	decode-and-forward
DFT	discrete Fourier transform
DR	D2D receiver
DSA	dynamic spectrum access
DT	D2D transmitter
eNB	evolved node B
FCC	Federal Communication Commission
FFT	fast Fourier transform
FPGA	field programmable gate array
IFFT	inverse fast Fourier transform
ISI	inter-symbol interference
LOS	line-of-sight
LTE	long term evaluation
LTE-A	long term evaluation advanced
LTF	long training field
MAC	media access control
MIMO	multiple input multiple output

mod	modulo operator
MRC	maximal ratio combining
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
NI	National Instruments
N-LOS	non line-of-sight
OSS	opportunistic spectrum sharing
PDF	probability density function
PER	packet error rate
PR	primary receiver
PSS	primary synchronization signal
PT	primary transmitter
QAM	quadrature amplitude modulation
QoS	quality of service
QPSK	quadrature phase shift keying
RF	radio frequency
SC-FDMA	single carrier frequency division multiple access
SDR	software defined radio
SE	spectral efficiency
SER	symbol error rate
SNR	signal-to-noise ratio

SR	secondary receiver
SSS	secondary synchronization signal
ST	secondary transmitter
STF	short training field
TDD	time division duplex
UE	user's equipment
URCM	UE relay confirmation message
USRP	universal software radio peripheral
WSN	wireless sensor networks

List of Symbols

$(\cdot)^*$	conjugate
$(\cdot)^T$	transpose
$E(\cdot)$	expectation
$z \sim \mathcal{CN}(\mu, \sigma^2)$	complex Gaussian random variable with mean μ and variance σ^2
N	number of subcarriers
D	number of subcarriers forward by ST to PR or ST to BS
ζ_{ij}	normalized distance between i^{th} transmitter and j^{th} receiver
$s_{p,k}$	primary signal
$s_{s,k}$	secondary signal
$\Psi_{1,k}$	channel coefficients corresponding to PT→PR
$\Psi_{2,k}$	channel coefficients corresponding to PT→ST
$\Psi_{3,k}$	channel coefficients corresponding to ST→PR
$\Psi_{4,k}$	channel coefficients corresponding to ST→SR
k	subcarrier index
$x \sim \varepsilon(\zeta)$	exponential random variable x with mean $\frac{1}{\zeta}$

l	path loss component
α	power allocation factor
R_T	primary system or cellular user target rate
R_{T_s}	secondary system or D2D user target rate
M	constellation size
	$\zeta_{2,T}$ transmute distance
$p_{p,k}$	power of k^{th} subcarrier at PT
$p_{s,k}$	power of k^{th} subcarrier at ST
P_{out}^p	primary system outage probability
η_{BER-SC}	primary BER for BER-SC
p_{cu}	power transmitted by CU
p_{dt}	Power transmitted by DT_i
s_{cu}	cellular user signal
s_{dt_i}	D2D user signal
$\emptyset$	null set
$\text{card}(\mathcal{S})$	Cardinality($\mathcal{S}$)
γ_1	instantaneous CU-BS channel gain
γ_{2i}	instantaneous CU- DT_i channel gain
γ_{3i}	instantaneous DT_i -BS channel gain
γ_{4i}	instantaneous DT_i - DR_i channel gain
$P_{BS,out}$	outage probability for CU-DT-BS link

$P_{BS,out}^{mrc}$	outage probability for CU-DT-BS with cellular link
P_{out}^{d2d}	D2D outage probability
$P_{cu,out}^{under}$	CU outage probability for underlay
$P_{dt,out}^{under}$	D2D outage probability for underlay
$P_{cu,out}^{over}$	CU outage probability for overlay
$P_{d2d,out}^{over}$	D2D outage probability for overlay
$P_{cu,out}^{coop}$	CU outage probability with C-D2D
θ	an angle between Cellular link and D2D interference link
B_N	subcarrier spacing

Introduction

1.1 Motivations and Objectives

Driven by increase in new wireless services and applications, as well as the addition of new wireless users, the demand for radio spectrum has grown day by day. It has led to an acute problem of spectrum scarcity. However, as some studies have shown [1], spectrum scarcity is primarily due to inefficient frequency allocations by government regulatory agencies rather than a physical shortage in the spectrum. The federal communications commission (FCC) has reported the temporal and geographic variations in spectrum utilization ranges from 15% to 85% [2].

As a consequence, researchers over the years have proposed alternative dynamic spectrum access techniques to improve spectral efficiency and capacity in radio communication environment, leading to the notion of cognitive radio. According to [3], “cognitive radio is a radio that employs model based reasoning to achieve a specified level of competence in radio-related domains”. Conceptually, cognitive radios have the capabilities to co-exist with the licensed users without degrading their performance. This technique allows the cognitive (unlicensed) user to acquire the authorized frequency band which is allocated to the primary (licensed) user without inflicting any undesirable interference to the primary signal transmission.

In recent times, cooperative relaying has been conceived in cognitive radio for “sensing and sharing” [4], [5]. In cooperative relaying, a relay can be used as a virtual antenna to improve the performance of a wireless system by achieving spatial diversity. A relay can acts as an amplify-and-forward (AF), decode-and-

forward (DF) or compressed-and-forward (CF) relay. Cooperative relaying for two-hop cognitive environment is considered in [6]. The cooperative cognitive system where a subset of the relay is used to create transmission opportunities via sensing the radio is considered in [7]. Cognitive radio networks support opportunistic spectrum sharing (OSS) [8] via granting secondary system (low priority) to share the spectrum of the primary user (higher priority) to utilize the radio spectrum more efficiently. Practical implementation of OSS for long term evolution-advanced (LTE-A) standard with carrier aggregation technique has been proposed in [9]. Furthermore, LTE in unlicensed band (LTE-U) has physical layer topology to do OSS in underutilized Wi-Fi bands, specifically in 5 GHz band [10], [11]. Here OSS plays a significant role in improving the spectrum use in Wi-Fi bands and provides new paradigm for the coexistence of LTE and Wi-Fi technologies.

One model to realize an OSS framework is through cooperative spectrum sharing (CSS) protocols [12, 13, 14]. In a conventional single carrier CSS protocol, the secondary system helps the primary system by acting as a relay for the primary system to achieve the target rate of communication in exchange for OSS by the secondary system. Some existing work on CSS is also based on interference limited systems [15], where the primary system can handle additional interference from other systems without affecting its quality-of-service (QoS). Most of the existing single carrier CSS protocols are interference limited and performance of the system may degrade due to interference from one system to another.

To cope with the problem of interference, in [16] a combination of multi-carrier modulation such as orthogonal frequency division multiplexing (OFDM) and DF relaying has been proposed for selective subcarrier pairing and power allocation. Specifically, more secondary system power is provided to the better channel by using subcarrier sharing and power allocation algorithms. In [17], a multi-carrier CSS protocol utilizing OFDM and AF relaying has been proposed. In this work, a joint optimization problem is formulated for selective subcarrier pairing and power allocation, wherein the secondary system uses a fraction of its subcarriers to boost the performance of the primary system. Results are shown for outage probability with respect to the transmission power of the secondary system. However, the analysis in [16], [17] is limited to optimizing the secondary system performance. Hence, the exact number of subcarriers relayed via the secondary transmitter to the

primary receiver has not been computed. Furthermore, no adaptive modulation has been used in the secondary transmitter to optimize the performance of the primary and secondary system.

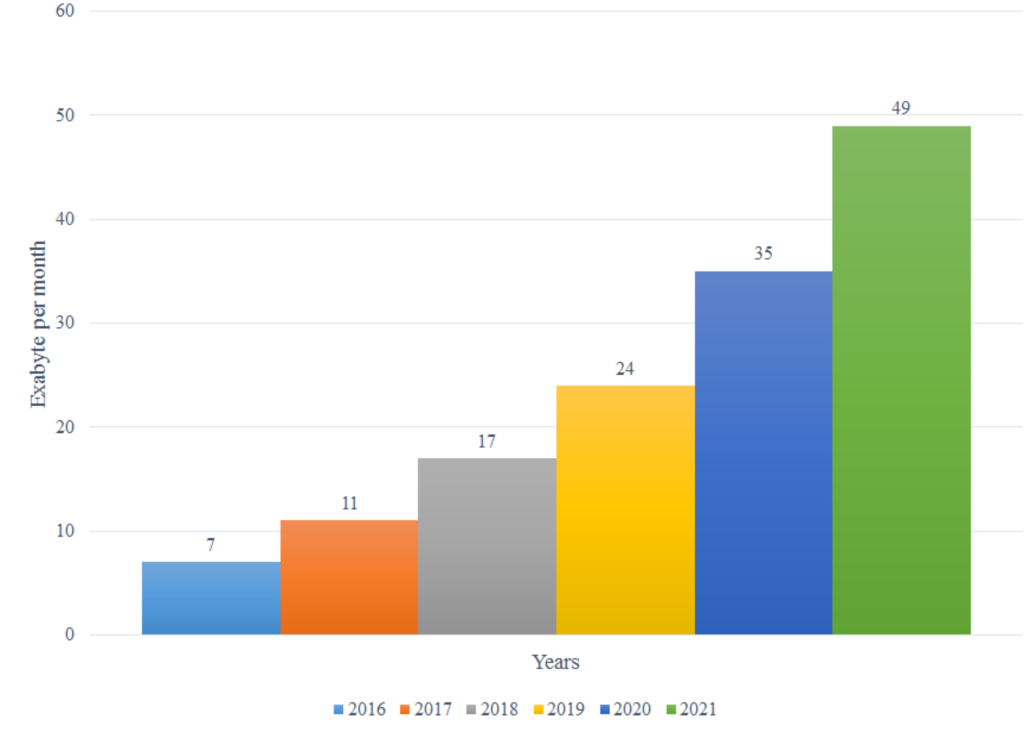


Figure 1.1. Mobile data traffic growth forecast [18]

Apart from acute spectrum scarcity, the phenomenal growth of bandwidth-exhaustive network applications (a.k.a. “Apps”) are also pushing the limits of existing cellular networks. The mobile data traffic is increasing rapidly, and quantitative studies [18] expects that the exponential growth would continue in the future as shown in the Fig. 1.1. Besides accommodating massive data traffic, service providers also need to focus on the QoS. Existing technologies may offer acceptable QoS in selected areas; however, they can not meet the huge capacity demands on the future wireless networks when cellular users are densely populated or are in close-proximity to each other, such as inside an office building, shopping malls, inside a stadium [19]. It lays the motivation to develop next generation cellular technologies which can provide higher data rate, low latency, and wider connectivity as compared to its predecessors.

Recently, device-to-device (D2D) communication [20] has been incorporated

as a part of LTE-A Release 12 and 13 to address some of the above challenges [21, 22]. D2D is also foreseen as one of the core technology of 5G to improve the spectral efficiency by leveraging the neighborhood information [23], [24]. In hindsight, D2D communication provides high capacity benefits to cellular users with minimal constraints on network up-gradation and maintenance. In a generic D2D framework, two cellular users living in proximity can form a direct link for data transmission without routing it through the evolved node B (eNB) / base station (BS). However, control or signaling information between the users is still carried out by the BS [25], [26].

Two commonly used D2D communication frameworks for the cellular networks are underlay and overlay D2D communication [27]. In underlay D2D communication, both cellular and D2D users simultaneously share the licensed cellular spectrum while maintaining the interference threshold, analogous to underlay cognitive radio communication [28]. However, in a D2D scenario, unlike cognitive radio, a D2D user belongs to the same cellular network, so it may not necessarily have low priority. Compared to underlay, in overlay D2D communication, BS allocates dedicated spectrum or time slots to D2D link as long as the QoS of the cellular user's is not compromised [29]. Although this eliminates the mutual interference between cellular and D2D link, however, it results into the inefficient utilization of available spectrum resources.

Underlay and overlay D2D frameworks are studied extensively in the literature, whereas, the cooperative D2D (C-D2D) framework is yet to be thoroughly investigated. In the C-D2D framework, a point-to-point D2D communication link is split into multiple phases among multiple entities in a coordinated way to achieve spatial performance gains. Fine-grained resource allocation for single channel C-D2D communication in the cellular network is proposed in [30]. In [30], a relay can cooperate with mobile users by either frame-by-frame or slot-by-slot scheduling. Further, the interference region of each node is defined to avoid collision with nearby transmitters. Results show the performance improvement in terms of minimum transmission rate if large number of channels are available. However, the scheme proposed in [30] is limited to the performance improvement for nearby mobile users (D2D) only. No insights were given for integration of cellular and D2D users to achieve spatial diversity.

In addition, most of the recent works on C-D2D framework have been restricted to the deployment of single or multiple user's equipment (UE) relays to offload the cellular traffic [31]. A systematic analytical model of the best D2D user selection scheme and number of D2D users that can be supported by a cellular user while satisfying the QoS of all engaged users has not been investigated yet.

Another issue related to D2D communication is the lack of D2D prototype testbeds to demonstrate the practical performance of such protocols. As a result, the performance evaluation of the existing D2D frameworks is limited to the computer simulations. However, most of the simulation models are unable to replicate the real wireless environment. Thus, analytical work on D2D communication can not be verified.

Although researchers have explored and investigated the domain of cognitive radio and D2D communication to improve the performance of existing cellular networks; however, there is the dearth of literature on utilizing cooperative cognitive radios and cooperative D2D communication for existing cellular networks. From the above discussion, it is evident that the CCR and C-D2D will further enhance the performance of cellular networks and will lay the foundation for next generation of cellular networks presumably 5G. Hence, the major objectives of the thesis are summarized below.

- Investigate the various OFDM based CSS protocols proposed for the cognitive radio system and identifying their pros and cons.
- Propose new subcarriers sharing schemes to enhance the primary and secondary performance and comparing it with conventional CSS protocols through simulation and analytical results.
- Investigate various radio access frameworks to facilitate D2D communication in cellular networks. Identify their pros and cons, and propose new methods to improve them.
- The trade-offs involved in incorporating one framework over another for integrating D2D communication in cellular networks.
- Among multiple available D2D users, identify the best D2D user to cooperate

with cellular user in order to achieve the required QoS. Investigate outage probability trade-offs between cooperation and without cooperation.

- As a proof-of-concept demonstration and performance assessment, designing and developing a software defined radio (SDR) based radio frequency (RF) testbed on the proposed D2D communication frameworks.
- Highlight the obtained analytical and measurement results under different scenarios and discuss the potential impact of such results on the next-generation cellular networks.

1.2 Major Contributions of the Thesis

Some of the major contributions of the thesis are summarized below along with the relevant publications.

- Proposed an OFDM-DF based opportunistic subcarriers sharing scheme for cooperative cognitive radios. According to this scheme, if secondary transmitter (ST) is located within the critical distance from the primary transmitter (PT), it can allocate few successfully decoded subcarriers to the primary receiver (PR) while remaining subcarriers can be used for secondary communication. Analytical expressions of outage probability for the primary and secondary system with critical distance have been derived [32], [33].
 - N. Gupta, V. A. Bohara, “A cognitive subcarrier sharing scheme for OFDM based decode-and-forward relaying system”, in *Proceedings of 10th International Conference on cognitive radio oriented wireless networks and communications, CrownCom 2015*, pp. 334-345, Doha, April 2015.
 - N. Gupta, V. A. Bohara, “Outage analysis of cooperative OFDM relaying system with opportunistic spectrum sharing” in *Proceedings of International Conference on Advances in Computing, Communications and Informatics (ICACCI)*, Sept 2014, pp. 2803-2807.
- Proposed an adaptive subcarrier sharing scheme for OFDM-based cooperative cognitive radios, which deduces the exact number of subcarriers that

need to be relayed by ST to PR to fulfill the target QoS of the primary system. In other words, the proposed scheme not only helps the primary user to achieve the target QoS but also helps the secondary user to utilize the remaining subcarriers for its own communication. We also derived the closed-form expressions for bit error rate (BER) and outage probability of the primary and secondary systems which employed OFDM based adaptive CSS protocol and bit error rate selection combining (BER-SC) as a signal combining technique [34, 35].

- N. Gupta, V. A. Bohara, “An Adaptive Subcarrier Sharing Scheme for OFDM-Based Cooperative Cognitive Radios”, in *IEEE Transactions on Cognitive Communications and Networking*, vol. 2, no. 4, pp. 370-380, Dec. 2016.
- S. Mittal, N. Gupta, V. A. Bohara “A BER Based Selection Combining Protocol for Adaptive Cooperative Cognitive Radios”, in *Wireless Personal Communications (Springer Journal)*, June 2017.
- S. Mittal, V. A. Bohara, N. Gupta, “A BER Based Selection Combining Protocol for Adaptive Cooperative Cognitive Radios”, poster in *European Conference on Networks and Communications (EUCNC-2016)*, Oulu, Finland, 2016.
- Investigated the rate and outage trade-offs for OFDMA based underlay, overlay, and C-D2D communication frameworks. Specifically, for underlay D2D framework, we proposed an angle constrained D2D communication for which the optimal distance between the cellular user (CU) and base station (BS) as well as the minimum value of angle θ (an angle between a cellular link and D2D interference link) is derived. It has been shown that as long as the angle between the cellular link and D2D interference link is greater than the optimal value of θ , the target rate and outage probability constraint of both the cellular and D2D users will be satisfied. We have also investigated the impact of CU-BS distance, angle θ , and cellular user outage probability constraint on different frameworks. By leveraging the above results, BS can select the cellular user which facilitates D2D communication while maintaining its QoS [36, 37].

- N. Gupta, V. A. Bohara, “Rate and Outage Trade-offs for OFDMA based Device to Device Communication Frameworks”, in *IEEE Access Journal*, vol. 5, pp. 14095-14106, 2017.
- N. Gupta, V. A. Bohara, “OFDMA Based Angle-Constrained Underlay Device-to-Device Communication”, accepted in *Proceedings of IEEE GLOBECOM 2017*, Singapore, Dec. 2017.
- N. Gupta, V. A. Bohara, “Subcarrier sharing scheme for overlay and cooperative D2D communication in cellular networks”, in *Proceedings of IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS) 2016*, Bangalore, 2016, pp. 1-6.
- Proposed a best D2D user selection scheme for an OFDMA based C-D2D framework, wherein multiple D2D pairs co-exist with a cellular user in a cell. Specifically, a subcarrier sharing scheme is proposed that facilitates M available D2D users to do D2D communication by sharing the spectrum of the single CU while satisfying the target QoS of the CU. The proposed scheme leads to considerable performance improvement for both cellular and D2D users. In addition to above, for fair distribution of available subcarriers among M D2D users, a novel round robin process with priority cube method is proposed. The proposed method helps the BS in fair allocation of resources to all D2D transmitters for D2D communication [38, 39].
 - N. Gupta, V. A. Bohara, “Angle-Constrained Underlay and Cooperative Device-to-Device Communication Frameworks”, submitted to *IEEE Transactions on Cognitive Communications and Networking*, Nov. 2017.
 - N. Gupta, D. Kumar, V. A. Bohara, “User Selection and Resource Allocation for OFDMA based Cooperative Device-to-Device Communication Framework”, submitted to *IEEE ICC*, 2018
 - N. Gupta, D. Kumar, V. A. Bohara, “Cooperative D2D Communication in Unlicensed Spectrum: Best User Selection and Resource Allocation” (under preparation).
- For proof of concept demonstration and performance assessment of the proposed adaptive and non-adaptive subcarrier sharing schemes, the C-D2D

framework has been implemented on an SDR based NI-USRP platform. Measurement results in a realistic indoor lab environment were obtained. Results show that the symbol error rate (SER) performance of the cellular user improves significantly with C-D2D. Further, there is a net increase in received signal to noise ratio (SNR) at BS. Hence, C-D2D framework facilitates D2D communication with acceptable SER [40, 41].

- N. Gupta, V. A. Bohara, V. K. Singh, “Design and measurement results for cooperative device to device communication,” accepted as a book chapter in *Resource Allocation in Next-Generation Broadband Wireless Access Networks* by IGI-Global, 2016
- S. Sharma, N. Gupta, V. A. Bohara, “Insights from the Measurement Results for Adaptive and Cooperative D2D Communication Framework”, accepted in *Proceedings of IEEE WCNC*, Barcelona, Spain, 2017.
- N. Gupta, V. K. Singh, S. Sharma, V. A. Bohara, “A proof-of-concept demonstration of cooperative D2D framework based on SDR”, accepted in *Proceedings of IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS) 2017*, Bhubaneswar, 2017.
- S. Sharma, N. Gupta, V. A. Bohara, “OFDMA-based Device-to-Device Communication Frameworks: Testbed Deployment and Measurement Results”, submitted to *IEEE Access Journal*, Jan. 2018.

1.2.1 Other contributions

The author of this thesis has also contributed to the following publications.

- S. Mittal, N. Gupta, V. A. Bohara, “A Cooperative Spectrum Sharing Protocol for Cognitive Two-way AF Relaying System” accepted in *Proceedings of IEEE TENSYP*, Cochin, 2017.
- N. Gupta, A. D. Singh, P. Shrivastava, V. A. Bohara, “A Two-Way Cooperative D2D Communication Framework for a Heterogeneous Cellular Network”, submitted to *Wireless Personal Communications (Springer Journal)*, Dec. 2017.

1.3 Organization of the Thesis

The remainder of the thesis is organized as follows. The remaining part of chapter 1 provides the necessary background knowledge about the cooperative relaying, cognitive radio, cooperative cognitive radio, and cooperative spectrum sharing. It is followed by a discussion on OFDM based CSS protocols and highlighted their pros and cons. Chapter 1 also discusses the concept of D2D communication for next generation cellular networks. Further, based on the integration of cellular and D2D users, several D2D communication frameworks such as underlay, overlay, and cooperative D2D are discussed. Apart from above, existing D2D based prototype testbeds are also showcased for performance assessment of D2D communication in a realistic scenario.

In Chapter 2, subcarrier sharing scheme for OFDM based cooperative cognitive radio is proposed. BER and outage probability of the primary and secondary systems which employ OFDM based CSS protocol is derived. Outage probability of the OFDM based nonadaptive CSS protocol is also derived. Analytical and simulation results are shown to validate the proposed schemes.

In Chapter 3, an OFDMA based angle constrained D2D communication is proposed. We analyze the performance of the underlay, overlay and C-D2D frameworks by deriving the closed-form expressions of outage probability for cellular and D2D users. Trade-offs involved in employing one framework over another are also investigated.

In Chapter 4, a best D2D user selection scheme for OFDMA based C-D2D framework is proposed. Closed-form expressions of the rate and outage probability for two cases i.e. with and without cellular link are derived. For fair distributions of subcarriers among M available D2D pairs, a novel round robin process with priority cube method is proposed. Analytical and simulation results for cellular and D2D users are provided to validate the proposed scheme.

Chapter 5 showcases the testbed for proof-of-concept demonstration and performance assessment of the proposed adaptive and non-adaptive C-D2D communication protocols. Measurement results are provided to validate the proposed frameworks.

Chapter 6 concludes the thesis and outline the possible directions for future

research.

1.4 Background and Preliminaries

1.4.1 Cognitive radio

It has been repeatedly said that next generation wireless standards will transform the way people access and communicate information. However, each new access technology puts an additional burden on the already constrained spectrum resources. As a consequence, there is an acute need for alternative spectrum access technique which will increase the spectral efficiency and capacity of wireless communication systems.

The term cognitive radio first mentioned in [3] has emerged as a promising spectrum sharing technology which allows spectrum reuse in space, frequency and time to solve the problem of spectrum scarcity. This technology allows the unlicensed (cognitive) user to acquire the authorized frequency band which is allocated to the primary (licensed) user without causing any hazardous interference to the primary signal transmission. Specifically, cognitive radio is an intelligent transceiver which is able to sense the surrounding communication environment and adapts the radio resources dynamically to provide acceptable QoS to the secondary user without affecting the QoS of the primary user [43]. The key elements of a cognitive radio network are highlighted in Fig. 1.2.

- **Spectrum Sensing:** A cognitive radio monitors the available spectrum bands to detect the spectrum holes. A spectrum hole is a part of the licensed spectrum with no or reduced primary user activity as shown in Fig. 1.3. Spectrum sensing also allows a cognitive radio to adapt its transmission parameters as per current RF environment knowledge.
- **Spectrum Analysis:** Cognitive radio estimates the characteristics of the detected spectrum holes to optimize the performance of both licensed and cognitive users.
- **Spectrum Decision:** A cognitive radio computes the transmission parameters such as mode of transmission, data rate, transmit power and the transmission

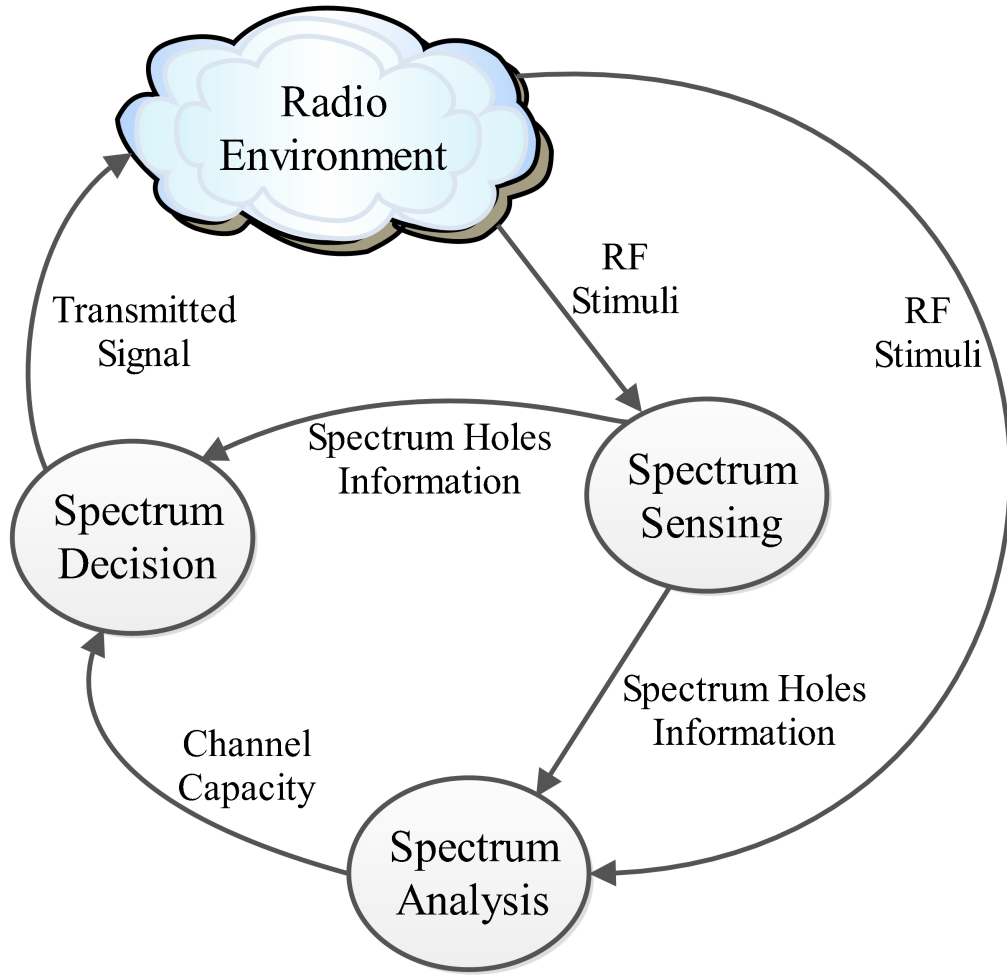


Figure 1.2. Cognitive cycle [42]

bandwidth. Then, an appropriate spectrum band is selected as per the user requirements and spectrum characteristics.

By following the cognitive cycle specified in Fig. 1.2, a cognitive user can utilize the spectrum holes for its communication. However, a cognitive radio should keep the track of RF environment which can change over time and space. If current spectrum becomes occupied for the next cycle then spectrum mobility [42] (switched to appropriate frequency band) must be performed for seamless transmission.

The success of a cognitive radio transmission primarily depends on the spectrum sharing process [44]. False sensing results can lead to the collision between the primary and secondary users (if detected unoccupied) or inefficient spectrum

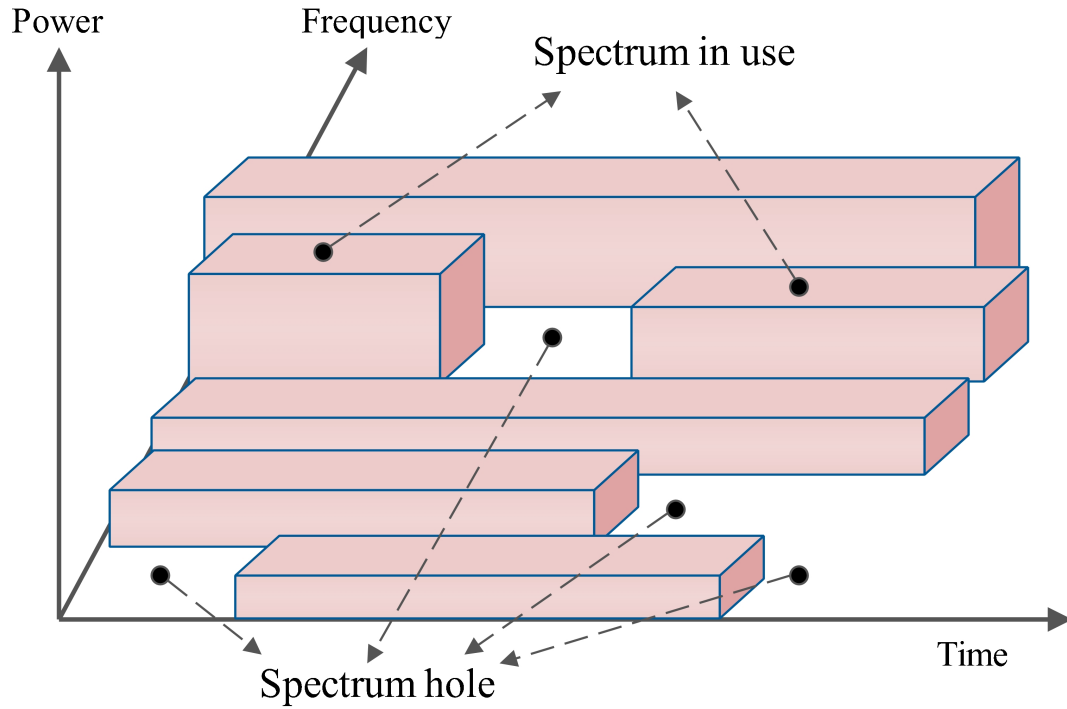


Figure 1.3. Spectrum hole [42]

utilization (if detected occupied) [7, 45, 46]. Thus, accurate spectrum sensing is prominent need to ensure the reliable communication. However, due to inconsistencies involved in wireless channels, spectrum sensing cannot promise the optimum reliability. Another limitation with a conventional cognitive radio network is incompetence in dense urban scenarios where the spectrum is generally crowded, and spectrum holes are tough to obtain.

1.4.2 Cooperative cognitive radio

Recently, cooperative relaying has been incorporated to facilitate spectrum sharing schemes in cognitive radios [47, 48]. It exploits the time and space diversity to combat multipath fading and shadowing effects in the wireless channel which leads to the performance improvement in cognitive radio network. The advantages of cooperative communication in cognitive radios are high throughput, better network coverage, and high reliability.

1.4.2.1 Cooperative relaying

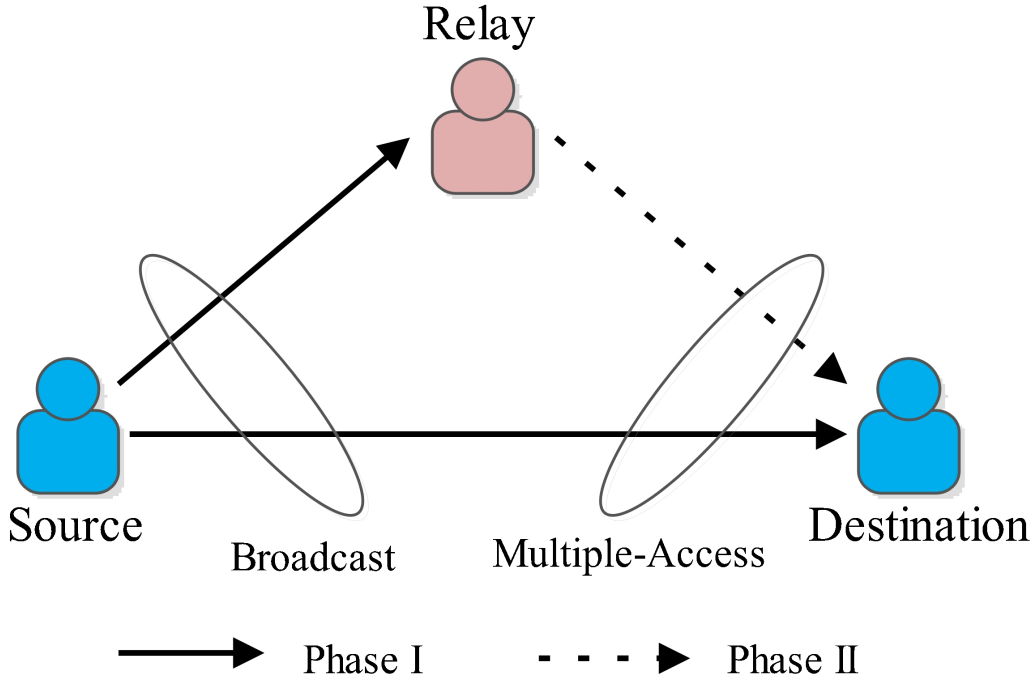


Figure 1.4. Cooperative relay network

In cooperative relaying, single or multiple relays are used to improve the performance of the wireless system by utilizing space and time diversity. A simplified cooperative relay network consists of a source, a destination, and a relay as shown in Fig. 1.4. According to the protocol, source to destination transmission is divided into two phases. In Phase I, the source transmits its data to the destination which is overheard by the relay. In Phase II, the relay forwards the source data to the destination. Thus, two-phase communication inheres spatial diversity making the source-destination communication reliable against transmission errors.

Depending on the data forward strategy, a relay can act as an AF, DF, or CF relay.

- **AF:** In AF relaying, a relay overhears the source data transmitted in Phase I. In Phase II, relay amplifies the source signal and retransmits it to the destination. At the destination, a signal combining technique such as MRC is employed to combine the signals received in two phases. AF relay is simple

to implement; however, its performance may suffer due to error propagation.

- **DF:** In DF relaying, a relay attempts to decode the source signal received in Phase I. If decoding is successful, relay regenerates the source signal and transmits it to the destination in Phase II. The destination employs a signal combining technique to combine the signals received in two phases. In DF relaying, no error propagation from the relay to the destination since relay decodes the source data before forwarding it to the destination. However, complexity is higher as compared to AF relay.
- **CF:** A CF relay is used when the relay node is unable to decode the source transmission received in Phase I. In such scenario; a reasonable alternative is to have a relay which describes its source transmission observations to the destination. In CF relay, the relay node first compresses its observation of the received signal and then forwards this compressed version to the destination. In contrast to DF relay, a CF relay performs better when it is close to the destination.

1.4.2.2 Cooperative spectrum sharing

The cooperative spectrum sharing (CSS) incorporates cooperative relaying in the cognitive radio network to increase throughput and reliability of the overall system. In CSS, when the target rate of the primary system falls below the particular threshold, then secondary system granted opportunistic spectrum sharing (OSS) to share the spectrum of the primary users. The schematic of a conventional CSS framework is shown in Fig. 1.5. Here, primary system comprises the primary transmitter (PT) and primary receiver (PR), while secondary system comprises the secondary transmitter (ST) and secondary receiver (SR). If primary system is unable to achieve its target rate of transmission by conventional direct PT-PR communication, then ST which acts as an AF or DF relay for the primary system will adopt two phases transmission protocol. In Phase I, PT broadcasts its data to PR which is overheard by ST and SR. In Phase II, ST linearly combined its own data with primary data and forwards it to PR and SR. At PR, MRC is employed to receive the signals in two phases. At SR, the interference component

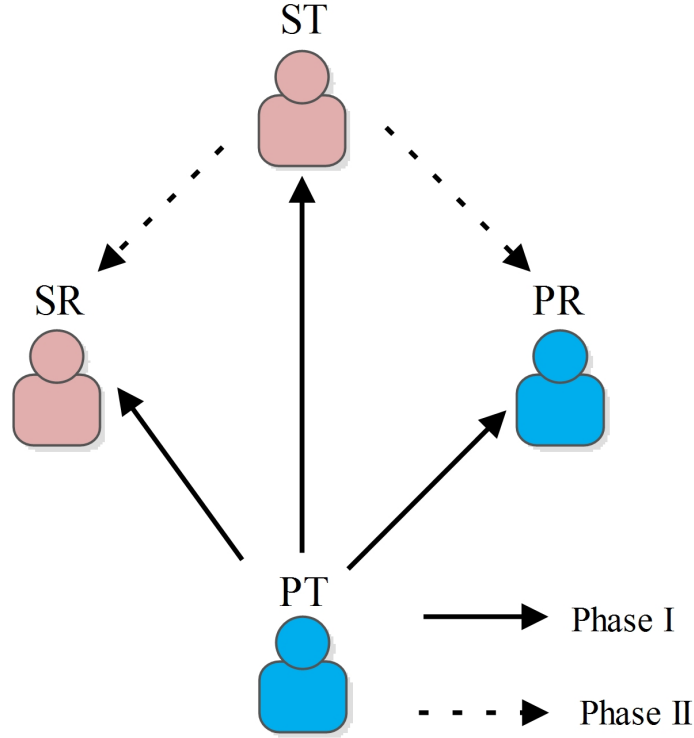


Figure 1.5. A simplified CSS protocol

of the primary signal can be canceled by successful decoding of the primary signal received in Phase I. Thus OSS is achieved by the secondary system.

Cooperative spectrum sharing for single carrier system has been proposed in [12, 13]. In [12], the regenerated primary signal at the secondary transmitter is combined with the secondary signal by providing a fraction of secondary power to the primary signal and remaining power to the secondary signal. A DF relay based two-phase hierarchical CSS protocol has been proposed in [49], wherein ST is equipped with multiple antennae. The proposed protocol does not require the transmit channel state information (CSI). Out of available M antennae, the signal can be transmitted from the randomly selected antenna, thus achieving significant performance improvement in terms of primary system outage probability. A relay based CSS protocol with multiple primary and secondary users with incomplete information is proposed in [50]. According to [50], each primary user (PU) offers a matching theory based relay power and spectrum access time combination to attract potential secondary user (SU). Utilizing matching theory, each SU mapped

with most suitable PU for maximizing its utility.

The above-proposed CSS protocols are limited to single carrier communication and non-adaptive mode of transmission. In addition, the outage performance of the single carrier based CSS protocols is degraded due to secondary signal interference at PR.

1.4.2.3 OFDM-based CSS protocol

To cope with the secondary user interference at the primary receiver, the combination of multi-carrier modulation such as OFDM and DF relaying is proposed in [16]. Here, primary and secondary user transmission is carried out on the orthogonal sets of subcarriers. Hence, no interference at PR due to secondary signal. A survey on radio resource management in cooperative OFDMA based cognitive radio network is presented in [51]. An overview of various resource allocation algorithm with fixed DF relays to enhance the performance of communication system is provided in [51]. The optimization of subcarrier power to maximize the cognitive system throughput without providing excessive interference to the primary system has been proposed in [52]. Similarly, in [17], a multi-carrier CSS protocol utilizing OFDM and AF relaying has been proposed. Here, the secondary system uses fraction of its subcarriers to boost the performance of the primary system.

However, the above OFDM based CSS protocols are nonadaptive in nature and analysis is limited to the computation of outage probability only, bit error rate (BER) for two phases DF protocol is not derived.

Incorporation of adaptive modulation in wireless communication systems has improved the receiver performance against fluctuating channel conditions [53], [54]. Adapting the transmission as per channel state information increases the average throughput and reduces the average probability of error. In adaptive modulation, the transmitter switches between multiple modulation schemes or constellation sizes depending on the channel conditions¹ while maintaining an acceptable BER performance [53]. For instance, if channel conditions are favorable, it can transmit signal with large constellation size to achieve high data rate, however, if channel conditions deteriorate, it can switch to small constellation size in order to maintain

¹It is assumed that CSI is available at the transmitter, or transmitted by the receiver to the transmitter through a feedback path [55],[56].

an acceptable BER. Incorporation of adaptive modulation in cooperative relaying requires BER analysis of combined signal received at the destination from source and relay [57], [58]. A detailed BER analysis of DF relaying has been given in [59]. However, the analysis is nonadaptive and limited to binary phase shifting keying (BPSK) modulation. Another work based on adaptive power and modulation has been demonstrated in [60] which is limited to AF relaying. In [61] BER analysis for adaptive DF relaying system has been proposed with bit error rate-selection combining (BER-SC) diversity scheme. However, the analysis is limited to single carrier cooperative relaying only and no secondary spectrum sharing has been considered. As evident from above, adaptive modulation has been actively used to enhance the performance of cooperative relaying protocols, however, to the best of our knowledge, its impact on OFDM based CSS protocols has not been investigated.

1.4.3 D2D communication

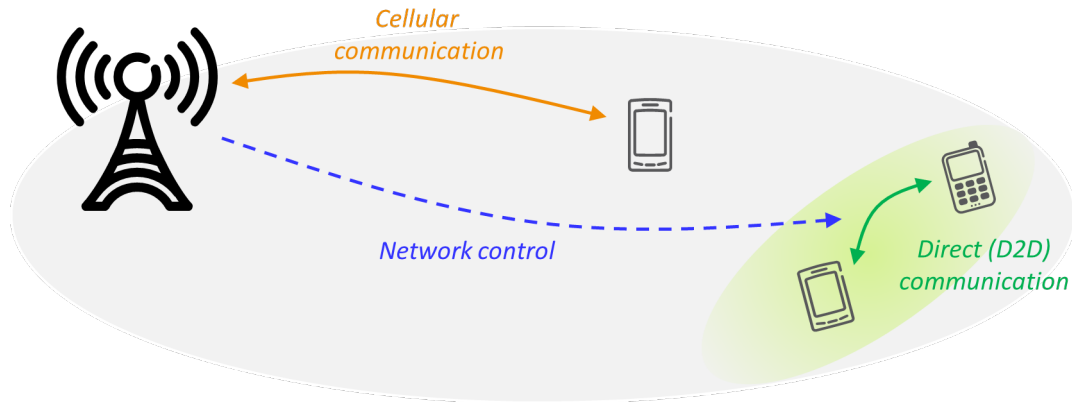


Figure 1.6. A simplified D2D communication integrated in a cellular network [62]

Similar to the cognitive radio, D2D communication is among the key technologies that can improve the spectrum utilization and capacity of next generation cellular networks [63]. Due to advent of new multimedia applications, there is an increasing demand to improve the capacity of 4th generation (4G)/beyond 4G cellular networks (i.e. next generation 5G cellular networks). One of the possible solutions to achieve high capacity is small cell networks (eg. micro-BS, femto-BS) [64]. In small cell network, cell size is reduced to increase the spectrum reuse

factor. Cellular user and BS are in close proximity to achieve high data rate and lower delay. However, there are issues based on construction and maintenance cost (eg. the backhaul bottleneck) [65].

