ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

MODE SELECTION RULES FOR DEVICE TO DEVICE COMMUNICATIONS: DESIGN CRITERIA AND PERFORMANCE METRICS

M.Sc. THESIS

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Department of Electronics and Communication Engineering

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Thesis Advisor: Assoc. Prof. Dr. Güneş KARABULUT KURT

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

CİHAZDAN CİHAZA İLETİŞİM İÇİN MOD SEÇİM KURALLARI: TASARIM KRİTERLERİ VE BAŞARIM METRİKLERİ

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Khalid MAHMOOD, a **M.Sc.** student of ITU **Institute of / Graduate School of Science Engineering and Technology** student ID **504111341**, successfully defended the **thesis** entitled "**MODE SELECTION RULES FOR DEVICE TO DEVICE COMMUNICATIONS: DESIGN CRITERIA AND PERFORMANCE METRICS**", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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FOREWORD

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This work has been mainly inspired by my desire to contribute to the development of mobile communication. I hope this will be the begining of such contributions.

January 2014 Khalid MAHMOOD

TABLE OF CONTENTS

Page

ABBREVIATIONS

3GPP : 3^{rd} Generation Patnership Project
AWGN : Additive White Gaussian Noise
BER : Bit Error Rate
BTS : Base Transceiver Station
CUE : Cellular User Equipment
D2D : Device-to-Device
E-UTRA : Evolved Universal Terrestrial Radio Access
IEEE : Institute of Electronics and Electrical Engineering
ILA : Interference Limited Area
IP : Internet Protocol
ISI : Inter Symbol Interference
ISR : Interference-to-Signal Ratio
LTE : Long Term Evolution
NLOS : Non Line Of Sight
ProSE : Proximity Service
PSD : Power Spectral Density
QoS : Quality of Service
ROC : Receiver Operating Characteristics
RRC : Radio Resource Control
RSSI : Received Signal Strength Indicator
Rx : Receiver
SINR : Signal-to-Interference and Noise Ratio
SNR : Signal-to-Noise Ratio
Tx : Transmission
UE : User Equipment
WAN : Wide Area Network

LIST OF TABLES

Page

LIST OF FIGURES

Page

MODE SELECTION RULES FOR DEVICE TO DEVICE COMMUNICATIONS: DESIGN CRITERIA AND PERFORMANCE METRICS

SUMMARY

In a traditional cellular network, user equipments (UEs) are connected to the base transciever stations (BTS) where they use the uplink and the downlink resources for communication with other UEs. While the demand of high data rate is increasing, new technology components need to be proposed to meet the requirements. Device-to-Device (D2D) communications is a term used to describe the new technology that allows two devices to communicate with each other directly without using the BTS or the access points of the network infrastructure. D2D communication can also be indirect while using the BTS as a relay. D2D communication leads to better network performance for a number of reasons such as offloading the cellular system, increasing the spectral efficiency, reducing the battery consumption, increased data rate.

Among the challenges of D2D communications are, the discovery of a new D2D communication pair and an optimum criterion mode selection rule for the new D2D pair. Once the discovery of the devices is succesful, the challenge arises of which mode should the D2D pair communication, either using the BTS as a relay or to have a direct link between each other without the involvement of BTS.

The purpose of this study was to propose mode selection rules for device-to-device communication. The proposed mode selection rules are composed of various selection rules and associated performance metrics. The Mode selection rules are ergodic channel capacity, signal to noise ratio (SNR), recieved signal strength indicator (RSSI), interference-to-signal ration (ISR) and distance comparisons. In addition, the detection problem for mode selection is modeled as a hypothesis test, and analytical expressions for correct detection, false alarm, and missed detection are derived.

The selection of mode is done through the maximum detection rule, where the maximum is selected for the capacity, SNR, distance, ISR and RSSI rules. There are many situations in which we are required to choose among several possibilities. For example, choosing which mode to select from different performance metrics, such as received signal strength indication (RSSI). If RSSI of direct mode is greater than that of indirect mode, direct mode is chosen. In this case, the selection involved making a decision among different choices. Such decision was made through hypothesis testing. A set of observations was made for direct and indirect mode of communication. Depending on the set of observations, a decision was made regarding the source of the observations. We can think of a hypothesis as a statement of a possible source of observations. The hypotheses for the RSSI was written as "RSSI for direct mode being higher than for the indirect mode", being the H_1 and "RSSI for direct mode being lower than for the indirect mode", being the H_0, null hypothesis.

For our simulations, we use the hypothesis that are defined for various mode selection rules to select the transmission mode. The hypothesis for capacity is selected when the capacity for either direct or indirect mode is greater than the other simulated value.

The hypothesis for SNR is selected when the SNR for either direct or indirect mode is greater than the other simulated value. The hypothesis for distance, is selected in a way such that when devices are within the distance threshold, direct mode provides a higher system capacity, which is the selected mode. When the devices are beyond the distance threshold, the indirect mode provides higher system capacity and is the selected mode. The distance threshold is selected based on numerical calculations. The hypothesis for ISR is selected when the ISR for either direct or indirect mode is greater than the other simulated value. The ISR value depends on the interference of device in D2D communication pair, with the cellular user equipment. The lesser the interference, the greater will be the ISR, which would increase the capacity of the D2D communication. The hypothesis for RSSI is selected when the RSSI for either direct or indirect mode is greater than the other simulated value.