Recently, the concept of D2D communication has been proposed for cellular networks [25], [26] to avail the high capacity benefits to cellular users with minimal constraints on maintenance and construction. In a generic D2D framework, two cellular users living in proximity can form a direct link for data transmission without routing it through the base station (BS). However, control or signaling information between the users is still carried out by the BS. A simplified form of integration of D2D communication in a cellular network is shown in 1.6. Traditionally, D2D technologies were restricted to short-range communication networks such as WiFi-Direct and Bluetooth working on unlicensed 2.4 GHz band [66]. The unlicensed bands are generally crowded with a large number of interferers; thus traditional D2D technologies do not provide the QoS and security as expected in the cellular networks. Several applications of D2D like proximity-based services, emergency communication, cellular traffic offloading, Internet-of-things (IoT) enhancement, etc. make it a viable candidate for next-generation 4.5G and 5G cellular networks [67],[68].

For resources utilization, D2D communication is categorized as inband and outband D2D communication. A schematic view of resource utilization for D2D users is shown in Fig. 1.7.

- **Inband D2D Communication:** In inband D2D, a user can share the licensed spectrum of the cellular user either in uplink or downlink of the cellular transmission as shown in Fig. 1.8. Inband D2D communication is also referred as LTE direct [69]. A D2D user can access the licensed cellular spectrum either in underlay (also known as non-orthogonal mode) or overlay (also known as orthogonal mode).
- **Outband D2D communication:** In outband D2D, the D2D communication takes place by exploiting the unlicensed spectrum such as industrial, scientific, and medical (ISM) bands (IEEE 802.11) or Bluetooth (IEEE 802.15).

In terms of network control, the D2D communication is classified as:

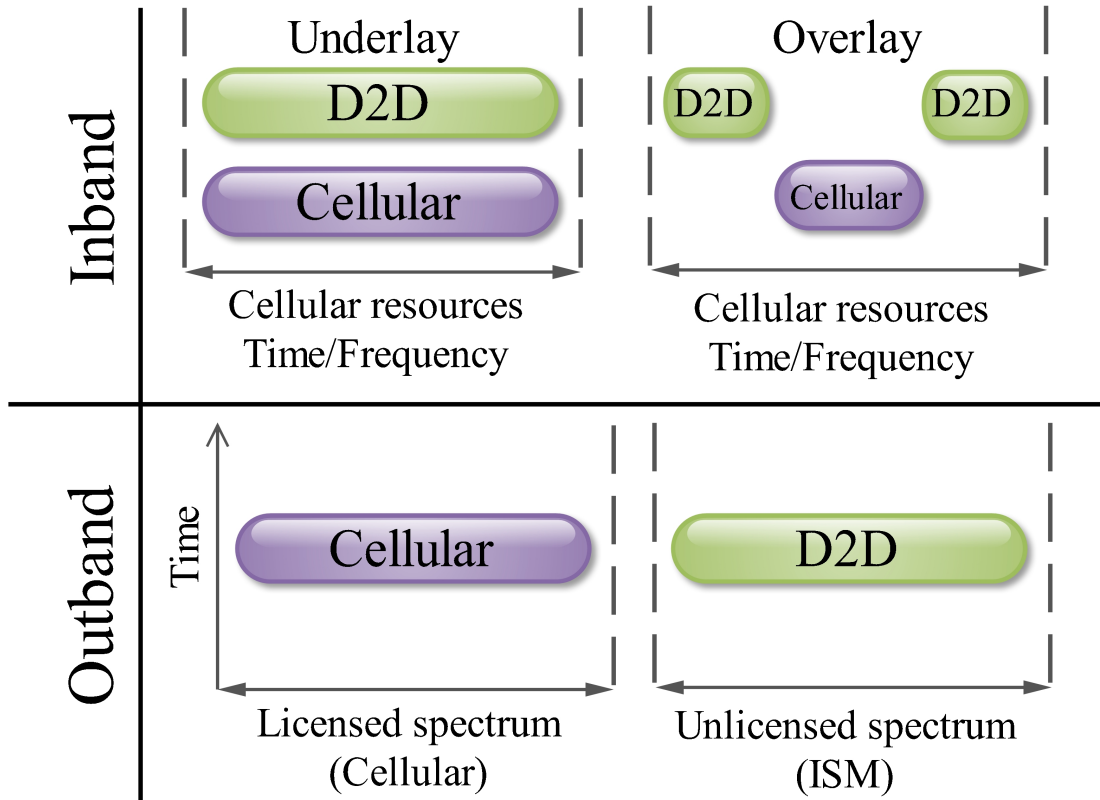


Figure 1.7. Resource allocation for D2D communication [69]

- Network assisted D2D: It is also known as infrastructure assisted D2D communication. In this mode, the BS is responsible for D2D discovery, resource allocation, connection setup, security and mobility management.
- Autonomous D2D: In this mode, similar to the Ad hoc network, the BS has no control over D2D communication. Such mode can be esteemed useful during the infrastructure failure.

The most common D2D communication frameworks for the cellular networks are underlay and overlay D2D communication [27].

1.4.3.1 Underlay D2D communication

In underlay D2D communication, both cellular and D2D users simultaneously share the licensed cellular spectrum while maintaining the interference threshold. The schematic of an underlay D2D communication framework is shown in Fig. 1.9.

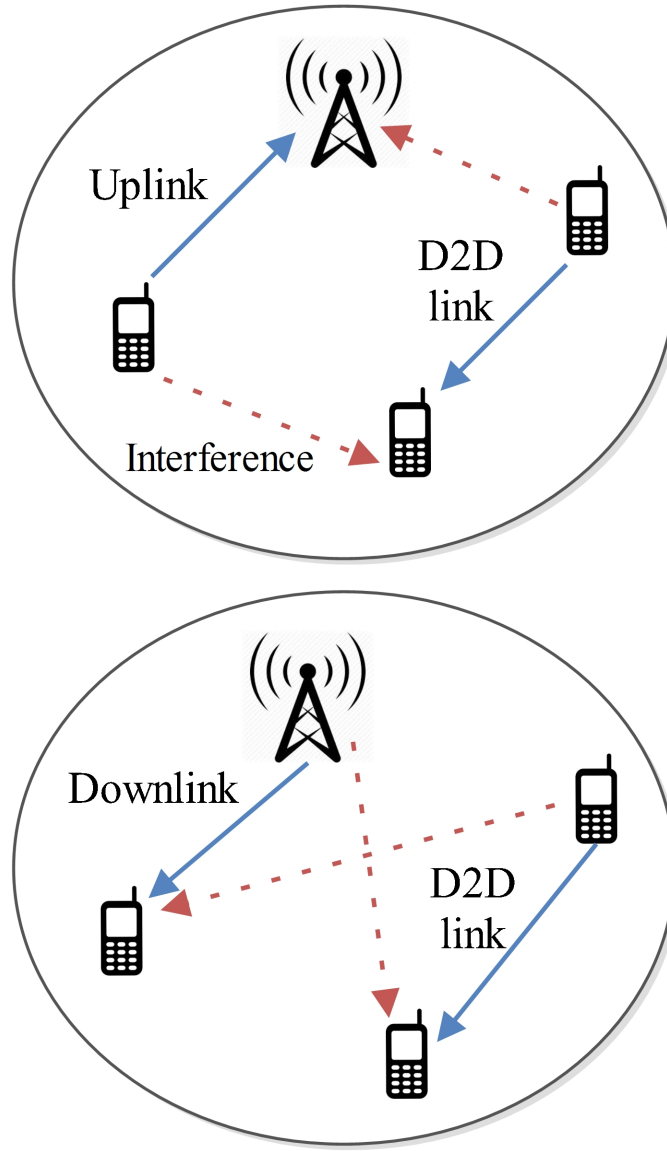


Figure 1.8. D2D using cellular uplink and downlink resources

Here, a D2D user shares the uplink resources of the cellular user, thus cellular and D2D transmission causes interference to each other. Specifically, at same time/frequency resource block, a cellular user and D2D Tx transmit their data to BS and D2D Rx respectively. Thus, BS receives interference from D2D Tx, whereas D2D Rx receives interference from the cellular user. Hence in underlay D2D framework, the biggest concern is to manage the interference caused by the cellular to D2D user and vice-versa. In [20], authors studied the interference man-

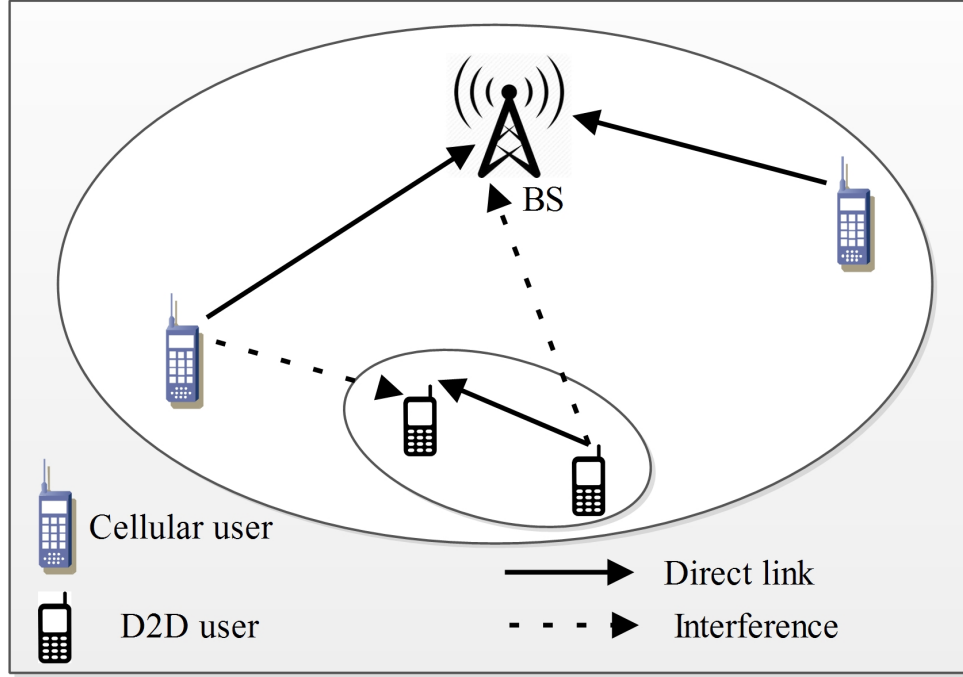


Figure 1.9. Underlay D2D communication

agement for underlay D2D framework in LTE-A cellular networks. In [70], the resource sharing between the D2D user and the cellular user is optimized while satisfying the individual power constraints. Distance constrained resource sharing criteria for underlay D2D cellular network is considered in [71]. Specifically, authors have formulated an analytical approach to find an optimum distance between the cellular user and D2D receiver to mitigate D2D interference.

1.4.3.2 Overlay D2D communication

Compared to underlay, in overlay D2D communication, BS allocates dedicated spectrum or time slots to D2D link as long as the QoS of the cellular user is not compromised [29]. It eliminates the mutual interference between cellular and D2D users. However, it may not utilize the available spectrum resources efficiently. A schematic of overlay D2D communication framework is shown in Fig. 1.10. Here, a D2D user shares the cellular uplink resources in an uninterrupted way. Specifically, if target QoS of the cellular uplink transmission is satisfied by the fraction of available time/frequency resource block, then BS allocated D subcarriers (or T_1 time) to the cellular user for BS transmission while remaining $N - D$ subcarriers

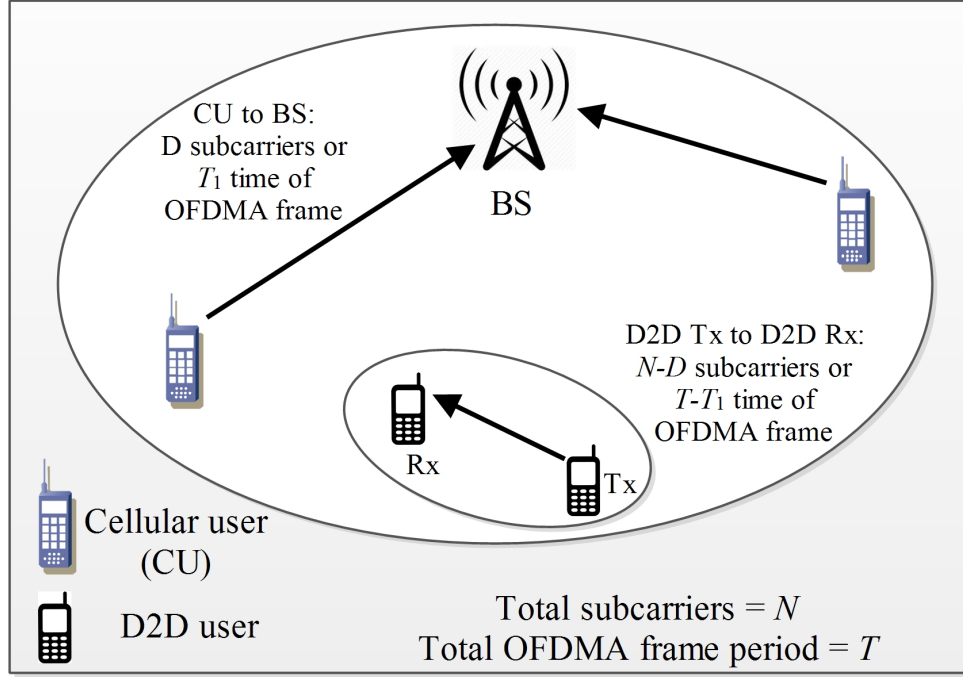


Figure 1.10. Overlay D2D communication

(or $T - T_1$ time) can be used for D2D communication. It is quite obvious that there will be no interference between cellular and D2D links, as both use orthogonal sets of subcarriers. A spectrum sharing protocol for D2D communication overlaying cellular mode is proposed in [72]. According to [72], the D2D users can assist bi-directional communication between the cellular users and BS, and at the same time communicate through a direct link with each other. Further, improved sum-rate derivation with power control mechanism for the cellular and D2D users are provided. A stochastic geometry approach to evaluating the performance of the D2D network over generalized fading channels is proposed in [73]. Closed-form expressions for spectral efficiency and outage probability are derived for the overlaid D2D network. However, the analysis in [72], [73] is limited to the D2D communication overlaying cellular networks. Comparison with underlay and other frameworks has not been discussed.

1.4.3.3 Cooperative D2D (C-D2D)

The C-D2D framework, a subclass of D2D communication has been recently proposed in [74, 75, 76, 77, 78]. In the C-D2D framework, a point-to-point D2D

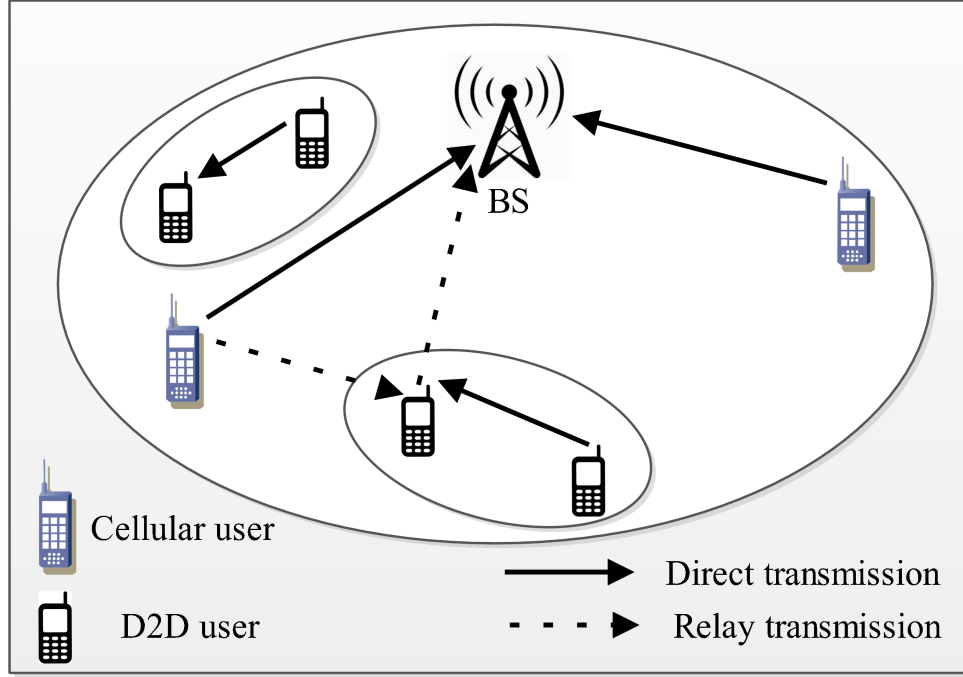


Figure 1.11. Relay based C-D2D communication [74]

communication link is split into multiple phases among multiple entities in a coordinated way to achieve spatial performance gains. In particular, a single or multiple nodes act as an AF or DF relay to increase the throughput of a C-D2D network. A schematic of relay based C-D2D framework is shown in Fig. 1.11. Here, the cellular uplink transmission is divided into two phases. In Phase I, cellular user broadcasts the signal to BS, overheard by D2D Tx. D2D Tx acts as a DF or AF relay for cellular transmission. In Phase II, D2D Tx decodes the received cellular signal and forwards it through the fraction of available time/frequency resource block to BS. D2D Tx can use the remaining time/frequency resource block for D2D communication to D2D Rx. In [74], authors introduce an adaptive mode selection scheme for D2D communication to ensure performance improvement for both cellular and D2D users. Numerical results in [74] demonstrate that the C-D2D framework outperforms the underlay and overlay D2D frameworks [79], [80] in terms of spectral efficiency. A cooperative beamforming and relay selection strategy to facilitate D2D communication in case of failure of communication infrastructure is proposed in [63]. However, the analysis in [63], [74] is limited to numerical results. Closed-form expression of outage probability is not derived.

Furthermore, the above proposed schemes are limited to single D2D pair.

1.4.3.4 C-D2D framework with multiple D2D users

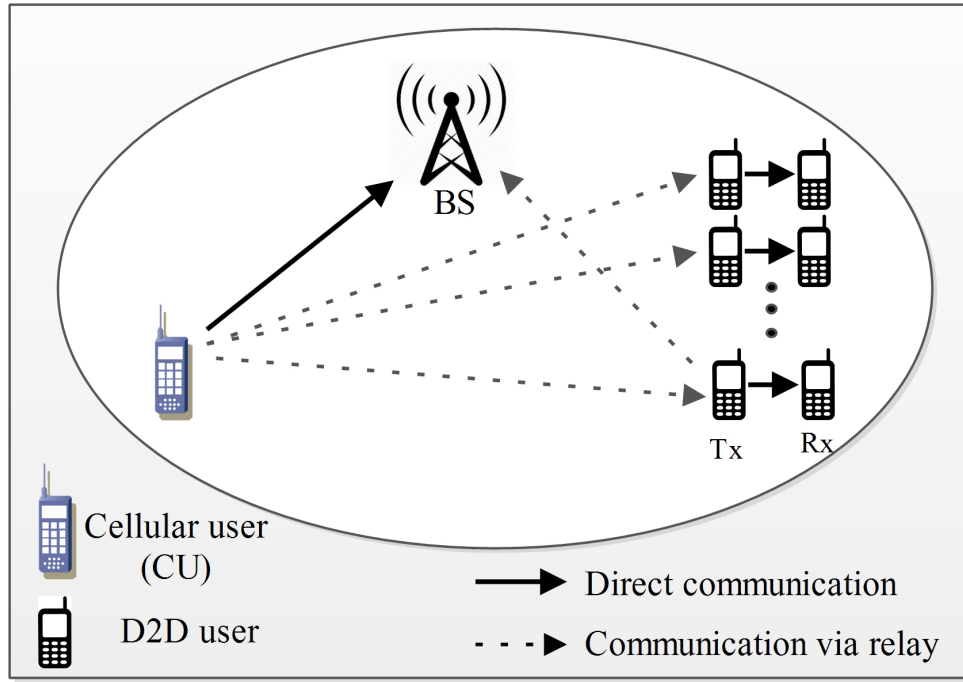


Figure 1.12. M UE Relay based C-D2D communication

Conventional cooperative diversity frameworks incorporate M user equipment (UE) relay nodes to provide spatial diversity. However, each relay node must transmit on orthogonal channels (either time or frequency) to avoid interference with each other, which results in inefficient utilization of the available resources [81]. The performance of the conventional cooperative diversity network can be further enhanced by incorporating UE relay selection [82], [83]. As a consequence, if M relays are available, only the optimal relay will participate to transmit the source data to the destination. A schematic of M D2D relay based C-D2D framework is shown in Fig. 1.12.

A DF relay-based cooperative diversity network with best relay selection has been proposed in [83]. A closed form expression for outage probability and average channel capacity are also derived. Results show that the best relay selection scheme outperforms the conventional cooperative diversity networks even at low SNRs.

In the context of C-D2D, the coverage area or service range of an eNB can be extended by selecting an in-coverage UE as a relay node to relay the information between eNB and out-coverage UE [21]. The timing and synchronization signals required to achieve the above as per LTE-A Release 12 and 13 are specified in [21]. A power efficient relay selection problem for the relay-assisted D2D network is formulated in [84] to minimize the resource requirement for D2D communication. However, relay nodes are assumed to be full duplex, thus limiting its practical significance. In [85], a relay-assisted D2D communication framework is proposed wherein D2D transmitter acts as a relay for the cellular link while simultaneously employing superposition coding in the downlink for D2D communication. In [86], a relay node is utilized to improve the QoS of D2D communication. An optimization problem is formulated to allocate resources to a relay in a multi-relay OFDMA based cellular network. The results obtained are compared with an underlay D2D communication. However, the scheme incurs overhead in terms of deployment of additional relay nodes to enhance D2D communication. Moreover, the analysis is limited to relay assisted D2D communication, the impact of D2D link on the performance of the cellular network is not considered.

1.4.3.5 Measurement results for D2D prototype testbed

The majority of the previous literature focuses on the numerical and analytical evaluation to perform resource allocation and throughput maximization for the D2D communication system. Analytical and simulation results can give useful insights on the performance of a particular scheme. However, most of the simulations models are unable to replicate the exact nature of wireless medium. This necessitates design and development of a testbed to verify the proposed algorithms. Thus, in order to augment the development of D2D communication, proposed schemes and protocols should be implemented and validated on a real world scenario through experimental testbed. Following are the purpose to be served by the experimental testbed:

- It can bridge the gap between simulation results and real experiment results.
- Practical demonstration can also address the interference from cellular to D2D users and vice versa.

- It will be able to highlight the strength and weakness of the proposed schemes that are hard to gauge in simulations.

Some of the requirements of a D2D communication testbed are:

- Software reconfigurability: A testbed should be software reconfigurable to control the physical or medium access control (MAC) layer functionality through software. For e.g., modulation, source coding, channel coding, interleaving can be implemented in software so that these parameters can be changed as per user's requirement.
- Cross layer support: The software should be able to integrate the functionality of all layers of the protocol stack.
- A testbed should be adaptive with respect to the communication environment. Thus, the real and controlled experiment can be performed in the different wireless environment.
- High speed analog to digital converters (ADC)/ digital to analog converters (DAC): A testbed should have high-resolution ADC and DAC to support computationally larger and complex algorithms.
- Multiple radio support: A testbed should be able to support multiple radios that can be used as a cellular or D2D users.

Recently, few testbeds have been developed to illustrate the performance of D2D communication in realistic scenario [87], [88]. For instance, in [88], a software defined radio (SDR) based channel opportunistic experimental analysis of outband D2D is proposed. Specifically, a throughput maximization problem defined as D2D opportunistic relay with QoS enforcement (DORE) is implemented to perform relay selection for D2D enabled user's equipment (UE). Results show notable performance improvement even with few active D2D relays. However, the implemented algorithm is limited to outband D2D.

An SDR based single hop D2D prototype is implemented in [87]. Measurement results were taken for direct and single hop D2D communication protocol, which showed that D2D communication reduces the transmission power of a cellular network. However, the implemented prototype was not tested on different D2D

modes. In [15], a testbed was designed and developed on the NI PXIe platform for the performance assessment of the CSS protocol. The performance of the system was quantified by measuring packet error rate (PER) and the spectrum access probability for the secondary system. However, the proposed CSS protocol was non-adaptive in nature.

1.5 Conclusion

In this chapter, we presented the motivation and objectives behind this thesis. We have also highlighted the major contributions of the thesis. Further, background knowledge about some of the prominent wireless techniques such as cognitive radio, cooperative relaying, and cooperative cognitive radio and their impact on the wireless networks were also discussed. In addition, CSS protocol is demonstrated to address the incompetence of conventional cognitive radios in the dense urban scenario. The contributions of the existing literature on conventional CSS and OFDM based CSS were also provided.

Further, it has been showed that how D2D communication can be integrated with existing cellular networks to achieve the capacity requirement of next generation cellular networks. Based on resource utilization, three different spectrum sharing frameworks (underlay, overlay, and C-D2D) were discussed, and their challenges to satisfy the performance constraint of both cellular and D2D users were also emphasized. The resource allocations for the C-D2D framework with multiple D2D users were also depicted. Apart from above, we have listed the requirement and purpose to be served by D2D based experimental testbed. We also discussed the issues with existing D2D based prototype testbed.

Subcarrier Sharing Schemes for OFDM-based Cooperative Cognitive Radios

From discussion and conclusion in chapter 1, it is quite obvious that the existing cooperative spectrum sharing schemes are interference limited and their performance may degrade due to interference from one system to another. In this chapter, in order to alleviate the above, we propose an OFDM-based subcarrier sharing scheme for cooperative cognitive radios [32]. By adopting the proposed scheme, opportunistic spectrum sharing can be achieved by the secondary system without interfering with the primary system since primary and secondary data are forwarded on orthogonal subcarriers. To further boost the performance of primary and secondary systems, we propose an adaptive subcarrier sharing scheme for OFDM-based cooperative cognitive radios [34]. The results show that outage probability with the proposed (adaptive) scheme outperforms the direct transmission and non-adaptive subcarrier sharing scheme.

2.1 Introduction

Incorporation of OFDM in cooperative cognitive radio networks facilitates subcarrier sharing to achieve spatial diversity with opportunistic spectrum access.

In this chapter, we have proposed the OFDM based subcarriers sharing scheme for cooperative cognitive radios. We have computed the outage probability as a performance metrics for primary and secondary systems for different numbers of subcarriers. Both primary and secondary systems are equipped with single antenna¹ and employ OFDM modulator-demodulator. Primary system comprises of primary transmitter (PT) and primary receiver (PR) while secondary system consists of secondary transmitter (ST) and secondary receiver (SR). According to the scheme, if the primary system is unable to achieve its target rate due to the poor link quality, then the secondary (cognitive) system helps the primary system via two phase DF relaying. The proposed scheme is classified into two categories:

- Non-adaptive CSS with maximal ratio combining (MRC) diversity
- Adaptive CSS with bit error rate selection combining (BER-SC) diversity

2.1.1 Non-adaptive CSS with MRC

In non-adaptive CSS with MRC diversity scheme, ST behaves as a DF relay for the primary system. In phase I, PT broadcasts the primary signal over N subcarriers to PR and ST. In Phase II, PT remains silent, and ST forwards the successfully decoded D subcarriers to PR in order to satisfy the target rate requirement of the primary system. The remaining $(N - D)$ subcarriers can be used by ST to transmit its own signal to SR. Hence, the secondary system while working as a relay for the primary system gets opportunistic spectrum access in exchange of fulfilling the target rate requirement of the primary system. The number of subcarriers (D) allocated to the primary system depend on the required target rate or QoS of the primary system. If primary system target rate changes, D also changes. Here we assume that the primary and secondary systems are following the same radio protocols. Results interpret the requirement of subcarriers relayed via ST to PR to fulfill the target rate of the primary system. As number of relayed subcarriers increases, primary outage probability decreases while secondary outage probability increases. Outage probability also depends on the distance between the PT and ST. As shown later, there will be a distance, conventionally defined

¹This is a reasonable assumption if we assume that both primary and secondary systems are small sized sensor node or a mobile terminal.

as a critical distance between PT and ST beyond which no spectrum sharing is possible. Critical distance² determines the limitations and region of validity of the proposed scheme. The significance of critical radial distance can be interpreted as if ST is located within this region; it is always possible to find a desired number of subcarriers at ST so that QoS of the primary system will not be compromised. Theoretical and simulation results are provided for outage probability for both primary and secondary systems. It has been shown through the results that, as long as ST lies within the critical distance, outage probability of proposed scheme will be less as compared to the direct transmission. Good agreement between the theoretical and simulation results validate the analytical results of the proposed scheme.

2.1.2 Adaptive CSS with BER-SC

In adaptive CSS with BER-SC diversity, it is assumed that the primary system uses the conventional nonadaptive mode of transmission wherein the subcarriers are modulated using BPSK modulation³, whereas, ST employs adaptive M -QAM modulation. According to the scheme, in Phase I, PT broadcasts the primary signal with BPSK modulation over N subcarriers which is received by ST and PR. In Phase II, ST forwards the decoded subcarriers to PR with larger constellation size (M) to fulfill the target rate requirement of the primary system without violating the BER constraint of PR. If ST uses M -ary quadrature amplitude modulation (M -QAM) to modulate the subcarriers before forwarding them to PR, then the maximum number of subcarriers that needs to be forwarded in order to maintain the target rate by ST to PR would be $N/\log_2(M)$. The remaining $N - (N/\log_2(M))$ subcarriers can be used by ST to transmit its own data to SR. Hence, OSS is achieved by the secondary system while working as a relay for the primary system.

However, as symbols coming from source and relay have dissimilar constellation size (M), maximum ratio combining (MRC) cannot be applied at destination [61]. Furthermore, the conventional selection combining (SC) cannot be applied either,

²It can also be termed as a critical radial distance [12].

³For ease of analysis, we have assumed that PT modulates the subcarriers with BPSK; however, the proposed analysis can be extended to the cases where PT uses some other form of modulation.

since branch with high SNR may not be the most reliable one as different constellation sizes have different error resistance capabilities. Hence, in the proposed scheme, at PR, BER-SC is employed to combine the signals received in two-phases. Specifically, PR decodes the signal of the branch having less BER. BER of each branch can be estimated *a priori* by received SNR level and transmitted constellation size (M).

In the proposed work, ST adapts its constellation size as per the normalized distance between ST and PR ⁴. In particular, ST modulates the subcarriers with large constellation size if the distance between ST and PR decreases. Thus, the primary system outage probability will reduce substantially with the increase in M . It is because, as M increases, constellation size increases and the number of bits per subcarrier also increases. In other words, instantaneous data rate with BER-SC increases, consequently outage probability decreases. However, with every increase in M , there would be a corresponding increase in BER, hence for a given distance and BER constraint, M cannot be increased beyond a point. To the best of our knowledge, proposed work is the first to investigate the impact of adaptive modulation on OFDM based CSS protocol. The main contributions of the proposed scheme are summarized as follows:

- Closed form expressions for outage probability of the primary and secondary systems which employ OFDM based nonadaptive CSS protocol and conventional MRC as a signal combining scheme has been derived.
- Closed form expressions for BER and outage probability of primary and secondary systems which employ OFDM based adaptive CSS protocol and BER-SC as a signal combining scheme has been derived.
- Proposed scheme deduces the exact number of subcarriers that need to be relayed by ST to PR to fulfill the target QoS of the primary system. In other words, it not only helps the primary system to achieve the target QoS but also helps the secondary system to utilize the remaining subcarriers for its own communication.

⁴Through control signalling involved, PR will be aware of the modulation scheme that will be used by the ST in Phase II [89], [90].

- Proposed scheme ensures the performance of secondary system irrespective of the availability of spectrum holes. Hence, the proposed scheme will be extremely attractive in dense urban scenarios where the spectrum is generally crowded and spectrum holes are hard to obtain.

The remainder of this chapter is organized as follows. Section 2.2 discusses system model and protocol description. Rate and outage probability of the primary and secondary system for adaptive and non adaptive CSS are provided in Section 2.3 and 2.4 respectively. Simulation results and discussion are provided in Section 2.5 and finally chapter is concluded in Section 2.6.

2.2 System Model and Protocol Description

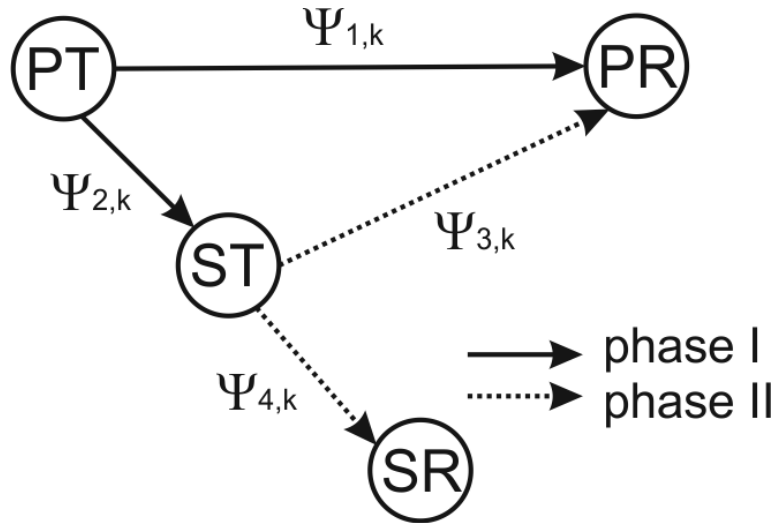


Figure 2.1. System model

The system configuration of the proposed subcarrier sharing scheme is shown in Fig. 2.1. The channels over the nodes are modelled as frequency non-selective Rayleigh block fading with $\Psi_{i,k} \sim \mathcal{CN}(0, \zeta_i^{-l})$, $i = 1, 2, 3, 4$, where ζ is the normalized distance between transmitter and receiver, and l is path loss exponent. Normalization is done with respect to distance between $PT \rightarrow PR$, hence, $\zeta_1 = 1$. The channel coefficient corresponding to $PT \rightarrow PR$ is $\Psi_{1,k}$ over subcarrier k ($1 \leq k \leq N$). Similarly channel coefficients between $PT \rightarrow ST$, $ST \rightarrow PR$ and $ST \rightarrow SR$ is denoted

by $\Psi_{2,k}, \Psi_{3,k}, \Psi_{4,k}$ respectively. The instantaneous channel gain for each subcarrier over different nodes can be defined as $\gamma_{1,k} = |\Psi_{1,k}|^2, \gamma_{2,k} = |\Psi_{2,k}|^2, \gamma_{3,k} = |\Psi_{3,k}|^2$ and $\gamma_{4,k} = |\Psi_{4,k}|^2$. The additive white Gaussian noise (AWGN) at each receiver PR, ST and SR is denoted as $n_{1,k}, n_{2,k}, n_{4,k} \sim \mathcal{CN}(0, \sigma_i^2), i = 1, 2, 4$ respectively. The primary and secondary signal is denoted as $s_{p,k}$ and $s_{s,k}$ respectively with zero mean and $E\{s_{p,k}^* s_{p,k}\} = E\{s_{s,k}^* s_{s,k}\} = 1$.

The protocol description for adaptive CSS with BER-SC diversity scheme is summarized in Algorithm 2.1. In the algorithm, R_N denotes the instantaneous rate⁵ of the primary system with N subcarriers whereas, R_T denotes the target rate of the primary system. D denotes the number of subcarriers forwarded by ST to PR in Phase II and η_{BER-SC} denotes the average BER for BER-SC scheme. PT checks whether it is able to achieve the target rate, R_T , by using conventional mode of transmission, else it broadcasts cooperative right-to-send (CRTS) message which includes R_T . PR responds to CRTS by cooperative clear-to-send (CCTS) message which includes the BER constraint of the primary system. ST overhears both CRTS and CCTS and if it is able to fulfill the target rate requirement of primary system then it transmits cooperative clear-to-help (CCTH)⁶ message to PT and PR. Consequently, the primary system switches to a two phase cooperative DF relaying protocol, where ST serves as a relay. However, if ST is unable to assist the primary system then it remains silent, and the primary system retains its transmission from PT-PR.

2.3 Rate and Outage Probability of Primary System

In this section, we derive the rate and outage probability of the primary system for three different scenarios, i.e. when primary system is working without cooperation, primary system is utilizing adaptive CSS protocol (in this case BER-SC will be applied at PR), and primary system is utilizing nonadaptive CSS protocol (in this case MRC will be applied at PR).

⁵Rate refers to the data rate in bits/s/Hz unless otherwise specified.

⁶Control messages like CRTS, CCTS and CCTH are implemented in medium access control (MAC) layer with an assumption of error free reception at corresponding receiver.

Algorithm 2.1 Protocol description

PT broadcasts primary signal $s_{p,k}$ over N subcarriers.

if $R_N < R_T$ **then**

The system switches to adaptive CSS protocol and two-phase transmission ensues.

- Phase I

Step 1. PT transmits CRTS which indicates R_T .

Step 2. PR receives CRTS and responds by CCTS (includes CSI and BER constraint of the primary system).

Step 3. ST overhears CRTS and CCTS.

Step 4. ST estimates channel gain of PT-ST, ST-PR link and size of M as per BER constraint, where $M = 2^k; k = 2, 4, 6$.

$i = 1$

for $k = 6 : -2 : 2$ **do**

$M(i) \leftarrow 2^k$

compute η_{BER-SC}

if $\eta_{BER-SC} \leq \text{BER constraint}$ **then**

return $M(i)$

Break

end if

$i \leftarrow i + 1$

end for

Step 5. If ST meets the given constraints then it transmits CCTH to PR which includes the constellation size M and number of subcarriers, D , else remains silent.

- Phase II

Step 1. ST transmits D subcarriers to PR and remaining $N - D$ subcarriers to SR with M -QAM.

Step 2. PR calculates BER as per received SNR level and size of M . It applies BER-SC to combine signals received in two time phases.

else PT-PR retains direct transmission.

2.3.1 Primary system outage probability without cooperation

In Phase I, $s_{p,k}$ is transmitted by PT, received by PR. The received signal at PR over subcarrier k is denoted as $\phi_k^{pr,1}$ and is given by,

$$\phi_k^{pr,1} = (p_{p,k})^{\frac{1}{2}} \Psi_{1,k} s_{p,k} + n_{1,k}. \quad (2.1)$$

The instantaneous rate without cooperation for all N subcarriers can be given as,

$$R_N = \sum_{k=1}^N \log_2 \left(1 + \frac{p_{p,k} \gamma_{1,k}}{\sigma_1^2} \right), \quad (2.2)$$

where $p_{p,k}$ is the power of k^{th} subcarrier at PT and σ_1^2 denotes noise variance at PR. The target rate of the primary system is R_T and outage occurs if $R_N < R_T$. When $p_{p,k} = p_p, \forall k$ and $\gamma_{1,k} = \gamma_1, \forall k$, the outage probability for the direct transmission can be defined as,

$$P_{out} = 1 - \exp \left(- \frac{\sigma_1^2 (2^{R_T/N} - 1) \zeta_1^l}{p_p} \right), \quad (2.3)$$

where ζ_1 is distance between PT and PR and l is path loss exponent.

2.3.2 Primary system rate and outage probability with adaptive CSS (BER-SC)

With cooperation, ST behaves as an adaptive DF relay so as to provide diversity gain to the primary system. In Phase I, PT broadcasts N OFDM subcarriers which carry N bits of data⁷ to PR and ST. Signal received by ST in Phase I is,

$$\phi_k^{st,1} = (p_{p,k})^{\frac{1}{2}} \Psi_{2,k} s_{p,k} + n_{2,k}, \quad (2.4)$$

where, $n_{2,k}$ is the AWGN over subcarrier k . The instantaneous rate of signal received at ST can be given as,

$$R_N^{Pt-St} = \frac{1}{2} \sum_{k=1}^N \log_2 \left(1 + \frac{p_{p,k} \gamma_{2,k}}{\sigma_2^2} \right), \quad (2.5)$$

where, factor $\frac{1}{2}$ is included as the transmission is divided into two phases and σ_2^2 denotes the AWGN variance at DT. When, $p_{p,k} = p_p, \forall k$ and $\gamma_{2,k} = \gamma_2, \forall k$, (2.5) will reduce to,

$$R_N^{Pt-St} = \frac{N}{2} \log_2 \left(1 + \frac{p_p \gamma_2}{\sigma_2^2} \right). \quad (2.6)$$

⁷As subcarriers are BPSK modulated.

If ST successfully decodes N subcarriers received in Phase I, it will use adaptive modulation to retransmit primary data to PR in Phase II. In Phase II, ST forwards D subcarriers to PR using M -QAM modulation (a larger constellation size than used by PT)⁸. PR will choose either to decode the signal from PT or ST. In the conventional cooperative relaying system, PR uses MRC to maximize the received SNR from various diversity branches. However, in order to apply MRC, all diversity branches should carry data belonging to same constellation size. MRC cannot be employed when PT and ST use different constellation sizes. For the case of adaptive modulation in two separate branches, one can use conventional SC which selects the branch with best SNR. However, when different constellation sizes are employed, the branch having maximum SNR may not necessarily be the most reliable branch due to different error probabilities of different constellation sizes. In this work, BER-SC (BER based SC) scheme is employed. In BER-SC, the receiver calculates BER of each branch (using SNR and constellation size) and then decodes the signal from the branch that has minimum BER. BER-SC reduces to conventional SC if same constellation size is employed in both PT and ST.

The instantaneous rate at PR after employing BER-SC of two phases transmission can be given as,

$$R_{BER-SC} = \begin{cases} \frac{1}{2} \sum_{k=1}^D \log_2(M) \log_2 \left(1 + \frac{p_{s,k} \gamma_{3,k}}{\sigma_1^2} \right) \\ + \frac{1}{2} \sum_{k=1}^{N-D} \log_2 \left(1 + \frac{p_{p,k} \gamma_{1,k}}{\sigma_1^2} \right); \eta_{ST} < \eta_{PT} \\ \frac{1}{2} \sum_{k=1}^N \log_2 \left(1 + \frac{p_{p,k} \gamma_{1,k}}{\sigma_1^2} \right); \text{otherwise} \end{cases}, \quad (2.7)$$

where, $p_{s,k}$ denotes the k^{th} subcarrier power at ST, η_{ST} denotes the BER between ST-PR link and η_{PT} denotes the BER between PT-PR link.

Without loss of generality, it is assumed that the power is uniformly distributed across all subcarriers

$$p_{p,k} = p_p, \forall k; p_{s,k} = p_s, \forall k; \gamma_{x,k} = \gamma_x, \forall k. \quad (2.8)$$

From (2.7) and (2.8), we can deduce,

⁸ST verifies whether it is possible to transmit primary data using larger constellation size than used by PT otherwise it will stick to same constellation size as used by PT (in this case ST will be pure relay and no secondary spectrum access will be possible).

$$R_{BER-SC} = \begin{cases} \frac{1}{2}D\log_2(M)\log_2\left(1 + \frac{p_s\gamma_3}{\sigma_1^2}\right) \\ + \frac{1}{2}(N-D)\log_2\left(1 + \frac{p_p\gamma_1}{\sigma_1^2}\right); \eta_{ST} < \eta_{PT} \\ \frac{1}{2}N\log_2\left(1 + \frac{p_p\gamma_1}{\sigma_1^2}\right); \text{otherwise} \end{cases} \quad (2.9)$$

On the other hand, if ST is unable to decode the primary signal received in Phase I then there will be no retransmission from ST to PR in Phase II. In order to transmit primary data from ST to PR, the maximum number of subcarriers that needs to be allocated for primary signal transmission will be, $D = N/\log_2(M)$. For instance, the maximum value of D when ST is using 4-QAM and 16-QAM will be $N/2$ and $N/4$ respectively.

The primary system outage probability with cooperation is,

$$P_{out}^p = \Pr(R_N^{Pt-St} > R_T) \Pr(R_{BER-SC} < R_T) \\ + \Pr(R_N^{Pt-St} < R_T) \Pr\left(\frac{1}{2}R_N < R_T\right). \quad (2.10)$$

Proposition 2.1 *The outage probability of the primary system with BER-SC diversity when using an adaptive CSS can be derived in closed form as:*

$$P_{out}^p = e^{-\frac{\zeta_2^l \sigma^2}{p_p} \rho_1} (1 - \zeta_1^l \chi) + \left(1 - e^{-\frac{\zeta_2^l \sigma^2}{p_p} \rho_1}\right) \left(1 - e^{-\frac{\zeta_1^l \sigma^2}{p_p} \rho_1}\right). \quad (2.11)$$

Proof : Proof of Proposition 2.1 is given in Appendix A.

2.3.2.1 BER-SC analysis

In BER-SC, the receiver decides to decode the signal from the branch having minimum BER by calculating the BER of individual branch using received SNR and constellation size. For Gray coded square M -QAM system, BER for each subcarrier conditioned on γ_i can be given as [91],

$$\eta_{M_iD}(\gamma_{iD}) \approx k_{M_i} Q\left(\sqrt{2d_{M_i}^2 \gamma_{iD}}\right), \quad (2.12)$$

where γ_{iD} stands for instantaneous channel gain between i node and destination,

$$k_{M_i} = \begin{cases} 1 & M_i = 2 \\ 2 \left(\frac{1 - \frac{1}{\sqrt{M_i}}}{\log_2 \sqrt{M_i}} \right) & M_i \geq 4 \end{cases}, \quad (2.13)$$

and

$$d_{M_i} = \begin{cases} 1 & M_i = 2 \\ \sqrt{\left(\frac{3}{M_i - 1} \right)} & M_i \geq 4 \end{cases}. \quad (2.14)$$

The average BER for BER-SC scheme can be written as [61],

$$\eta_{BER-SC} = \varphi_{PT-ST} \eta_{PT-PR} + (1 - \varphi_{PT-ST}) \eta_{comb-PR}, \quad (2.15)$$

where, φ_{PT-ST} denotes the average packet error rate between PT-ST. η_{PT-PR} denotes the average BER for PT-PR link, and $\eta_{comb-PR}$ denotes the average BER at PR using BER-SC. The average BER for M -QAM, Rayleigh fading channel can be approximated as [91],

$$\eta_{ij} \approx \int_0^\infty k_{M_i} Q \left(\sqrt{2d_{M_i}^2 \gamma_{ij}} \right) \frac{1}{\bar{\gamma}_{ij}} \exp \left(-\frac{1}{\bar{\gamma}_{ij}} \gamma_{ij} \right) \quad (2.16)$$

$$= \frac{1}{2} k_{M_i} \left(1 - \sqrt{\frac{d_{M_i}^2 \bar{\gamma}_{ij}}{1 + d_{M_i}^2 \bar{\gamma}_{ij}}} \right), \quad (2.17)$$

where, $\bar{\gamma}_{ij} = E[\gamma_{ij}]$. Hence,

$$\begin{aligned} \eta_{PT-ST} &\approx \int_0^\infty k_{M_{PT}} Q \left(\sqrt{2d_{M_{PT}}^2 \gamma_2} \right) \frac{1}{\bar{\gamma}_2} \exp \left(-\frac{1}{\bar{\gamma}_2} \gamma_2 \right) \\ &= \frac{1}{2} k_{M_{PT}} \left(1 - \sqrt{\frac{d_{M_{PT}}^2 \zeta_2^{-l} \Gamma}{1 + d_{M_{PT}}^2 \zeta_2^{-l} \Gamma}} \right), \end{aligned} \quad (2.18)$$

where, $\Gamma = \frac{p_p}{\sigma^2} = \frac{p_s}{\sigma^2}$.

Without loss of generality, it is assumed that all subcarriers in an OFDM symbol are independent of each other; hence packet error rate can be calculated

as,

$$\begin{aligned}\varphi_{PT-ST} &= 1 - (1 - \vartheta_{PT-ST})^{\frac{N}{\log_2(M_{PT})}} \\ &= 1 - \left(1 - \frac{1}{2}k_{M_{PT}}\log_2(M_{PT}) \left(1 - \sqrt{\frac{d_{M_{PT}}^2 \zeta_2^{-l} \Gamma}{1 + d_{M_{PT}}^2 \zeta_2^{-l} \Gamma}}\right)\right)^{\frac{N}{\log_2(M_{PT})}},\end{aligned}\quad (2.19)$$

where, ϑ_{PT-ST} denotes the symbol error rate between PT and ST, and $\vartheta \approx \eta_{PT-ST} \log_2(M_{PT})$. M_{PT} denotes the constellation size of the symbol transmitted by PT.

The average value of $\eta_{comb-PR}$ can be obtained as [61],

$$\begin{aligned}\eta_{comb-PR} &\approx \frac{1}{2}k_{M_{PT}} \left(1 - \sqrt{\frac{d_{M_{PT}}^2 \zeta_1^{-l} \Gamma}{1 + d_{M_{PT}}^2 \zeta_1^{-l} \Gamma}}\right) + \frac{1}{2}k_{M_{ST}} \left(1 - \sqrt{\frac{d_{M_{ST}}^2 \zeta_3^{-l} \Gamma}{1 + d_{M_{ST}}^2 \zeta_3^{-l} \Gamma}}\right) \\ &\quad - \left(\frac{1}{2} \frac{k_{M_{PT}} d_{M_{ST}}^2 \zeta_3^{-l} + k_{M_{ST}} d_{M_{PT}}^2 \zeta_1^{-l}}{d_{M_{PT}}^2 \zeta_1^{-l} + d_{M_{ST}}^2 \zeta_3^{-l}}\right) \left(1 - \sqrt{\frac{\lambda}{1 + \lambda}}\right),\end{aligned}\quad (2.20)$$

where, $\lambda = \frac{d_{M_{PT}}^2 \zeta_1^{-l} \Gamma d_{M_{ST}}^2 \zeta_3^{-l}}{d_{M_{PT}}^2 \zeta_1^{-l} + d_{M_{ST}}^2 \zeta_3^{-l}}$ and M_{ST} is defined as a symbol constellation size from ST-PR.

After substituting (2.18), (2.19) and (2.20) into (2.15), we will get η_{BER-SC} .

$$\begin{aligned}\eta_{BER-SC} &\approx \left(1 - (1 - \log_2(M_{PT}) \Theta_{M_{PT}}(\zeta_2^{-l} \Gamma))^{\frac{N}{\log_2 M_{PT}}}\right) \Theta_{M_{PT}}(\zeta_1^{-l} \Gamma) \\ &\quad + (1 - \log_2(M_{PT}) \Theta_{M_{PT}}(\zeta_2^{-l} \Gamma))^{\frac{N}{\log_2 M_{PT}}} \\ &\quad \times \left[\Theta_{M_{PT}}(\zeta_1^{-l} \Gamma) + \Theta_{M_{ST}}(\zeta_3^{-l} \Gamma) \right. \\ &\quad \left. - \left(\frac{1}{2} \frac{k_{M_{PT}} d_{M_{ST}}^2 \zeta_3^{-l} + k_{M_{ST}} d_{M_{PT}}^2 \zeta_1^{-l}}{d_{M_{PT}}^2 \zeta_1^{-l} + d_{M_{ST}}^2 \zeta_3^{-l}}\right) \left(1 - \sqrt{\frac{\lambda}{1 + \lambda}}\right)\right].\end{aligned}\quad (2.21)$$

where,

$$\Theta_M(\zeta^{-l} \Gamma) = \frac{1}{2}k_M \left(1 - \sqrt{\frac{d_M^2 \zeta^{-l} \Gamma}{1 + d_M^2 \zeta^{-l} \Gamma}}\right). \quad (2.22)$$

From (2.21), we can calculate the BER performance of the primary system with BER-SC. Furthermore we can simplify (2.21) for high Γ (i.e. $\Gamma \rightarrow \infty$). The asymptotic BER expression for BER-SC is given as Proposition 2.

Proposition 2.2 *A simplified asymptotic BER expression for BER-SC is,*

$$\eta_{BER-SC} \stackrel{\Gamma \rightarrow \infty}{\approx} \frac{1}{(Z_{BER-SC} \Gamma)^2}, \quad (2.23)$$

where,

$$Z_{BER-SC} = 4d_{MPT}^2 d_{MST}^2 \sqrt{\zeta_1^{-l} \zeta_3^{-l}} \left(k_{MPT}^2 d_{MST}^4 \tau^{-1} + 3d_{MPT}^2 d_{MST}^2 (k_{MPT} + d_{MST}) \right)^{-\frac{1}{2}}, \quad (2.24)$$

$$\tau = \frac{1}{N} \frac{\zeta_2^{-l}}{\zeta_3^{-l}}, \quad (2.25)$$

Proof : Proof of Proposition 2.2 is given in Appendix B.

2.3.2.2 Critical distance for BER-SC

For a given target rate there will always be a critical distance $\zeta_{2,B}$ (distance between PT and ST) beyond which no spectrum sharing is possible. In other words, if ST is located $\geq \zeta_{2,B}$ from PT then primary system outage probability with cooperation will always be greater than outage probability with direct transmission, even if ST works as a pure relay. Hence, critical distance is defined as,

$$1 - e^{\left(-\frac{\sigma_1^2 (2^{R_T/N} - 1) \zeta_1^l}{p_p} \right)} < e^{-\frac{\zeta_2^l \sigma^2}{p_p} \rho_1} (1 - \zeta_1^l \chi) + \left(1 - e^{-\frac{\zeta_2^l \sigma^2}{p_p} \rho_1} \right) \left(1 - e^{-\frac{\zeta_1^l \sigma^2}{p_p} \rho_1} \right). \quad (2.26)$$

From (2.26), we can deduce,

$$\zeta_{2,B} = \left[\frac{p_p}{\rho_1 \sigma^2} \ln \left(\frac{\Phi_4 - \Phi_2}{\Phi_3 - \Phi_2} \right) \right]^{\frac{1}{t}}, \quad (2.27)$$

where, $\Phi_4 = (1 - \zeta_1^l \chi)$, $\Phi_2 = \left(1 - e^{-\frac{\zeta_1^l \sigma^2}{p_p} \rho_1} \right)$ and $\Phi_3 = 1 - e^{-\frac{\sigma_1^2 (2^{R_T/N} - 1) \zeta_1^l}{p_p}}$.

From (2.27), the critical distance $\zeta_{2,B}$ for different target rates can be calculated. The critical distances for some of the predefined target rates with $p_p/\sigma^2 = 20$ dB, $p_s/\sigma^2 = 20$ dB are given in Table I.

Table 2.1. $\zeta_{2,B}$ for predefined target rate R_T

R_T	8	16	32	64
$\zeta_{2,B}$	1.95	2.08	2.15	1.86

2.3.3 Primary system rate and outage probability with nonadaptive CSS (MRC)

Out of total N subcarriers received from PT, ST decodes and forwards only D subcarriers to PR. The primary and secondary system will use conventional non-adaptive mode of transmission. The instantaneous rate at PR after maximal ratio combining (MRC) of two transmission phases with a condition of successful decoding of primary signal $s_{p,k}$ at ST is,

$$R_{PR}^{MRC} = \frac{1}{2} \sum_{k=1}^D \log_2 \left(1 + \frac{p_{p,k} \gamma_{1,k}}{\sigma_1^2} + \frac{p_{s,k} \gamma_{3,k}}{\sigma_1^2} \right) + \frac{1}{2} \sum_{k=1}^{N-D} \log_2 \left(1 + \frac{p_{p,k} \gamma_{1,k}}{\sigma_1^2} \right), \quad (2.28)$$

where, factor $\frac{1}{2}$ is due to two phase transmission. From (2.8), (2.28) reduces to,

$$R_{PR}^{MRC} = \frac{D}{2} \log_2 \left(1 + \frac{p_p \gamma_1}{\sigma_1^2} + \frac{p_s \gamma_3}{\sigma_1^2} \right) + \frac{N-D}{2} \log_2 \left(1 + \frac{p_p \gamma_1}{\sigma_1^2} \right). \quad (2.29)$$

Proposition 2.3 *The outage probability of the primary system for nonadaptive CSS (with MRC) can be derived in closed form as,*

$$P_{out}^p = e^{-\frac{\zeta_2^l \sigma^2}{p_p} \rho_1} (1 - e^{-\zeta_1^l \alpha} - \zeta_1^l \Upsilon_1) + \left(1 - e^{-\frac{\zeta_2^l \sigma^2}{p_p} \rho_1}\right) \left(1 - e^{-\frac{\zeta_1^l \sigma^2}{p_p} \rho_1}\right), \quad (2.30)$$

where,

$$\Upsilon_1 = \int_{\gamma_1=0}^{\alpha} e^{\left(\delta_2 \gamma_1 - \frac{\delta_1}{\gamma_1^{\frac{1}{D}-1}}\right)} d\gamma_1, \quad (2.31)$$

$$\delta_1 = \frac{\zeta_3^l \Lambda^{\frac{1}{D}}}{p_s p_p^{\frac{N}{D}-1}}, \text{ and } \delta_2 = \frac{\zeta_3^l p_p}{p_s} - \zeta_1^l. \quad (2.32)$$

Proof : Proof of the proposition 2.3 is given in Appendix C.

2.3.3.1 Critical distance for MRC

At critical distance $\zeta_{2,M}$ or beyond, the primary system outage probability with MRC will always be greater than outage probability with direct transmission.

$$1 - e^{\left(-\frac{\sigma_1^2 (2^{R_T/N} - 1) \zeta_1^l}{p_p}\right)} < e^{-\frac{\zeta_2^l \sigma^2}{p_p} \rho_1} (1 - e^{-\zeta_1^l \alpha} - \zeta_1^l \Upsilon_1) + \left(1 - e^{-\frac{\zeta_2^l \sigma^2}{p_p} \rho_1}\right) \left(1 - e^{-\frac{\zeta_1^l \sigma^2}{p_p} \rho_1}\right). \quad (2.33)$$

From (2.33), the critical distance with MRC can be derived as,

$$\zeta_{2,M} = \left[\frac{p_p}{\rho_1 \sigma^2} \ln \left(\frac{\Phi_1 - \Phi_2}{\Phi_3 - \Phi_2} \right) \right]^{\frac{1}{l}}, \quad (2.34)$$

where, $\Phi_1 = (1 - e^{-\zeta_1^l \alpha} - \zeta_1^l \Upsilon_1)$.

Similarly, from (2.34), the critical distance $\zeta_{2,M}$ can be calculated. The critical distances for some of the predefined target rates with $p_p/\sigma^2 = 20$ dB, $p_s/\sigma^2 = 20$ dB and best possible value of D with MRC are given in Table II.

Table 2.2. $\zeta_{2,M}$ for predefined target rate R_T

R_T	8	16	32	64
$\zeta_{2,M}$	2.86	2.9	2.56	1.92

2.4 Rate and Outage Probability of Secondary System

In transmission Phase II, ST transmits adaptively modulated D subcarriers to PR via $\Psi_{3,k}$ link and remaining $N - D$ subcarriers to SR via $\Psi_{4,k}$ link. Signal received by SR in Phase II is,

$$\phi_k^{sr,2} = (p_{s,k})^{\frac{1}{2}} \Psi_{4,k} s_{s,k} + n_{2,k}, \quad (2.35)$$

where, $s_{s,k}$ is a M -QAM modulated secondary signal whereas order of M depends on the BER constraint. The average BER for Gray coded square M -QAM system can be calculated from (2.16).

The instantaneous rate at SR is given by,

$$R_S = \frac{1}{2} \sum_{k=1}^{N-D} \log_2(M) \log_2 \left(1 + \frac{p_{s,k} \gamma_{4,k}}{\sigma_4^2} \right). \quad (2.36)$$

Assuming, $p_{s,k} = p_s, \forall k$ and $\gamma_{4,k} = \gamma_4, \forall k$, (2.36) can be deduced as,

$$R_S = \frac{1}{2} (N - D) \log_2(M) \log_2 \left(1 + \frac{p_s \gamma_4}{\sigma_4^2} \right). \quad (2.37)$$

If the target rate for secondary system is defined as R_{Ts} , then the outage will occur when $\Pr(R_S < R_{Ts})$.

$$\Pr(R_S < R_{Ts}) = \Pr \left(\gamma_4 < \frac{\rho_2 \sigma_4^2}{p_s} \right) = 1 - e^{-\frac{\zeta_4^l \sigma_4^2}{p_s} \rho_2}, \quad (2.38)$$

where, $\gamma_4 \sim \exp(\zeta_4^l)$ and $\rho_2 = 2^{\frac{2R_{Ts}}{\log_2(M)(N-D)}} - 1$.

2.5 Simulation Results and Discussion

In this section, we show the results for BER with respect to ζ_2 (distance between PT-ST) and outage probability with respect to D (number of subcarriers forwarded by ST to PR). For ease of simulation, the nodes PT, ST, SR, PR are considered to be co-linear [12]. The PT is located at the location (0,0) in the two-dimensional plane while PR is located at (1,0) i.e. $\zeta_1 = 1$. SR lies in between PT and PR on coordinates (0.75,0), and ST moves along the X-axis. We have chosen target rate for both primary and secondary system $R_T = N = 64$, where N denotes the total number of subcarriers forwarded by PT to PR and ST. The subcarrier power has been normalized with respect to receiver noise variance i.e. $p_p/\sigma^2 = p_s/\sigma^2 = 20$ dB and the path loss exponent has been set to $l = 4$.

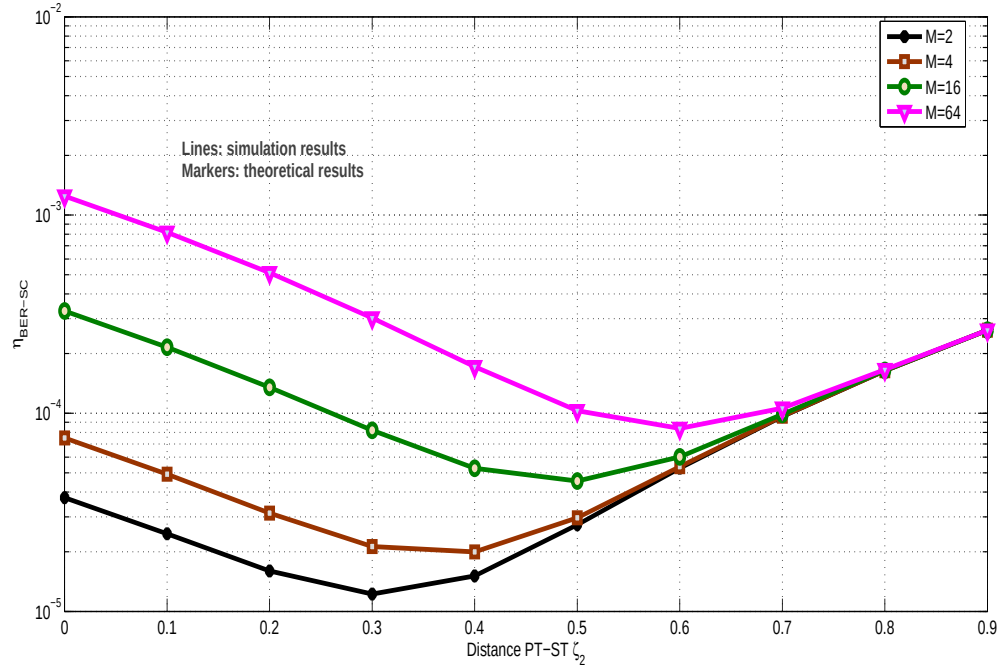


Figure 2.2. Primary system BER vs distance between PT-ST

Fig. 2.2 shows the BER (for BER-SC) vs ζ_2 for different constellation sizes. For $M = 2$ and $0 < \zeta_2 < 0.3$, BER decreases with increase in ζ_2 . This phenomenon can be explained as follows. As the distance between PT-ST increases, the distance between ST-PR decreases, thus overall average BER, (2.15), also reduces. When

$\zeta_2 = 0.3$ and $M = 2$, φ_{PT-ST} attains some small value, and consequently major contribution in η_{BER-SC} is due to $\eta_{comb-PR}$ which is decreasing with decrease in distance between ST-PR. However, for $\zeta_2 > 0.3$, BER increases continuously with respect to ζ_2 , consequently, the value of φ_{PT-ST} increases, thus decoding of subcarriers at ST becomes the limiting factor for BER.

For larger constellation sizes like $M = 4, 16$ or 64 , BER increases with increase in M . This phenomenon is quite obvious since for M -QAM modulation with fixed bandwidth and power, the probability of error increases with M . From Fig. 2.2, we can see that, BER decreases first with increase in ζ_2 for all values of M i.e $M = 2, 4, 16, 64$. However, after reaching a certain distance between PT-ST, BER increases. In order to quantify this behavior of BER, we have introduced the term "transmute distance" $\zeta_{2,T}$. It is defined as a distance between PT-ST beyond which BER increases instead of decreasing. This phenomenon occurs at $\zeta_{2,T}$ because φ_{PT-ST} attains significantly higher value. In other words, successful decoding of subcarriers at ST decreases when ST is located at $\geq \zeta_{2,T}$, consequently BER increases. The transmute distance for different values of M has been given in Table III.

Table 2.3. $\zeta_{2,T}$ for predefined constellation size M

M	2	4	16	64
$\zeta_{2,T}$	0.3	0.4	0.5	0.6

For $\zeta_2 > 0.8$, there is no change in BER with any subsequent change in constellation size at ST, as beyond this distance φ_{PT-ST} would attain a very high value and thus saturating η_{BER-SC} .

Fig. 2.3 shows the theoretical and simulation results of the primary system outage probability (BER-SC) (2.11) with respect to the number of subcarriers required for cooperation. To find the outage probability, the target rate of the primary system has been set to R_T and adaptive modulation is applied at ST for BER constraint of 10^{-4} . From Fig. 2.3, it is quite obvious that as the number of forwarded subcarriers ' D ' from ST-PR increases, the outage probability decreases. For $\zeta_2 = 0.2$, $M = 4$ and $D > 10$, the outage probability with cooperation is less than direct transmission. Hence, ST needs to forward only 10 subcarriers

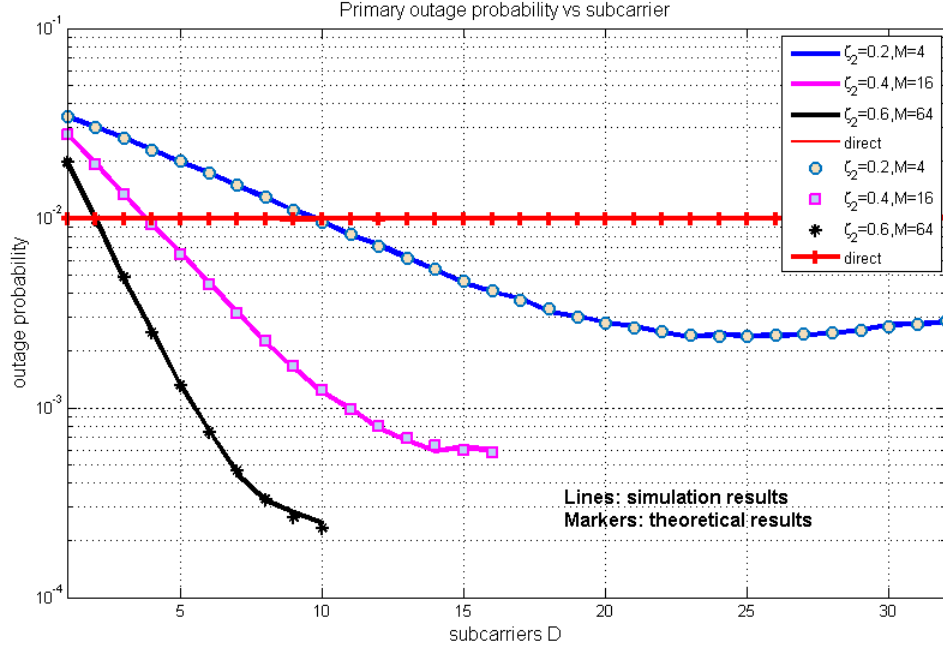


Figure 2.3. Primary system outage probability (BER-SC) vs D subcarriers

to PR, to keep the primary system performance same as direct transmission. As a consequence, secondary system can use the remaining ' $N - D$ ' subcarriers to transmit its own data to the secondary receiver. It creates a win-win situation for both primary and secondary system, as the primary system can achieve its target rate of communication in exchange for allowing secondary user to access part of its spectrum. For instance, ST can forward $N/\log_2(M)$ (32 for 4-QAM) successfully decoded subcarriers to PR while remaining $N - (N/\log_2(M))$ subcarriers can be used for secondary communication. It proves that proposed scheme is beneficial for both primary and secondary systems.

However, for $D > 23$, $M = 4$, outage probability gets stagnant. It is due to the fact that, when D attains a particular value i.e. ($D = 23$, $M = 4$), $\Pr(R_{BER-SC} < R_T)$ attains a very small value and decoding of primary signal at ST becomes the bottleneck for outage probability. Thus, any subsequent increase in D will not have any significant impact on the primary system outage probability.

Let us put a BER constraint of 10^{-4} for the primary system. An interesting observation that can be made from Fig. 2.2 is that, at $\zeta_2 = 0.4$, all the values of M except $M = 64$ satisfy this BER constraint. Hence, if we select $M = 16$, we

get maximum throughput while fulfilling the BER constraint. It is also evident from Fig. 2.3 that for the case, $D > 4$, outage probability with cooperation would be less than direct transmission. Here, ST can forward maximum 16 subcarriers (corresponding to 16, 16-QAM symbols) to PR thus remaining 48 subcarriers can be used for secondary communication. Similarly, at $\zeta_2 = 0.6$, BER for $M = 2$, $M = 4$, $M = 16$, $M = 64$ is less than 10^{-4} , consequently, we can choose $M = 64$ to obtain maximum throughput. In this case, only 2 subcarriers (corresponding to 2, 64-QAM symbols) are required to achieve same outage probability as direct transmission and remaining subcarriers ($64 - 2 = 62$) can be used for secondary transmission. From the above discussion, it is quite obvious that the number of subcarriers available for secondary communication is directly proportional to the constellation size used by ST for primary data transmission. Hence, for a given ζ_2 and BER constraint, if the value of M increases, corresponding throughput of secondary system also increases.

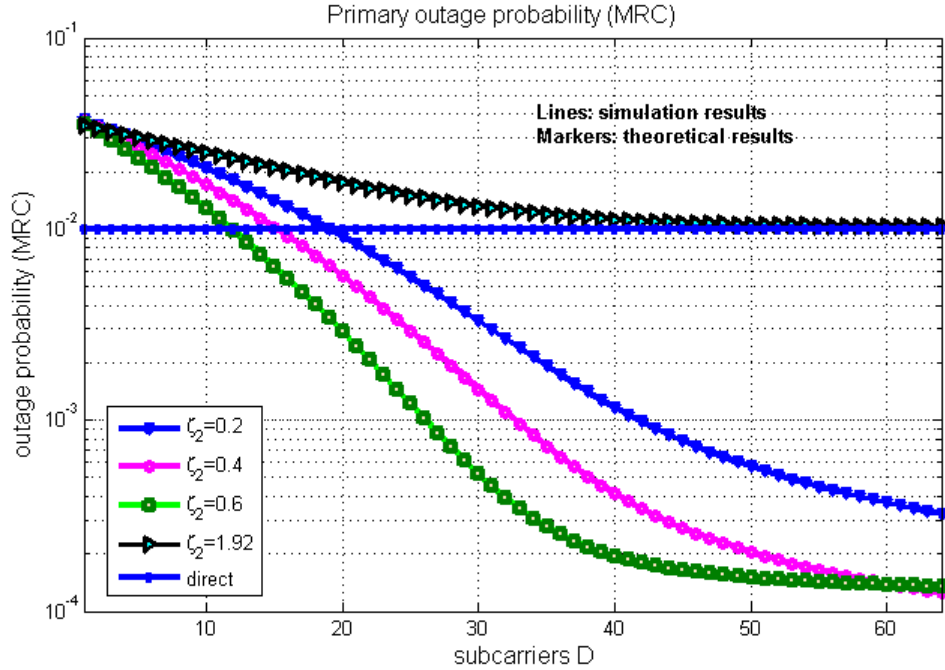


Figure 2.4. Primary system outage probability with MRC vs D subcarriers

Fig. 2.4 shows the theoretical and simulation results of the primary system outage probability with MRC with respect to the number of subcarriers required for cooperation. A trend similar to BER-SC is also observed in Figure 2.4, i.e. outage

probability decreases with the increase in the number of subcarriers. However, unlike BER-SC, adaptive modulation cannot be applied at ST when PR uses MRC to combine the signals⁹. With MRC, for $\zeta_2 = 0.2$, $D > 19$ subcarriers¹⁰ are required to achieve the outage probability less than direct transmission, whereas in case of BER-SC, to achieve same outage performance the number of subcarriers required were $D = 5$. Hence, BER-SC with adaptive modulation at ST outperforms MRC. Similarly, for $\zeta_2 = 0.4$ and $\zeta_2 = 0.6$, the required number of subcarriers with MRC are $D > 16$ and $D > 12$ respectively, whereas with BER-SC it is $D > 4$ and $D > 2$ respectively. For $\zeta_2 = 1.92$, which is defined as a critical distance with MRC, no OSS is possible, as outage probability with cooperation is always higher than direct transmission.

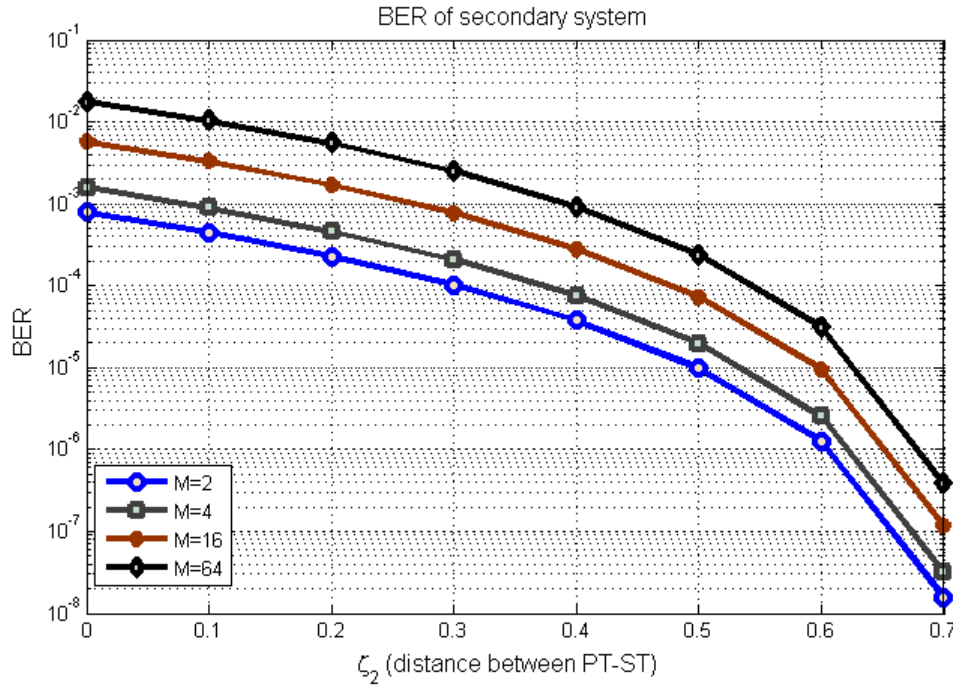


Figure 2.5. BER (secondary system) vs ζ_2 (distance between PT-ST)

Fig. 2.5 shows BER of secondary system with respect to ζ_2 for different constellation sizes. From Fig. 2.5, it is quite obvious that BER decreases with increase in

⁹As stated earlier, in order to apply MRC, the transmitted signals from PT and ST should have same constellation sizes, which might not be feasible if constellation size at ST changes adaptively.

¹⁰Assuming both PT and ST are using conventional nonadaptive BPSK mode of transmission.

ζ_2 . As discussed earlier, SR is located at coordinates $(0.75, 0)$ in a two-dimensional plane while ST is moving along the x axis. Therefore as the distance between PT-ST increases, distance between ST-SR decreases, thus decreasing the BER at SR. In addition, BER increases with increase in the value of M .

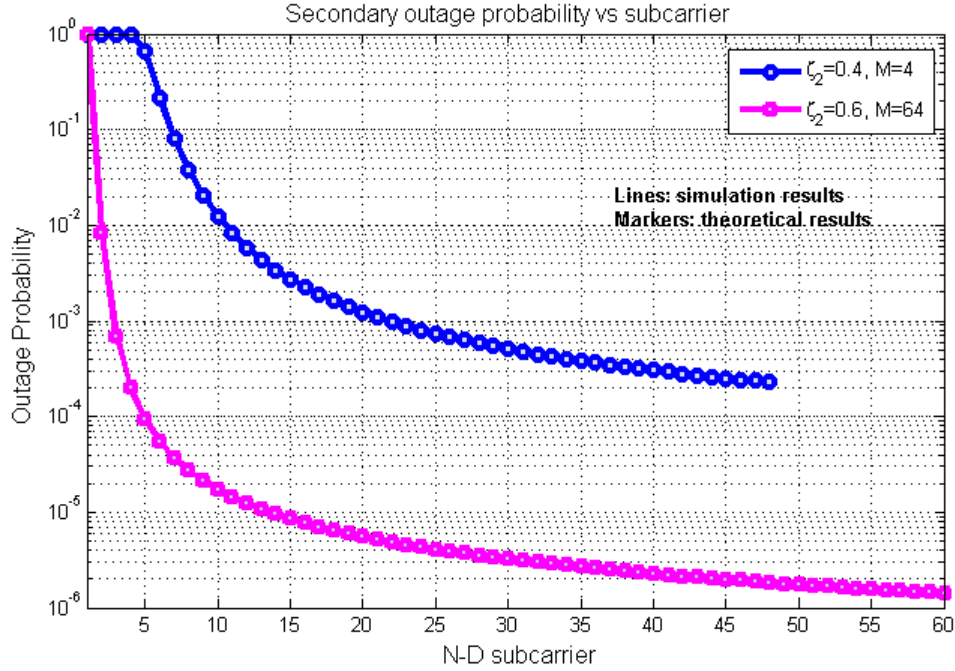


Figure 2.6. Outage probability of secondary system vs subcarriers $N - D$

Fig. 2.6 shows the outage probability of secondary system with respect to $N - D$ subcarriers for $\zeta_2 = 0.4$ and $\zeta_2 = 0.6$. The target rate and BER constraint for the secondary system have been set to $R_{T_S} = N$ and 10^{-4} , whereas $\frac{p_{SS}}{\sigma^2} = 20$ dB. Outage probability decreases with the increase in $N - D$ subcarriers. As discussed earlier, for $\zeta_2 = 0.4$, the maximum value of subcarriers, D , that can be forwarded by ST to PR would be equal to 16. Hence $N - D = 48$ subcarriers are available at ST for secondary data transmission. Here, ST is using 4-QAM modulation scheme to transmit its own data to SR while fulfilling the BER constraint of 10^{-4} . For $\zeta_2 = 0.6$, the distance between ST and SR gets reduced, i.e., $\zeta_3 = 0.15$, thus there is a huge improvement in terms of outage probability. Moreover, at this distance ST can use $M = 64$ constellation size to further increase the instantaneous rate while fulfilling BER constraint of the secondary system. Hence, a substantial improvement has been observed in the outage probability. For instance, at $\zeta_2 = 0.6$

and $N - D = 60$, $\Pr(R_S < R_{T_s}) \approx 10^{-6}$.

2.6 Conclusion

In this chapter, an subcarrier sharing scheme has been proposed in which the secondary system gains opportunistic spectrum sharing by assisting the primary system to achieve its target rate of communication. In particular, ST by acting as a DF relay allocates some of its subcarriers for primary data transmission. ST uses the remaining subcarriers for its own transmission. As a primary contribution, the closed form expressions of the outage probability for the primary and secondary systems for adaptive (BER-SC) and nonadaptive (MRC) CSS protocol has been derived. Analytical expression of critical distance which is defined as a distance between PT and ST nodes beyond which no spectrum sharing is possible has also been computed. Critical distance determines the limitation and region of validity of the proposed scheme. The proposed scheme is applicable in dense urban scenarios where the spectrum is generally crowded, and spectrum holes are hard to obtain as the performance of the secondary system can be maintained regardless of the availability of spectrum holes. Good agreement between the theoretical expressions and simulation results verify the results obtained in this paper.

Subcarrier Sharing Schemes for OFDMA-based Device to Device Communication Frameworks

3.1 Introduction

As we showed in the previous chapter, the performance of the cooperative cognitive radio system can be improved by adopting OFDM-based adaptive subcarrier sharing scheme with BER-SC diversity. In D2D scenario, unlike cognitive radio, D2D user belongs to the same cellular network, thus it may not necessarily have low priority. Besides, most of the previous works on D2D communication have been restricted to only one framework; trade-off involved in employing one framework over other has often been overlooked.

Motivated by above, in this chapter, we analyze the underlay, overlay and C-D2D frameworks for the cellular network. Specifically, we assess the benefits involved in selecting one D2D framework over another when multiple D2D users coexist with the cellular users in the same cell. The proposed system architecture consists of a circular cell with a BS in the center of a cell operating on a licensed frequency band. OFDMA has been used as an access technology through which allocated spectrum is divided into a number of orthogonal subcarriers with same subchannel bandwidth. Each cellular link (from BS to CU or vice versa) has been

assigned a number of subcarriers (e.g., N) for its communication. It is assumed that BS supports operator controlled D2D communication [92], wherein apart from the cellular links between mobile users and BS, there exist couples of mobile users which when given an opportunity would like to communicate directly via D2D link [20]. In the present context, mobile user in a cellular link is denoted by the cellular user (CU), and two mobile users which would like to do D2D communication are denoted as D2D transmitter (DT) and D2D receiver (DR) respectively. DT-DR exists as a D2D pair. On a specified time-frequency resource block, one D2D pair can share the spectrum of the CU by one of the specified frameworks i.e. underlay, overlay or C-D2D. It is worth mentioning that BS is still responsible for peer discovery, link establishment and subcarrier allocation to the D2D user over D2D link [74].

The major contributions of the proposed work are summarized as follows:

- Investigate the rate and outage trade-offs of OFDMA based underlay, overlay, and C-D2D communication frameworks.
- Specifically,
 - For underlay framework, we proposed an angle constrained D2D communication for which the optimal distance between the CU and BS as well as the minimum value of angle θ (an angle between a cellular link and D2D interference link) is derived. It has been shown that as long as the angle between the cellular link and D2D interference link is greater than the optimal value of θ , the target rate and outage probability constraint of both the cellular and D2D users will be satisfied. Further, the simulation results also show that for fixed ζ_{c_iB} (distance between a CU and BS), D2D outage probability decreases with increase in θ , whereas cellular outage probability is independent of θ . By leveraging the above results, BS can select the CU which facilitates DT-DR communication while maintaining its QoS.
 - For overlay and C-D2D framework, an optimal subcarrier sharing scheme is proposed, which not only helps the cellular user to achieve the target QoS but also helps the D2D users to communicate with each other.

Our results show that the proposed subcarrier sharing scheme leads to considerable performance improvement for both cellular and D2D users.

- The impact of CU-BS distance, angle θ , and cellular user outage probability constraint on different frameworks have been investigated. Through the obtained results it has been shown that for high cellular outage probability constraint and large CU-BS distance, C-D2D framework attains less D2D outage probability as compared to underlay and overlay frameworks. These results can be utilized by the BS to select an optimal D2D framework while satisfying the outage probability constraint of cellular and D2D users.
- The performance of all the three frameworks has been quantified by obtaining closed-form expressions of outage probability for cellular and D2D users.

The remainder of this chapter is organized as follows. Section 3.2 discusses the system model. Rate and outage probability expressions for cellular and D2D links with proposed scheme are given in Section 3.3. Simulation results are provided in Section 3.4, and finally, the conclusion is drawn in Section 3.5.

3.2 System Model and Protocol Description

The system model for underlay, overlay, and C-D2D frameworks are shown in Fig. 3.1, 3.2 and 3.3 respectively. The system model consists of a small cell of radius $\mathcal{R}$. The cell has a BS located at the center, M cellular users, and R D2D (or DT-DR) pairs. Specifically, a cellular user is denoted as CU_i , where $i=1,2,\dots,M$ and a DT-DR pair is denoted as $\text{DT}_j\text{-DR}_j$, where $j=1,2,\dots,R$. In line with LTE-A cellular standard, OFDMA has been used as an access technology through which the available spectrum is divided among the M cellular users by allocating each of them N orthogonal subcarriers¹. A D2D pair may through one of the above frameworks utilizes the same spectrum as allocated to a cellular user CU_i . Channels over the nodes are modeled as frequency non-selective Rayleigh

¹Although the results have been illustrated assuming OFDMA as a multiple access technique, the results can be easily extended to SC-FDMA whereby assuming that subcarrier mapping for the cellular users occurs after discrete Fourier transform (DFT).

fading with $\Psi_{xy,k} \sim \mathcal{CN}(0, \zeta_{xy}^{-l})$, where ζ_{xy} is the distance between the respective transmitter ‘ x ’ and receiver ‘ y ’, and l is path loss exponent. $x \in \{c_i, t_j\}$, $y \in \{B, t_j, r_j\}$; $i=1,2,\dots,M$, $j=1,2,\dots,R$, where c_i denotes the i_{th} cellular user i.e. CU $_i$, B denotes BS, t_j and r_j denote j^{th} D2D pair i.e. DT $_j$ and DR $_j$ respectively. $\zeta_{c_i B}$ denotes the distance between CU $_i$ -BS. Similarly, the distance between CU $_i$ -DT $_j$, DT $_j$ -BS and DT $_j$ -DR $_j$ is denoted by $\zeta_{c_i t_j}$, $\zeta_{t_j B}$ and $\zeta_{t_j r_j}$ respectively. In line with conventional D2D communication, it is assumed that the distance between DT $_j$ and DR $_j$ is negligible as compared to the distance between CU $_i$ and DT $_j$, i.e. $\zeta_{t_j r_j} \ll \zeta_{c_i t_j}$, thus CU $_i$ is equidistant from DT $_j$ and DR $_j$ i.e. $\zeta_{c_i t_j} = \zeta_{c_i r_j}$. The channel coefficient corresponds to CU $_i$ -BS link is $\Psi_{c_i B, k}$ over subcarrier k ($1 \leq k \leq N$). Similarly, channel coefficient between CU $_i$ -DT $_j$, DT $_j$ -BS, and DT $_j$ -DR $_j$ is denoted by $\Psi_{c_i t_j, k}$, $\Psi_{t_j B, k}$, $\Psi_{t_j r_j, k}$ respectively. The instantaneous channel gain for each subcarrier is defined as $\gamma_{xy,k} = |\Psi_{xy,k}|^2$. The AWGN at each receiver BS, DT $_j$ and DR $_j$ is denoted as $n_{B,k}$, $n_{t_j,k}$, $n_{r_j,k} \sim \mathcal{CN}(0, \sigma_j^2)$. The cellular and D2D user’s signals transmitted on k^{th} subcarrier are denoted as $s_{c_i,k}$ and $s_{d_j,k}$ respectively with zero mean and $E\{s_{c_i,k}^* s_{c_i,k}\} = E\{s_{d_j,k}^* s_{d_j,k}\} = 1$.