Later, we introduced different shadowing components as a Gaussian distribution with zero mean and variance σ_i^2 to the mode selection rules. The simulation is done again, but with the addition of shadowing to the mode selection rules. The direct and indirect links for these rules are than calculated. Using the hypothesis that is defined for every mode selection rule, mode is selected by the maximum decision rule. The values of mode selection rules, with and without addition of shadowing are compared. If proper decision was made on selection of a mode, than we said that a correct detection is made. Values of probability of correct detection for every mode selection rules are saved and used to show the performance of the overall system for correct detection. Depending on the hypothesis, decision is made. If false alarm or missed detection is made while selecting a mode, the performance of the overall system degrades. For example, when indirect mode was to be choosen, but direct mode is choosen, a false alarm has been created. The probability of false alarm is calculated for every mode selection rules and used to show the performance of the overall system for false alarm. Similarly, when direct mode was to be choosen, but indirect mode is selected, a missed detection occurs. The probability of missed detection is calculated for every mode selection rules and used to show the performance of the overall system.

The results of probability of correct detection, false alarm and missed detection are shown graphically for every mode selection rule. The graphs for probability of correct detection are compared for every mode selection rule and analyzed that which mode selection rule has the best performance. Similarly the graphs for probability of false alram are compared for every mode selection and analyzed that which mode selection rule has the best performance. The graphs for probability of missed detection are compared for every mode selection rule and analyzed that which mode selection rule has the best performance. Later receiver operating characteristics (ROC) for mode selection rules are shown graphically, in which probability of correct detection is shown with respect to probability of false alarm.

CİHAZDAN CİHAZA İLETİŞİM İÇİN MOD SEÇİM KURALLARI: TASARIM KRİTERLERİ VE BAŞARIM METRİKLERİ

ÖZET

Geleneksel bir hücresel ağda, kullanıcı cihazlar (UEs) diğer UE'ler ile haberleşmek için, mobil cihazdan baz istasyon yönünde ve baz istasyonından mobil cihaz yönünde radyo kaynaklarını kullandıkları alıcı-verici baz istasyonlarına (BTS) bağlanırlar. Yüksek veri hızı talebi artarken, gereksinimleri karşılamak için yeni teknoloji bileşenlerinin önerilmesi gerekir.Cihazdan-cihaza (D2D) haberleşme; iki cihazın birbirleriyle BTS veya şebeke altyapısı erişim noktalarını kullanmaksızın doğrudan haberleşme kurmalarına izin veren yeni teknolojiyi tanımlamak için kullanılan bir terimdir. D2D haberleşme aynı zamanda, BTS'nin bir röle olarak kullanıldığı dolaylı yoldan da kurulabilir. D2D haberleşme, birkaç nedenle daha iyi bir şebeke performansı verebilir. Bu nedenler; D2D haberleşme, BTS'nin hücresel sistemin yükünü boşaltmaya yardımcı olur, spektrum verimliliğini artırır, bit hızını artırır, pil tüketimi azalır ve BTS'nin bir altyapı arızası yaşadığı hallerde D2D haberleşme, bir yedek haberleşme olarak kullanılabilir.

D2D haberleşme birkaç fayda sağlamakla birlikte belli zorluklar da getirmektedir. D2D'nin getirdiği zorluklar arasında; cihazların ne zaman bir D2D haberleşme için bir bağlantı gerektirdiği, yeni bir D2D haberleşme çiftinin nasıl bulunacağı ve yeni D2D çifti için mod seçim kuralının optimum kriterinin ne olacağı gibi sorular yer alır. Cihazlar başarıyla bulunduğu anda D2D çiftinin haberleşmei için hangi modun kullanılması gerektiği sorunu gündeme gelir. Buna göre röle olarak BTS'in kullanılmasına mı yoksa BTS'yi işe hiç karıştırmadan aralarında doğrudan bir bağlantı kurulması mı karar verilmelidir.

Bu çalışmasın amacı, bir D2D haberleşmeine sahip olabilecek cihazları bulmak ve haberleşmein ya BTS olmaksızın ya da röle olarak kullanmak suretiyle BTS ile kurulduğu bir mod seçim kuralı önermektir. Araştırmamızı dört bölüme ayırdık. İlk bölümde, cihazların BTS kapsamı içinde yerleştirildiği sistem modelimizi tanımladık. Cihazlar rastgele yerleştirildikten sonra çeşitli seçim kurallarından oluşan mod seçim kurallarını tanımladık ve performans metrikleri ile ilişkilendirdik. Düşündüğümüz mod seçim kuralları, ergodik kanal kapasitesi, sinyal-gürültü oranı (SNR), alınan sinyal gücü göstergesi (RSSI), girişim-sinyal oranı (ISR) ile mesafe kıyaslamalarıdır. İkinci bölümde, mod seçimi için saptama sorunu bir hipotez testi olarak modellendi ve doğru saptama, yanlış alarm ile kaçan saptama için analitik ifadeler türetildi. Hipotez sınama ile analitik ifadeler her bir mod seçim kuralı için gösterildi ve en iyi performansı yakalamak için karşılaştırıldı. Üçüncü bölümde, ilk bölümde tanıtılan mod seçim kuralları için gölgelendirme getirdik ve bu mod seçim kuralları için eşitlikler türettik. Sonuçlar gölgeleme uygulanmadan önceki ve sonraki mod seçim kuralları ile karşılaştırıldı. Dördüncü bölümde ise farklı senaryolarla simülasyonlar gerçekleştirdik.

Mod seçimi; kapasite, SNR, mesafe, ISR ve RSSI kuralları için maksimum saptama kuralıyla yapıldı. Birkaç ihtimal için seçim yapmamızı gerektirecek pek çok durum mevcut.