The links between DT $_j$ -BS and CU $_i$ -BS are separated by angle θ_{ij} as shown in the Fig. 3.1. Hence the distance $\zeta_{c_i t_j}$ can be defined in terms of $\zeta_{c_i B}$, $\zeta_{t_j B}$, and angle θ_{ij} as [93],

$$\zeta_{c_i t_j} = \sqrt{\zeta_{c_i B}^2 + \zeta_{t_j B}^2 - 2\zeta_{c_i B}\zeta_{t_j B}\cos\theta_{ij}}. \quad (3.1)$$

In underlay framework, each cellular user can transmit N subcarriers to BS via $\Psi_{c_i B, k}$ link for uplink transmission as shown in the Fig. 3.1. Since the cellular user and a D2D user share the same spectrum (or same set of resource blocks), BS allows a DT $_j$ -DR $_j$ pair to do D2D communication using the spectrum allocated to the cellular user as long as interference threshold requirement of both the cellular and D2D users are satisfied. BS and DR $_j$ will receive interference signals from DT $_j$ and CU $_i$ through $\Psi_{t_j B, k}$ and $\Psi_{c_i r_j, k}$ links respectively. However, as $\zeta_{t_j r_j} \ll \zeta_{c_i B}$, the transmission power requirement for the D2D user will be less as compared to the cellular user. Thus, the amount of interference at BS from DT $_j$ will be considerably less than that from CU $_i$ to DR $_j$. This framework has been evaluated by deriving the outage probability and optimal value of θ_{ij} for various $\zeta_{c_i B}$. Thus from $\zeta_{c_i B}$ and θ_{ij} , BS can find a cellular user that can coexist with DT $_j$ -DR $_j$ pair.

In overlay framework, a part of the cellular spectrum is allocated for D2D

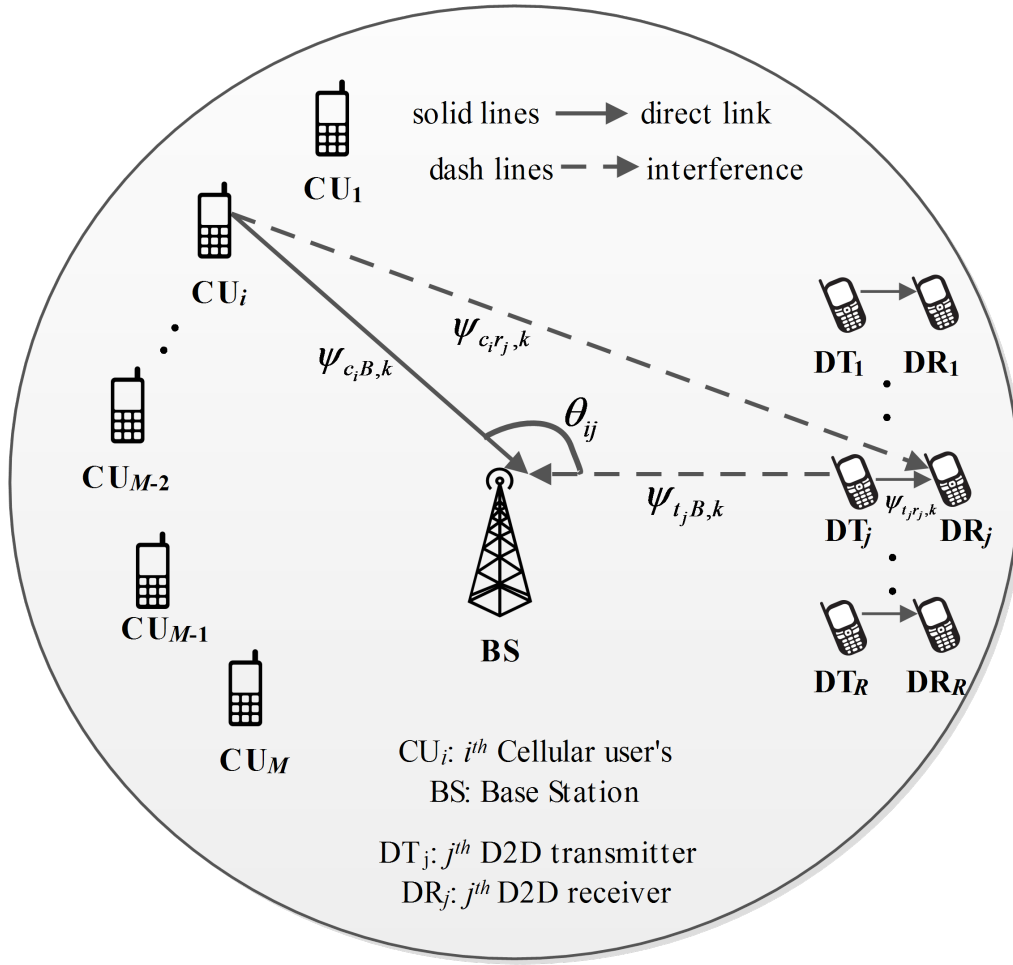


Figure 3.1. System model (underlay framework)

communication as shown in Fig. 3.2. For instance, if QoS requirement of a cellular user ‘CU_i’ can be satisfied by few subcarriers (say $D < N$), then BS allocates D subcarriers to CU_i for transmission via $\Psi_{c_i B, k}$ link while remaining $N - D$ subcarriers can be used for D2D communication between DT_j and DR_j. It is quite obvious that there will be no interference between cellular and D2D links, as both use orthogonal sets of subcarriers. BS is still responsible for mapping of DT_j- DR_j and CU_i.

In a C-D2D framework, a D2D user helps a cellular user to achieve the desired QoS by acting as a relay in exchange for accessing the cellular spectrum. Specifically, by utilizing spatial diversity, a D2D user helps a cellular user to achieve the desired target rate, and as quid pro quo D2D user is allowed to access the cellular

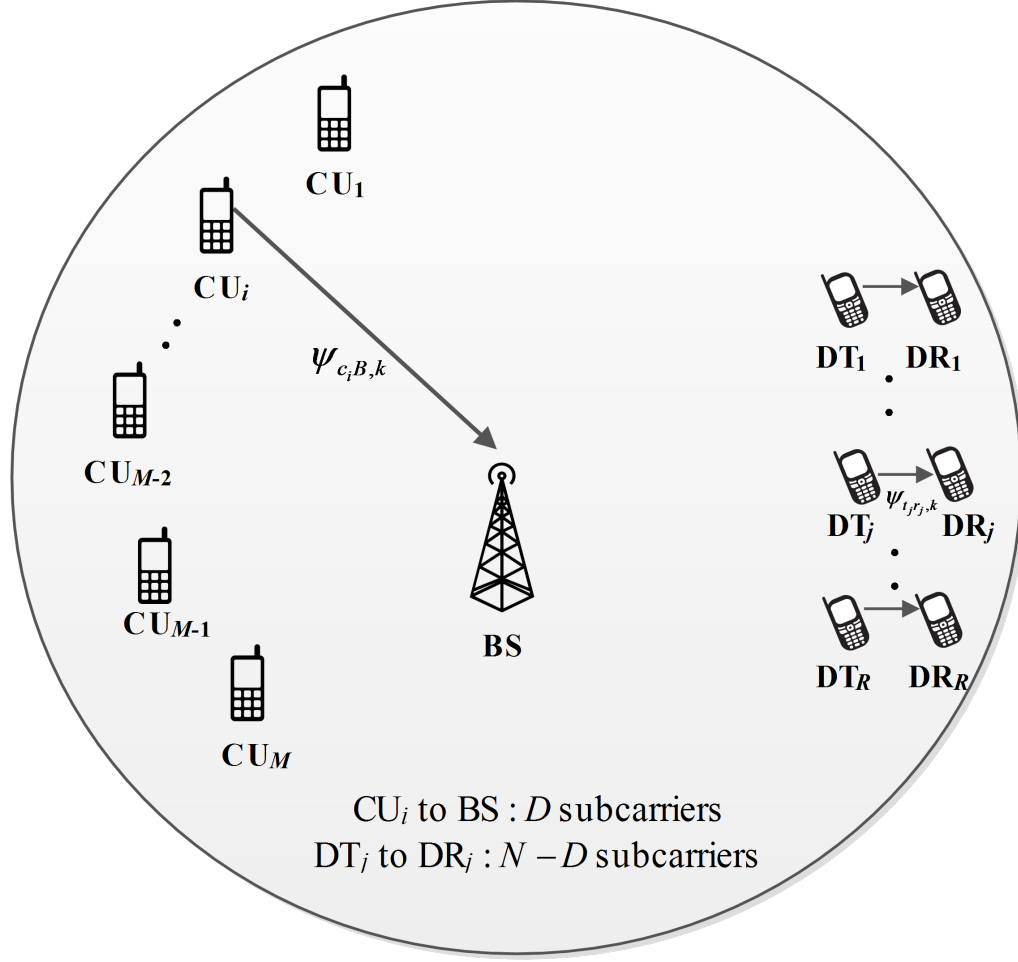


Figure 3.2. System model (overlay framework)

user spectrum. From proposed analysis, BS discovers an optimal CU_i which can form a C-D2D framework with a DT_j - DR_j to facilitate D2D communication while satisfying the QoS of both the cellular and D2D user. As shown in Fig. 3.3, for C-D2D framework, the total transmission is divided into two phases². In Phase I, CU_i broadcasts signal to BS via $\Psi_{c_i B, k}$ link, which is overheard by DT_j via $\Psi_{c_i t_j, k}$ link. DT_j attempts to decode the cellular signal received in Phase I. If the decoding is successful,³ it helps the cellular user by allocating few subcarriers (for instance D) for uplink transmission via $\Psi_{t_i B, k}$ link. The number of subcarriers, D , to be

²Control protocol involved in C-D2D framework is in line with [12], [34], [33].

³If DT_j is not able to decode cellular subcarrier in Phase I, then outage will occur, and no retransmission of cellular signal would be possible in Phase II. However, particular subcarrier can be used by DT_j for D2D communication.

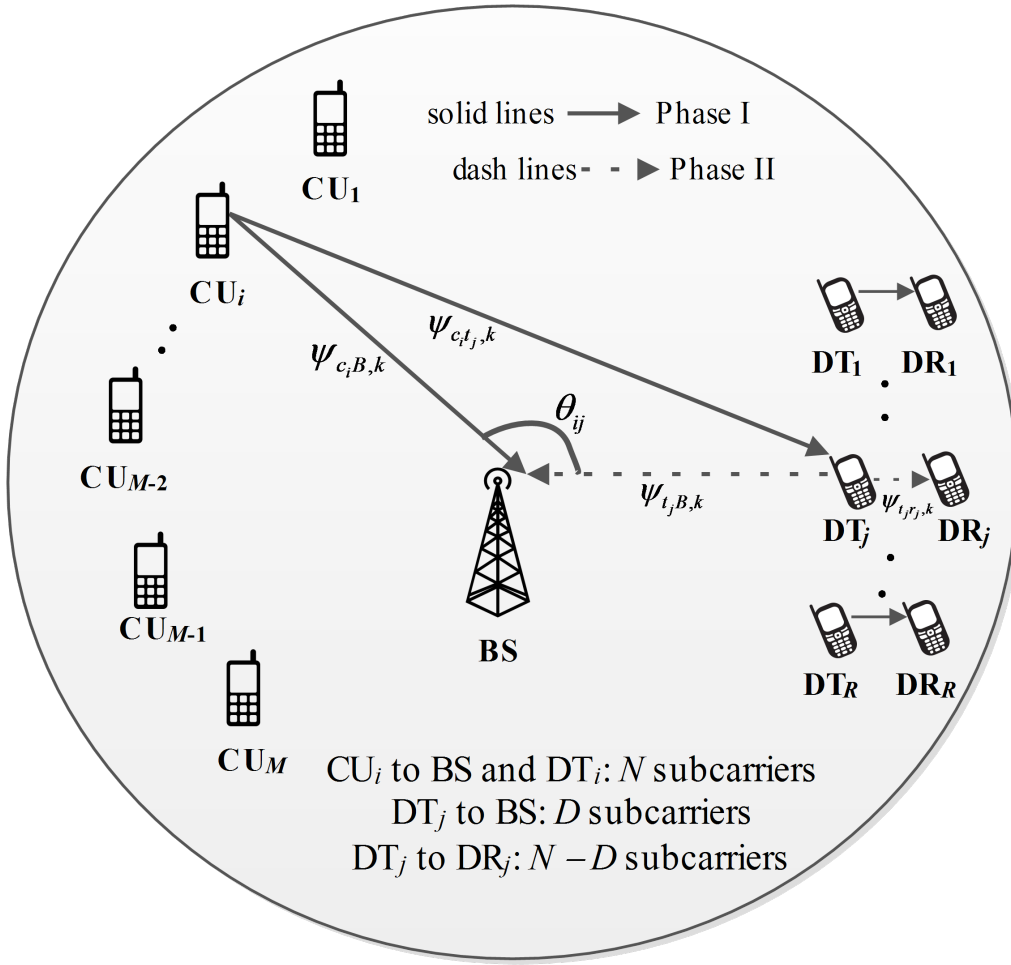


Figure 3.3. System model (C-D2D framework)

allocated for DT_j to BS transmission is selected based on the QoS requirement of CU_i. The remaining subcarriers ($N - D$) can be used by DT_j to transmit its signal to DR_j. Hence, a C-D2D framework represents a mutually beneficial scenario for both cellular and D2D user. D2D user assists the cellular user in exchange for accessing the cellular spectrum. We have quantified the performance of C-D2D framework by deriving the exact number of subcarriers ($D \leq N$) that needs to be allocated for DT_j to BS transmission to fulfill the target QoS of the cellular user.

3.3 Rate and Outage Probability

In this section, closed-form expressions for the rate and outage probability of the cellular and D2D user for the three frameworks have been derived.

3.3.1 Rate and outage probability with underlay framework

3.3.1.1 Cellular rate and outage probability

In underlay framework, a cellular user CU_i transmits N allocated subcarriers to BS. Signal $s_{c_i,k}$ is transmitted by CU_i , and is received by BS on $\Psi_{c_i B,k}$ link. During the same time, signal $s_{d_j,k}$ is transmitted by DT_j to DR_j on $\Psi_{t_j r_j,k}$. The received signal at BS over subcarrier k is denoted as ϕ_k^{BS} and is given by,

$$\begin{aligned} \phi_k^{BS} = (p_{cu,k})^{\frac{1}{2}} \Psi_{c_i B,k} s_{c_i,k} + (p_{dt,k})^{\frac{1}{2}} \Psi_{t_j B,k} s_{d_j,k} + n_{B,k} \\ ; 1 \leq k \leq N, 1 \leq i \leq M, 1 \leq j \leq R \end{aligned} \quad (3.2)$$

where, $p_{cu,k}$ denotes cellular signal power, whereas, $p_{dt,k}$ denotes D2D power on k^{th} subcarrier.

The instantaneous rate received at BS will be,

$$R_{cu}^{under} = \sum_{k=1}^N \log_2 \left(1 + \frac{p_{cu,k} \gamma_{c_i B,k}}{\sigma_j^2 + p_{dt,k} \gamma_{t_j B,k}} \right). \quad (3.3)$$

If the target rate for CU_i to BS is R_{th}^c , then outage occurs when $R_{cu}^{under} < R_{th}^c$. Thus, outage probability for the cellular transmission for underlay framework can be defined as,

$$P_{cu,out}^{under} = \Pr\{R_{cu}^{under} < R_{th}^c\}. \quad (3.4)$$

Without loss of generality, it is assumed that the power and channel gain are uniformly distributed across all the subcarriers,

$$p_{cu,k} = p_{cu}, \forall k; p_{dt,k} = p_{dt}, \forall k; \gamma_{xy,k} = \gamma_{xy}, \forall k. \quad (3.5)$$

Thus, from (3.3) and (3.5), (3.4) can be defined as,

$$\begin{aligned}
P_{cu,out}^{under} &= \Pr \left\{ N \log_2 \left(1 + \frac{p_{cu} \gamma_{c_i B}}{\sigma_j^2 + p_{dt} \gamma_{t_j B}} \right) < R_{th}^c \right\} \\
&= \Pr \left\{ \frac{\gamma_{c_i B}}{\sigma_j^2 + p_{dt} \gamma_{t_j B}} < \frac{2^{\frac{R_{th}^c}{N}} - 1}{p_{cu}} \right\} \\
&= \Pr \left\{ \gamma_{c_i B} < \mu (\sigma_j^2 + p_{dt} \gamma_{t_j B}) \right\}, \tag{3.6}
\end{aligned}$$

where,

$$\mu = \frac{2^{\frac{R_{th}^c}{N}} - 1}{p_{cu}}. \tag{3.7}$$

As $\gamma_{t_j B} \sim \exp(\zeta_{t_j B}^l)$, thus,

$$\mu (\sigma_j^2 + p_{dt} \gamma_{t_j B}) > 0. \tag{3.8}$$

To solve (3.6), we need to find out joint probability density function of independent and exponential random variables $\gamma_{c_i B}$ and $\gamma_{t_j B}$ which can be represented as,

$$\zeta_{c_i B}^l e^{-\zeta_{c_i B}^l \gamma_{c_i B}} \zeta_{t_j B}^l e^{-\zeta_{t_j B}^l \gamma_{t_j B}}. \tag{3.9}$$

Proposition 3.1 *The closed form expression for cellular outage probability with underlay framework can be given as:*

$$P_{cu,out}^{under} = 1 - \frac{\zeta_{t_j B}^l e^{-\zeta_{c_i B}^l \mu \sigma_j^2}}{\left(\zeta_{t_j B}^l + \mu p_{dt} \zeta_{c_i B}^l \right)}. \tag{3.10}$$

Proof :

$$\begin{aligned}
P_{cu,out}^{under} &= \int_{\gamma_{t_j B}=0}^{\infty} \int_{\gamma_{c_i B}=0}^{\mu(\sigma_j^2 + p_{dt} \gamma_{t_j B})} \zeta_{c_i B}^l e^{-\zeta_{c_i B}^l \gamma_{c_i B}} \zeta_{t_j B}^l e^{-\zeta_{t_j B}^l \gamma_{t_j B}} d\gamma_{c_i B} d\gamma_{t_j B} \\
&= 1 - \zeta_{t_j B}^l e^{-\zeta_{c_i B}^l \mu \sigma_j^2} \int_{\gamma_{t_j B}=0}^{\infty} e^{-\gamma_{t_j B} (\zeta_{t_j B}^l + \mu p_{dt} \zeta_{c_i B}^l)} d\gamma_{t_j B}. \tag{3.11}
\end{aligned}$$

After simplifying (3.11), we obtain (3.10).

Corollary 3.1 $\zeta_{c_i B}$, for a fixed cellular outage probability constraint and fixed p_{cu} ,
We can rewrite (3.10) as,

$$\begin{aligned} P_{cu,out}^{under}(\zeta_{t_j B}^l + \mu p_{dt} \zeta_{c_i B}^l) &= \zeta_{t_j B}^l + \mu p_{dt} \zeta_{c_i B}^l - \zeta_{t_j B}^l e^{-\zeta_{c_i B}^l \mu \sigma_j^2} \\ \zeta_{c_i B}^l (\mu p_{dt} (P_{cu,out}^{under})) + \zeta_{t_j B}^l e^{-\zeta_{c_i B}^l \mu \sigma_j^2} &= \zeta_{t_j B}^l (1 - P_{cu,out}^{under}). \end{aligned} \quad (3.12)$$

From (3.12), $\zeta_{c_i B}$ is given as,

$$\zeta_{c_i B}^l = \frac{C_4 + \frac{C_1}{C_3} W\left(-\frac{C_2 C_3}{C_1} e^{-\frac{C_3 C_4}{C_1}}\right)}{C_1}, \quad (3.13)$$

where,

$$\begin{aligned} C_1 &= \mu p_{dt} (P_{cu,out}^{under} - 1), \\ C_2 &= \zeta_{t_j B}^l, \\ C_3 &= \mu \sigma_j^2, \\ C_4 &= \zeta_{t_j B}^l (1 - P_{cu,out}^{under}). \end{aligned}$$

and $W(.)$ is a Lambert W function [94].

Corollary 3.2 p_{cu} , for a fixed cellular outage probability constraint and fixed $\zeta_{c_i B}$,
From (3.12), the closed form expression of μ is given as :

$$\mu = \frac{A_4 + \frac{A_1}{A_3} W\left(-\frac{A_2 A_3}{A_1} e^{-\frac{A_3 A_4}{A_1}}\right)}{A_1}, \quad (3.14)$$

where,

$$\begin{aligned} A_1 &= \zeta_{c_i B}^l p_{dt} (P_{cu,out}^{under} - 1), \\ A_2 &= \zeta_{t_j B}^l, \\ A_3 &= \zeta_{c_i B}^l \sigma_j^2, \\ A_4 &= \zeta_{t_j B}^l (1 - P_{cu,out}^{under}). \end{aligned}$$

From (3.7) and (3.14),

$$p_{cu} = \frac{\left(2^{\frac{R_{th}^c}{N}} - 1\right) A_1}{A_4 + \frac{A_1}{A_3} W\left(-\frac{A_2 A_3}{A_1} e^{-\frac{A_3 A_4}{A_1}}\right)}. \quad (3.15)$$

3.3.1.2 D2D rate and outage probability

The received signal at DR_j over subcarrier k is denoted as ϕ_k^{DR} which is equal to,

$$\begin{aligned} \phi_k^{DR} &= (p_{dt,k})^{\frac{1}{2}} \Psi_{t_j r_j, k} s_{d_j, k} + (p_{cu,k})^{\frac{1}{2}} \Psi_{c_i t_j, k} s_{c_i, k} + n_{r_j, k} \\ &; 1 \leq k \leq N, 1 \leq i \leq M, 1 \leq j \leq R \end{aligned} \quad (3.16)$$

where $s_{c_i, k}$ acts as an interference at DR_j. The instantaneous rate received at DR_j,

$$R_{d2d}^{under} = \sum_{k=1}^N \log_2 \left(1 + \frac{p_{dt,k} \gamma_{t_j r_j, k}}{\sigma_j^2 + p_{cu,k} \gamma_{c_i t_j, k}} \right). \quad (3.17)$$

The target rate of D2D transmission is R_{th}^d and outage occurs if $R_{d2d}^{under} < R_{th}^d$. Thus, the outage probability for D2D user for underlay framework can be given as,

$$P_{dt, out}^{under} = \Pr\{R_{dt}^{under} < R_{th}^d\}. \quad (3.18)$$

From (3.5) and (3.17), (3.18) can be rewritten as,

$$\begin{aligned} P_{dt, out}^{under} &= \Pr \left\{ N \log_2 \left(1 + \frac{p_{dt} \gamma_{t_j r_j}}{\sigma_j^2 + p_{cu} \gamma_{c_i t_j}} \right) < R_{th}^d \right\} \\ &= \Pr \left\{ \gamma_{t_j r_j} < \beta (\sigma_j^2 + p_{cu} \gamma_{c_i t_j}) \right\}, \end{aligned} \quad (3.19)$$

where, $\beta = \frac{2^{\frac{R_{th}^d}{N}} - 1}{p_{dt}}$. As $\gamma_{c_i t_j} \sim \exp(\zeta_{c_i t_j}^l)$, thus,

$$\beta (\sigma_j^2 + p_{dt} \gamma_{c_i t_j}) > 0. \quad (3.20)$$

Proposition 3.2 *Following the steps of (3.10), the D2D outage probability with*

underlay framework can be derived as,

$$P_{dt,out}^{under} = 1 - \frac{\zeta_{c_{it_j}}^l e^{-\zeta_{t_j r_j}^l \beta \sigma_j^2}}{\left(\zeta_{c_{it_j}}^l + \beta p_{cu} \zeta_{t_j r_j}^l\right)}. \quad (3.21)$$

Corollary 3.3 θ_{ij} which will satisfy a fixed D2D outage probability constraint. We can rewrite (3.21) as,

$$P_{dt,out}^{under}(\zeta_{c_{it_j}}^l + \beta p_{cu} \zeta_{t_j r_j}^l) = \zeta_{c_{it_j}}^l + \beta p_{cu} \zeta_{t_j r_j}^l - \zeta_{c_{it_j}}^l e^{-\zeta_{t_j r_j}^l \beta \sigma_j^2}, \quad (3.22)$$

$$\zeta_{c_{it_j}}^l = \frac{\beta p_{cu} \zeta_{t_j r_j}^l (1 - P_{dt,out}^{under})}{P_{dt,out}^{under} - 1 + e^{-\zeta_{t_j r_j}^l \beta \sigma_j^2}}, \quad (3.23)$$

$$\zeta_{c_{it_j}}^l = Z(\text{let}) \quad (3.24)$$

where Z is $\frac{\beta p_{cu} \zeta_{t_j r_j}^l (1 - P_{dt,out}^{under})}{P_{dt,out}^{under} - 1 + e^{-\zeta_{t_j r_j}^l \beta \sigma_j^2}}$. Substituting (3.24) in (3.1), we obtain θ_{ij} as,

$$\theta_{ij} = \cos^{-1} \frac{\zeta_{c_{iB}}^2 + \zeta_{t_{jB}}^2 - Z^{\frac{2}{l}}}{2\zeta_{c_{iB}}\zeta_{t_{jB}}}. \quad (3.25)$$

θ_{ij} is a very useful parameter. For fixed $\zeta_{c_{iB}}$, D2D outage probability decreases with increase in θ_{ij} , whereas cellular outage probability is independent of θ_{ij} . It helps the BS to select the CU_i which can facilitate DT_j – DR_j communication with minimal interference to each other.

Lemma 3.1 *Estimating the range of $\zeta_{c_{it_j}}$*

Since, $\cos(\theta_{ij})$ ranges from $[-1,1]$, hence (3.25) can be written as,

$$-1 \leq \frac{\zeta_{c_{iB}}^2 + \zeta_{t_{jB}}^2 - Z^{\frac{2}{l}}}{2\zeta_{c_{iB}}\zeta_{t_{jB}}} \leq 1 \quad (3.26)$$

$$\begin{aligned} -2\zeta_{c_{iB}}\zeta_{t_{jB}} &\leq \zeta_{c_{iB}}^2 + \zeta_{t_{jB}}^2 - Z^{\frac{2}{l}} \leq 2\zeta_{c_{iB}}\zeta_{t_{jB}} \\ |\zeta_{c_{iB}} - \zeta_{t_{jB}}| &\leq Z^{\frac{1}{l}} \leq |\zeta_{c_{iB}} + \zeta_{t_{jB}}|. \end{aligned} \quad (3.27)$$

From (3.24),

$$|\zeta_{c_{iB}} - \zeta_{t_{jB}}| \leq \zeta_{c_{it_j}} \leq |\zeta_{c_{iB}} + \zeta_{t_{jB}}|. \quad (3.28)$$

3.3.2 Rate and outage probability with overlay framework

3.3.2.1 Cellular rate and outage probability

In overlay framework, BS allocates a part of the cellular spectrum to the D2D user as long as QoS of the cellular user is not compromised. To determine whether a part of the cellular spectrum (or set of subcarriers) can be allocated to the D2D user, BS calculates R_N (maximum achievable data rate) of the cellular link by assuming that all subcarriers participated in CU_{*i*} to BS communication, and no subcarriers were allocated to the D2D user. If $R_N > R_{th}^c$, where R_{th}^c denotes target rate of the cellular system, then BS assigns few subcarriers (e.g., D) to the cellular user, which helps in maintaining the desired QoS with acceptable outage probability constraint. The remaining $N - D$ subcarriers are allocated for D2D communication.

Suppose signal $s_{c_i,k}$ is transmitted by CU_{*i*}, and received by BS. The received signal at BS over subcarrier k is denoted as ϕ_k^{BS} which is equal to,

$$\phi_k^{BS} = (p_{cu,k})^{\frac{1}{2}} \Psi_{c_i B,k} s_{c_i,k} + n_{B,k} ; 1 \leq k \leq N, 1 \leq i \leq M \quad (3.29)$$

BS first calculates R_N by assuming that CU_{*i*} is transmitting all N subcarriers to BS.

$$R_N = \sum_{k=1}^N \log_2 \left(1 + \frac{p_{cu,k} \gamma_{c_i B,k}}{\sigma_j^2} \right), \quad (3.30)$$

If $R_N > R_{th}^c$, CU_{*i*} will transmit D subcarriers to BS. The instantaneous rate with D subcarriers is given as,

$$R_{cu}^{over} = \sum_{k=1}^D \log_2 \left(1 + \frac{p_{cu,k} \gamma_{c_i B,k}}{\sigma_j^2} \right), \quad (3.31)$$

The target rate of uplink transmission is R_{th}^c and outage occurs if $R_{cu}^{over} < R_{th}^c$. From (3.5) and (3.31), the outage probability for the cellular transmission can be derived as,

$$P_{cu,out}^{over} = 1 - \exp \left(- \frac{\sigma_j^2 (2^{R_{th}^c/D} - 1) \zeta_{c_i B}^l}{p_{cu}} \right). \quad (3.32)$$

3.3.2.2 D2D rate and outage probability

Since for overlay framework subcarrier allocation for cellular and D2D users are orthogonal; hence there is no interference between the cellular and D2D user. Signal $s_{d_j,k}$ is transmitted by DT_j to DR_j. The received signal at DR_j over subcarrier k is denoted as ϕ_k^{DR} which is equal to,

$$\phi_k^{DR} = (p_{dt,k})^{\frac{1}{2}} \Psi_{t_j r_j, k} s_{d_j, k} + n_{r_j, k}; N - D \leq k \leq N, 1 \leq j \leq R, \quad (3.33)$$

where $p_{dt,k}$ denotes D2D signal power for k^{th} subcarrier. The instantaneous rate for $N - D$ subcarriers is given as,

$$R_{d2d}^{over} = \sum_{k=1}^{N-D} \log_2 \left(1 + \frac{p_{dt,k} \gamma_{t_j r_j, k}}{\sigma_j^2} \right). \quad (3.34)$$

The target rate of D2D transmission is R_{th}^d and outage occurs if $R_{d2d}^{over} < R_{th}^d$. From (3.5) and (3.34), the outage probability for D2D transmission can be defined as,

$$P_{d2d,out}^{over} = 1 - \exp \left(- \frac{\sigma_j^2 (2^{R_{th}^d / (N-D)} - 1) \zeta_{t_j r_j}^l}{p_{dt}} \right). \quad (3.35)$$

3.3.3 Rate and outage probability with C-D2D

3.3.3.1 Cellular rate and outage probability

In the C-D2D framework, DT_j acts as a DF relay between CU_i and BS to provide spatial diversity to the cellular user. In return, BS allows D2D user to access the cellular spectrum. The C-D2D communication is achieved by adopting the following two-phase transmission protocol [12]. In Phase I, CU_i broadcasts N subcarriers to BS which is overheard by DT_j. Signal received by DT_j is,

$$\phi_k^{DT_j, 1} = (p_{cu,k})^{\frac{1}{2}} \Psi_{c_i t_j, k} s_{c_i, k} + n_{t_j, k}; 1 \leq K \leq N, 1 \leq i \leq M, 1 \leq j \leq R. \quad (3.36)$$

The instantaneous rate at DT_j can be given as,

$$R_N^{cu-dt} = \frac{1}{2} \sum_{k=1}^N \log_2 \left(1 + \frac{p_{cu,k} \gamma_{c_i t_j, k}}{\sigma_j^2} \right). \quad (3.37)$$

From (3.5), (3.37) can be deduced to,

$$R_N^{cu-dt} = \frac{N}{2} \log_2 \left(1 + \frac{p_{cu} \gamma_{c_i t_j}}{\sigma_j^2} \right), \quad (3.38)$$

where the factor $\frac{1}{2}$ is due to the fact that the whole transmission is divided into two phases. DT_j attempts to decode the cellular data received from CU_i in Phase I. If the decoding is successful, DT_j allocates D subcarriers to cellular data while remaining $N - D$ subcarriers are allocated for DT_j to DR_j communication⁴. The instantaneous rate at BS after maximal ratio combining (MRC) of two phases transmission with a condition of successful decoding of cellular signal $s_{c_i,k}$ at DT_j is,

$$\begin{aligned} R_{cu}^{coop} &= \frac{1}{2} \sum_{k=1}^D \log_2 \left(1 + \frac{p_{cu,k} \gamma_{c_i B,k}}{\sigma_j^2} + \frac{p_{dt,k} \gamma_{t_j B,k}}{\sigma_j^2} \right) \\ &+ \frac{1}{2} \sum_{k=1}^{N-D} \log_2 \left(1 + \frac{p_{cu,k} \gamma_{c_i B,k}}{\sigma_j^2} \right). \end{aligned} \quad (3.39)$$

From (3.5), (3.39) can be rewritten as,

$$\begin{aligned} R_{cu}^{coop} &= \frac{D}{2} \log_2 \left(1 + \frac{p_{cu} \gamma_{c_i B}}{\sigma_j^2} + \frac{p_{dt} \gamma_{t_j B}}{\sigma_j^2} \right) \\ &+ \frac{N-D}{2} \log_2 \left(1 + \frac{p_{cu} \gamma_{c_i B}}{\sigma_j^2} \right). \end{aligned} \quad (3.40)$$

In a case of unsuccessful decoding at DT_j, there will be no transmission from DT_j to BS in Phase II. However, BS may still be able to receive the cellular signal from CU_i-BS link. Thus, the cellular outage probability with C-D2D is,

$$\begin{aligned} P_{cu,out}^{coop} &= \Pr(R_N^{cu-dt} > R_{th}^c) \Pr(R_{cu}^{coop} < R_{th}^c) \\ &+ \Pr(R_N^{cu-dt} < R_{th}^c) \Pr\left(\frac{1}{2} R_N < R_{th}^c\right), \end{aligned} \quad (3.41)$$

⁴It is obvious that $D \leq N$, for the cases where $D = N$, DT_j will be pure relay [32].

where R_N can be found from (3.30).

$$\Pr\left(\frac{1}{2}R_N < R_{th}^c\right) = \Pr\left(\gamma_{c_i B} < \frac{\rho_1 \sigma_j^2}{p_{cu}}\right) = 1 - e^{-\frac{\zeta_{c_i B}^l \sigma_j^2}{p_{cu}} \rho_1}. \quad (3.42)$$

$$\Pr(R_N^{cu-dt} < R_{th}^c) = \Pr\left(\gamma_{c_i t_j} < \frac{\rho_1 \sigma_j^2}{p_{cu}}\right) = 1 - e^{-\frac{\zeta_{c_i t_j}^l \sigma_j^2}{p_{cu}} \rho_1}, \quad (3.43)$$

where, $\gamma_{c_i B} \sim \exp(\zeta_{c_i B}^l)$, $\gamma_{c_i t_j} \sim \exp(\zeta_{c_i t_j}^l)$, and $\rho_1 = 2^{\frac{2R_{th}^c}{N}-1}$.

Similarly,

$$\Pr(R_N^{cu-dt} > R_{th}^c) = \Pr\left(\gamma_{c_i t_j} > \frac{\rho_1 \sigma_j^2}{p_{cu}}\right) = e^{-\frac{\zeta_{c_i t_j}^l \sigma_j^2}{p_{cu}} \rho_1}. \quad (3.44)$$

Further,

$$\begin{aligned} \Pr(R_{cu}^{coop} < R_{th}^c) = & \Pr\left(\left[1 + \frac{p_{cu} \gamma_{c_i B}}{\sigma_j^2} + \frac{p_{dt} \gamma_{t_j B}}{\sigma_j^2}\right]^D \right. \\ & \left. \left[1 + \frac{p_{cu} \gamma_{c_i B}}{\sigma_j^2}\right]^{N-D} < 2^{2R_{th}^c}\right). \end{aligned} \quad (3.45)$$

Let, $\sigma_j^2 = \sigma^2; \forall j$, and $\frac{p_{cu} \gamma_{c_i B}}{\sigma^2} + \frac{p_{dt} \gamma_{t_j B}}{\sigma^2} \gg \sigma^2$, we can rewrite (3.45) as,

$$\begin{aligned} & = \Pr\left((p_{cu} \gamma_{c_i B} + p_{dt} \gamma_{t_j B})^D (p_{cu} \gamma_{c_i B})^{N-D} < 2^{2R_{th}^c} \sigma^{2N}\right) \\ & = \Pr\left((p_{cu} \gamma_{c_i B} + p_{dt} \gamma_{t_j B}) < \frac{(2^{2R_{th}^c} \sigma^{2N})^{\frac{1}{D}}}{(p_{cu} \gamma_{c_i B})^{\frac{N-D}{D}}}\right) \\ & = \Pr\left(\gamma_{t_j B} < \frac{\Gamma^{\frac{1}{D}}}{p_{dt} (p_{cu} \gamma_{c_i B})^{\frac{N-D}{D}}} - \frac{p_{cu} \gamma_{c_i B}}{p_{dt}}\right), \end{aligned} \quad (3.46)$$

where, $\Gamma = 2^{2R_{th}^c} \sigma^{2N}$.

Let,

$$\frac{\Gamma^{\frac{1}{D}}}{p_{dt} (p_{cu} \gamma_{c_i B})^{\frac{N-D}{D}}} - \frac{p_{cu} \gamma_{c_i B}}{p_{dt}} = \beta(\gamma_{c_i B}), \quad (3.47)$$

where, $\gamma_{t_j B} \sim \exp(\zeta_{t_j B}^l)$.
 Since,

$$\beta(\gamma_{c_i B}) > 0, \quad (3.48)$$

$$\frac{\Gamma^{\frac{1}{D}}}{p_{dt} (p_{cu} \gamma_{c_i B})^{\frac{N-D}{D}}} - \frac{p_{cu} \gamma_{c_i B}}{p_{dt}} > 0. \quad (3.49)$$

Simplifying (3.49), we will get,

$$\gamma_{c_i B} < \frac{\Gamma^{\frac{1}{N}}}{p_{cu}} = \alpha \text{ (let)}. \quad (3.50)$$

As $\gamma_{c_i B}$ and $\gamma_{t_j B}$ are independent exponential random variable, it's joint probability density function is given as (3.9). Hence,

$$\begin{aligned} & \Pr(\gamma_{t_j B} < \beta(\gamma_{c_i B})) \\ &= \int_{\gamma_{c_i B}=0}^{\alpha} \int_{\gamma_{t_j B}=0}^{\beta(\gamma_{c_i B})} \zeta_{c_i B}^l e^{-\zeta_{c_i B}^l \gamma_{c_i B}} \zeta_{t_j B}^l e^{-\zeta_{t_j B}^l \gamma_{t_j B}} d\gamma_{c_i B} d\gamma_{t_j B} \\ &= \int_{\gamma_{c_i B}=0}^{\alpha} \zeta_{c_i B}^l e^{-\zeta_{c_i B}^l \gamma_{c_i B}} \left(1 - e^{-\zeta_{t_j B}^l \beta(\gamma_{c_i B})}\right) d\gamma_{c_i B} \\ &= 1 - e^{-\zeta_{c_i B}^l \alpha} - \zeta_{c_i B}^l \Upsilon_1, \end{aligned} \quad (3.51)$$

where,

$$\Upsilon_1 = \int_{\gamma_{c_i B}=0}^{\alpha} e^{\left(\vartheta_2 \gamma_{c_i B} - \frac{\vartheta_1}{\gamma_{c_i B}^{\frac{N}{D}-1}}\right)} d\gamma_{c_i B}, \quad (3.52)$$

$$\vartheta_1 = \frac{\zeta_{t_j B}^l \Gamma^{\frac{1}{D}}}{p_{dt} p_{cu}^{\frac{N}{D}-1}}, \quad \vartheta_2 = \frac{\zeta_{t_j B}^l p_{cu}}{p_{dt}} - \zeta_{c_i B}^l. \quad (3.53)$$

(3.52) is intractable, however, if we substitute, $\vartheta_2 = 0$ i.e. $\frac{\zeta_{c_i B}^l}{\zeta_{t_j B}^l} = \frac{p_{cu}}{p_{dt}}$, (3.52) can be reduced to,

$$\Upsilon_1 = \int_{\gamma_{c_i B}=0}^{\alpha} e^{-\vartheta_1 \gamma_{c_i B}^{-(\frac{N}{D}-1)}} d\gamma_{c_i B}. \quad (3.54)$$

Now, substitute $\gamma_{c_i B}^{-\frac{N-D}{D}} = t$. So (3.54) reduces to,

$$\Upsilon_1 = \frac{D}{N-D} \int_{\alpha^{-\frac{N-D}{D}}}^{\infty} t^{-\frac{N}{N-D}} e^{-\vartheta_1 t} dt. \quad (3.55)$$

From [95], (3.55) can be solved as,⁵

$$\Upsilon_1 = (-1)^{n+1} \vartheta_1^n \frac{Ei(-\vartheta_1 u)}{n!} + \frac{e^{-\vartheta_1 u}}{u^n} \quad (3.56)$$

where, $n = \frac{D}{N-D}$, $u = \alpha^{-\frac{N-D}{D}}$ and Ei stands for exponential integral.