Örneğin alınan sinyal gücü göstergesi (RSSI) gibi farklı performans metriklerinden seçim yapmak için modu seçmek. Şayet doğrudan modun RSSI değeri dolaylı moddan daha yüksek ise doğrudan mod seçiler. Bu durumda seçim farklı seçenekler arasında karar vermeyi içerdi. Böyle bir karar hipotez sınama yoluyla yapıldı. Doğrudan ve dolaylı haberleşme modları için bir dizi gözlem yapıldı. Gözlem dizisine bağlı olarak gözlem kaynağı ile ilgili bir karar alındı. Hipotezi, olası gözlem kaynağına ilişkin bir ifade olarak düşünebiliriz. RSSI için kurulan hipotez, "doğrudan mod için RSSI dolaylı mod için RSSI'dan büyüktür" ifadesi H_1 ve "doğrudan mod için RSSI dolaylı mod için RSSI'dan küçüktür" ifadesi H_0 sıfır hipotez olarak yazıldı. Tasarım kriterlerimiz belirlendikten sonra, sistemimizin etkinliğini kontrol etmek için simülasyonlar yapmamız gerekmektedir.

Simülasyonlarımız için transmisyon modunu seçmek üzere çeşitli mod seçim kuralları için tanımlanan hipotezleri kullandık. Kapasite için hipotez, doğrudan ya da dolaylı mod için kapasite diğer simüle edilmiş değerden daha büyük olduğunda seçildi. SNR için hipotez, doğrudan ya da dolaylı mod için SNR diğer simüle edilmiş değerden daha büyük olduğunda seçildi. Mesafe için hipotez, cihazlar mesafe eşiğindeyken doğrudan mod daha yüksek bir sistem kapasitesi sağlayacak şekilde seçildi ki bu da, seçili moddur. Cihazlar mesafe eşiğinin dışındayken, dolaylı mod daha yüksek bir sistem kapasitesi sağlamıştır ve bu da seçili moddur. Mesafe eşiği, sayısal hesaplamalara dayalı olarak seçildi. ISR için hipotez doğrudan ya da dolaylı mod için ISR diğer simüle edilmiş değerden daha büyük olduğunda seçildi. ISR değeri hücresel kullanıcı ekipmanı ile D2D haberleşme çiftinde cihazın girişimine bağlıdır. Girişim daha az olduğunda ISR daha büyük oldu ki, bu da D2D haberleşmeinin kapasitesini arttırmıştır. RSSI için hipotez, doğrudan ya da dolaylı mod için RSSI diğer simüle edilmiş değerden daha büyük olduğunda seçildi. Birbirine yakın cihazlar için RSSI, cihazlar birbirinden uzak iken olduğundan daha yüksek oldu.

Daha sonra mod seçim kurallarına, varyanslı bir Gauss dağılımı olarak farklı gölgeleme bileşenleri ekledir. Her kural için gölgeleme bileşenleri, bu özel mod seçim kuralının özelliklerine göre rasgele oluşturuldu. Simülasyon, mod seçim kurallarına gölgeleme eklenerek tekrar yapıldı. Mod seçim kuralları için doğrudan ve dolaylı linkler daha sonra hesaplandı. Her mod seçim kuralı için tanımlanan hipotezler kullanılarak, maksimum karar kuralıyla mod seçildi. Mod seçim kurallarının değerleri gölgelemeli veya gölgeleme eklenmeden karşılaştırıldı. Bir mod seçiminde uygun karar alınmış ise, o zaman doğru tespitin yapıldığını söyledik. Her mod seçim kuralı için doğru saptama olasılığının değerleri kaydedildi ve doğru saptama için genel sistem performansını göstermek için kullanıldı. Hipoteze bağlı olarak karar verildi. Mod seçerken yanlış bir karar alındığı takdirde, genel sistem performansı düştü. Örneğin; dolaylı modun seçilmesi gerekirken doğrudan mod seçildiği takdirde, yanlış alarm oluştu. Yanlış alarm olasılığı her mod seçim kuralı için hesaplandı ve yanlış alarm için genel sistem performansını göstermek üzere kullanıldı. Benzer şekilde, doğrudan modun seçilmesi gerekirken dolaylı mod seçildiği takdirde, kaçan bir saptama oluştu. Kaçan saptama olasılığı her mod seçim kuralı için hesaplandı ve genel sistem performansını göstermek için kullanıldı.

Doğru saptama, yanlış alarm ve kaçan saptamanın olasılık sonuçları, her bir mod seçim kuralı için grafik olarak gösterildi. Doğru saptama olasılığına ait grafikler her bir mod seçim kuralı için karşılaştırıldı ve hangi mod seçimin en iyi performansı verdiğine ilişkin olarak analiz edildi. Benzer şekilde yanlış alarm olasılık grafikleri de her bir mod seçim kuralı için karşılaştırılıp hangi mod seçim kuralının en iyi performansı verdiğine ilişkin olarak analiz edildi. Kaçan saptama olasılık grafikleri de, her bir mod seçim kuralı için karşılaştırılıp, hangi mod seçim kuralının en iyi performansı verdiğine ilişkin olarak analiz edildi. Daha sonra mod seçim kuralları için alıcı çalışma karakteristik özellikleri (ROC), doğru saptama olasılığının yanlış alarm olasılığına bağlı olarak ifade edildiği grafiksel biçimde gösterildi.

1. INTRODUCTION

1.1 Cellular Communication

Cellular communication has grown comprehensively since the start of era where people can make or receive calls from almost anywhere. Cellular communication is supported with a infrastructure known as the cellular network. A cellular network is a wireless network ditributed over large geographical areas through cells. A cell is referred to as basic part of a cellular network which is divided into smaller area. Each cell includes a fixed location transceiver which is known as a base transceiver system (BTS). In a cellular network every cell can have a different set of frequency and channels to avoid interference. User equipment (UE) is a mobile device in the cellular network that is connected to the BTS using a wireless link. A BTS has limited coverage within the area of the cell. Depending on the geography of a cell, coverage area can be different for every cell. For the UE to continue using the services of cellular network while moving from one cell to another, certain techniques have been identified and are used so the wireless link is not broken. When traffic is carried from the BTS to the UE, we call that as downlink and when the traffic is carried from UE to the BTS, we call that as uplink. In a cellular network, UEs cannot have a direct communication with each other.

1.2 Motivation and Problem Statement

The number of mobile subscribers has increased remarkably in recent years. Nowadays mobile devices are not only used for phone calls (voice traffic), but they can be also connected to the Internet and provide a wide range of data services. On the other hand, traffic is growing quickly and mobile subscribers expect data performance of cellular systems to be similar to that off fixed lines. For these reasons, major effort has been spent in recent years on development of techniques where device-to-device (D2D) communications are allowed.

D2D communication represents a new technology component which allows devices in close proximity to communicate directly instead of relaying the signal through the base transceiver station. The advantages of D2D communications are:

- Offloading the cellular system,
- Increasing the spectral efficiency,
- Reduced battery consumption,
- Increased data rate,
- Robustness to infrastructure failures and thereby also enabling new services.

Some appealing applications of D2D communications can be: video streaming, online gaming, media downloading, peer to-peer file sharing. Although D2D communications provide several benefits for local-area services in cellular networks, a main challenge about selection of communication mode is introduced. D2D communications would be able to operate in various modes, to achieve the maximum system performance. The modes for D2D communication can be categorized as follows:

- *Direct mode*: The devices communicate directly with each other,
- *Indirect mode*: The devices communicate indirectly with the base transceiver station (BTS) acting as a relay [1].

To achieve the maximum system performance, the problem is defined as that when should the D2D communication be used instead of a traditional cellular communication and which mode of communication should be chosen for the D2D communication for better performance? Also we need to address another question: should the mode be chosen on some performance metric or should the D2D communication have separate resources assigned by the BTS.

In order to address the mentioned problems, we need to define scenarios in which D2D communication will be used instead of traditional cellular communication. To determine the selection of D2D communication, research is performed with respect to modulation techniques, fading, interference and so on. After introduction of D2D communication, we need to determine which mode of communication should be used for the D2D links to achieve the maximum system performance. Recent research has been done on mode selection algorithms of D2D communications as an underlay to cellular networks. D2D communication between two UEs, in spectrum managed by the cellular networks occurs in three steps, which are: In step 1, the originating UE has discovered the expression of the UE that is interested to initiate communication. In step 2, the originating UE is performing direct alert and initiates the process to setup the D2D link. In step 3, the originating UE is performing direct communication with the terminating UE. Figure 1.1, shows us the concept of D2D communication underlaying cellular network. In traditional cellular network, UEs are using the uplink and downlink resources of the BTS in order to communicate with each other [2]. When the UEs are in close proximity or can have a D2D communication, then these UEs form a D2D pair, and the remaining UEs continue to use the BTS as mode of communication with other UEs.

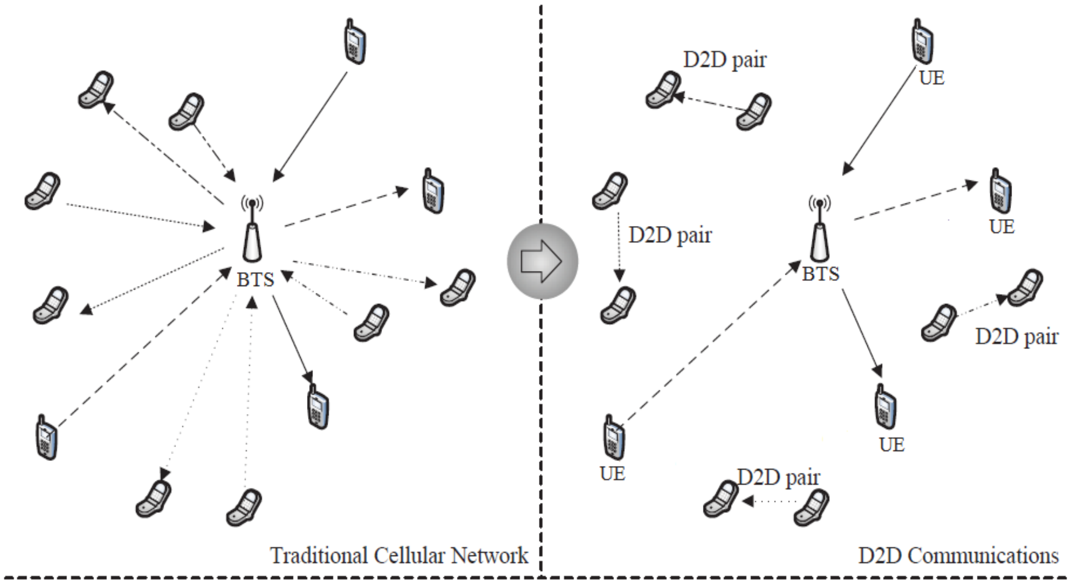

Figure 1.1 : D2D communication underlaying a traditional cellular wireless communications system.