Hence, from (3.42),(3.43),(3.44),(3.51), the outage probability for the C-D2D framework can be given as,

$$P_{cu,out}^{coop} = e^{-\frac{\zeta_{c_i t_j}^l \sigma^2}{p_{cu}} \rho_1} (1 - e^{-\zeta_{c_i B}^l \alpha} - \zeta_{c_i B}^l \Upsilon_1) + \left(1 - e^{-\frac{\zeta_{c_i t_j}^l \sigma^2}{p_{cu}} \rho_1}\right) \left(1 - e^{-\frac{\zeta_{c_i B}^l \sigma^2}{p_{cu}} \rho_1}\right). \quad (3.57)$$

3.3.3.2 D2D rate and outage probability

In Phase II, DR_j will receive $N - D$ subcarriers via $\Psi_{t_j r_j, k}$ link. Hence signal received by DR_j will be,

$$\phi_k^{DR,2} = (p_{dt,k})^{\frac{1}{2}} \Psi_{t_j r_j, k} s_{d_j, k} + n_{r_j, k}; 1 \leq K \leq N, 1 \leq j \leq R. \quad (3.58)$$

The instantaneous rate at DR_j is given as,

$$R_{d2d}^{coop} = \frac{1}{2} \sum_{k=1}^{N-D} \log_2 \left(1 + \frac{p_{dt,k} \gamma_{t_j r_j, k}}{\sigma_j^2} \right). \quad (3.59)$$

If the target rate for D2D communication is R_{th}^d , then the outage will occur when $\Pr(R_{d2d}^{coop} < R_{th}^d)$. From (3.5) and (3.59),

$$\Pr(R_{d2d}^{coop} < R_{th}^d) = \Pr \left(\gamma_{t_j r_j} < \frac{\rho_2 \sigma^2}{p_{dt}} \right) = 1 - e^{-\frac{\zeta_{t_j r_j}^l \sigma^2}{p_{dt}} \rho_2}, \quad (3.60)$$

⁵In this chapter, we have solved (3.52) numerically to obtain the analytical plots.

where $\gamma_{t_j r_j} \sim \exp\left(\zeta_{t_j r_j}^l\right)$ and $\rho_2 = 2^{\frac{2R_{th}^d}{(N-D)}} - 1$.

3.4 Simulation Results and Discussion

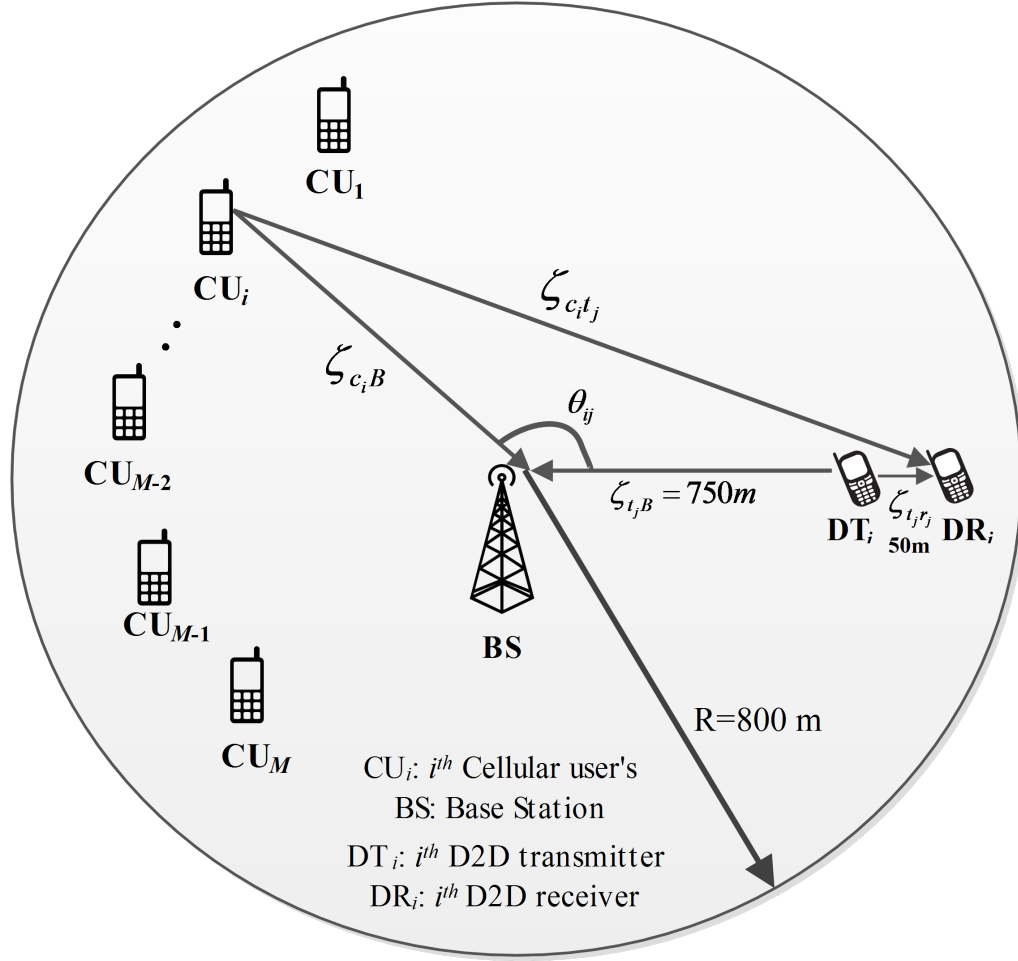


Figure 3.4. Simulation model

Table 3.1. Simulation parameters

N	32 subcarriers
R_{th}^c	1 b/s/Hz
R_{th}^d	1 b/s/Hz
σ^2	-120dbm
l	4 (urban area)
$\zeta_{t_j B}$	750m
$\zeta_{t_j r_j}$	50m

In this section, we have plotted the simulation results for the outage probability of cellular and D2D user for the three frameworks. Further, in order to verify the analytical derivations, simulation results have also been compared with theoretical results. Fig. 3.4 depicts the simulation model. As discussed before, the simulation model consists of a circular microcell of radius $\mathcal{R} = 800\text{m}$, where BS is located at the center of the cell. A D2D user⁶ lie at the cell boundary, and the distance between $\text{DT}_j\text{--DR}_j$ is assumed to be 50 meters *i.e.* $\zeta_{t_j r_j} = 50\text{m}$. Distance between BS and a D2D user is set to 750 meters *i.e.* $\zeta_{t_j B} = 750\text{m}$. The parameters used for simulation are listed in Table 3.1. We have chosen target rate for both cellular and D2D link as $R_{th}^c = R_{th}^d = 1 \text{ b/s/Hz}$, $N = 32$ is the total number of subcarriers preassigned by BS to CU_i .

⁶For simulation, a D2D pair is considered which can map to an optimal CU_i for subcarrier sharing by BS. However, the analysis presented in the chapter is applicable for multiple D2D pairs as each CU_i has its individual N allocated subcarrier for uplink transmission.

Table 3.2. Upper limit of ζ_{c_iB} which satisfies the outage probability constraint of a cellular user for underlay framework

Fixed p_{cu} to calculate max ζ_{c_iB}				
p_{cu} (in Watts)	$P_{cu,out}^{under} = 10^{-1}$	$P_{cu,out}^{under} = 10^{-2}$	$P_{cu,out}^{under} = 10^{-3}$	$P_{cu,out}^{under} = 10^{-4}$
0.1	<i>All values</i>	701.57	393.74	221.41
0.01	714.75	394.52	221.46	124.51
0.001	401.93	221.85	124.53	70.02

Table 3.2 shows the upper limit (maximum value) of ζ_{c_iB} (distance between CU_i and BS) for fixed p_{cu} for the underlay framework, below which the given outage probability constraint of a cellular user is always satisfied. It can also be seen from Table 3.2, that for a particular p_{cu} , ζ_{c_iB} decreases with cellular outage constraint. Essentially, when $p_{cu} = 0.1W$, to satisfy $P_{cu,out}^{under} = 10^{-2}$, $\zeta_{c_iB} \leq 701.57m$.

Table 3.3. Lower limit of θ_{ij} which satisfies the Outage Probability constraint of a D2D User for a fixed ζ_{c_iB} and $p_{cu} = 0.1W$ for underlay framework.

Fixed ζ_{c_iB} and $p_{cu} = 0.1$ to calculate min θ_{ij}				
ζ_{c_iB} (in meters)	$P_{dt,out}^{under} = 10^{-1}$	$P_{dt,out}^{under} = 10^{-2}$	$P_{dt,out}^{under} = 10^{-3}$	$P_{dt,out}^{under} = 10^{-4}$
750	21°	39°	73°	<i>Nil</i>
600	19°	41°	81°	<i>Nil</i>
300	<i>All values</i>	26°	108°	<i>Nil</i>
200	<i>All values</i>	<i>All values</i>	129°	<i>Nil</i>

Table 3.3 gives the minimum value of angle θ_{ij} (in degrees) which satisfies the given outage probability constraint of cellular and D2D user for fixed value of ζ_{c_iB} . For instance, when $p_{cu} = 0.1$ and $\zeta_{c_iB} = 600$, $\theta_{ij} \geq 41^\circ$ is required to satisfy the D2D outage constraint⁷ of 10^{-2} . Hence, from Table 3.2 and 3.3, BS

⁷ $\zeta_{c_iB} = 600$ satisfies the cellular outage constraint of 10^{-2} , (see Table 3.2)

can select an optimal cellular user for underlaying D2D communication to satisfy the outage constraints for both cellular as well as D2D users. Maximum value (optimal) of θ_{ij} is 180° i.e. when $\theta_{ij} = 180^\circ$, D2D system attains minimum outage probability. In Table 3.3, *Nil* signifies that D2D outage constraint will not be satisfied irrespective of the value of θ_{ij} , whereas, *All values* states that D2D outage constraint will always be satisfied irrespective of value of θ_{ij} .

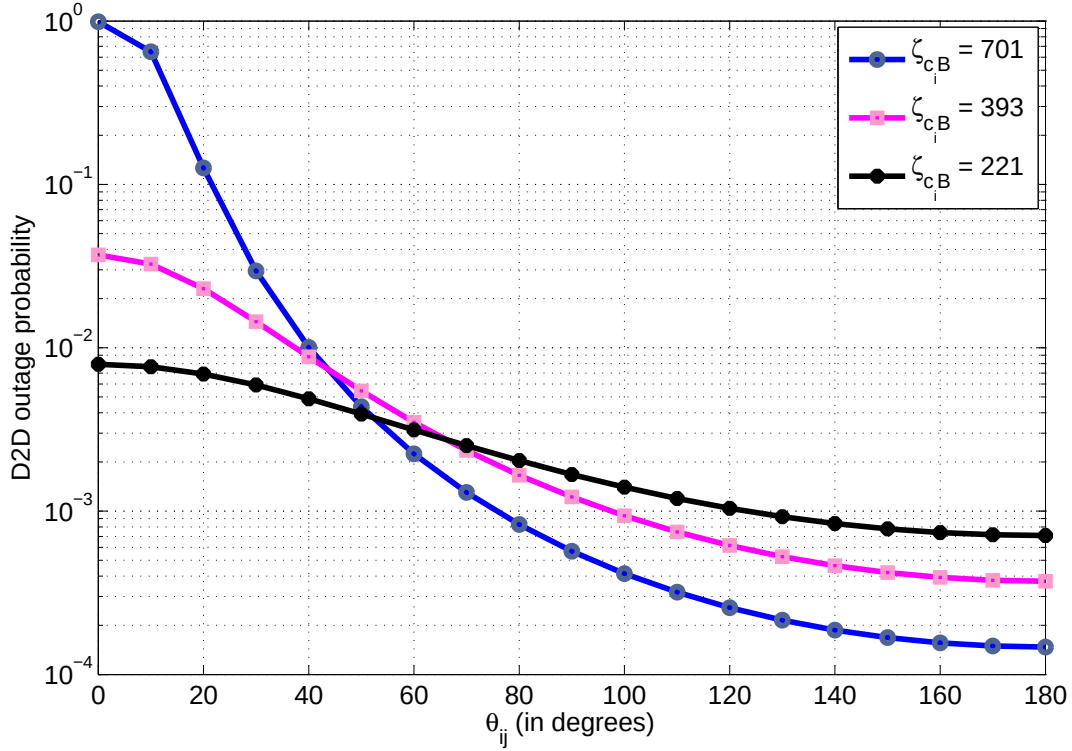


Figure 3.5. D2D outage probability vs angle θ_{ij} for underlay framework

Fig. 3.5 shows D2D outage probability with respect to θ_{ij} (in degrees) for three distances $\zeta_{cB} = 701, 393, 221$ meters for underlay framework. These distances satisfy the cellular outage constraint of $10^{-2}, 10^{-3}, 10^{-4}$ respectively, when $p_{cu} = 100$ mW (as seen from Table 3.2). D2D subcarrier power p_{dt} has been set to 1 mW. D2D outage probability decreases with increase in θ_{ij} . This is quite obvious that for fixed ζ_{cB} , as θ_{ij} increases, $\zeta_{c_{it_j}}$ also increases, thus CU_i moves away from DT_j causing less interference at DT_j , consequently D2D outage probability decreases. For $\zeta_{cB} = 701$, if θ_{ij} ranges from 0 to 50° , the cellular user will be close to DT_j – DR_j pair, thus outage probability is comparatively high. If θ_{ij} approaches

180° , $\zeta_{c_{itj}}$ becomes large, consequently, CU_i will cause less interference to D2D user, thus resulting in low outage probability. On the contrary, for $\zeta_{c_{iB}} = 221$, for low range of θ_{ij} , D2D outage probability is comparatively low. If θ_{ij} varies from 50° to 180° , D2D outage probability is higher as compare to other distances.

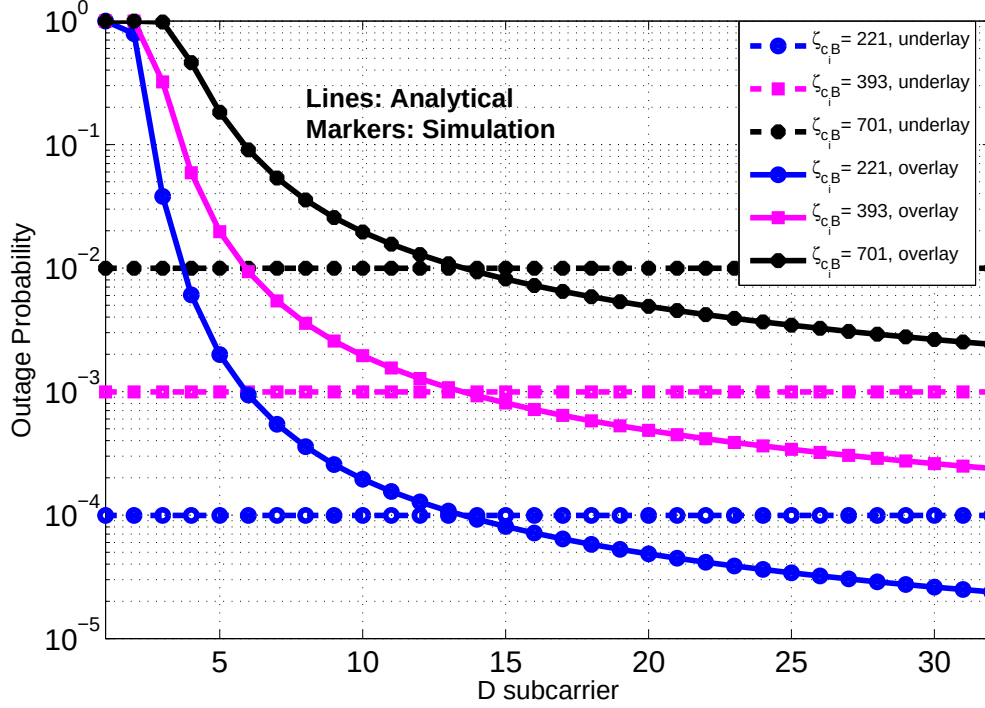


Figure 3.6. Cellular outage probability for underlay and overlay frameworks

Fig. 3.6 shows the theoretical and simulation results of the outage probability of the cellular user for overlay and underlay frameworks. For overlay framework, D orthogonal subcarriers are used for cellular communication, whereas for underlay framework, all N subcarriers are used for cellular communication. Results have been plotted for different CU_i –BS distances, i.e. $\zeta_{c_{iB}} = 221$ m, 393 m and 701 m, and $p_{cu} = 100$ mW, $p_{dt} = 1$ mW (for underlay) and $\theta_{ij} = 180^\circ$ (best case for underlay). Overlay outage probability is independent on θ_{ij} . For overlay framework, when number of subcarriers are allocated for CU_i to BS transmission, outage probability decreases, whereas, for underlay framework, outage probability is independent of D . For $\zeta_{c_{iB}} = 221$ m, cellular outage probability for underlay framework is 10^{-4} , whereas, to achieve same outage probability via overlay framework, BS

needs to allocate $D \geq 14$ subcarriers for cellular communication. However, remaining $N - D$ i.e. 18 subcarriers can be used for D2D communication. Similar observations can be made for other two distances $\zeta_{c_iB} = 393$, $\zeta_{c_iB} = 701$.

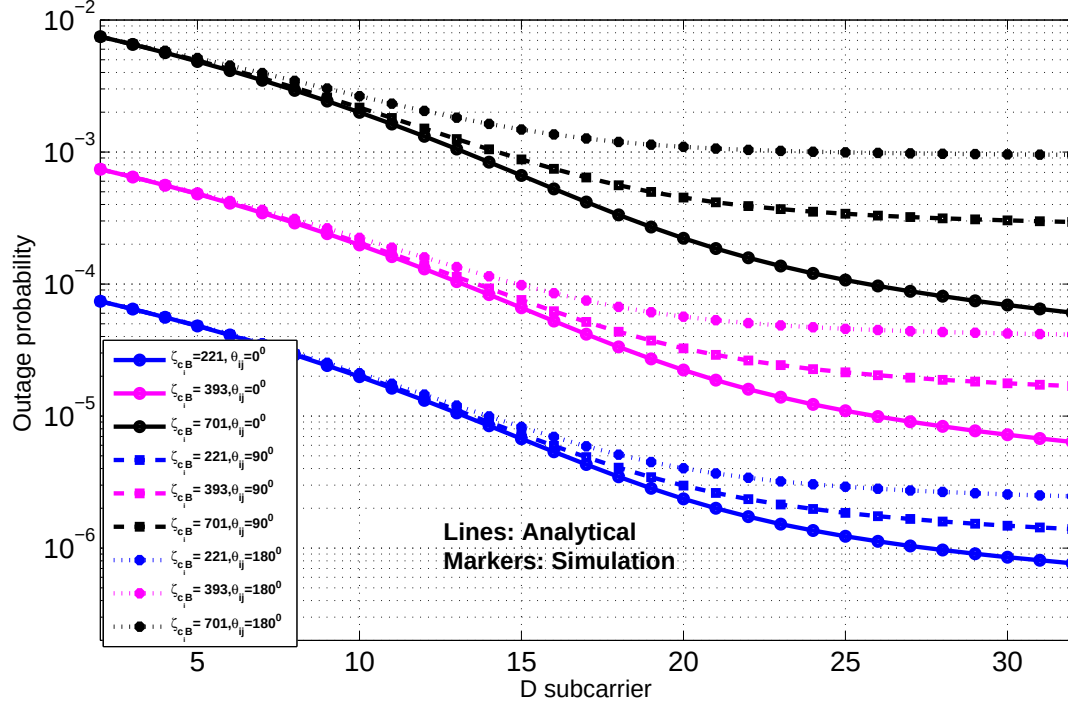


Figure 3.7. Cellular outage probability for C-D2D framework

Fig. 3.7 shows the outage probability of CU_i -BS link vs number of subcarriers allocated by DT_j under C-D2D framework. Subcarrier power has been set to $p_{cu} = 100\text{mW}$. Outage probability has been plotted for three distances, $\zeta_{c_iB} = 221\text{m}$, 393m and 701m for different θ_{ij} (0° , 90° , 180°). Outage probability increases with increase in ζ_{c_iB} , and decreases with decrease in θ_{ij} . From Fig. 3.7, it can be observed that as D increases, outage probability decreases. It is evident as with the increase in D , rate at BS with MRC increases, consequently outage probability decrease. For $\zeta_{c_iB} = 221$, if DT_j forwards only 2 subcarriers to BS, the outage probability achieved is less than 10^{-4} . Hence, remaining $N - D = 30$ subcarriers are available for D2D communication. If we compare Fig. 3.6 and Fig. 3.7, it is also evident that C-D2D framework outperforms underlay and overlay frameworks.

Another observation that can be made from Fig. 3.7 is for $\zeta_{c_iB} = 221$, outage probability is almost constant from $D = 1$ to $D = 13$. This can be explained

as follows. For a low value of D , the outage probability with C-D2D mainly depends on direct CU_i -BS transmission rather than relayed transmission. As direct CU_i -BS distance is fixed to $\zeta_{c_iB} = 221$, therefore changes in θ_{ij} has low impact on outage probability. However, for higher values of D , more subcarriers are relayed by DT_j to BS, whose impact largely reduces the outage probability. Further, as θ_{ij} increases, successful decoding of subcarriers at DT_j becomes the limiting factor, consequently, outage probability increases.

For, $\zeta_{c_iB} = 701$, $\theta_{ij} = 180$, and $D \geq 20$, outage probability decreases slowly and is almost stagnant. It is due to the fact that at this distance ζ_{c_iB} is quite large, so again successful decoding of subcarriers at DT_j becomes the bottleneck for outage probability.

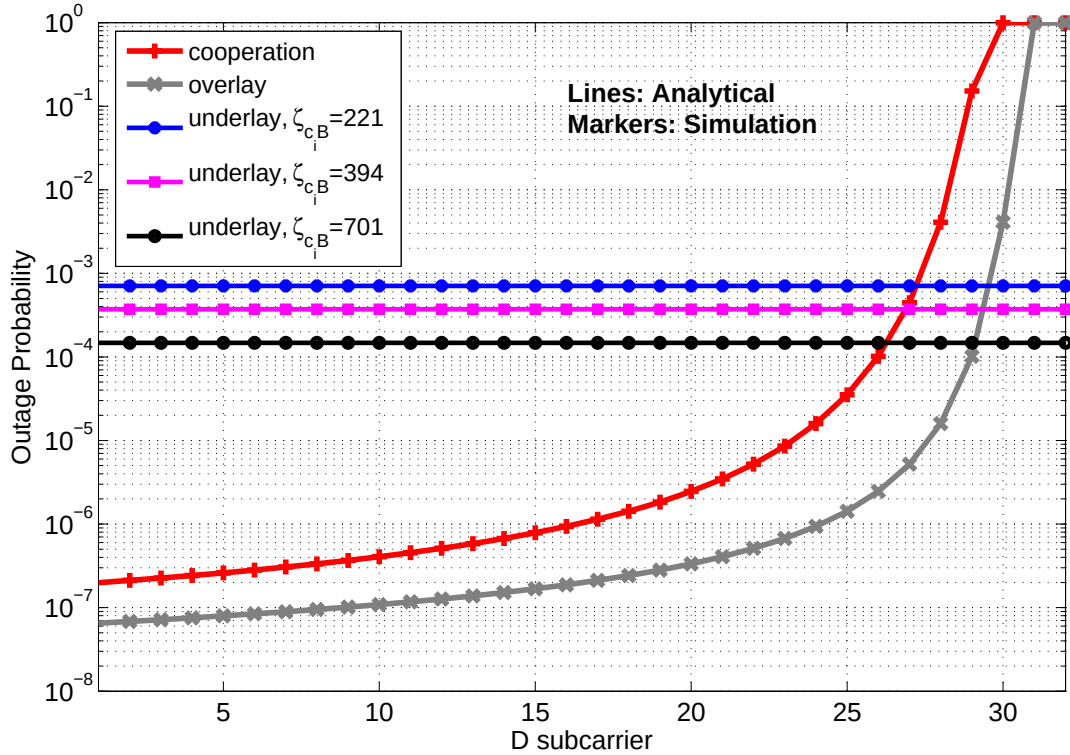


Figure 3.8. D2D outage probability vs subcarriers

Fig. 3.8 shows the outage probability of D2D user for the three frameworks. For overlay and C-D2D frameworks, $N - D$ orthogonal subcarriers can be used for D2D communication, whereas for underlay framework, all N subcarriers can be used for D2D communication. θ_{ij} has been set to its optimal value, i.e. $\theta_{ij} = 180^\circ$. From

Table 3.4. D2D outage probability corresponding to cellular outage probability constraint

Cellular outage constraint	10^{-2}	10^{-3}	10^{-4}	10^{-5}
Underlay	Satisfied	Satisfied	NS	NS
Overlay ($N - D$)	24	18	NS	NS
C-D2D ($N - D$)	31	30	18	6
D2D Outage (underlay)	0.37×10^{-3}	0.37×10^{-3}	1	1
D2D outage (overlay)	0.94×10^{-7}	0.15×10^{-6}	1	1
D2D outage (C-D2D)	0.19×10^{-6}	0.21×10^{-6}	0.67×10^{-6}	10^{-4}

Fig. 3.8, it can be seen that, for overlay and C-D2D frameworks, as D increases, outage probability increases, whereas underlay framework is independent of D . For underlay framework, as ζ_{c_iB} increases, D2D outage probability decreases as interference generated by CU_i to DR_j decreases.

Let us assume a scenario in which cellular system would like to maintain an acceptable QoS by putting a constraint on outage probability, i.e. $P_{cu,out} \leq 10^{-4}$. For underlay framework, as observed in Fig. 3.6, this cellular outage probability constraint will be satisfied when $\zeta_{c_iB} = 221$ and $\theta_{ij} = 180^\circ$. Further, it can be seen from Fig. 3.8 that D2D user can obtain an outage probability of $\approx 10^{-3}$. With overlay and C-D2D framework, $D \geq 14$ and $D \geq 1$ subcarriers are required respectively to satisfy the cellular outage probability constraint. The D2D outage probability for $D = 14$ (overlay) and $D = 1$ (C-D2D) is 1.51×10^{-7} and 1.98×10^{-7} respectively. Hence, overlay and C-D2D frameworks achieve a significantly lower outage probability for the D2D user as compared to underlay framework.

When $\zeta_{c_iB} = 394$, overlay framework can never satisfy the cellular outage constraint i.e. $P_{cu,out} \leq 10^{-4}$, even if they use all N subcarriers for cellular. A similar observation can be made for underlay framework. However, with C-D2D, only $D \geq 14$ subcarriers are required to achieve the cellular outage constraint. Thus, remaining $N - D$ subcarriers in the C-D2D framework can be used for D2D communication. Similar pattern appears when $\zeta_{c_iB} = 701$. Hence, from above it is evident that, for high cellular outage constraint and large CU_i –BS distance, C-D2D framework completely outperforms the other two frameworks.

Table 3.4 compares the D2D outage probability corresponding to the cellular

outage probability constraint for underlay, overlay, and C-D2D frameworks. From Table 3.4, we can observe that,

- For underlay framework, we can achieve the D2D outage probability = 0.37×10^{-3} while satisfying the low cellular outage probability constraint (i.e. $P_{cu,out} \geq 10^{-3}$). However, we can not satisfy the high cellular outage probability constraint (i.e. $P_{cu,out} \leq 10^{-4}$). Hence, D2D outage probability will be 1 for such cases.
- For overlay and C-D2D frameworks, $N - D$ denotes the number of subcarriers available for D2D communication while satisfying the prescribed cellular outage probability constraint. For instance, for cellular outage constraint = 10^{-3} , the number of subcarriers available for D2D communication with overlay framework is 18, whereas with C-D2D framework is 30.
- For low cellular outage constraint (i.e. $P_{cu,out} \geq 10^{-3}$), D2D overlay outage probability is slightly less than the C-D2D outage probability. In this case, the overlay framework performs better than the other two frameworks.
- For high cellular outage constraint (i.e. $P_{cu,out} \leq 10^{-4}$), the C-D2D framework completely outperforms the underlay and overlay frameworks. For both frameworks, we can not achieve $P_{cu,out} \leq 10^{-4}$, even if cellular user transmits all N subcarriers to BS.

3.5 Conclusion

This chapter investigated the OFDMA based underlay, overlay, and C-D2D communication frameworks in cellular networks. By utilizing one of the above frameworks, a D2D user can share the spectrum of the cellular user. The three frameworks were evaluated by deriving the closed form expressions of the outage probability for the cellular and D2D users. The impact of distance between the BS and cellular users, as well as between the cellular and D2D users was also analyzed on the basis of outage performance of the cellular and D2D users. Results interpret that for high cellular outage constraint, the C-D2D framework outperforms the underlay and overlay D2D frameworks.

Best D2D User Selection for C-D2D Framework

4.1 Introduction

In chapter 3, we showed that for high cellular outage probability constraint, C-D2D framework outperforms the other two D2D frameworks. To further augment the development of C-D2D communication for cellular networks, in this chapter, we propose the best D2D UE selection scheme for an OFDMA based C-D2D framework. In the proposed framework, multiple D2D UE pairs coexist with a cellular user. Further, a subcarrier sharing scheme is also proposed to facilitate D2D communication between cellular and D2D users. The system architecture consists of a BS which is deployed at the center of a circular cell. The UEs can be segregated into two types: cellular UEs and D2D UEs. OFDMA has been used as an access technology through which allocated spectrum is divided into a number of orthogonal subcarriers with equal subchannel bandwidth. It is assumed that BS supports operator-controlled D2D communication [92], wherein apart from the cellular links between mobile users and BS, there exist multiple D2D UEs which would like to communicate directly via D2D link [20].

In the present context, cellular UE is denoted as cellular user (CU), D2D UEs are denoted as D2D transmitter (DT) and D2D receiver (DR) respectively. DT-DR exists as a D2D pair. Further, it is assumed that each cell consists of L cellular

users and each cellular link has been assigned N number of subcarriers for its uplink transmission. On a specified time-frequency resource block, one cellular link and M D2D links are active. In line with conventional in-band D2D framework, CU and M D2D pairs share the same spectrum allocated to a CU by BS. It is worth mentioning that BS is still responsible for peer discovery, link establishment and subcarrier allocation to D2D user over D2D link [74].

In a conventional C-D2D framework, the uplink transmission is divided into two orthogonal time phases. In Phase I, CU broadcasts N allotted subcarriers to BS, which is also overheard by M DTs. Here we define the decoding set $\{S\}$ as a set of DTs which are able to decode the subcarriers successfully received in Phase I. From set $\{S\}$, the best DT is selected based on the received SNR at BS. BS notifies the CU and other DTs regarding the selected DT UE, denoted as DT_i^s . DT_i^s acts as a DF relay for cellular uplink transmission. In Phase II, DT_i^s forwards D subcarriers to BS for uplink transmission. The number of subcarriers D to be allocated for DT to BS transmission is decided based on the QoS requirement of CU. The remaining $N - D$ subcarriers are equally distributed among M DTs for D2D communication. In particular, each DT will be assigned $\lfloor \frac{N-D}{M} \rfloor$ subcarriers for D2D communication in a round-robin (RR) process¹, and remaining $[(N - D) \bmod M]$ subcarriers will be shared among DTs as per priority cube method explained in later part of the chapter². Hence, M D2D users can do D2D communication by utilizing the spectrum of single CU while satisfying the target QoS of CU. However, please note that for a fixed D2D outage probability, there will be a trade-off in cellular outage probability performance and the number of D2D users that can be supported by a CU.

The major contributions of the proposed work is summarized as follows:

- A best D2D UE selection scheme for an OFDMA based cooperative D2D framework is proposed. The performance of the proposed scheme has been analyzed by deriving the closed-form expression for outage probability for two cases:

– **CU-DT-BS link**, applicable when no direct cellular uplink communi-

¹Round-robin process is adopted so that all the DTs get a fair chance of transmission to their respective DRs.

²Here *mod* denotes modulo operator.

cation is possible.

- **CU-DT-BS with cellular link**, applicable when direct cellular link is available along with CU-DT-BS link. In this case, BS applies maximal ratio combining (MRC) to combine the signal received in two phases.
- A subcarrier sharing scheme is proposed that facilitates M D2D UEs to do D2D communication by sharing the spectrum of the single CU while satisfying the target QoS of the CU. As shown later, this leads to considerable performance improvement for both CU and D2D UEs. Multiple DTs provide full diversity gain to CU due to the participation of best DT only.
- For fair distribution of $N - D$ subcarriers among M DTs, a novel round robin process with priority cube method is proposed. The proposed method helps the BS in fair allocation of resources to all DTs for D2D communication.
- For a given distance and transmit power, the maximum value of M is derived which satisfies the target rate and outage probability constraint of the D2D users. This closed-form expression can be utilized by BS to map the optimal number of DT-DR pair with each CU while satisfying the QoS of CU and D2D users.
- The proposed work also analyzes the trade-off between the cellular outage probability constraint and the maximum number of D2D pairs that can be supported. It has been shown that as M increases, cellular outage probability decreases whereas D2D outage probability increases.

The rest of the chapter is organized as follows: Section 4.2 discusses the system model and provides the protocol description. Selection procedure for best DT UE and priority cube method for subcarrier sharing are also proposed in Section 4.2. Section 4.3 and 4.4 present the derivations and expressions of the rate and the outage probability for cellular and D2D links respectively. The derivation for optimal M is also provided in Section 4.4. Simulation results are provided in Section 4.5, and finally, conclusions follow in section 4.6.

4.2 System Model and Protocol Description

The system model for the proposed framework is shown in Fig. 4.1. We consider a cellular system consisting of a circular cell with radius R . The cell has a BS located at the center. Multiple CUs and DT-DR pairs exist within a cell. On a specified time-frequency resource block, a CU and M D2D (or DT-DR) pairs are active as shown in Fig. 4.1. The channels over the nodes are modelled as Rayleigh block fading with $\Psi_{j,k} \sim \mathcal{CN}(0, \zeta_j^{-l})$; $j = 1, 2, 3, 4$ where ζ is the distance between transmitter and receiver and l is path loss exponent. The channel coefficient corresponding to CU-BS is $\Psi_{1,k}$ over subcarrier k ($1 \leq k \leq N$). Similarly channel coefficient between CU-DT $_i$, DT $_i$ -BS and DT $_i$ -DR $_i$ is denoted by $\Psi_{2i,k}$, $\Psi_{3i,k}$ and $\Psi_{4i,k}$ respectively, $\forall i = 1, 2..M$. The instantaneous channel gain for each subcarrier is denoted as $\gamma_{xy,k} = |\Psi_{xy,k}|^2$. The additive white Gaussian noise (AWGN) at each receiver BS, DT $_i$ and DR $_i$ is denoted as $n_{1,k}, n_{2i,k}, n_{4i,k} \sim \mathcal{CN}(0, \sigma_j^2)$. The cellular and D2D user's signals transmitted on k^{th} subcarrier are denoted as $s_{cu,k}$ and $s_{dt_i,k}$ respectively with zero mean and $E\{s_{cu,k}^* s_{cu,k}\} = E\{s_{dt_i,k}^* s_{dt_i,k}\} = 1$.

The protocol description for the proposed scheme is summarized in Algorithm 4.2. In the algorithm, P_{out}^{ac} denotes the acceptable cellular outage probability constraint, R_{2i} and R_{3i} denote the achievable rate of CU-DT $_i$ and DT $_i$ -BS links respectively whereas, R_T denotes the target rate of the cellular user. Since all the CU UEs and DT UEs are part of the same cell, it is assumed that they follow the same physical layer architecture [96]. Timing and frequency synchronization is initiated by primary synchronization signal (PSS) and secondary synchronization signal (SSS) as specified in LTE Release-12. BS facilitates D2D discovery and maps M DT-DR pair to each CU to share the cellular spectrum based on proximity [97], [98]. BS broadcasts PSS and SSS signals for frequency and time synchronization, which also indicates the cell identity, mode of transmission (duplex etc.), and information about discovered D2D UEs. After receiving PSS/SSS, each CU transmits an acknowledgement message with R_T and P_{out}^{ac} to BS. BS estimates the channel gain and achievable rate of CU-DT $_i$, DT $_i$ -BS and DT $_i$ -DR $_i$ links. It creates a set $\mathcal{S} = \{i | i = 1, .., M, R_{2i} > R_T\}$, of DT $_i$ which can successfully decode the cellular signal. Within $\mathcal{S}$, DT $_i^s$ which achieves the maximum SNR at BS is selected as a best D2D UE to relay cellular data to BS. BS notifies CU and DTs about

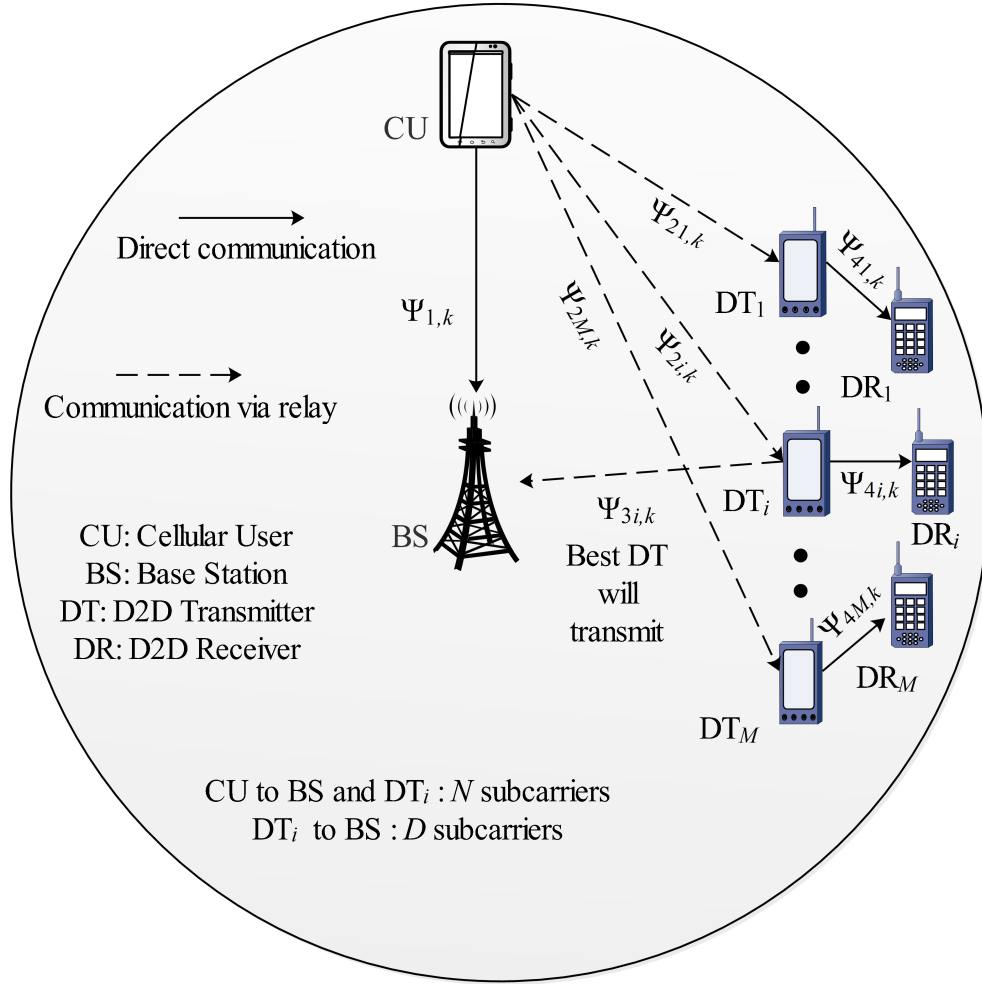


Figure 4.1. System Model with Multiple DTs and Multiple DRs

the selected DT_i^s through UE relay confirmation message (URCM). After listening URCM, two phase transmission takes place where the selected DT_i^s serves as a relay.

For fair distribution of $N - D$ subcarriers among M DTs, we propose a round robin process with priority cube method. The proposed method has been summarized in Algorithm 4.3. S_{dt_i} denotes the number of subcarriers belonging to D2D user DT_i , where $1 \leq i \leq M$. S_{dt_j} denotes the number of subcarriers belonging to user DT_j , where j denotes the pointer to DT. Initially, $\lfloor \frac{N-D}{M} \rfloor \times M$ subcarriers are equally distributed among all DTs. The remaining $(N - D) \bmod M$ subcarriers are distributed to DTs as per the indication, given by the pointer j . For next

Algorithm 4.2 Selection Procedure of Best DT UE

Step 1. BS broadcasts PSS and SSS.

Step 2. CU transmits a confirmation message with R_T and P_{out}^{ac} .

Step 3. BS estimates channel gain and achievable rate of CU-DT_{*i*}, DT_{*i*}-BS and DT_{*i*}-DR_{*i*} links.

Step 4. Create an empty set $\mathcal{S}$.

```

for  $i = 1 : 1 : M$  do
  if  $R_{2i} > R_T$  then
    Add DTi to  $\mathcal{S}$ .
  end if

```

```

end for

```

```

if set  $\mathcal{S} = \emptyset$  then

```

```

   $flag = 1$ 

```

```

else

```

DT_{*i*}^s which achieves maximum SNR at BS is selected as a relay DT UE. BS also estimates the number of subcarriers, D for which the outage probability P_{out}^{ac} satisfied.

```

  for  $k = 1 : 1 : N$  do

```

```

    if  $\Pr(R_{3i} > R_T) == P_{out}^{ac}$  then

```

```

       $D = k$ 

```

```

      break

```

```

    end if

```

```

  end for

```

```

  end if

```

Step 5. BS sends URCM to CU and DTs.

transmission, the pointer is shifted to $j + 1$.

To illustrate, let us suppose during the first transmission, $N = 32$, $D = 15$, and $M = 5$. Hence, $N - D = 17$ subcarriers are available for distribution among 5 DTs. If the pointer is set to $j = 1$ i.e. DT₁, each DT_{*i*} will get 3 subcarriers for D2D communication, and remaining $(N - D) \bmod M = 2$ subcarriers will be shared by DT₁ and DT₂, since the pointer j showed DT₁. For the next transmission, the pointer will be set to $j = 3$. Hence, during next transmission, distribution of $(N - D) \bmod M$ subcarriers will start from DT₃.

Algorithm 4.3 Round robin process with priority cube for subcarriers sharing between DTs

Create a set $\mathcal{S}_\uparrow = \lfloor \frac{N-D}{M} \rfloor * M$
 Create another set $\mathcal{S}_\downarrow = (N - D) \bmod M$
 $\text{DT}_i; 1 \leq i \leq M$
 S_{dt_i} denotes number of subcarriers belonging to user DT_i
 Set a pointer $j = 1$
 while $\mathcal{S}_\uparrow$ is non-empty **do**
 $S_{dt_i} = S_{dt_i} + 1; \forall i$
 end while
 while $\mathcal{S}_\downarrow$ is non-empty **do**
 $S_{dt_j} = S_{dt_j} + 1$
 $j = (j \bmod M) + 1$
 end while

4.3 Cellular Rate and Outage Probability

In this section, closed-form expressions for the rate and outage probability of the cellular user for two cases i.e CU-DT-BS link and CU-DT-BS with cellular link are derived.