When D2D communication is selected instead of traditional cellular communication, some UEs form D2D pairs and are connected directly to each other, which reduces the number of wireless links from the BTS, hence offloading the cellular network. The channels that were being used for the uplink and downlink by the BTS for cellular communication also become vacant once the D2D communication is setup between UEs, increasing the spectrum efficiency.

The frequency band used for D2D communication can be the same as that used in cellular communication or it could be a different frequency band to avoid radio interference with the cellular communication. The D2D sessions that take place are under the supervision of the cellular network. This suggests that the BTS covering the area in which the UEs are present is administrating and managing the communication links. The BTS controls and specifies what goes on in the particular area that the BTS covers. This control functionality is necessary so when ever the D2D communication takes place in the licensed frequency band, the interference must be restricted which is caused by D2D links on the normal cellular communication. Additionally, D2D links may interfere with each other as well. The mode selection of the D2D links is achieved by comparing various performance metrics and a mode selection rule is defined of when to choose which mode for D2D communication.

1.3 Scope of Research

The purpose of this thesis is to present a strategy for the mode selection of D2D communication in a cellular network. The research consists of three parts:

(a) we define our system model where devices are placed within the coverage area of the BTS. Once the devices have been placed randomly, we analytically derive equations describing what signal-to-noise ratio (SNR), channel capacity, received signal strength indicator (RSSI), interference-to-signalrRatio (ISR) and distance should be for mode selection of D2D links. These values are defined for every link that is possible, either between devices, i.e. the direct link, or the devices through the BTS, i.e. indirect link. For the equations we propose a threshold value for the D2D links. This threshold value determines which mode should be selected.

(b) We propose a method to use the equations in a practical way where we introduce shadowing to the mode selection rules, which are defined in (a), and derive equations with for the rules. Once the mode selection rules have been defined with introduction of shadowing, we compare the mode selection rules after addition of shadowing with the ones that were without shadowing. Using these results we derive equations for missed detection, false alarm and correct detection probabilities for various performance metrics.

(c) We perform simulations with different scenarios to analyze the results obtained with our mode selection rules for D2D links. These simulations are varied, to get the better result, which could be used as the proposed mode selection rule.

1.4 Literature Review

In cellular network, the UEs are transmitting signals to BTS and receiving signals from BTS periodically, even when they are idle. In this way, there are always weak connections between the devices and BTS, and they can set up a connection immediately when there is a need for that. On contrary, there is no such a connection between the devices, so they need to discover their neighbors which meet the requirement of starting D2D communication directly. In the past, cellular operators did not consider D2D communication as a method to enhance the performance of cellular network because effect of D2D communication is limited to local communication services. However, as mobile applications based on proximity of mobile devices become popular, cellular operators are considering introducing D2D communication into the cellular networks [3]. From this perspective, the procedure of D2D communication can be divided into two phases, which are discovery phase and the communication phase. In the discovery phase, the devices should search and discover the near by devices that can have a D2D communication and setup a D2D link between them. In the communication phase, the D2D link has been setup and the devices are ready to communicate with each other. The discovery phase is the prerequisite for the communication phase, since for communication between devices, the discovery should have been made and a D2D link been setup. In [4], the devices search for the potential candidates in proximity which is preparing to set up D2D communication, while in the communication phase, the devices establish connections directly to use applications based on D2D communications. Later the authors discuss issues in radio resource management that include mode selection, scheduling, channel quality estimation and power control in mixed D2D and cellular environment. Using these issues, they design and simulate a system to indicate that D2D communication not only helps to improve the energy efficiency but it also reduces the probability of infeasibility of a target spectrum efficiency.

The mode selection for D2D communication has been a topic of intense research [5-23]. The related work is described in more detail below. In [5], a mode selection algorithm was proposed for both single-cell and multiple-cell scenarios where each cell includes one D2D link and one cellular link. The quality of D2D link and cellular link was taken into consideration while defining the algorithm that would select the mode. The algorithm also selects the mode for uplink and downlink that achieves the highest sum-rate while satisfying the signal to interference-plus-noise ratio (SINR) constraints of the cellular network. The transmission power of D2D and cellular UE (CUE) is varied for different modes to maximize the throughput. The mode selection region results were based on the simulations and were without theoretical results. In [6], a mode selection rule with respect to received power was derived. Whenever the received power at one of the D2D terminals was higher than that from BTS direct communication was selected. Using the received power rule, the author derived handoff algorith for multi cell scenario in which the performance of the cellular system got better. In [7], the authors defines a mode selection algorithm, in which both the devices are close to each other for direct communication but the power efficiencies are different. The algorithm proposes to jointly allocate power and subcarrier and to select transmission mode and modulation for multiple D2D links and multiple cellular links. The algorithm only considered cellular and dedicated modes for the D2D links. Moreover, the key assumption in the work was that user equipment always cooperate to achieve the globally optimal solution. In [8], the authors addresses the joint resource allocation and mode selection problem in a D2D communications integrated orthogonal frequency-division multiplexing (OFDMA) system, in which he aims to optimize downlink power consumption. The transmission power for every user is calculated with its average channel gain. The user with the largest power decrement is noted and the transmitted power of the D2D pair for D2D communication is compared with the transmitted power of BTS. It was shown that BTS saves more transmitted power with increase in D2D pair's.