4.3.1 CU-DT-BS link

Signal $s_{cu,k}$ is transmitted by CU, and is received by DTs via $\Psi_{2i,k}$ link. The signal received at DT_i over subcarrier k is denoted as $\xi_k^{DT_i}$ and is given by,

$$\xi_k^{DT_i} = (p_{cu,k})^{\frac{1}{2}} \Psi_{2i,k} s_{cu,k} + n_{2i,k}, 1 \leq k \leq N, \forall i, \quad (4.1)$$

where $p_{cu,k}$ denotes cellular signal power over k^{th} subcarrier. The instantaneous rate of the signal received at DT_i with N subcarriers is given as,

$$R_{2i}^{CU-DT_i} = \frac{1}{2} \sum_{k=1}^N \log_2 \left(1 + \frac{\gamma_{2i,k} p_{cu,k}}{\sigma^2} \right), \quad (4.2)$$

where $\frac{1}{2}$ is due to two phases transmission.

In Phase II, out of total N subcarriers received from CU, DT_i^s (selected DT UE) will decode and forward only D subcarriers to BS. The instantaneous rate at

BS after two phase transmission is given as,

$$R_{BS}^{c-d2d} = \frac{1}{2} \sum_{k=1}^D \log_2 \left(1 + \max_{i=1,2,\dots,M} \frac{\gamma_{3i,k} p_{dt,k}}{\sigma^2} \right), \quad (4.3)$$

where $p_{dt,k}$ is the subcarrier power belonging to DT_i .

If R_T denotes the target rate of transmission, then the probability that no DT_i is able to decode the cellular signal is given by,

$$\begin{aligned} P_1 &= \Pr(R_{21}^{CU-DT_1} < R_T) \Pr(R_{22}^{CU-DT_2} < R_T) \dots \\ &\quad \Pr(R_{2M}^{CU-DT_M} < R_T) \\ &= \prod_{i=1}^M \Pr(R_{2i}^{CU-DT_i} < R_T). \end{aligned} \quad (4.4)$$

Without loss of generality, it is assumed that the power and channel gain are uniformly distributed across all the subcarriers [34],

$$p_{cu,k} = p_{cu}, \forall k; p_{dt,k} = p_{dt}, \forall k; \gamma_{xy,k} = \gamma_{xy}, \forall k. \quad (4.5)$$

From (4.2) and (4.5),

$$\Pr(R_{2i}^{CU-DT_i} < R_T) = \Pr\left(\gamma_{2i} < \frac{\rho_1 \sigma^2}{p_{cu}}\right) = 1 - e^{\frac{-\zeta_{2i}^l \sigma^2}{p_{cu}} \rho_1} \quad (4.6)$$

where, ζ_{2i} denotes distance between CU and DT_i . Substituting (4.6) into (4.4), we get

$$P_1 = \prod_{i=1}^M \left(1 - e^{\frac{-\zeta_{2i}^l \sigma^2}{p_{cu}} \rho_1} \right). \quad (4.7)$$

Probability that at least one DT_i is able to decode the cellular signal is given as,

$$P_1' = 1 - P_1 \quad (4.8)$$

Substituting (4.7) into (4.8), we get

$$P'_1 = 1 - \prod_{i=1}^M \left(1 - e^{-\frac{\zeta_{2i}^l \sigma^2}{p_{cu}} \rho_1} \right) \quad (4.9)$$

Thus, the outage probability for CU-DT-BS link can be given as,

$$P_{BS,out} = P'_1 \Pr(R_{BS}^{c-d2d} < R_T) + P_1. \quad (4.10)$$

Further, from (4.3) and (4.5),

$$\begin{aligned} \Pr(R_{BS}^{c-d2d} < R_T) &= \Pr \left(\max_{i=1,\dots,M} \gamma_{3i} < \frac{(2^{2R_T/D} - 1)\sigma^2}{p_{dt}} \right) \\ &= \prod_{i=1}^M \Pr \left(\gamma_{3i} < \frac{\rho_2 \sigma^2}{p_{dt}} \right) \\ &= \prod_{i=1}^M \left(1 - e^{-\frac{\zeta_{3i}^l \sigma^2}{p_{dt}} \rho_2} \right), \end{aligned} \quad (4.11)$$

where $\rho_1 = (2^{2R_T/N} - 1)$, $\rho_2 = (2^{2R_T/D} - 1)$, $\gamma_{2i} \sim \exp(\zeta_{2i}^l)$, and $\gamma_{3i} \sim \exp(\zeta_{3i}^l)$.

Substituting (4.7), (4.9), and (4.11) in (4.10), we get

$$\begin{aligned} P_{BS,out} &= \left[1 - \prod_{i=1}^M \left(1 - e^{-\frac{\zeta_{2i}^l \sigma^2}{p_{cu}} \rho_1} \right) \right] \prod_{i=1}^M \left(1 - e^{-\frac{\zeta_{3i}^l \sigma^2}{p_{dt}} \rho_2} \right) \\ &\quad + \prod_{i=1}^M \left(1 - e^{(-\zeta_{2i}^l \sigma^2 \rho_1 / p_{cu})} \right). \end{aligned} \quad (4.12)$$

4.3.2 CU-DT-BS with cellular link

4.3.2.1 For direct CU-BS transmission

In Phase I, CU transmits N subcarriers to BS and each DT $_i$. The received signal at BS over subcarrier k is,

$$\xi_k^{BS} = (p_{cu,k})^{\frac{1}{2}} \Psi_{1,k} s_{cu,k} + n_{1,k}, \quad 1 \leq k \leq N. \quad (4.13)$$

The instantaneous rate at BS for all N subcarriers is given as

$$R_N = \sum_{k=1}^N \log_2 \left(1 + \frac{\gamma_{1,k} p_{cu,k}}{\sigma^2} \right). \quad (4.14)$$

The target rate of the system is R_T and outage occurs if $R_N < R_T$. Therefore, the outage probability for CU-BS link is,

$$P_{out} = \Pr(R_N < R_T) \quad (4.15)$$

From (4.5) and (4.14),

$$\Pr(R_N < R_T) = \Pr \left(\gamma_1 < \frac{(2^{R_T/N} - 1)\sigma^2}{p_{cu}} \right) \quad (4.16)$$

where $\gamma_1 \sim \exp(\zeta_1^l)$. Hence,

$$P_{out} = \left(1 - e^{-\frac{(2^{R_T/N} - 1)\sigma^2 \zeta_1^l}{p_{cu}}} \right). \quad (4.17)$$

4.3.2.2 For transmission with C-D2D

In Phase II, out of total N subcarriers received from CU, DT_i^s decodes and forward only D subcarriers to BS. BS employs MRC [12], [34] to combine the signals received in two phases³. The instantaneous rate at BS after two phases transmission is,

$$\begin{aligned} R_{BS}^{MRC} &= \frac{1}{2} \sum_{k=1}^D \log_2 \left(1 + \frac{p_{cu,k} \gamma_{1,k}}{\sigma^2} + \max_{i=1,2,..M} \frac{p_{dt,k} \gamma_{3i,k}}{\sigma^2} \right) \\ &+ \frac{1}{2} \sum_{k=1}^{N-D} \log_2 \left(1 + \frac{p_{cu,k} \gamma_{1,k}}{\sigma^2} \right). \end{aligned} \quad (4.18)$$

When decoding set $\mathcal{S} = \emptyset$, then there will be no transmission from DT_i to BS in Phase II. However, BS would still be able to receive the cellular signal from CU-BS link.

³BS has CSI information of DT_i^s -BS link.

Thus, the cellular outage probability for CU-DT-BS with cellular link is defined as,

$$P_{BS,out}^{mrc} = P'_1 \Pr(R_{BS}^{MRC} < R_T) + P_1 \Pr\left(\frac{1}{2}R_N < R_T\right). \quad (4.19)$$

Proposition 4.1 *The cellular outage probability for CU-DT-BS with cellular link can be derived in closed form as:*

$$\begin{aligned} P_{BS,out}^{mrc} = & \left(1 - \prod_{i=1}^M \left(1 - e^{-\frac{\zeta_{2i}^l \sigma^2}{p_{cu}} \rho_1}\right)\right) \left[1 - e^{-\zeta_1^l \alpha} \right. \\ & + \zeta_1^l \left(-\frac{M}{1!} \Upsilon_1 + \frac{M(M-1)}{2!} \Upsilon_2 + \dots + \right. \\ & \left. \left. (-1)^M \frac{M(M-1)\dots(M-(n-1))}{M!} \Upsilon_M\right) \right] \\ & + \left[\prod_{i=1}^M \left(1 - e^{-\frac{\zeta_{2i}^l \sigma^2}{p_{cu}} \rho_1}\right)\right] \left(1 - e^{-\frac{\zeta_1^l \sigma^2}{p_{cu}} \rho_1}\right). \end{aligned} \quad (4.20)$$

Proof : Proof of the Proposition 4.1 is given in Appendix D.

4.4 D2D Rate and Outage Probability

In Phase II, DT_i^s will transmit D subcarriers to BS. The remaining $N - D$ subcarriers will be assigned to all the DTs as per the round robin process with priority cube as summarized in Algorithm 4.3. This process may lead to two further possibilities:

1. When $\mathcal{S} = \emptyset$, all N subcarriers can be used for DT_i - DR_i communication.
2. When $\text{card}(\mathcal{S}) \geq 1$, $N - D$ subcarriers will be transmitted to DR_i .

Signal $s_{dt_i,k}$ is transmitted by DT_i over k_{th} subcarrier. The received signal at DR_i is,

$$\phi_k^{DR_i} = (p_{dt,k})^{\frac{1}{2}} \Psi_{4i,k} s_{dt_i,k} + n_{4i,k} \quad (4.21)$$

If there are M number of DT-DR pairs, the minimum instantaneous rate at DR_i , for $\mathcal{S} = \emptyset$,

$$R_1 = \frac{1}{2} \sum_{k=1}^{\lfloor \frac{N}{M} \rfloor} \log_2 \left(1 + \frac{p_{dt,k} \gamma_{4i,k}}{\sigma^2} \right). \quad (4.22)$$

The minimum instantaneous rate at DR_i for $\mathbf{card}(\mathcal{S}) \geq 1$,

$$R_2 = \frac{1}{2} \sum_{k=1}^{\lfloor \frac{N-D}{M} \rfloor} \log_2 \left(1 + \frac{p_{dt,k} \gamma_{4i,k}}{\sigma^2} \right) \quad (4.23)$$

If the target rate for D2D communication is R_{T_s} , then the total outage probability is,

$$P_{out}^{d2d} = P_1 \Pr(R_1 < R_{T_s}) + P_1' \Pr(R_2 < R_{T_s}). \quad (4.24)$$

From (4.5), (4.22) and (4.23),

$$\begin{aligned} \Pr(R_1 < R_{T_s}) &= \Pr \left(\gamma_{4i} < \frac{(2^{2R_{T_s} \lfloor M/N \rfloor} - 1) \sigma^2}{p_{dt}} \right) \\ &= \left(1 - e^{-\frac{\zeta_{4i}^l \sigma^2}{p_{dt}} \rho_1'} \right), \text{ and} \end{aligned} \quad (4.25)$$

$$\begin{aligned} \Pr(R_2 < R_{T_s}) &= \Pr \left(\gamma_{4i} < \frac{(2^{2R_{T_s} \lfloor M/(N-D) \rfloor} - 1) \sigma^2}{p_{dt}} \right) \\ &= \left(1 - e^{-\frac{\zeta_{4i}^l \sigma^2}{p_{dt}} \rho_2'} \right), \end{aligned} \quad (4.26)$$

where, $\gamma_{4i} \sim \exp(\zeta_{4i}^l)$, $\rho_1' = (2^{2R_{T_s} \lfloor M/N \rfloor} - 1)$ and $\rho_2' = (2^{2R_{T_s} \lfloor M/(N-D) \rfloor} - 1)$.

Thus, from (4.7), (4.9), (4.25) and (4.26), the total D2D outage probability can be derived as,

$$\begin{aligned} P_{out}^{d2d} &= \prod_{i=1}^M \left[1 - e^{-\frac{\zeta_{2i}^l \sigma^2}{p_{cu}} \rho_1} \right] \left(1 - e^{-\frac{\zeta_{4i}^l \sigma^2}{p_{dt}} \rho_1'} \right) \\ &\quad + \left(1 - e^{-\frac{\zeta_{4i}^l \sigma^2}{p_{dt}} \rho_2'} \right) \left[1 - \prod_{i=1}^M \left(1 - e^{-\frac{\zeta_{2i}^l \sigma^2}{p_{cu}} \rho_1} \right) \right]. \end{aligned} \quad (4.27)$$

4.4.1 Derivation for optimal M

We can determine the maximum value of M that can satisfy the D2D outage probability constraint.

Assuming, $\zeta_{2i}^l = \zeta_2^l$ and $\zeta_{4i}^l = \zeta_4^l \forall i$ in (4.27),

$$P_{out}^{d2d} = P^M \left(1 - e^{-\frac{\zeta_4^l \sigma^2}{p_{dt}} \rho_1'} \right) + \left(1 - e^{-\frac{\zeta_4^l \sigma^2}{p_{dt}} \rho_2'} \right) [1 - P^M], \quad (4.28)$$

where,

$$P = \left(1 - e^{-\frac{\zeta_2^l \sigma^2}{p_{cu}} \rho_1} \right).$$

Rearranging (4.28), we can write,

$$P^M = \frac{P_{out}^{d2d} - \left(1 - e^{-\frac{\zeta_4^l \sigma^2}{p_{dt}} \rho_2'} \right)}{\left(1 - e^{-\frac{\zeta_4^l \sigma^2}{p_{dt}} \rho_1'} \right) - \left(1 - e^{-\frac{\zeta_4^l \sigma^2}{p_{dt}} \rho_2'} \right)}. \quad (4.29)$$

Taking logarithmic on both sides, we get

$$M = \frac{\log_2 \left[\frac{P_{out}^{d2d} - \left(1 - e^{-\frac{\zeta_4^l \sigma^2}{p_{dt}} \rho_2'} \right)}{\left(1 - e^{-\frac{\zeta_4^l \sigma^2}{p_{dt}} \rho_1'} \right) - \left(1 - e^{-\frac{\zeta_4^l \sigma^2}{p_{dt}} \rho_2'} \right)} \right]}{\log_2 P}, \quad (4.30)$$

or,

$$M = \log_P \left[\frac{P_{out}^{d2d} - \left(1 - e^{-\frac{\zeta_4^l \sigma^2}{p_{dt}} \rho_2'} \right)}{\left(1 - e^{-\frac{\zeta_4^l \sigma^2}{p_{dt}} \rho_1'} \right) - \left(1 - e^{-\frac{\zeta_4^l \sigma^2}{p_{dt}} \rho_2'} \right)} \right]. \quad (4.31)$$

4.5 Simulation Results

This section shows the simulation results for the outage probability for two cases: CU-DT-BS link and CU-DT-BS with cellular link. Further, in order to verify the analytical derivations, the simulation results have also been compared with theoretical results. The radial distance between CU and BS is set to 800 m, i.e.

$\zeta_1 = 800$. DT_i – DR_i pair lie in between CU-BS, and radial distance between them is fixed to 50 m, i.e $\zeta_{4i} = 50$. Without loss of generality, it is assumed that each DT_i is equidistant from CU, which is set to 500m, i.e. $\zeta_{2i} = 500$ and, thus $\zeta_{3i} = 300$. We have chosen the target rate for both cellular and D2D link as $R_T = R_{T_s} = 1$ bit/sec/Hz and $N = 32$ denotes the total number of subcarriers. The cellular and D2D subcarrier power has been set to 100 mW (i.e. $p_{cu} = p_{dt} = 100\text{mW}$), whereas noise variance, $\sigma^2 = -120$ dBm, and the path loss exponent has been set to $l = 4$ (considering urban area).

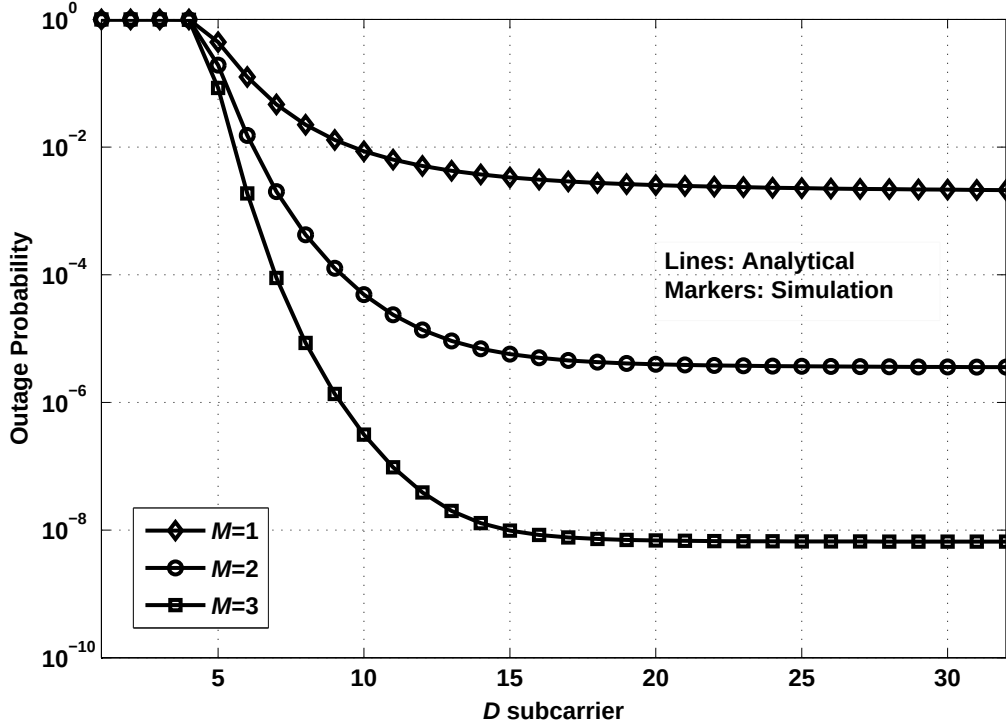


Figure 4.2. Cellular outage probability for CU-DT-BS link

Fig. 4.2 shows the analytical and simulation results for the cellular outage probability vs number of subcarriers D for the case of CU-DT-BS link. The results have been plotted for $M = 1, 2, 3$. As the number of forwarded subcarriers D from DT_i^s to BS increases, the outage probability decreases. The outage probability also decreases with increase in M . For instance, when $M = 3$, $D = 10$, the cellular outage probability, $P_{out} < 10^{-6}$. Hence, remaining $N - D = 22$ subcarriers can be shared by DTs for D2D communication. From Fig. 4.2, we can observe that the outage probability becomes stagnant for a given value of particular threshold (for

instance $D \geq 15$). This phenomenon can be explained as follows. AS DT_i^s is a DF relay, it forwards the successfully decoded subcarriers to BS, hence, as D increase, R_{BS}^{c-d2d} increases, consequently outage probability decreases. For $D \geq 15$, decoding of subcarriers at DT_i^s becomes the bottleneck for outage probability due to large distance between CU- DT_i^s , i.e. $\zeta_{2i} = 500$ m. Thus, any further increase in D will not have any impact on the outage probability.

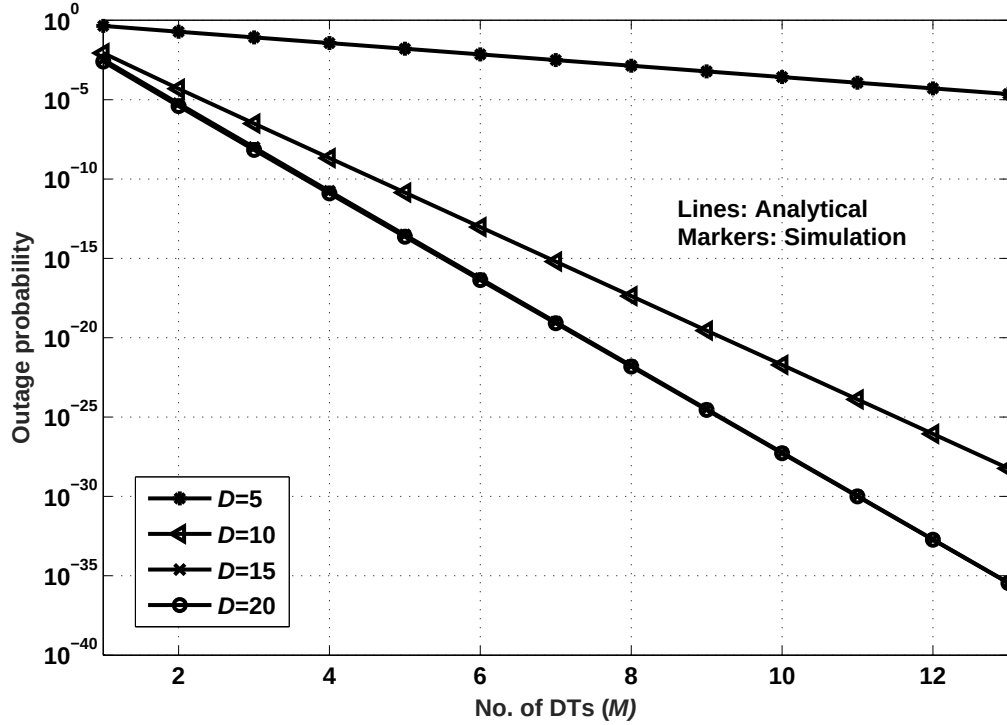


Figure 4.3. Cellular outage probability vs number of DTs for CU-DT-BS link

Fig. 4.3 shows the analytical and simulation results of the cellular outage probability vs number of DTs for CU-DT-BS link case. Results are also plotted for different number of subcarriers, i.e. $D = 5, 10, 15$, and 20 . From Fig. 4.3, we can observe that as number of DTs (M) increases, the outage probability decreases. Moreover, for a particular M , with increase in D outage probability reduces to a great extent. For instance, when $M = 8$, $D = 5$, outage probability $P_{out} < 10^{-3}$, whereas, for $M = 8$, $D = 10$, $P_{out} < 10^{-16}$, thus outage probability reduces significantly with increase in M or D . However, for $D = 15$ and $D = 20$, P_{out} is almost same for all values of M . This occurs due to the phenomenon discussed earlier for the case of Fig. 4.2. At $D = 15$, P_{out} is almost stagnant, and there will

be no improvement in outage probability with any further increment in D .

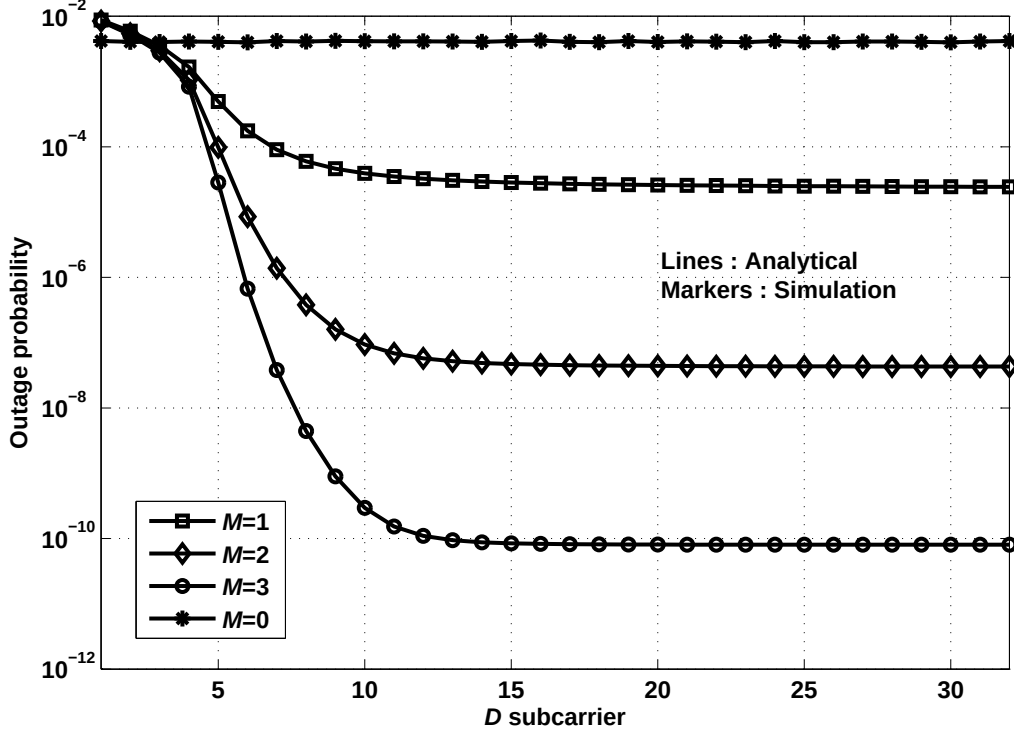


Figure 4.4. Cellular outage probability for CU-DT-BS with cellular link

Fig. 4.4 shows the analytical and simulation results of the outage probability vs number of subcarriers D for the case of CU-DT-BS with cellular link. In this case, MRC is employed at BS to combine the signals received in two phases. A trend similar to CU-DT-BS link is observed in Figure 4.4, i.e. outage probability decreases with the increase in D . The results have been plotted for 3 DT_i . $M = 0$ corresponds to direct cellular uplink transmission i.e. without relay. For instance, $M = 1$, $D = 7$, $P_{BS,out}^{mrc}$ is slightly less than 10^{-4} , whereas, for $M = 2$, $D = 7$, $P_{BS,out}^{mrc} \approx 10^{-6}$, thus, $P_{BS,out}^{mrc}$ reduces significantly with increase in M . Similar to Fig. 4.2, outage probability becomes stagnant for $D \geq 15$. This is due to the fact that when D approaches to some high value (i.e. $D \geq 15$), $\Pr(R_{BS}^{MRC} < R_T)$ attains very small value and decoding of the cellular signal at DT_i becomes the limiting factor of $P_{BS,out}^{mrc}$. Thus, further increase in D will not impact the outage probability. For a particular M and D , outage performance of CU-DT-BS with cellular link is better than CU-DT-BS link. This is due to the availability of CU-BS link for MRC. Hence, for CU-DT-BS with cellular link, more number of subcarriers are

available for D2D communication while satisfying the outage probability constraint of cellular user.

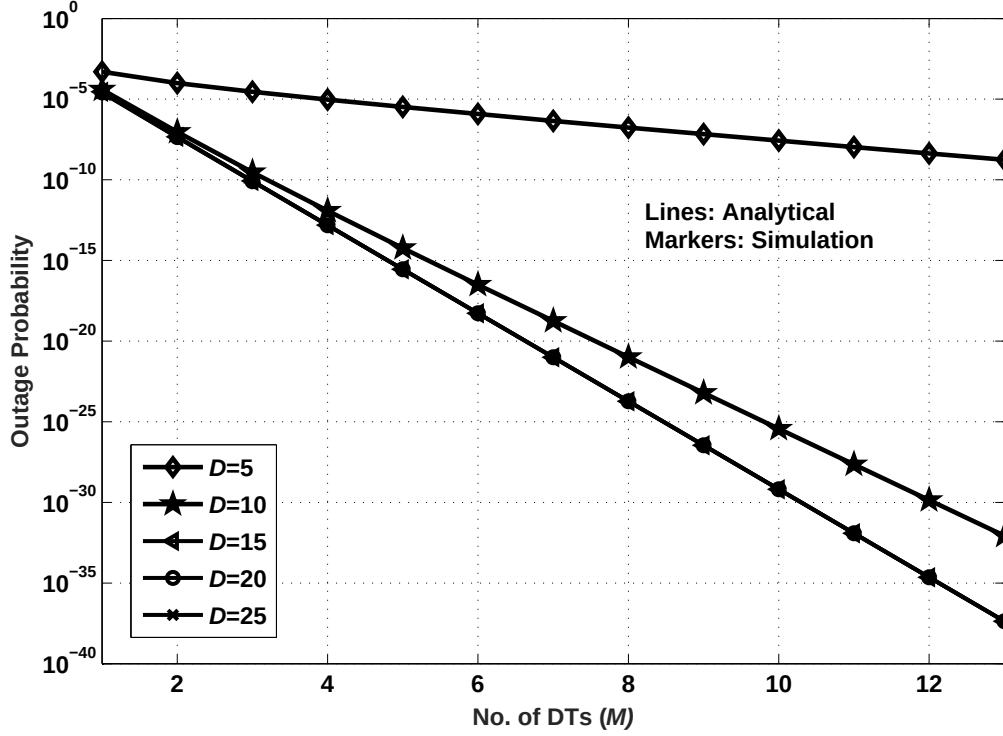


Figure 4.5. Cellular outage probability vs number of DTs for CU-DT-BS with cellular link

Fig. 4.5 shows the analytical and simulation results of the cellular outage probability vs number of DTs for CU-DT-BS with cellular link. Results are also plotted for different number of subcarriers, i.e. $D = 5$ to 25 with interval of 5. Trend similar to Fig. 4.3 is observed in Fig. 4.5, i.e. for different values of D , the cellular outage probability decreases with increase in M . For instance, $D = 5$, $M = 4$, $P_{BS,out}^{mrc} \approx 10^{-5}$, whereas for same D and M , cellular outage probability is in the order of 10^{-2} for CU-DT-BS link. For $D \geq 15$, there is no further improvement in the outage probability with respect to M . However, for $D = 15$, $P_{BS,out}^{mrc}$ decrease very rapidly with respect to M . Even though, for $M = 4$, $P_{BS,out}^{mrc} \approx 10^{-13}$. Hence, for this case, $N - D = 17$ subcarriers can be shared by DTs for DT communication.

Fig. 4.6 shows the D2D outage probability vs D subcarriers for 3 DTs, i.e. $M = 1, 2, 3$. For a particular M , D2D outage probability increases with increase in D . It is due to the fact that as D increase, $N - D$ decreases, thus subcarriers

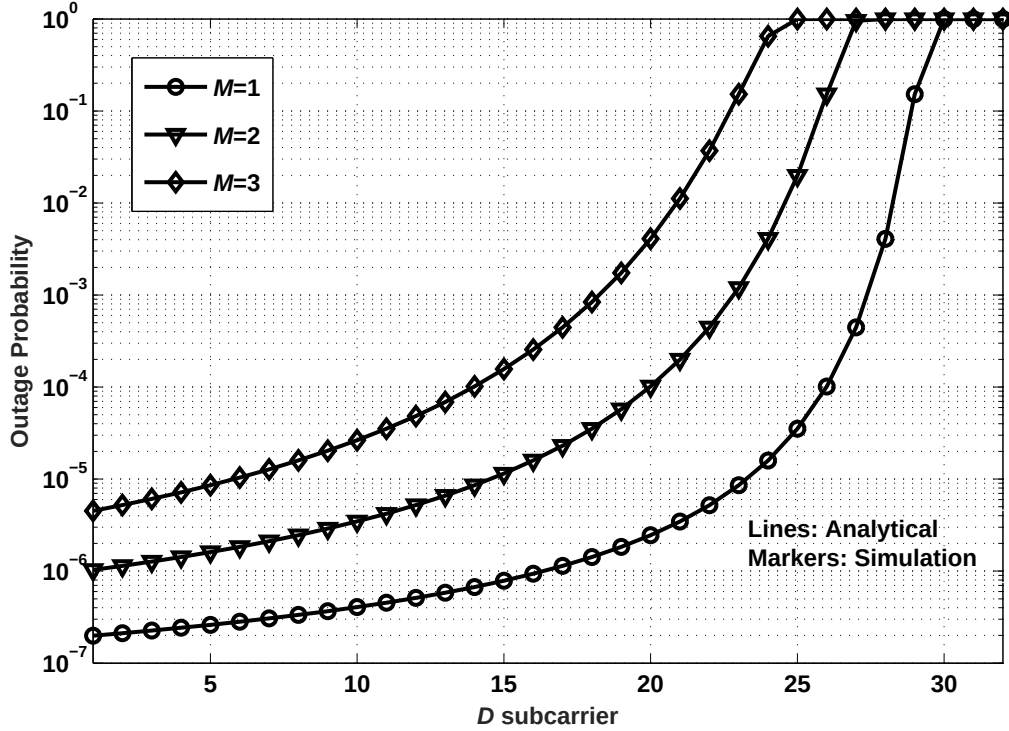


Figure 4.6. D2D outage probability vs subcarriers

available for D2D communication decreases, consequently D2D outage probability increases. Another trend can be observed from Fig. 4.6 that, as M increases, P_{out}^{d2d} also increases. This can be explained as follows. For instance, when $D = 16$, $N - D = 16$ subcarriers are available for D2D communication, that needs to be shared equally among all M DTs as per the analysis given in Algorithm 4.3. For $D = 16$, $M = 1$, all remaining $N - D = 16$ subcarriers are used by single DT-DR pair, and thus $P_{out}^{d2d} \approx 10^{-6}$, whereas, for $M = 2$, each DT-DR pair has $\lfloor \frac{N-D}{M} \rfloor = 8$ subcarriers available for D2D communication, thus $P_{out}^{d2d} \approx 10^{-5}$. Hence, there is a trade-off between D2D outage performance and the number of D2D users that can be supported.

Table 4.1 provides the number of subcarriers D required for cellular transmission and the respective D2D outage probability corresponding to the cellular outage constraint. Results have been computed for $M = 1, 2, 3$ for both cases i.e. CU-DT-BS link and CU-DT-BS with cellular link. From Table 4.1, we can observe that for a particular M , and cellular outage constraint, CU-DT-BS with cellular link has less D2D outage probability as compared to other cases. Further, for $M = 1$,

Table 4.1. D2D outage probability for CU-DT-BS link (case-I) and CU-DT-BS with cellular link (case-II) corresponds to cellular outage constraint

Cellular outage constraint		10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}
D for $M = 1$	Case-I	10	-	-	-	-	-	-
	Case-II	1	5	7	-	-	-	-
D for $M = 2$	Case-I	7	8	9	-	-	-	-
	Case-II	1	4	5	6	8	10	-
D for $M = 3$	Case-I	6	7	7	8	10	11	15
	Case-II	1	4	5	6	6	7	8
D2D outage for $M = 1$	Case-I	4.069×10^{-7}	-	-	-	-	-	-
	Case-II	1.989×10^{-7}	2.606×10^{-7}	3.061×10^{-7}	-	-	-	-
D2D outage for $M = 2$	Case-I	2.111×10^{-6}	2.457×10^{-6}	2.896×10^{-6}	-	-	-	-
	Case-II	1.031×10^{-6}	1.423×10^{-6}	1.608×10^{-6}	1.833×10^{-6}	2.457×10^{-6}	3.463×10^{-6}	-
D2D outage for $M = 3$	Case-I	1.038×10^{-5}	1.275×10^{-5}	1.275×10^{-5}	1.593×10^{-5}	2.642×10^{-5}	3.526×10^{-5}	1.568×10^{-4}
	Case-II	4.512×10^{-6}	7.183×10^{-6}	8.577×10^{-6}	1.038×10^{-5}	1.038×10^{-5}	1.275×10^{-5}	1.593×10^{-5}

Table 4.2. Maximum D2D pairs (M) for different D2D outage probability constraint

D2D outage constraint	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
$N - D = 31$	$M = 10$	$M = 9$	$M = 7$	$M = 5$	$M = 4$	$M = 2$
$N - D = 27$	$M = 9$	$M = 7$	$M = 6$	$M = 5$	$M = 3$	$M = 2$
$N - D = 22$	$M = 7$	$M = 6$	$M = 5$	$M = 4$	$M = 3$	$M = 2$
$N - D = 17$	$M = 6$	$M = 5$	$M = 4$	$M = 3$	$M = 2$	$M = 1$
$N - D = 12$	$M = 4$	$M = 3$	$M = 3$	$M = 2$	$M = 2$	-
$N - D = 7$	$M = 3$	$M = 2$	$M = 2$	$M = 1$	-	-

with CU-DT-BS link, the minimum cellular outage probability can be achieved is slightly less than 10^{-2} , even if all N subcarriers are used for cellular transmission, whereas for the case of CU-DT-BS with cellular link, $D = 7$ subcarriers are required to achieve the cellular outage constraint of 10^{-4} , thus remaining subcarriers can be used for D2D communication. Hence for a particular power and target rate profile, high cellular outage constraint with low D2D outage probability can be achieved by CU-DT-BS with cellular link. However, there is a trade-off in cellular outage constraint and D2D outage probability. For high cellular outage probability constraint, D would be high, thus less number of subcarriers are available to share among M DTs, consequently D2D outage probability will be high.

From Fig. 4.5 and Fig. 4.6, we can observe that cellular outage probability decreases with increase in M , whereas D2D outage probability increases with increase in M . Hence, for a particular D2D outage probability constraint, there is

trade-off in between cellular outage probability and number of D2D pairs (M). Table 4.2 provides the maximum number of DT-DR pairs (M) that can be used to satisfy a particular D2D outage probability constraint. Results have been computed for different number of $N - D$ subcarriers available for D2D transmission i.e. $N - D = 31, 27, 22, 17, 12$ and 7 . From Table 4.2, we can observe that for a particular $N - D$, the number of DT-DR pair (M) decreases with increase in D2D outage probability constraint. For instance, $N - D = 27$, P_{out}^{d2d} constraint $= 10^{-3}$, the maximum value of $M = 6$, whereas for same number of subcarriers to achieve the P_{out}^{d2d} constraint $= 10^{-5}$, maximum $M = 3$. Hence M decreases with increase in D2D outage probability constraint.

4.6 Conclusion

This chapter proposed a best D2D user selection protocol for cooperative D2D framework wherein multiple D2D users coexist with a cellular user. In particular, among the M available D2D pairs, DT_i^s (selected D2D user) helps the cellular user by relaying few of its subcarriers to BS. In return, multiple D2D users shares the cellular spectrum in a round-robin process with priority cube method to facilitate D2D communication. The rate and the outage probability of the proposed framework has been derived for two cases: CU-DT-BS link and CU-DT-BS with cellular link. In addition, a closed-form expression for the optimal value of number of D2D pairs (M) satisfying the target rate and outage probability constraint of cellular and D2D users is derived. Simulation results verified the accuracy of the derived expressions. Results show that the proposed best D2D selection framework outperforms the conventional C-D2D framework.

Testbed Implementation and Protocol Analysis for D2D Communication Frameworks

5.1 Introduction

Most of the prior work in D2D communication has been restricted to either analytical evaluation or performance assessment through extensive simulation set-up with very few measurement results. Further, lack of measurement testbeds creates an ambiguity on the veracity of theoretical/simulation results which tend to make a lot of assumptions which may not be valid in real world scenarios. Recently few testbeds have been developed to measure the performance of D2D communication frameworks in realistic scenarios. For instance, [99] focuses on the design of compact full duplex multiple-input multiple-output (MIMO) radios which are implemented in D2D underlaying cellular network. For the full duplex MIMO operation, proposed coupled structure consists of two components: a compact and power-efficient, dual-polarization-based analog solution and a LTE-based per-subcarrier digital self-interference canceller. Normalized synchronized peak (NSP) index switching algorithm is also proposed to initiate full duplex communications via a timing synchronization. A major implication from this experimental evaluation is that, even when a user utilizes the maximum transmitted power, full duplex

MIMO radio designed for users is still able to acquire throughput gain in an indoor mobile network. However, the implemented prototype was not tested on different D2D modes, and it was non-adaptive in nature.

In this chapter, as a proof-of-concept demonstration and performance assessment, the C-D2D framework has been implemented on a software reconfigurable (NI) USRP-2922 platform [100]. The quantitative results are obtained by measuring SER for both cellular and D2D users. Measurement results show that the SER performance of the cellular user improves significantly with C-D2D. In addition, there is a net increase in received SNR at BS. Moreover, C-D2D framework facilitates D2D communication with acceptable SER.

In the second part of the chapter, an adaptive C-D2D framework is proposed to facilitate D2D communication in the cellular network. Specifically, we employ adaptive modulation and coding (AMC) in conventional C-D2D framework to enhance the performance of both CU and DT. Measurement results shown that the proposed framework outperforms the conventional C-D2D framework.

In the third part of the chapter, a novel adaptive interference aware underlay D2D (U-D2D) framework is proposed. By utilizing the proposed framework, it is possible to protect the cellular user from excessive interference by D2D transmitter, thus maintaining the desired QoS at CU. Measurement results of the proposed scheme are compared with the conventional underlay D2D framework. Results show that adaptive interference aware underlay D2D framework improves the BER and spectral efficiency (SE) of the overall system when compared to the conventional U-D2D framework.

The remainder of this chapter is organized as follows. Section 5.2 discusses the Implementation and measurement setup for all three proposed frameworks. Measurement results and discussion are provided in Section 5.3, and finally conclusion is drawn in Section 5.4.

5.2 Implementation and Measurement Setup

The testbed consists of four nodes namely CU, BS, DT, and DR. Each node is implemented on NI USRP-2922 platform. The physical layer modem is programmed to follow the OFDM standards in IEEE 802.11a. All nodes except DR are time

synchronized in time division duplex (TDD), which is required to execute two phases DF protocol.

Measurements were taken in a wireless system laboratory (Shannon laboratory) within our institute¹. The lab has the number of workstations preloaded with NI-Labview software for the staff and students. The lab environment is fairly dynamic due to consistent human traffic. A photo of the measurement setup for LOS is shown in Fig. 5.1. The measurement layout for CU-BS in line-of-sight (LOS) and non-LOS (NLOS) are shown in Fig. 5.2 and 5.3 respectively. This set-up includes 4 USRPs along with a master control computer connected with a switch. The role of four USRPs is to provide user defined radio capability as a CU, BS, DT and DR nodes. All USRP antennas are installed at the height of 1.4m from floor level. Two types of measurements were taken. In first, CU-BS path is in LOS, and in second, CU-BS path is obstructed by a wall to create NLOS condition as shown in Fig. 5.3. DT is in LOS with CU and BS, and DR is in LOS with DT. As a benchmark for comparison, measurements for direct CU-BS transmission were also taken. All nodes are transceivers operating in time division duplex (TDD) mode, except for DR which only needs to receive data. The nodes are time synchronized through their respective CPU clocks. This time synchronization is necessary for the execution of the two-phases cooperative D2D protocol.

5.2.1 Protocol implementation (C-D2D)

Field trials were conducted in an indoor lab environment and received SNR and SER for the cellular and D2D users for different distances were measured to quantify their respective performance.