In [9], authors focused on the reliability improvement by the mode selection based on outage probability. The authors focused on robust receive technique to cellular interference. The demodulation of the received signal was considered either by canceling the interference or by taking it as noise. The BTS calculates the outage probability for the modes, and compares them to select a mode. However authors did not consider BTS being used as a relay for indirect communication and lacked performance metrics. In [10], author focuses on modes for D2D communication by providing a simple solution with criteria containing the received signal strength over the D2D link and the distance between devices. When the distance between the devices decreases and has a higher value of received signal strength, then mode is selected when devices can have a direct link. If the criteria wasn't met than devices use conventional cellular communication. In [11], a solution for selection of mode is proposed through cooperative groups. Every D2D link has a different transmission power. The devices nearby with low transmission power and the least SINR form a group. Depending on the group, a mode is defined for the D2D link. In [12], optimal communication modes for all devices in the system are derived in terms of equations that capture network information such as link gains, power allocation of devices and SINR. The distance between devices was defined to be less. The mode selection algorithm decides the mode to select based on these parameters. In [13], the authors focus on a distance dependent mode selection algorithm in D2D communication. The maximum transmit power of each user in different modes is defined w.r.t. the distance. An optimum power allocation for each mode is defined. If the user is within a region, transmit powers are compared and optimum mode is selected. In [14], authors considered mode selection with power control in a single cell that includes one D2D link and one cellular user subject to spectral efficiency restrictions and maximum transmission power or energy constraints. Authors first studied a sum-rate maximization problem where cellular and D2D communication are competing services. Afterwards they studied the sum-rate maximization problem under rate constraints where cellular users have higher priority with a guaranteed minimum transmission rate. It is found that the optimization problem can be either solved in closed-form or searched from a finite set except for the cellular mode with a maximum power constraint. Using the power constraints the mode selection was selected. In [15], the authors select distance as a metric that will help in the communication mode selection decision. The SINR for the devices is calculated at the BTS and at the devices that are the D2D pair. Comparing the values with respect to the distance from the BTS and devices, mode is selected. Later a maximum value of distance is calculated to show when D2D mode is better then the cellular mode. In [16], the authors propose mode selection algorithm for single cell scenario. The SINR distribution of the cellular link and D2D link is formulated. The position of one D2D user in the D2D pair is fixed and the maximum distance between the D2D pair is forced. Transmission power of the D2D users is reduced to control the impact of D2D communication over cellular communication. As a result D2D communication achieves a higher SINR than the cellular communication becoming the more suitable mode of communication.

D2D communication being very popular these days has brought interest of various companies which are now standardizing the technology. They propose proximity service (ProSe) in which the devices are discovered, the challenges faced while discovering a device, and after discovery the communication either with or without network assistance. The proposals are explained further. In [17], Huawei proposes proximity service (ProSe) discovery. The ProSe discovery is divided into two parts: device level discovery and application level discovery. Device level discovery means a UE searches and finds another UE that is in the same proximity region. UE can broadcast a device id, which can be used to be discovered and also detect the device id of another UE if the discovery functionality is activated. To protect the privacy of UE, the device id broadcasted in the air could be a temporary one and allocated by network. The network can update the device id allocated to the UE to avoid the easy association with a user. The network could also control and manage the resources for device discovery considering the interferences, efficiency. Application level discovery focuses more on the proximity-based applications that means the application running on the UE side finds another user being in proximity, for example a user running Skype application can find another user running Skype application when they are in the same proximity.

In [18], ITRI proposes a solution in which the UEs can discover other UEs in the proximity region with or without permission of other UEs. In this case, discovery scenraios are intiated with or without the network assistance. But the network should have the preferences for discovery. This helps the network to increase the performance. In [19], scenarios are characterized where communication link with the cellular network is isolated. The isolation means that the UEs are in network coverage but want to communicate with each other without any restriction from the cellular network. Further it is explained that the UE can communicate directly with another UE or can have a group communication mode. In [20], Motorola proposes a solution for direct mode of communication in which every UE in the ProSe will have access to the Allowed ProSe contact list, which would help the UEs to start a D2D link by using lesser resources. The list could be edited by the user where he/she could add or delete anyone from the list. In [21], Alcatel-Lucent proposes circumstances in which D2D communication can occur. One of them being that the device broadcasts information and the device that is supposed to receive it, gets the information and decodes it. The other being that the device discovers another device that is within the same proximity and the devices can discover each other. Once the devices are discovered, they periodically check whether they are still in the same proximity. Once discovered the devices can have a D2D communication. In [22], Qualcomm proposes a solution for direct discovery for devices in network coverage and out of network coverage. There are three phases that occur before the direct communication between two UEs can commence, which are: *Discovery phase:* the originating UE has discovered the expression of the UE that is interested to initiate communication to. This is a continuous operation and may not be triggered on demand. *D2D connectivity phase:* the originating UE is performing direct alert and initiates the process to setup the D2D link. *Direct communication phase:* the originating UE is performing direct communication with the terminating UE. In [23], Intel proposes a solution where the ProSe servers store the information of the users that want to have a D2D communication, irrespective of when. The information that is stored in the servers is the location, friend list, and other information that will help the server to locate the user if they wish to follow up with the direct communication.

There have been recent work on the resource allocation of D2D communication, which improve the performance of D2D communication [24], [25], [26]. In [24], the authors propose a solution where radio resources of cellular network can be utilized efficiently by introducing D2D communications because D2D users can reuse radio resources of conventional cellular networks to transmit a signal for direct communication. However, since D2D and cellular UEs can cause interference to each other, effect of interference between D2D and cellular UEs on the performance of the networks should be analyzed and coordinated to avoid performance degradation of the cellular networks. Doppler provided expressions for probability of existence of a D2D link as long as resource sharing does not cause the cellular link signal to interference-plus-noise ratio (SINR) to fall below a minimum value. A multihop scenario connecting two D2D users was investigated and shown that spectral efficiency of the cellular network increases [25]. In [26], the authors investigated the resource allocation problem for multiple cellular users and multiple D2D links. The resource blocks of cellular users in uplink and downlink are scheduled to D2D connections for which the network throughput increases. The problem of maximizing the sum-rate of the primary cellular users and secondary D2D users was formulated as a mixed-integer non-linear program with SINR constraints for cellular and D2D communications. Then, a greedy heuristic algorithm was proposed to schedule the resource blocks in uplink and downlink. A D2D link is assigned with a resource block (RB) used by a cellular user such that the interference channel gains from D2D communications to cellular communications are minimized. Note that, the cellular user with a higher channel quality will share the resource with a D2D link which causes lower interference. However, the spectrum may not be efficiently utilized since one RB can be shared with at most one D2D link.

Various contributions have been done, to minimize the effect of interference of the D2D communication, increasing the data rate and improving the reliability of D2D communication modes [27], [28], [29]. In [27], the authors proposed a mechanism in which the BTS controls the maximum transmit power of D2D transmitter. By limiting the maximum transmit power, mechanisms that controlled and limited interference of D2D communications to the cellular networks were illustrated and shown how it enhanced the overall throughput in the network by relaying D2D traffic through the cellular network. In [28], [29], authors proposed a interference limited area (ILA) control scheme which does not allow the coexistence of CUEs and a D2D pair in the same proximity region. If the CUEs are located in the ILA and the interference to signal ratio (ISR) at the D2D receiver is greater than a threshold, the performance of the D2D link is observed. Using ILA control scheme, ergodic capacity of the D2D link was calculated and shown that it enhances the overall capacity of cellular networks and D2D pairs since the CUE interferer is not present in that particular area. It was also shown that in how much area, does the D2D communication has a better ergodic capacity than to that of cellular communication.

1.5 Thesis Overview

In Chapter 2, the wireless communication systems which are relevant for this research are introduced, which include small scale fading, large scale fading and the path-loss. Later we introduce a system model, to illustrate the idea of D2D communication in cellular networks, followed by the derivation of equations describing the system parameters. To achieve a higher performance, we define different modes for different scenarios, so the mode that has a higher performance, would be chosen as the proposed mode of communication. In Chapter 3, we propose a framework for mode selection that is composed of various selection rules and associated performance metrics, which are the system parameters. Furthermore, we model proposed mode selection rules as hypothesis testing, where we define and calculate the analytical expressions for probability of correct detection, missed detection and false alarm. These analytical expressions help the BTS to choose the mode for D2D communication. In Chapter 4, we have performed simulations with various scenarios to show results obtained with the methods. The simulation results are compared and summarized. All simulations are performed in MATLAB®.

The contribution of this thesis is to introduce different mode selection mechanism for D2D communication. In previous works, mode selection algorithms were defined either with respect to SINR or received power but were mostly restricted to the D2D pair being near to each other, so that only direct communication would be done as a result. For our thesis, we have defined mode selection algorithms for various parameters and a thorough study for the parameters has been done before defining the mode selection algorithm. The mode selection rules are defined from the performance metrics using hypothesis testing. Using the hypothesis testing, analytical expressions for probability of correct detection, false alarm and missed detection are calculated, which help the BTS to increase the performance of the system, by choosing the proposed mode selection rule. The results of this thesis are published in an international conference ISSPIT held in Athens, Greece on 12-15 Decemeber 2013.

2. SYSTEM MODEL FOR D2D COMMUNICATION

In this chapter, a description is given for the system model of D2D communication in a cellular network. Different channel models are defined for the D2D communication, which are then used to define system parameters for different modes of D2D communication. The modes for D2D communication are further explained which could either be direct or indirect mode of communication. For every link, mode of communication is defined and system parameters are found by simulation which will be further described in the upcoming chapters.

2.1 System Model

In a traditional cellular communications, the BTS is used to send and receive traffic of the UEs that are either within its coverage area or in the neighbouring area. The radio path of this cellular communication consists of two parts: the path from the base transceiver station to the receiver and the path from the transmitter to the base transceiver station. A D2D link is a single direct path from transmitter to receiver. We consider a single cell system with radius, R. The mobile station D_1 is located at the $<x_1,y_1>$ coordinates, which is the source node. The mobile station D_2 is located at the $<x_2,y_2>$ coordinates, which is the destination node. D_1 is fixed while D_2 is randomly placed within the radius, R. The BTS is placed in the center of the cell. Figure. 2.1, illustrates the system model. We consider two classes of users, cellular user equipment (CUE) and device to device user equipments (D_1 and D_2). CUE will be communicating through the BTS. D2D pair would have some interference either on the uplink or on the downlink with the CUE if it is in close proximity. Every link created between the devices or between device and BTS is treated and analyzed separately for a better understanding of the system. The further sections explain which parameters are calculated and analyzed for every link created.