In Phase I, CU broadcast N QPSK modulated subcarriers to BS and DT. DT receives the data transmitted by CU and decodes it. In Phase II, DT forwards QPSK modulated $D = N/2$ subcarriers to BS, whereas, remaining $N/2$ subcarriers are transmitted to DR for D2D communication². BS will apply MRC to combine the signals received in two phases. Received SNR and SER have been measured and calculated for different distances for both cellular and D2D system. In addition

¹[https://www.iiitd.ac.in/facilities/labs/shannon lab](https://www.iiitd.ac.in/facilities/labs/shannon%20lab)

²Please note that DT will send only half of the data it received from CU to BS using $N/2$ subcarriers, remaining $N/2$ subcarriers are reserved for D2D communication

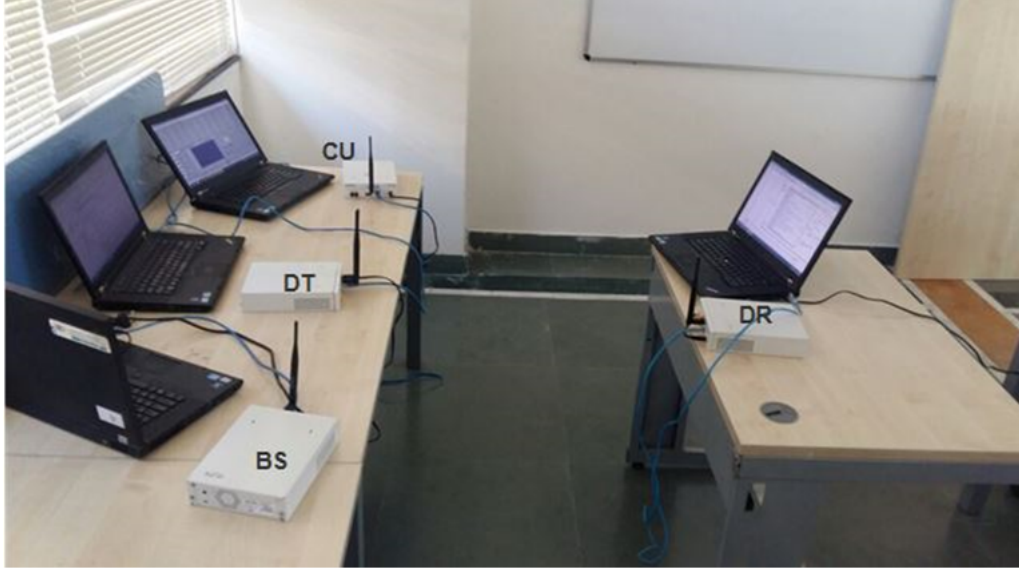


Figure 5.1. Measurement setup for LOS

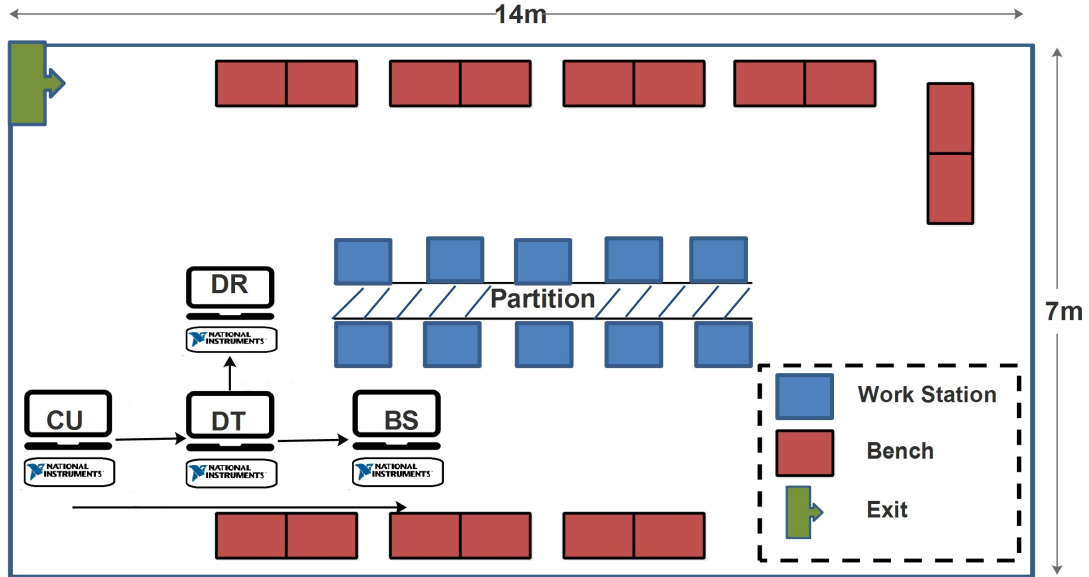


Figure 5.2. Measurement layout for LOS

to above, measurements were also taken for different transmitter gain which can be varied in USRP. In order to compare the performance of the proposed scheme, we have also measured the received SNR and SER for direct CU-BS transmission (i.e. without C-D2D). Results show that the proposed subcarrier sharing scheme outperforms the direct CU-BS communication as well as it is beneficial for both

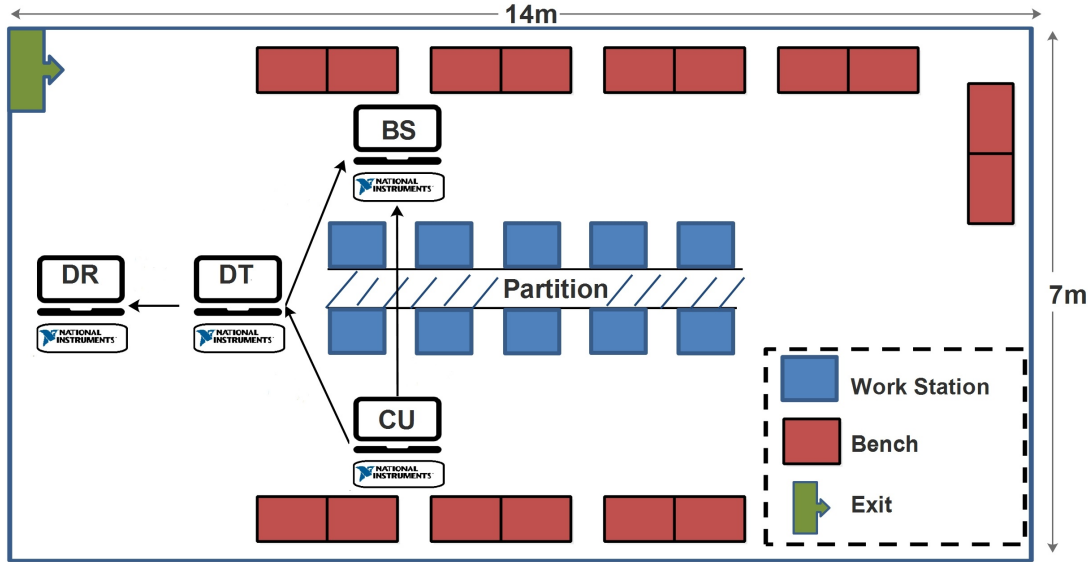


Figure 5.3. Measurement layout for NLOS

cellular and D2D users.

5.2.1.1 Power measurement set-up

The transmit power for the corresponding USRP gain has been measured by CXA 900A signal analyzer. The power measurement set-up has been shown in Fig. 5.4. The power has been measured from -5 dB to 20 dB Tx gain with an interval of 5 dB. The power corresponding to -5 dB Tx gain is measured to be -47 dBm. Every 5 dB increase in Tx gain results into 5 dBm increase in measured power. Hence power corresponding to 20 dB Tx gain is measured as -22 dBm.

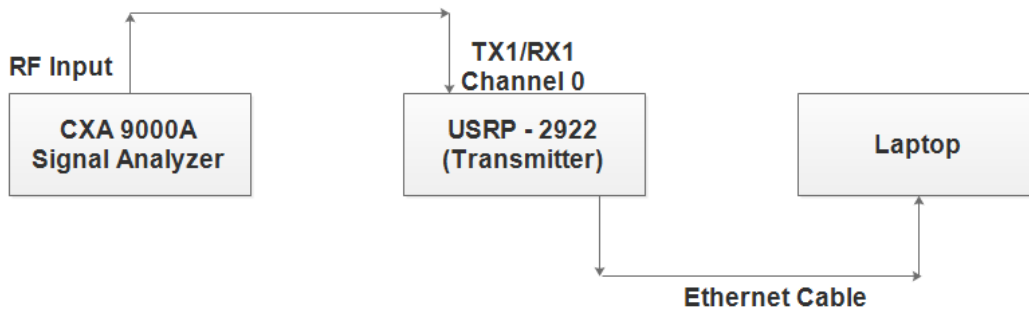


Figure 5.4. Power measurement set-up

The average path loss value between two nodes for different distances are shown

Table 5.1. Path Loss with respect to transmit gain

Tx Gain (dB)	Path Loss (dB)		
	$d=0.5\text{m}$	$d=2\text{m}$	$d=3\text{m}$
-5	45.2	58.2	60.2
0	47.6	57.6	62.6
5	49.2	58.2	61.2
10	49.1	57.1	60.1
15	46.2	56.2	59.2
20	42.0	49.1	50.1

in Table 5.1. For instance, Tx gain = 5 dB, $d = 3\text{m}$, the average path loss is measured as 61.2 dB. From free space path loss equation [101], the path loss exponent for direct CU-BS link is calculated as 3.5.

5.2.1.2 Frame structure

Each transmitted OFDM frame consists of short training field (STF), long training field (LTF), and data payload. STF and LTF are used for coarse synchronization and initial channel estimation respectively. Total data bits per frame are 720, which are coded with (7, [133 171]) convolution code with the code rate of 1/2. The coded bits are further QPSK modulated to generate 720 data symbols. Each frame consists of 15 OFDM symbols, and each OFDM symbol consists of 48 QPSK modulated data symbols and 4 pilots. A cyclic prefix (CP) of duration 16 samples is also appended for each OFDM symbol. IFFT/FFT length is 64. Total RF bandwidth is 20 MHz, and the carrier frequency is 2.4 GHz. Both transmitters CU and DT use same modulation format, i.e., QPSK.

5.2.2 Protocol implementation (adaptive C-D2D)

Similar to conventional C-D2D framework, the testbed consists of four nodes, i.e., CU, BS, DT and DR. The distance between CU-BS, CU-DT, DT-BS, and DT-DR are denoted as d_1 , d_2 , d_3 , and d_4 respectively. In the proposed framework, a DT helps the CU to achieve its QoS by acting as a DF relay in exchange for cellular spectrum. In Phase I, CU broadcasts the cellular signal with QPSK modulation

over N subcarriers which is received by BS and DT. In Phase II, DT forwards the decoded subcarriers to BS with larger constellation size ($M > 4$) to enhance the SE of CU. If DT uses M -QAM to modulate the subcarriers before forwarding them to BS, then the maximum number of subcarriers that needs to be forwarded by DT to BS would be $N/\log_2(M)$. Thus, remaining $N - (N/\log_2(M))$ subcarriers can be used by DT to transmit its data to DR. At BS, BER-SC [34] is employed to combine the signals received in two-phases. Specifically, BS decodes the signal of the branch having lower BER.

We have conducted field trials and measured BER and SE in the indoor lab environment for both cellular and D2D users at different distances. Measurements have been taken for CU-BS LoS and N-LOS scenarios, whereas, DT is always in LOS with other nodes. As a benchmark for comparison, BER and SE for direct CU-BS transmission, i.e., without C-D2D are also measured. It is shown that when AMC is employed along with BER-SC, it significantly improves the BER and SE performances of the cellular user.

5.2.2.1 Protocol flowchart

The protocol flowchart for the proposed adaptive C-D2D framework is shown in Fig. 5.5. In phase I, CU broadcasts QPSK modulated N subcarriers with convolution coding rate (CCR) = $1/2$ to BS which are overheard by DT. DT tries to decode the CU data received in Phase I. In phase II, based on the distance between CU-DT, i.e., d_2 , DT will transmit data to BS and DR as per the following cases.

Case I - For $d_2 = 2.5\text{m}$, $d_3 = d_4 = 2.5\text{m}$: $D = N/\log_2(M)$ subcarriers (where $M = 16$) are transmitted from DT to BS.

Case II - For $d_2 = 3.5\text{m}$ and $d_3 = d_4 = 1.5\text{m}$: $D = N/\log_2(M)$ subcarriers (where $M = 64$) are transmitted from DT to BS.

At BS, BER-SC [34] is employed to combine the signals received in two-phases. Specifically, BS decodes the signal of the link having less BER. The results have been measured for CCR = $1/3$, $1/2$ and $2/3$. For both cases, remaining $N - D$ subcarriers are transmitted from DT to DR. Thus, proposed scheme facilitates the D2D communication along with cellular communication while maintaining the BER constraint of CU.

Here, BS received P number of packets from both CU and DT. BER of each

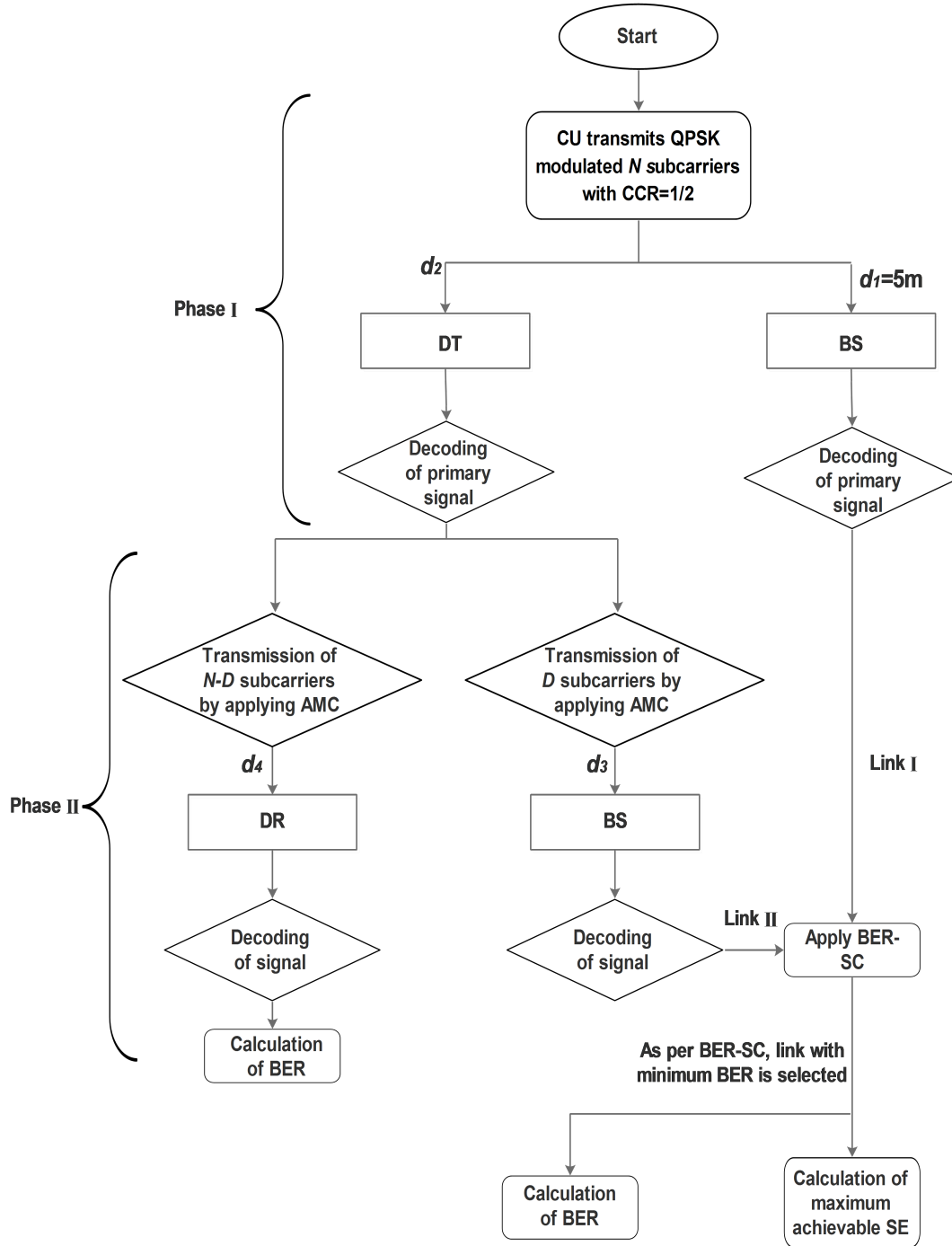


Figure 5.5. Measurement flowchart for adaptive C-D2D

packet received from CU and DT are compared, and the packet with less BER is selected. Let p_1 denotes the number of packets of the link I (refer Fig. 5.5) which

have less BER than link II while p_2 denotes the number of packets of link II which have less BER than the link I, where $p_1 + p_2 = P$. Thus, as per BER-SC, BS will select p_1 packets from the link I, and p_2 packets from the link II.

Moreover, for a particular distance, measurements were taken for different transmit gain (Tx gain) of USRP. Further to quantify the performance, we have also calculated maximum achievable SE. Results show that proposed subcarrier sharing scheme with AMC outperforms the direct CU-BS communication as well it is beneficial for both cellular and D2D users

5.2.2.2 Frame structure and power measurement set-up

The physical layer parameters implemented on the system are shown in Table 5.2. Each transmitted OFDM symbol consists of STF and LTF for synchronization and channel estimation. Total bits per frame are 720 which are encoded with CCR = 1/3, 1/2, 2/3 with the constraint length of 7. These coded bits are further modulated with one of the modulation schemes: QPSK, 16-QAM or 64-QAM to generate 720, 360 or 240 data symbols respectively. Each OFDM symbol consists of 48 modulated data symbols and 4 pilots. A CP of duration 16 samples is also appended with each OFDM symbols.

Table 5.2. Physical layer parameters

Parameters	Values
Modulation	QPSK, 16 QAM and 64 QAM
CCR	1/2, 1/3 and 2/3
IFFT/FFT length (N_{FFT})	64
RF bandwidth (B)	20 MHz
Carrier frequency	2.4 GHz
Subcarrier spacing (B_N)	312.5 kHz
Symbol time per subchannel (T_N)	4 μ sec
Data interval time (T_{data})	3.2 μ sec
Guard interval (GI) time (T_{GI})	0.8 μ sec
IFFT/FFT (T_{FFT}) period	4 μ sec
Short training sequence (T_{short})	4 μ sec
Long training sequence (T_{long})	8 μ sec

To increase the range of transmitting power, we employ a power amplifier³ (PA) ADL5545 with DC power supply⁴ PWS2326 at CU. To increase the Tx gain to 22 dB at CU, DC power supply PWS2326 parameters are configured with voltage $V = 4.78$ V and current $I = 0.056$ A. The transmitted power at the USRP output gain has been measured by CXA 900A signal analyzer. The power has been measured from 27 dB to 52 dB Tx gain with an interval of 5 dB. The power corresponding to 27 dB Tx gain is measured to be -38 dBm. Every 5 dB increase in Tx gain results into 5 dBm increase in measured power. Hence power corresponding to 52 dB Tx gain is measured as -13 dBm.

5.2.2.3 Spectral efficiency

We have taken $N_{FFT} = 64$. However, only 48 subcarriers are used for data transmission, i.e., $N_d = 48$. 4 pilot symbols are used for channel estimation. 12 null subcarriers are also added (including DC) to avoid spectrum leakage to adjacent bands. The length of the cyclic prefix, $\mu = 16$ samples. Therefore, each OFDM symbol has N_t total number of samples, where, $N_t = N_{FFT} + \mu = 80$ (including both data and cyclic prefix). The convolutional code is used as an error correction code with three possible CCR = 1/3, 1/2 and 2/3.

Since bandwidth, $B = 20$ MHz (which is equal to sampling rate $1/T_s$), thus, subcarrier bandwidth (B_N) is equal to

$$B_N = \frac{B}{N} \text{ Hz.} \quad (5.1)$$

Each symbol is represented by k bits, where :-

$$k = \log_2(M) \text{ bits,} \quad (5.2)$$

where M denotes constellation size.

OFDM block duration (OFDM symbol + CP) is :-

$$T_N = N_t \times T_s. \quad (5.3)$$

³PA is manufactured by Analog Devices and has voltage range of 4.75-5.25 V and supply current of 56 mA

⁴PWS2326 is manufactured by Tektronix and has voltage range of 0-32 V and current range of 0-6 A.

According to [53], maximum data rate (DR) (bps) for an OFDM system with N_d subcarriers is given as,

$$DR = \frac{N_d \times CCR \times k}{T_N} bps. \quad (5.4)$$

As discussed above, CU broadcasts P packets which are received by DT and BS. In BER-SC, BS calculates BER of each link, i.e., CU-BS (direct) and DT-BS (with AMC) and then decodes the signal of each branch that has minimum BER. Let the number of packets for CU-BS link which have BER is less than DT-BS link is p_1 . Thus, the remaining number of packets in DT-BS link is $p_2 = P - p_1$ which have less BER than CU-BS link. Thus, DR_{av} is given as,

$$DR_{av} = \frac{p_1}{P} \times DR_{(CU-BS)} + \frac{p_2}{P} \times DR_{(DT-BS)} bps, \quad (5.5)$$

where, $DR_{(CU-BS)}$ and $DR_{(DT-BS)}$ are the average data rate for CU-BS link and DT-BS link respectively.

Similar to DR_{av} , maximum achievable SE of a proposed AMC model is calculated in terms of average spectral efficiency SE_{av} . As shown later in results section SE_{av} of proposed AMC scheme, shows a significant improvement as compared to the SE of direct D2D communication.

$$SE_{av} = \frac{p_1}{P} \times SE_{(CU-BS)} + \frac{p_2}{P} \times SE_{(DT-BS)} bps/Hz, \quad (5.6)$$

where, $SE_{(CU-BS)}$ and $SE_{(DT-BS)}$ are maximum achievable SE of CU-BS and DT-BS link respectively.

5.2.3 Protocol implementation (adaptive interference aware U-D2D)

5.2.3.1 Protocol flowchart

The protocol flowchart for the proposed adaptive interference aware U-D2D communication framework is illustrated in Fig. 5.6. Here, we assume that both cellular and D2D system uses the OFDM modulator/demodulator for the transmitted/received signals respectively. The cellular signal from CU interferes to D2D

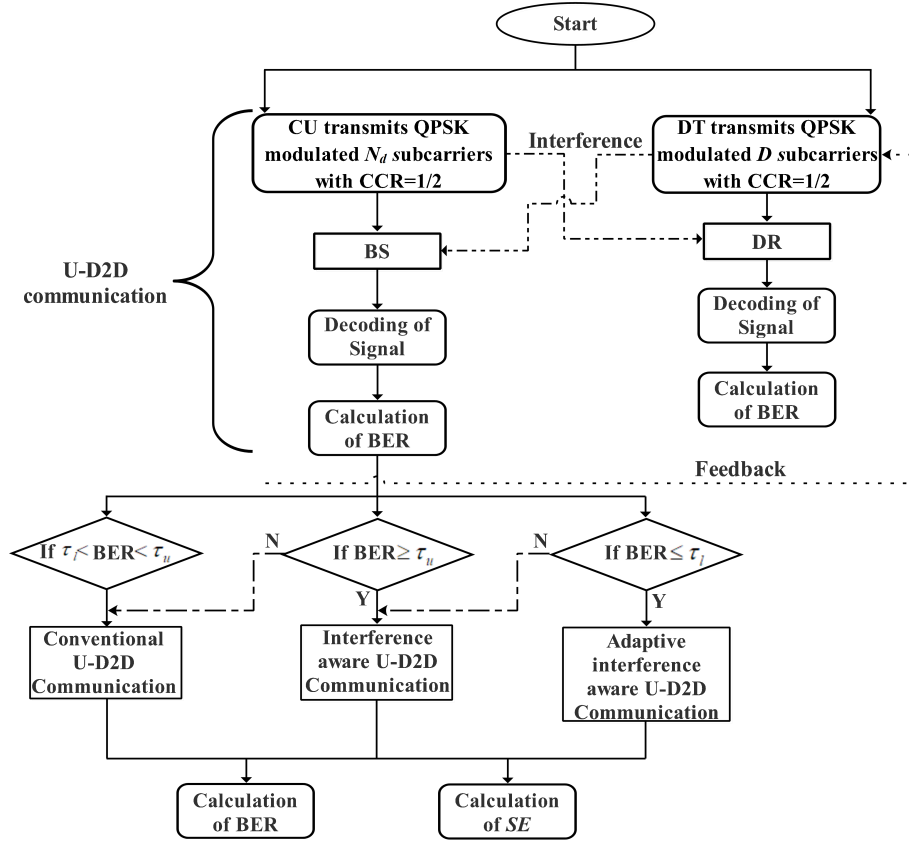


Figure 5.6. Measurement flowchart for adaptive interference aware U-D2D

signal at DR while the transmitted signal from DT interferes to cellular signal at BS. By utilizing the CSI of CU-BS link, DT can estimate the BER of the received signal at BS.

On the basis of cellular BER threshold (τ) at BS, the OFDM data subcarriers are divided into three modes:

- **U-D2D communication mode** - Subcarriers (ς) those BER ranges from τ_l (lower threshold) to τ_u (upper threshold) i.e. $\tau_l < \text{BER} < \tau_u$ are categorized under this mode. Here, CU and DT transmits N_d and D subcarriers to BS and DR respectively, where $N_d = D$. Specifically, in this mode, CU transmits N_d subcarriers to BS and at the same time, DT transmits its data to DR over same sets of subcarriers, thus interfering with each other.
- **Interference aware U-D2D communication mode** - In this mode, by

utilizing the CSI of CU-BS link, DT-DR communication is suppressed particularly for those subcarriers (δ) which have BER greater than τ_u , i.e., $\text{BER} \geq \tau_u$. Thus, there will be no interference at BS for δ subcarriers. Hence, BER performance at BS will improve. Here, $D = N_d - \delta$.

- **Adaptive interference aware U-D2D communication mode** - Two possible cases are discussed below:

Case I - For particular subcarrier, when $\text{BER} \leq \tau_l$, CU adapts its constellation size with M-QAM as per cellular BER constraint to improve the SE of the overall system.

Case II - For a particular subcarrier, after adopting Case-I, if BER exceeds τ_u , then that subcarrier is transmitted with interference aware U-D2D communication mode only.

To quantify the performance of above modes, we have also measured maximum achievable SE . Results show that proposed adaptive interference aware U-D2D communication scheme outperforms the conventional U-D2D communication as well it is beneficial for both cellular and D2D users.

5.2.3.2 Spectral efficiency

In this section, we calculate the average data rate (DR_{av}) and maximum achievable SE for the interference aware U-D2D framework.

For the case of adaptive interference aware U-D2D communication mode, CU broadcasts n_1 number of subcarriers with $M = 4$ (i.e. QPSK), and n_2 number of subcarriers with $M = 16$ constellation size (i.e. 16-QAM). Hence, average DR DR_{av} is given by,

$$DR_{av} = \frac{CCR}{T_N} \times (k_1 p_1 + k_2 p_2) \quad (5.7)$$

Here, $k_1 = \log_2(4)$ and $k_2 = \log_2(16)$ for QPSK and 16 QAM modulation, respectively.

Similarly to DR_{av} , maximum achievable SE of a proposed framework is calculated in terms of average spectral efficiency SE_{av} . As shown later in the results section, SE_{av} of proposed adaptive interference aware U-D2D communication mode

shows a significant improvement as compared to the SE of conventional U-D2D communication.

$$SE_{av} = \frac{DR_{av}}{B} \text{ bps/Hz}. \quad (5.8)$$

The frame structure and measurement setup for U-D2D framework are similar to the adaptive C-D2D framework (refer Section 5.2.2.2).

5.3 Results and Discussion

5.3.1 C-D2D

In this section, we have shown the measurement results for the proposed framework. In the measurements, we assume $p_{CU} = p_{DT}$ and the measurements are repeated with different transmitter gains to obtain the data points for each of the average received SNR at DR and BS. In order to have a fair comparison with the direct transmission, the total received SNR is divided by factor 2 for C-D2D. Nodes CU, DT, BS, and DR are arranged as per the configuration given in Fig. 5.2 and 5.3 for LOS and NLOS respectively. The distances between different nodes were selected based on the maximum transmit power and receiver sensitivity of the USRP-2922 [100].

As discussed before, the total transmission was divided into two phases. In Phase I, 1000 packets were transmitted from CU to BS which is overheard by DT. In Phase II, DT sends superimposed cellular and D2D data to BS and DR respectively. Each SER plot is calculated by averaging over 1000 data frames. The average received SNR at DR and BS is calculated by taking the average of the SNR received from CU. Noise variance at each node was measured to be -115 dBm.

Table 5.3 and 5.4 shows the received SNR with C-D2D and direct CU-BS for LOS and N-LOS respectively. d denotes the distance between CU-BS, and DT is placed in between CU-BS as shown in Fig. 5.3. Received SNR has been measured for $d = 0.5\text{m}$, 2m and 3m , whereas transmit gain varies from -5 dB to 20 dB with 5 dB interval. From Table 5.3 and 5.4, we can observe that for constant distance, when transmit gain increases, received SNR for direct and C-D2D also increases. On the other hand, received SNR decreases with increase in CU-BS distance. It is

Table 5.3. Received SNR with C-D2D and direct for LOS

Tx Gain (dB)	Received SNR (dB)					
	For $d=0.5\text{m}$		For $d=2\text{m}$		For $d=3\text{m}$	
	Direct	C-D2D	Direct	C-D2D	Direct	C-D2D
-5	24	25	9	15	7	10
0	25	27	15	23	17	20
5	29	31	20	23	17	20
10	34	36	26	28	23	23
15	41	41	31	33	28	31
20	55	55	43	46	42	44

Table 5.4. Received SNR with C-D2D and direct for NLOS

Tx Gain (dB)	Received SNR (dB)					
	For $d=0.5\text{m}$		For $d=2\text{m}$		For $d=3\text{m}$	
	Direct	C-D2D	Direct	C-D2D	Direct	C-D2D
-5	15	17	7	8	4	6
0	16	19	11	14	9	11
5	19	23	16	17	14	15
10	25	28	22	24	18	21
15	32	33	27	29	25	26
20	37	38	33	35	31	31

worth noting that for the same distance and Tx gain, C-D2D has higher received SNR as compared to direct transmission. For instance, from Table 5.3, for Tx gain = 0 dB, $d = 3\text{m}$, received SNR for direct CU-BS is 10 dB, whereas with C-D2D it is 14 dB. Similarly, from Table 5.4, for same Tx gain and distance, received SNR for direct CU-BS is 9 dB, whereas with C-D2D it is 11 dB. Further, it can also be observed that the received SNR for LOS is higher than N-LOS.

Table 5.5 shows the received SNR with respect to Tx gain for DT-DR transmission link for three different distances i.e. $d_1 = 0.75\text{m}$, 1m and 1.5m , where d_1 denotes distance between DT-DR. From Table 5.5, we can observe that, received SNR increases with increase in Tx gain, whereas, it decreases as d_1 increases. For instance, Tx gain = 5 dB, $d_1 = 1\text{m}$, received SNR is 26 dB. If Tx gain increases

Table 5.5. Received SNR for DT-DR

Tx Gain (dB)	Received SNR (dB)		
	For $d_1=0.25\text{m}$	For $d_1=1\text{m}$	For $d_1=1.5\text{m}$
-5	26	21	14
0	28	23	18
5	33	26	23
10	38	29	27
15	43	36	33
20	55	48	46

to 15 dB, received SNR increases to 36 dB (for same distance).

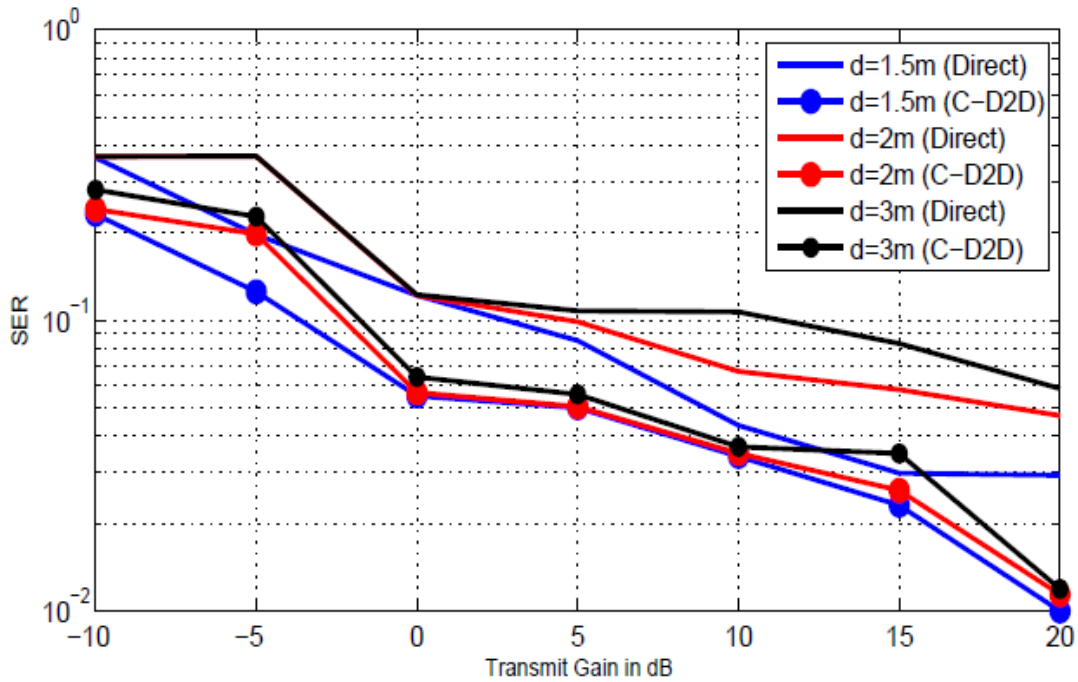
**Figure 5.7.** SER vs Tx gain for C-D2D and direct (LOS)

Fig. 5.7 shows the performance comparison of direct CU-BS communication (LOS) and communication with the proposed C-D2D framework in terms of SER. SER is calculated by comparing the received symbols with the transmitted symbols to find the number of symbols received in error and then normalizing it with the total number of transmitted symbols. Results have been plotted for SER vs transmit gain for three different distances. From Fig. 5.7, it is quite evident that

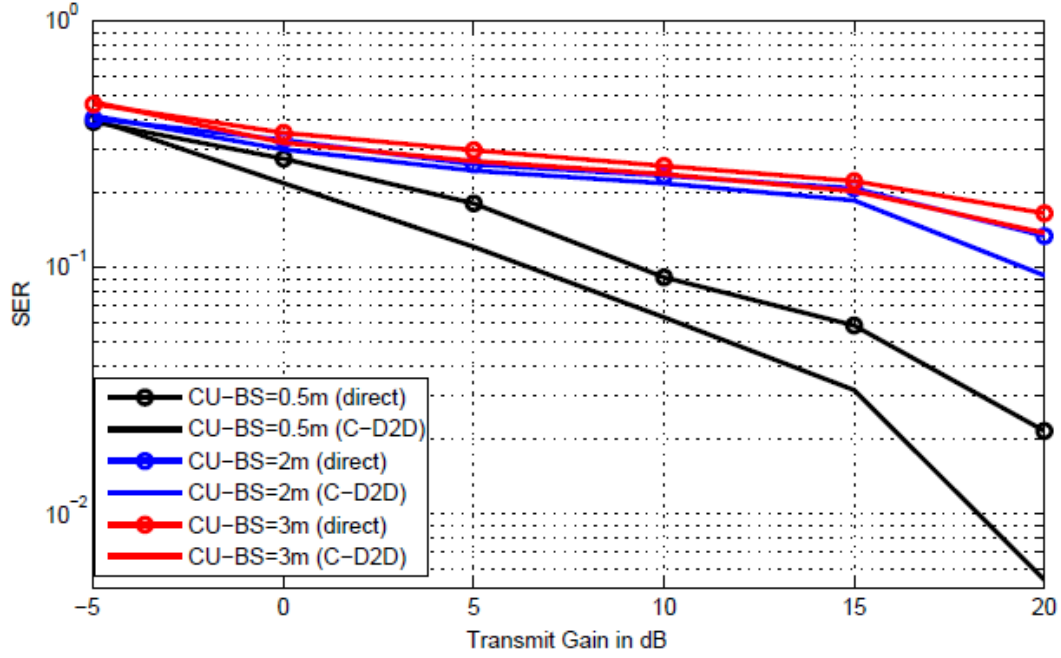


Figure 5.8. SER vs Tx gain for C-D2D and direct (NLOS)

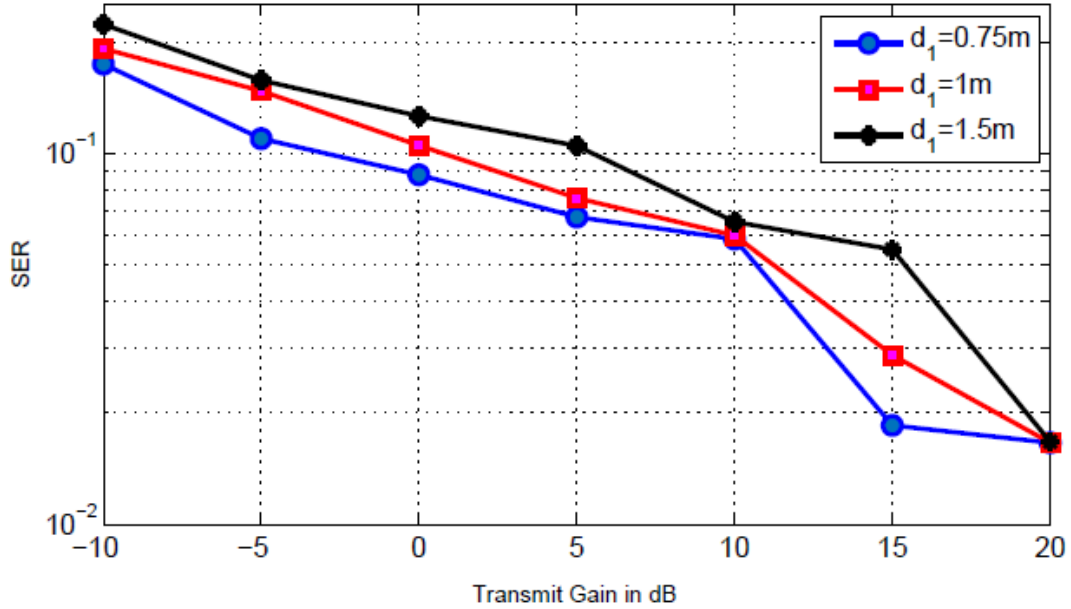


Figure 5.9. SER vs Tx gain for DT-DR link

as transmit gain increases SER for both direct and C-D2D decreases. For instance, when $d = 1.5m$, and transmit gain = 5 dB, SER for direct CU-BS is 0.063 and with C-D2D it is 0.031. Similar trends are observed for other distances. Hence,

the proposed C-D2D framework improves SER of the cellular user as compared to direct CU-BS transmission.

Fig. 5.8 shows the performance comparison of direct CU-BS communication (NLOS) and C-D2D in terms of SER. Trends similar to LOS is also observed here, i.e., SER decreases with increase in transmit gain. However, at a particular distance and transmit power SER with NLOS is higher as compared to SER with LOS.

Fig. 5.9 shows the SER vs transmit gain for D2D system. Results have been plotted for three distances ($d_1 = 0.75\text{m}$, 1m and 1.5m). From Fig. 5.9, we can see that the SER decreases with increase in transmit gain. For instance, when $d_1 = 1.5\text{m}$, Tx gain = 5, $\text{SER} \approx 10^{-1}$.

5.3.2 Adaptive C-D2D

As discussed before, there are two phases of transmission. In Phase I, 1000 packets were transmitted from CU to BS which is overheard by DT. In phase II, DT sends superimposed cellular and D2D data to BS and DR respectively. At BS, BER-SC is employed, and BER is calculated by comparing the received (demodulated and decoded) symbols with the transmitted symbols to find the error, and then the error is averaged over 1000 frames.

Fig. 5.10 shows the performance comparison of direct CU-BS (LOS) communication and the proposed adaptive C-D2D framework in terms of BER. From Fig. 5.10, it is quite obvious that as Tx gain increases, the BER for both direct and C-D2D decreases. For instance, when Tx gain = 37 dB, BER for direct CU-BS with $M = 4$ and $\text{CCR} = 1/2$ is 0.0861. On the other hand, for same Tx gain, BER with $M = 16$ and $\text{CCR} = 1/3$ is 0.0449 (for adaptive C-D2D). Similar trends are observed for different constellations and CCR. Hence, the proposed protocol improves BER of the cellular user as compared to direct CU-BS transmission.

Fig. 5.11 shows the performance comparison of direct CU-BS (N-LOS) with adaptive C-D2D in terms of BER. Similar to the results of LOS, BER decreases as Tx gain increases. For instance, when Tx gain = 37 dB, BER for direct CU-BS with $M = 4$ and $\text{CCR} = 1/2$ is 0.105. On the other hand, for same Tx gain, BER with $M = 16$ and $\text{CCR} = 1/3$ is 0.0582 (for adaptive C-D2D). It is quite obvious

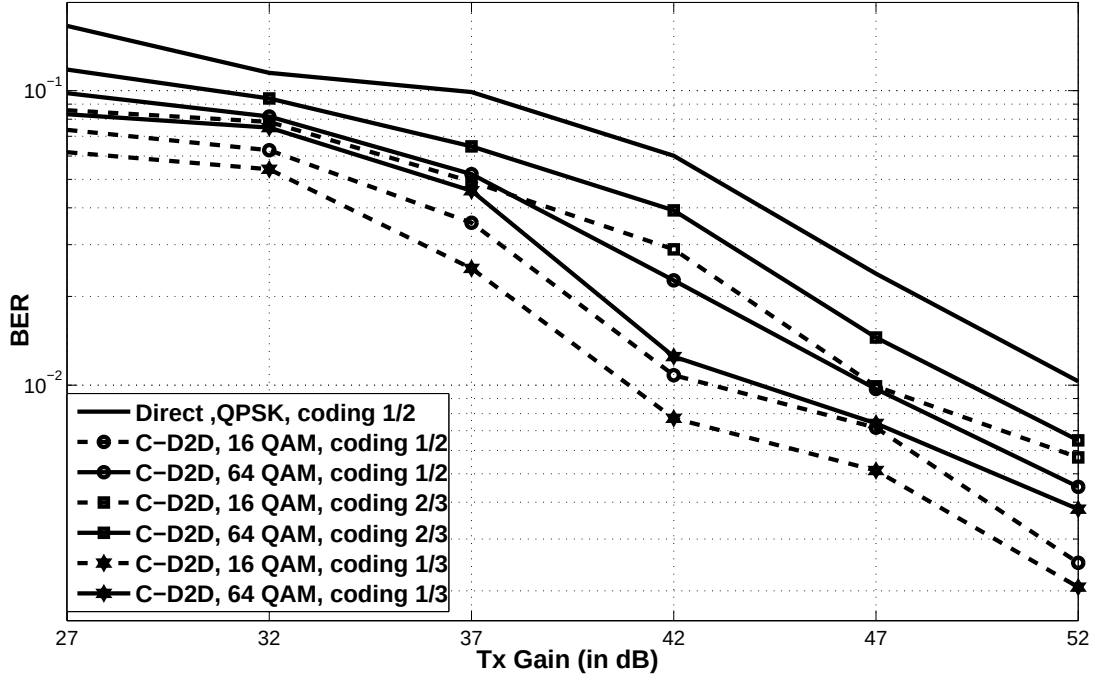


Figure 5.10. BER vs Tx gain for adaptive C-D2D (LOS) communication

Table 5.6. *DR* and maximum achievable *SE* for C-D2D communication

Link, modulation and coding	<i>DR</i> (Mbps)	<i>SE</i> (bps/Hz)
CU-BS, QPSK (direct), coding 1/2	12	0.6
CU-DT, QPSK, coding 1/2 and DT-BS, 16 QAM, coding 1/2	16.656	0.8328
CU-DT, QPSK, coding 1/2 and DT-BS, 64 QAM, coding 1/2	19.392	0.9696
CU-DT, QPSK, coding 1/2 and DT-BS, 16 QAM, coding 2/3	19.04	0.9520
CU-DT, QPSK, coding 1/2 and DT-BS, 64 QAM, coding 2/3	21.504	1.0752
CU-DT, QPSK, coding 1/2 and DT-BS, 16 QAM, coding 1/3	13.812	0.6906
CU-DT, QPSK, coding 1/2 and DT-BS, 64 QAM, coding 1/3	17.052	0.8526

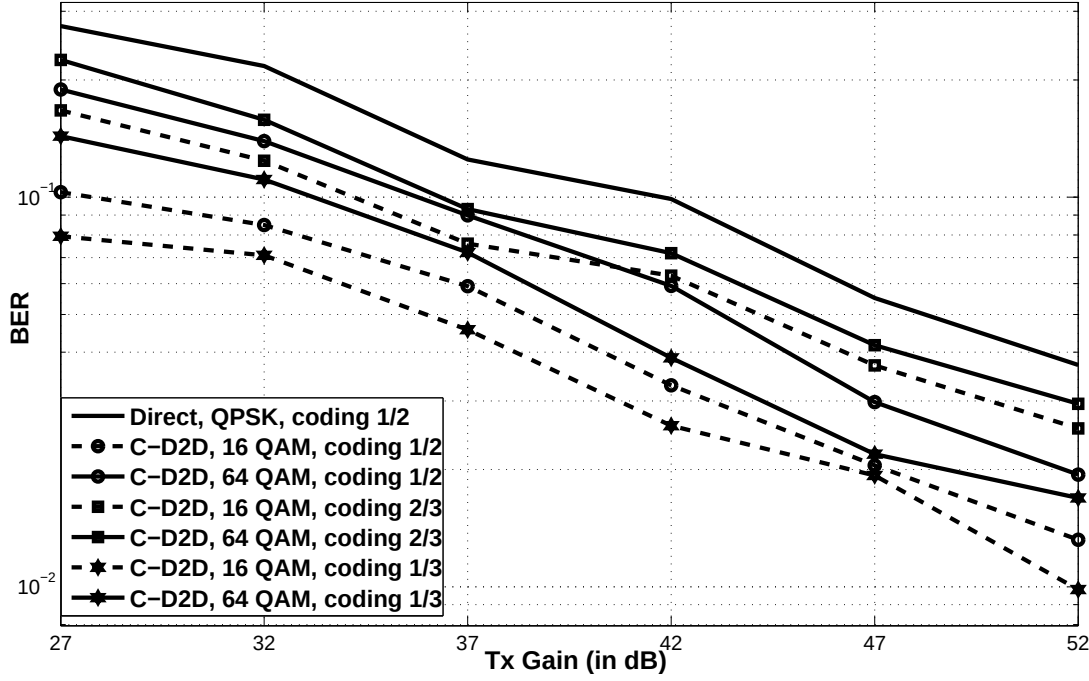


Figure 5.11. BER vs Tx gain for adaptive C-D2D (N-LOS) communication

that the BER performance of the proposed scheme for LOS scenario is better than the NLOS scenario.

Fig. 5.12 shows the BER vs Tx gain for DT-DR link. BER decreases when the Tx gain increases. Here, DT transmits its data to DR with 16-QAM or 64-QAM and CCR = 1/3, 1/2, 2/3.

Table 5.6 shows SE_{av} and DR_{av} for CU-BS (direct) and proposed C-D2D scheme. From Table 5.6, we can observe that SE_{av} calculated for adaptive C-D2D is greater than SE for CU-BS (direct) communication. For instance, for CU-BS (direct), $M = 4$, CCR = 1/2, $SE = 0.6$ bps/Hz and $DR = 12$ Mbps, whereas, for adaptive C-D2D, with $M = 64$, CCR = 2/3 (for DT-BS (LOS)), $SE_{av} = 1.0752$ bps/Hz and $DR_{av} = 21.504$ Mbps. Hence, we can conclude that adaptive C-D2D improves the SE_{av} and DR_{av} of the cellular user.

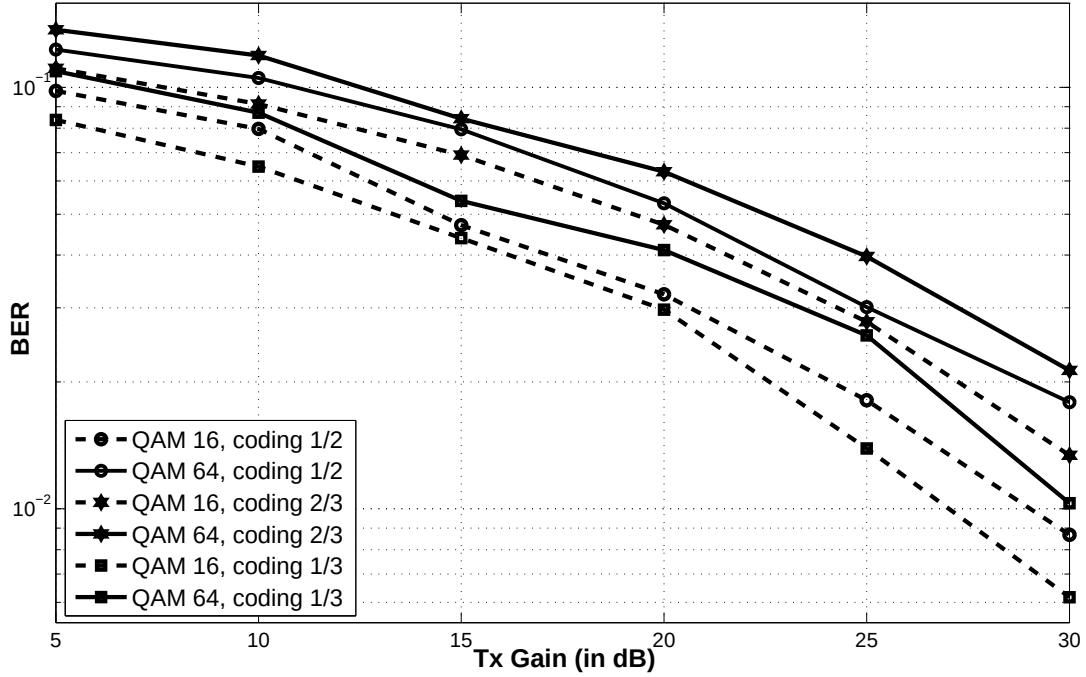


Figure 5.12. BER vs Tx gain for DT-DR link

5.3.3 Adaptive interference aware U-D2D

In this section, we show the measurement results for the adaptive interference aware U-D2D framework, and for the benchmark of comparison measurement results for conventional U-D2D are also obtained.

We follow the OFDM specifications⁵ as laid down in 802.11g standard operating at industrial, scientific, and medical radio (ISM) band of 2.4 GHz [102].

BER is calculated by an taking average of P number of packets allocated over N_d subcarriers. The distance between nodes was selected on the basis of transmitting power and receiver sensitivity of USRP-2922 i.e. $d_1=2\text{m}$, $d_2=0.5\text{m}$, $d_3=1.5\text{m}$ and $d_4=2.25\text{m}$. The DT Tx gain is fixed at 0 dB. Noise variance at each node was measured to be -115 dBm. The values of τ_u and τ_l are 0.07 and 0.004 respectively.

We have taken $N_{FFT} = 64$, and 48 subcarriers are used for data transmission i.e. $N_d = 48$. Four pilot symbols are used for channel estimation. 12 null subcarriers

⁵Since it is a proof-of-concept demonstration, we restricted our implementation to OFDM standards of 802.11g in ISM band of 2.4 GHz. However, these measurements can be reproduced on any other standard or frequency band.

are also added (including DC) to avoid spectrum leakage to adjacent bands. The length of the cyclic prefix, $\mu = 16$ samples. Therefore, each OFDM block has N_t number of samples, where, $N_t = N_{FFT} + \mu = 80$ (including both data and cyclic prefix). The convolution code is used as an error correction code with $CCR = 1/2$.

Table 5.7. Distribution of subcarriers with respect to τ

CU Tx Gain (in dB)	Number of subcarriers in U-D2D communication (ς)	Number of subcarriers in interference aware U-D2D communication (δ)	Number of subcarriers in adaptive interference aware U-D2D communication (ζ)
10	29	19	0
15	37	11	0
20	7	5	36
25	6	1	41
30	0	0	48

Table 5.7, shows the number of subcarriers for the different mode of communication on the basis of BER threshold at BS. From Table 5.7, we can observe as Tx gain increases, ζ increases, whereas ς , and δ decreases. In particular, when CU Tx gain=10 dB, $\varsigma=29$, $\delta=19$ and $\zeta=0$, while when CU Tx gain=25 dB, $\varsigma=6$, $\delta=1$ and $\zeta=41$. Hence, for high Tx gain, more subcarriers can be transmitted by adaptive interference aware U-D2D mode.

CU Gain (in dB)	Number of subcarriers in adaptive interference aware U-D2D communication		DR_{av} (Mbps)	SE_{av} (bps/Hz)
	n_1	n_2		
10	48	0	12	0.6
15	48	0	12	0.6
20	30	18	16.5	0.825
25	25	23	17.75	0.8875
30	22	26	18.5	0.925

Table 5.8. DR_{av} and maximum achievable SE_{av} for adaptive interference aware U-D2D

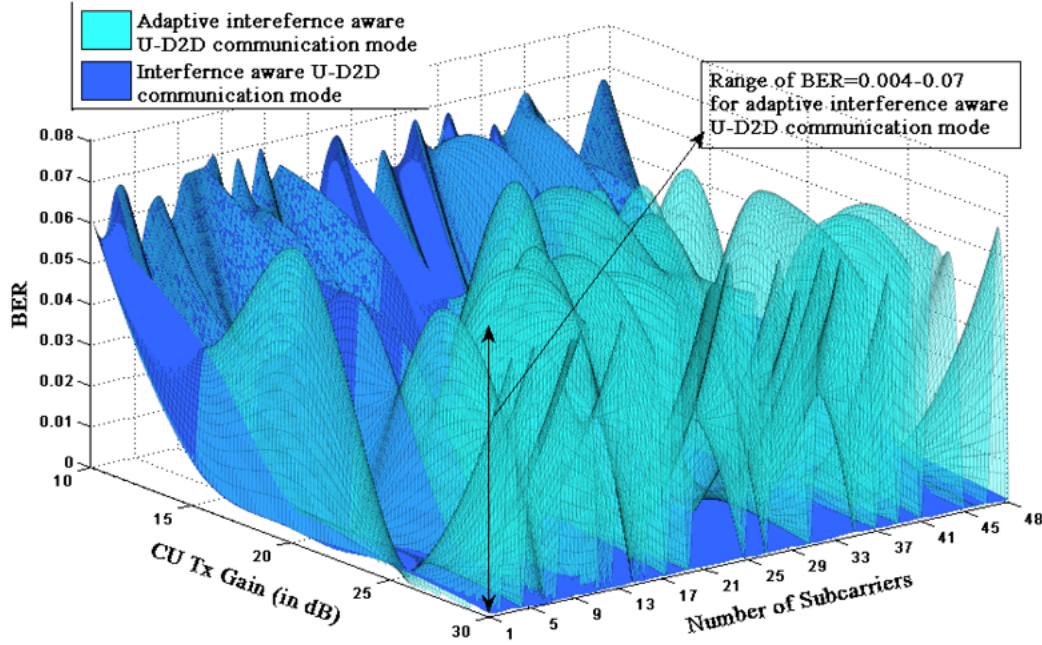


Figure 5.13. BER vs Tx gain of CU vs number of subcarriers for adaptive interference aware U-D2D communication at DT Tx gain=0 dB

Fig. 5.13 shows the performance comparison of interference aware U-D2D communication and adaptive interference aware U-D2D communication mode in terms of BER. Here, for a particular subcarrier, if BER is less than τ_l then it is modulated by 16-QAM, thus increasing SE . If the BER for adaptive interference aware U-D2D communication mode is greater than τ_u , then that particular subcarrier is transmitted with interference aware U-D2D communication mode.

From Table 5.8, we can observe that maximum available SE_{av} increases with increase in CU Tx gain. For instance, at CU Tx gain=15 dB, selected mode will be U-D2D only, therefore maximum achievable SE_{av} =0.6 bps/Hz while at CU Tx gain=25, n_1 =25, and n_2 =23. Hence, the maximum achievable SE_{av} increases to 0.8875 bps/Hz. Thus, for high CU gain, the proposed scheme improves SE of CU as compared to the conventional U-D2D communication mode.

5.4 Conclusion

An experimental testbed for the C-D2D framework was designed and implemented using (NI) USRP-2922 devices. The performance of the testbed is measured in terms of received SNR and SER. Results show that the C-D2D framework improves the QoS of the cellular user, and in addition pave the way for D2D communication. Further, an adaptive C-D2D framework is proposed to facilitate D2D communication in the cellular network. Measurement results show that the adaptive C-D2D outperforms the conventional C-D2D framework. In addition, an adaptive interference aware underlay D2D framework is proposed to protect the cellular user from excessive interference from the D2D user. Measurement results show that the proposed framework improves BER as well as the spectral efficiency of the overall system as compared to conventional underlay D2D framework.

Conclusions and Future Work

The explosion of mobile data traffic raises the problem of spectrum scarcity, and it is one of primary driving force for the next generation cellular networks. There are various solutions proposed to increase the efficiency of existing cellular networks. This thesis investigated two promising solutions to alleviate the above problem: cooperative spectrum sharing and device to device communication.

The research work presented in the thesis are categorized into four parts. In the first part, an OFDM based subcarrier sharing scheme is proposed in which the secondary system attains OSS by helping the primary system to achieve its target rate of communication. The proposed scheme is classified into two categories: (i) non-adaptive CSS with MRC diversity (ii) adaptive CSS with BER-SC diversity. As a primary contribution, for both categories, closed-form expressions of outage probability for the primary and secondary systems are derived. Analytical expression of critical distance which determines the region of validity of the proposed scheme is also derived. The proposed scheme alleviates the problem of secondary signal interference at the primary system as occurs in single carrier based CSS protocols. Moreover, incorporation of adaptive modulation at ST increases the throughput of the primary system while satisfying its BER constraint. Results show that, depending on the distance between PT and ST, it is possible to find the exact number of subcarriers that can be forwarded by ST to PR for both adaptive and nonadaptive CSS protocols. Thus, remaining subcarriers can be used for secondary system transmission.

In the second part, we presented the OFDMA based angle constraint D2D

communication. Rate and outage probability trade-offs of three D2D frameworks: underlay, overlay, and C-D2D are computed. The closed-form expressions of the outage probability for all three frameworks are derived. Specifically, for underlay framework, the optimal distance between CU-BS and the minimum value of angle θ (an angle between cellular link and D2D interference link) is also derived. By using above parameters, BS can select a CU which can facilitate D2D communication while satisfying its QoS. For overlay and C-D2D frameworks, an optimal subcarrier sharing scheme is proposed which leads to performance gains for the cellular and D2D users. There is good agreement between the analytical and simulation results. The results also showed that for high cellular outage constraint, C-D2D framework outperforms the other two frameworks.

In the third part, we augment the development of C-D2D, by proposing a best D2D user selection protocol for the C-D2D framework wherein multiple D2D users co-exist with the cellular users in the same cell. Specifically, among M available D2D pairs, selected D2D user (based on received SNR) helps the CU by relaying few subcarriers for uplink cellular transmission. In return, M D2D UE can share the spectrum of single CU while satisfying the target QoS of CU. In addition, for fair distribution of remaining subcarriers among M D2D pairs, a novel round robin method with priority cube is also proposed. The rate and outage probability of the proposed framework are derived for two cases:

- CU-DT-BS link (without MRC at BS)
- CU-DT-BS with cellular link (with MRC at BS).

For given distance, power and target rate, an optimal value of M is also derived. By using M , BS maps the optimal number of D2D pairs with each CU while satisfying the QoS of both cellular and D2D users. Simulation results show that the proposed best D2D user selection scheme outperforms the conventional C-D2D framework.

In the fourth part, we have designed and implemented an experimental testbed for the C-D2D framework on NI-USRP 2922 platform. Further, measurement results for OFDMA based C-D2D framework are also obtained. In an adaptive C-D2D framework, we employ adaptive modulation and coding (AMC) at DT to enhance the throughput of both cellular and D2D users. The measurement results

are obtained in terms of SER and received SNR. The spectral efficiency of the proposed scheme is also computed. It is shown that the proposed framework significantly improves the SER and BER of both cellular and D2D users as compared to conventional direct communication.

6.1 Future work

In this section, we present the exciting directions for future work.

- In this thesis, we consider a single cell scenario with an assumption of negligible inter-cell interference. A straightforward extension of our work is the investigation of the behavior of proposed scheme in the multi-cell scenario or multi tier heterogeneous network.
- In this thesis, we assume that all subcarriers carry equal power and wireless channel is modeled as Rayleigh frequency flat. As a part of future work, the proposed work can be extended for frequency selective channel with variable subcarrier power. Apart from above, different level of adaptation such as bin level, frame level, subcarrier level can be adopted at different wireless nodes.
- For the measurement results, only one D2D pair is considered. As a part of future work, multiple D2D pairs can be used to scale the performance of the proposed scheme with the increase in density of devices. In addition, practical performance of the best D2D user selection scheme for C-D2D framework proposed in Chapter 4 can be obtained in a realistic scenario. Furthermore, the experiments have been performed in an indoor laboratory environment. It would be interesting to see the performance assessment in challenging outdoor environment.
- Finally, in the higher frequency band (for e.g. mmWave), integration of D2D communication and massive MIMO would be interesting. The mmWave system requires directivity gain to counter the severe channel attenuations. This directionality can lead to performance gains for D2D communication due to less multi user interference in mmWave network.

Appendix A

Derivation of primary system outage probability for adaptive CSS with BER-SC diversity

Proof of Proposition 2.1: From (2.10),

$$P_{out}^p = \Pr(R_N^{Pt-St} > R_T) \Pr(R_{BER-SC} < R_T) + \Pr(R_N^{Pt-St} < R_T) \Pr\left(\frac{1}{2}R_N < R_T\right). \quad (\text{A.1})$$

where,

$$\Pr\left(\frac{1}{2}R_N < R_T\right) = \Pr\left(\gamma_1 < \frac{\rho_1 \sigma^2}{p_p}\right) = 1 - e^{-\frac{\zeta_1^l \sigma^2}{p_p} \rho_1} \quad (\text{A.2})$$

and,

$$\Pr(R_N^{Pt-St} < R_T) = \Pr\left(\gamma_2 < \frac{\rho_1 \sigma^2}{p_p}\right) = 1 - e^{-\frac{\zeta_2^l \sigma^2}{p_p} \rho_1}. \quad (\text{A.3})$$

Similarly,

$$\Pr(R_N^{Pt-St} > R_T) = \Pr\left(\gamma_2 > \frac{\rho_1 \sigma^2}{p_p}\right) = e^{-\frac{\zeta_2^l \sigma^2}{p_p} \rho_1}. \quad (\text{A.4})$$

As $\gamma_1 \sim \exp(\zeta_1^l)$, $\gamma_2 \sim \exp(\zeta_2^l)$, and $\rho_1 = 2^{\frac{2R_T}{N}-1}$, we can have

$$\Pr(R_{BER-SC} < R_T) = \Pr\left(\left(1 + \frac{p_s \gamma_3}{\sigma^2}\right)^{bD} \left(1 + \frac{p_p \gamma_1}{\sigma^2}\right)^{N-D} < 2^{2R_T}\right), \quad (\text{A.5})$$

where $b = \log_2(M)$.

Let $\frac{p_p \gamma_1}{\sigma^2} \gg 1$ and $\frac{p_s \gamma_3}{\sigma^2} \gg 1$. Thus, (A.5) can be deduced to,

$$\approx \Pr \left(\left(\frac{p_s \gamma_3}{\sigma^2} \right)^{bD} \left(\frac{p_p \gamma_1}{\sigma^2} \right)^{N-D} < 2^{2R_T} \right) \quad (\text{A.6})$$

$$\approx \Pr \left(\gamma_3 < \frac{\Delta}{\gamma_1^{\frac{N-D}{bD}}} \right). \quad (\text{A.7})$$

where,

$$\Delta = \frac{\left(2^{2R_T} \sigma^{2N} \right)^{1/bD}}{p_s p_p^{\frac{N-D}{bD}}}. \quad (\text{A.8})$$

As γ_1 and γ_3 are independent exponential random variable, it's joint probability density function can be represented as $\zeta_1^l e^{-\zeta_1^l \gamma_1} \zeta_3^l e^{-\zeta_3^l \gamma_3}$.

Therefore,

$$\Pr \left(\gamma_3 < \frac{\Delta}{\gamma_1^{\frac{N-D}{bD}}} \right) = \int_{\gamma_1=0}^{\infty} \int_{\gamma_3=0}^{\frac{\Delta}{\gamma_1^{\frac{N-D}{bD}}}} \zeta_1^l e^{-\zeta_1^l \gamma_1} \zeta_3^l e^{-\zeta_3^l \gamma_3} d\gamma_1 d\gamma_3. \quad (\text{A.9})$$

After solving inner integral, we will get,

$$\Pr \left(\gamma_3 < \frac{\Delta}{\gamma_1^{\frac{N-D}{bD}}} \right) = 1 - \zeta_1^l \int_{\gamma_1=0}^{\infty} \exp \left[- \left(\zeta_1^l \gamma_1 + \frac{\zeta_3^l \Delta}{\gamma_1^{\frac{N-D}{bD}}} \right) \right] d\gamma_1. \quad (\text{A.10})$$

Therefore,

$$\Pr(R_{BER-SC} < R_T) = 1 - \zeta_1^l \chi; \eta_{ST} < \eta_{PT} \quad (\text{A.11})$$

where,

$$\chi = \int_{\gamma_1=0}^{\infty} \exp \left[- \left(\zeta_1^l \gamma_1 + \frac{\zeta_3^l \Delta}{\gamma_1^{\frac{N-D}{bD}}} \right) \right] d\gamma_1. \quad (\text{A.12})$$

Hence from (A.2),(A.3),(A.4),(A.11), the primary system outage probability is,

$$P_{out}^p = e^{-\frac{\zeta_2^l \sigma^2}{p_p} \rho_1} (1 - \zeta_1^l \chi) + \left(1 - e^{-\frac{\zeta_2^l \sigma^2}{p_p} \rho_1} \right) \left(1 - e^{-\frac{\zeta_1^l \sigma^2}{p_p} \rho_1} \right). \quad (\text{A.13})$$

Asymptotic expression for η_{BER-SC}

Proof of Proposition 2.2: In this appendix, we present the derivation of asymptotic approximation for η_{BER-SC} . To derive asymptotic expression, we have used following approximation,

$$1 - \sqrt{\frac{a}{1+a}} \stackrel{a \rightarrow \infty}{\approx} \frac{1}{2a} - \frac{3}{8a^2} + \dots \quad (\text{B.1})$$

where (B.1) is derived by Taylor's series expansion and after truncation higher order terms, we can neglect all terms other than $\frac{1}{2a}$ in (B.1).

Using above approximation, we can define (2.18) as,

$$\eta_{PT-ST} \approx \frac{k_{M_{PT}}}{4d_{M_{PT}}^2 \zeta_2^{-l} \Gamma}. \quad (\text{B.2})$$

Similarly, (2.19) can be approximated as,

$$\varphi_{PT-ST} \approx \frac{Nk_{M_{PT}}}{4d_{M_{PT}}^2 \zeta_2^{-l} \Gamma}, \quad (\text{B.3})$$

In the similar way, (2.20) can be deduce to,

$$\eta_{comb-PR} \approx \frac{3}{16} \frac{k_{M_{PT}} + k_{M_{ST}}}{d_{M_{PT}}^2 d_{M_{ST}}^2 \zeta_1^{-l} \zeta_3^{-l} \Gamma^2}. \quad (\text{B.4})$$

By substituting (B.1), (B.3) and (B.4) in (2.15), we will get (2.23).

Derivation of primary system outage probability for nonadaptive CSS with MRC

Proof of Proposition 2.3. The outage probability of primary system for nonadaptive CSS with MRC [32] can be defined as,

$$P_{out}^p = \Pr(R_N^{Pt-St} > R_T) \Pr(R_{PR}^{MRC} < R_T) + \Pr(R_N^{Pt-St} < R_T) \Pr\left(\frac{1}{2}R_N < R_T\right) \quad (C.1)$$

$$\Pr(R_{PR}^{MRC} < R_T) = \Pr\left(\left(1 + \frac{p_p \gamma_1}{\sigma_1^2} + \frac{p_s \gamma_3}{\sigma_1^2}\right)^D \left(1 + \frac{p_p \gamma_1}{\sigma_1^2}\right)^{N-D} < 2^{2R_T}\right). \quad (C.2)$$

Let $\sigma_1^2 = \sigma_2^2 = \sigma_3^2 = \sigma^2$,

$$= \Pr\left(\left(1 + \frac{p_p \gamma_1}{\sigma^2} + \frac{p_s \gamma_3}{\sigma^2}\right)^D \left(1 + \frac{p_p \gamma_1}{\sigma^2}\right)^{N-D} < 2^{2R_T}\right). \quad (C.3)$$

Let $\frac{p_p \gamma_1}{\sigma^2} + \frac{p_s \gamma_3}{\sigma^2} \gg \sigma^2$, Now (C.3) deduce to

$$= \Pr\left((p_p \gamma_1 + p_s \gamma_3)^D (p_p \gamma_1)^{N-D} < 2^{2R_T} \sigma^{2N}\right), \quad (C.4)$$

$$= \Pr \left((p_p \gamma_1 + p_s \gamma_3) < \frac{(2^{2R_T} \sigma^{2N})^{\frac{1}{D}}}{(p_p \gamma_1)^{\frac{N-D}{D}}} \right), \quad (\text{C.5})$$

$$= \Pr \left(\gamma_3 < \frac{\Lambda^{\frac{1}{D}}}{p_s (p_p \gamma_1)^{\frac{N-D}{D}}} - \frac{p_p \gamma_1}{p_s} \right). \quad (\text{C.6})$$

where $\Lambda = 2^{2R_T} \sigma^{2N}$

Let's

$$\frac{\Lambda^{\frac{1}{D}}}{p_s (p_p \gamma_1)^{\frac{N-D}{D}}} - \frac{p_p \gamma_1}{p_s} = \beta(\gamma_1), \quad (\text{C.7})$$

where $\gamma_3 \sim \exp(\zeta_3^l)$ and for exponential random variable,

$$\beta(\gamma_1) > 0 \quad (\text{C.8})$$

$$\frac{\Lambda^{\frac{1}{D}}}{p_s (p_p \gamma_1)^{\frac{N-D}{D}}} - \frac{p_p \gamma_1}{p_s} > 0. \quad (\text{C.9})$$

Simplifying (C.9), we will get,

$$\gamma_1 < \frac{\Lambda^{\frac{1}{N}}}{p_p} = \alpha(\text{let}). \quad (\text{C.10})$$

As γ_1 and γ_3 are independent exponential random variable, it's joint probability density function can be represented as $\zeta_1^l e^{-\zeta_1^l \gamma_1} \zeta_3^l e^{-\zeta_3^l \gamma_3}$

$$\Pr(\gamma_3 < \beta(\gamma_1)) = \int_{\gamma_1=0}^{\alpha} \int_{\gamma_3=0}^{\beta(\gamma_1)} \zeta_1^l e^{-\zeta_1^l \gamma_1} \zeta_3^l e^{-\zeta_3^l \gamma_3} d\gamma_1 d\gamma_3 \quad (\text{C.11})$$

$$= \int_{\gamma_1=0}^{\alpha} \zeta_1^l e^{-\zeta_1^l \gamma_1} \left(1 - e^{-\zeta_3^l \beta(\gamma_1)} \right) d\gamma_1 \quad (\text{C.12})$$

$$= 1 - e^{-\zeta_1^l \alpha} - \zeta_1^l \Upsilon_1 \quad (\text{C.13})$$

where Υ_1 , and δ_1 , δ_2 has been given in (2.31) and (2.32) respectively.

After substituting (A.2), (A.3), (A.4) and (C.13) in (C.1), we will get (2.30).

(2.31) is intractable, however, if we substitute, $\delta_2 = 0$ i.e. $\frac{\zeta_1^l}{\zeta_3^l} = \frac{p_p}{p_s}$, (2.31) can be deduced to,

$$\Upsilon_1 = \int_{\gamma_1=0}^{\alpha} e^{-\delta_1 \gamma_1} e^{-\left(\frac{N}{D}-1\right)} d\gamma_1. \quad (\text{C.14})$$

Substitute $\gamma_1^{-\frac{N-D}{D}} = t$ in (C.14),

$$\Upsilon_1 = \frac{D}{N-D} \int_{\alpha^{-\frac{N-D}{D}}}^{\infty} t^{-\frac{N}{N-D}} e^{-\delta_1 t} dt. \quad (\text{C.15})$$

From [95], (C.15) can be solved as,¹

$$\Upsilon_1 = (-1)^{n+1} \delta_1^n \frac{Ei(-\delta_1 u)}{n!} + \frac{e^{-\delta_1 u}}{u^n} \sum_{k=0}^{n-1} \frac{(-1)^k \delta_1^k u^k}{n(n-1)\dots(n-k)} \quad (\text{C.16})$$

where, $n = \frac{D}{N-D}$ and $u = \alpha^{-\frac{N-D}{D}}$

Hence, from (A.2),(A.3),(A.4),(C.13) the primary outage probability,

$$P_{out}^p = e^{-\frac{\zeta_2^l \sigma^2}{p_p} \rho_1} (1 - e^{-\zeta_1^l \alpha} - \zeta_1^l \Upsilon_1) + \left(1 - e^{-\frac{\zeta_2^l \sigma^2}{p_p} \rho_1}\right) \left(1 - e^{-\frac{\zeta_1^l \sigma^2}{p_p} \rho_1}\right). \quad (\text{C.17})$$

¹However, we have solved (2.31) numerically to obtain the theoretical plots.

Appendix D

Derivation of the cellular outage probability for CU-DT-BS with cellular link

Proof of Proposition 4.1: From (4.19)

$$P_{BS,out}^{mrc} = P'_1 \Pr(R_{BS}^{MRC} < R_T) + P_1 \Pr\left(\frac{1}{2}R_N < R_T\right), \quad (D.1)$$

where R_N can be found from (4.14).

From (4.5) and (4.14),

$$\Pr\left(\frac{1}{2}R_N < R_T\right) = \Pr\left(\gamma_1 < \frac{\rho_1 \sigma^2}{p_{cu}}\right) = 1 - e^{-\frac{\zeta_1^l \sigma^2}{p_{cu}} \rho_1}. \quad (D.2)$$

P_1 denotes the probability that no DT_i is able to decode and is given by ,

$$P_1 = \prod_{i=1}^M \Pr(R_{2i}^{CU-DT} < R_T) = \prod_{i=1}^M \left(1 - e^{-\frac{\zeta_{2i}^l \sigma^2}{p_{cu}} \rho_1}\right). \quad (D.3)$$

$$P'_1 = 1 - P_1 = 1 - \prod_{i=1}^M \left(1 - e^{-\frac{\zeta_{2i}^l \sigma^2}{p_{cu}} \rho_1}\right). \quad (D.4)$$

Further,

$$Pr(R_{BS}^{MRC} < R_T) = Pr \left(\left(1 + \frac{\gamma_1 p_{cu}}{\sigma^2} + \max_{i=1,2..M} \frac{\gamma_{3i} p_{dt}}{\sigma^2} \right)^D \left(1 + \frac{\gamma_1 p_{cu}}{\sigma^2} \right)^{N-D} < 2^{2R_T} \right). \quad (D.5)$$

$$\begin{aligned} &= Pr \left(\left(1 + \frac{\gamma_1 p_{cu}}{\sigma^2} + \max_{i=1,2..M} \frac{\gamma_{3i} p_{dt}}{\sigma^2} \right) < \frac{(2^{2R_T})^{\frac{1}{D}}}{\left(1 + \frac{\gamma_1 p_{cu}}{\sigma^2} \right)^{\frac{N-D}{D}}} \right) \\ &= Pr \left(\max_{i=1,2..M} \frac{\gamma_{3i} p_{dt}}{\sigma^2} < \frac{(2^{2R_T})^{\frac{1}{D}}}{\left(1 + \frac{\gamma_1 p_{cu}}{\sigma^2} \right)^{\frac{N-D}{D}}} - \frac{\gamma_1 p_{cu}}{\sigma^2} - 1 \right) \\ &= Pr \left(\max_{i=1,..,M} \gamma_{3i} < \frac{\sigma^2}{p_{dt}} \left[\frac{\Lambda}{\left(1 + \frac{\gamma_1 p_{cu}}{\sigma^2} \right)^{\frac{N-D}{D}}} - \frac{\gamma_1 p_{cu}}{\sigma^2} - 1 \right] \right), \end{aligned} \quad (D.6)$$

where $\Lambda = 2^{2R_T/D}$.

Let,

$$\frac{\sigma^2}{p_{dt}} \left[\frac{\Lambda}{\left(1 + \frac{\gamma_1 p_{cu}}{\sigma^2} \right)^{\frac{N-D}{D}}} - \frac{\gamma_1 p_{cu}}{\sigma^2} - 1 \right] = \beta(\gamma_1) \quad (D.7)$$

where, $\gamma_{3i} \sim \exp(\zeta_{3i}^l)$ and for exponential random variable,

$$\beta(\gamma_1) > 0$$

$$\frac{\sigma^2}{p_{dt}} \left[\frac{\Lambda}{\left(1 + \frac{\gamma_1 p_{cu}}{\sigma^2} \right)^{\frac{N-D}{D}}} - \frac{\gamma_1 p_{cu}}{\sigma^2} - 1 \right] > 0 \quad (D.8)$$

After simplifying (D.8) we get,

$$\gamma_1 < \frac{(\Lambda^{\frac{D}{N-1}} - 1)\sigma^2}{p_{cu}} = \alpha \text{ (let)}.$$

As γ_1 and γ_{3i} are independent exponential random variables, the joint probability density function can be represented as $\zeta_1^l e^{-\zeta_1^l \gamma_1} \zeta_{3i}^l e^{-\zeta_{3i}^l \gamma_{3i}}$

$$\begin{aligned}
Pr \left(\max_{i=1,\dots,M} \gamma_{3i} < \beta(\gamma_1) \right) &= \int_{\gamma_1=0}^{\alpha} \zeta_1^l e^{-\zeta_1^l \gamma_1} \left(\prod_{i=1}^M \int_{\gamma_{3i}=0}^{\beta(\gamma_1)} \zeta_{3i}^l e^{-\zeta_{3i}^l \gamma_{3i}} d\gamma_{3i} \right) d\gamma_1 \\
&= \int_{\gamma_1=0}^{\alpha} \zeta_1^l e^{-\zeta_1^l \gamma_1} \left(\prod_{i=1}^M \left(1 - e^{-\zeta_{3i}^l \beta(\gamma_1)} \right) \right) d\gamma_1 \\
&= 1 - e^{-\zeta_1^l \alpha} + \zeta_1^l \left(-\frac{M}{1!} \Upsilon_1 + \frac{M(M-1)}{2!} \Upsilon_2 + \dots \right. \\
&\quad \left. + (-1)^M \frac{M(M-1)\dots(M-(n-1))}{M!} \Upsilon_M \right). \tag{D.9}
\end{aligned}$$

where,

$$\Upsilon_n = \int_{\gamma_1=0}^{\alpha} e^{(\Delta_{2n}\gamma_1 - \Delta_{1n}(\gamma_1))} d\gamma_1, n = 1, 2 \dots M, \tag{D.10}$$

$$\Delta_{2n} = n\delta_2 - \zeta_1^l, \Delta_{1n}(\gamma_1) = n\delta_1, \tag{D.11}$$

$$\delta_2 = \frac{\zeta_{3n}^l p_{cu}}{p_{dt}}, \delta_1 = \frac{\zeta_{3n}^l \sigma^2}{p_{dt}} \left[\frac{\Lambda}{\left(1 + \frac{\gamma_1 p_{cu}}{\sigma^2}\right)^{\frac{N-D}{D}}} - 1 \right] \tag{D.12}$$

Hence, substituting (D.2), (D.3), (D.4) and (D.9) into (D.1), we will get $P_{BS,out}^{mrc}$ as (4.20).

Moreover,

$$\begin{aligned}
Pr \left(\max_{i=1,\dots,M} \gamma_{3i} < \beta(\gamma_1) \right) &= \int_{\gamma_1=0}^{\alpha} \zeta_1^l e^{-\zeta_1^l \gamma_1} \left(\prod_{i=1}^M \left(1 - e^{-\zeta_{3i}^l \beta(\gamma_1)} \right) \right) d\gamma_1 \\
&= I_i(\text{let}) \tag{D.13}
\end{aligned}$$

For $M = 1$, the integral reduces to

$$\begin{aligned}
I_1 &= \int_{\gamma_1=0}^{\alpha} \zeta_1^l e^{-\zeta_1^l \gamma_1} \left(1 - e^{-\zeta_{31}^l \beta(\gamma_1)} \right) d\gamma_1 \\
&= 1 - e^{-\zeta_1^l \alpha} - \zeta_1^l \Upsilon_1. \tag{D.14}
\end{aligned}$$

For $M = 2$, the integral becomes

$$\begin{aligned} I_2 &= \int_{\gamma_1=0}^{\alpha} \zeta_1^l e^{-\zeta_1^l \gamma_1} \left(1 - e^{-\zeta_{31}^l \beta(\gamma_1)}\right) \left(1 - e^{-\zeta_{32}^l \beta(\gamma_1)}\right) d\gamma_1 \\ &= 1 - e^{-\zeta_1^l \alpha} - 2\zeta_1^l \Upsilon_1 + \zeta_1^l \Upsilon_2. \end{aligned} \quad (\text{D.15})$$

Similarly, For $M = 3$,

$$I_3 = 1 - e^{-\zeta_1^l \alpha} - 3\zeta_1^l \Upsilon_1 + 3\zeta_1^l \Upsilon_2 - \zeta_1^l \Upsilon_3. \quad (\text{D.16})$$

Hence, from (D.14), (D.15), (D.16), the general expression of $Pr(\max_{i=1,\dots,M} \gamma_{3i} < \beta(\gamma_1))$ will be derived as (D.9).

Author's Publications

Journal Papers

1. S. Sharma, N. Gupta, V. A. Bohara, "OFDMA-based Device-to-Device Communication Frameworks: Testbed Deployment and Measurement Results", submitted to *IEEE Access Journal*, Jan. 2018
2. N. Gupta, V. A. Bohara, "Angle-Constrained Underlay and Cooperative Device-to-Device Communication Frameworks", submitted to *IEEE Transactions on Cognitive Communications and Networking*, Nov. 2017.
3. N. Gupta, V. A. Bohara, "Rate and Outage Trade-offs for OFDMA based Device to Device Communication Frameworks", in *IEEE Access Journal*, vol. 5, pp. 14095-14106, 2017.
4. S. Mittal, N. Gupta, V. A. Bohara "A BER Based Selection Combining Protocol for Adaptive Cooperative Cognitive Radios", in *Wireless Personal Communications (Springer Journal)*, vol. 97, issue 2, pp. 24972510, June 2017.
5. N. Gupta, V. A. Bohara, "An Adaptive Subcarrier Sharing Scheme for OFDM-Based Cooperative Cognitive Radios", in *IEEE Transactions on Cognitive Communications and Networking*, vol. 2, no. 4, pp. 370-380, Dec. 2016.

Book Chapter

1. N. Gupta, V. A. Bohara, V. K. Singh, “Design and measurement results for cooperative device to device communication,” , accepted as a book chapter in *Resource Allocation in Next-Generation Broadband Wireless Access Networks by IGI-Global*, 2016

Conference Papers

1. N. Gupta, D. Kumar, V. A. Bohara, “User Selection and Resource Allocation for OFDMA based Cooperative Device-to-Device Communication Framework”, submitted to *IEEE ICC*, 2018
2. S. Sharma, N. Gupta, V. A. Bohara, “Insights from the Measurement Results for Adaptive and Cooperative D2D Communication Framework”, accepted in *Proceedings of IEEE WCNC*, Barcelona, Spain, 2017.
3. N. Gupta, V. A. Bohara, “OFDMA Based Angle-Constrained Underlay Device-to-Device Communication”, accepted in *Proceedings of IEEE GLOBECOM 2017*, Singapore, Dec. 2017.
4. N. Gupta, V. K. Singh, S. Sharma, V. A. Bohara, “A proof-of-concept demonstration of cooperative D2D framework based on SDR”, accepted in *Proceedings of IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS) 2017*, Bhubaneswar, 2017.
5. S. Mittal, N. Gupta, V. A. Bohara, “A Cooperative Spectrum Sharing Protocol for Cognitive Two-way AF Relaying System” accepted in *Proceedings of IEEE TENSYP, Cochin*, 2017.
6. N. Gupta, V. A. Bohara, “Subcarrier sharing scheme for overlay and cooperative D2D communication in cellular networks”, in *Proceedings of IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS) 2016*, Bangalore, 2016, pp. 1-6.

7. S. Mittal, V. A. Bohara, N. Gupta, “A BER Based Selection Combining Protocol for Adaptive Cooperative Cognitive Radios”, poster in *European Conference on Networks and Communications (EUCNC-2016)*, Oulu, Finland, 2016.
8. N. Gupta, V. A. Bohara, “A cognitive subcarrier sharing scheme for OFDM based decode-and-forward relaying system”, in *Proceedings of 10th International Conference on cognitive radio oriented wireless networks and communications, CrownCom 2015*, pp. 334-345, Doha, April 2015.
9. N. Jain, S. Sharma, A. Vashistha, V. A. Bohara, N. Gupta, “Cooperative spectrum Sharing using Transmit Antenna Selection for Cognitive Radio Systems, ” in *Proceedings of 10th international conference workshop, Crown-Com*, Doha, 2015, pp. 780-789.
10. N. Gupta, V. A. Bohara, “Outage analysis of cooperative OFDM relaying system with opportunistic spectrum sharing” in *Proceedings of International Conference on Advances in Computing, Communications and Informatics (ICACCI)*, Sept 2014, pp. 2803-2807.

Under preparation

1. N. Gupta, D. Kumar, V. A. Bohara, “Cooperative D2D Communication in Unlicensed Spectrum: Best User Selection and Resource Allocation.”
2. N. Gupta, A. D. Singh, P. Shrivastava, V. A. Bohara, “A Two-Way Cooperative D2D Communication Framework for a Heterogeneous Cellular Network.”

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