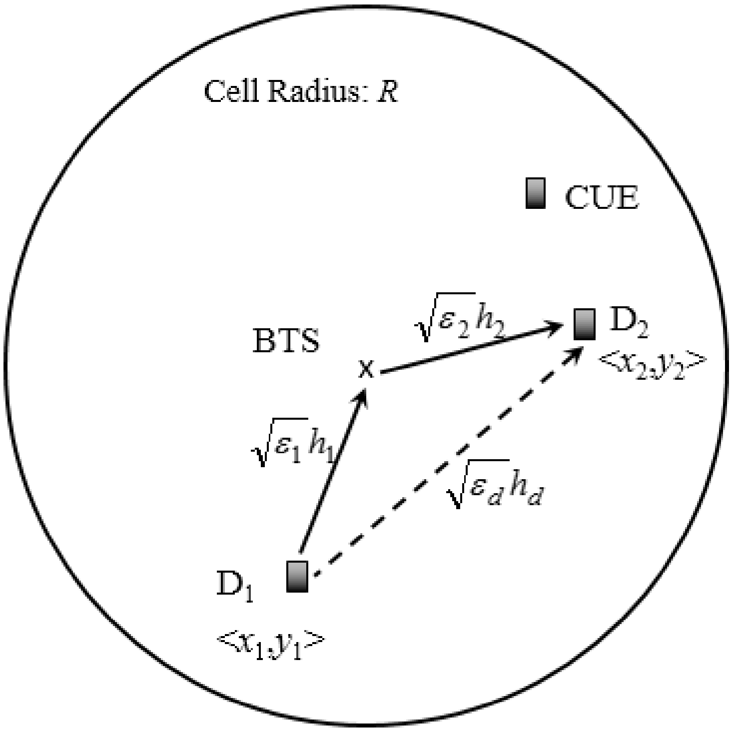

Figure 2.1 : System model of D2D communication

2.2 Channel Model

In a wireless system, the radiated electromagnetic wave transmitted reacts in a complicated way with the medium before it is received at the receiver. There are reflections from various buildings, signal is scattered from surface of objects and diffraction of the radiated electromagnetic waves from moving or stationary objects. In digital communication theory the most frequently assumed model for a transmission channel is the additive white Gaussian noise (AWGN) channel. AWGN is a channel model in which white noise with a spectral density is added to the set of frequencies used by the channel. However, for many communication systems the AWGN channel is not an ideal model, hence they need to resort to more precise and complicated channel models. One basic type of non-Gaussian channel, which frequently occurs in practice, is the fading channel model. A typical example of such a fading channel is the mobile radio channel, where the small antennas of portable units pick up several multipath reflections. As a result, the incident wave interacts with surface irregularities via diffraction, shadowing, scattering, reflecting, and absorption, creating a variety of limited waves [30],[31]. The surface iregularities are shown in Figure 2.2.

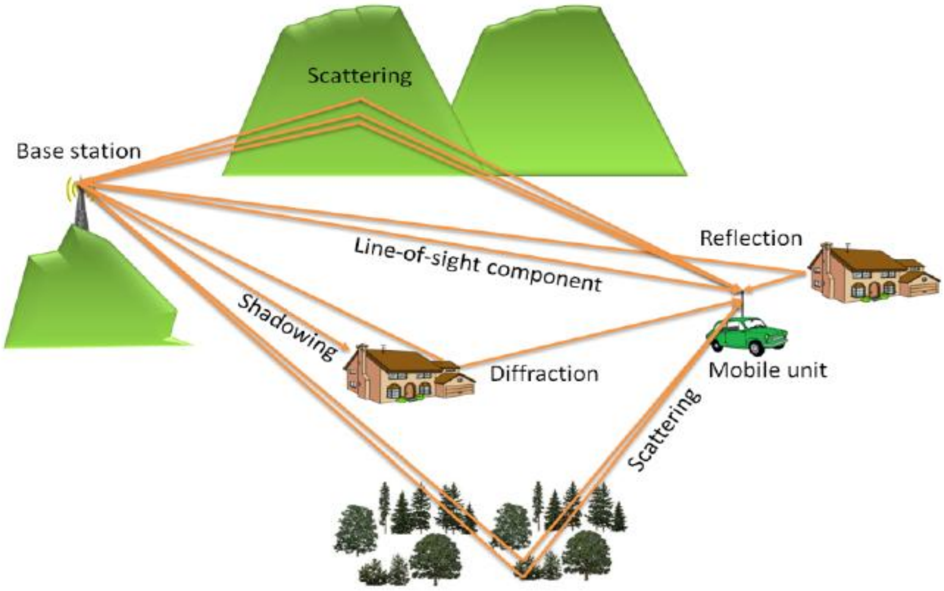

Figure 2.2 : Surface irregularities of a mobile radio scenario [30], [31]

These limited waves depend on the physical properties of the buildings and the surface structure such as the geographical location of the receiver, transmitter and other objects which cause reflection or refraction, the geometrical proportions and the line of sight component. At every point in space, limited waves interfere with each other and, possibly, with the direct wave, building up an irregular electromagnetic field. While on the other side, the signal power tends to decrease with distance and the existence of large scatterers such as trees, buildings, and mountains because of attenuation or fading. In the communications literature, most often we encounter two types of fading definitions for the mobile radio channel, and they are called *small-scale fading* and *shadowing*. These are further defined below.

2.2.1 Small-scale fading

Small-scale fading is a characteristic of radio propogation resulting from objects that cause multiple reflections, diffraction and scattering before being received at the receiver. Each wave is distorted in amplitude and phase.

The four main physical factors which influence small-scale fading in the radio propagation channel are:

- Multipath propagation,

- Speed of the mobile receivers and transmitters,
- Speed of surrounding objects and
- Transmission bandwidth of the signal.

The four main physical factors influencing small-scale fading in the radio propagation are further explained as below.

a) Multipath propagation

Multipath propagation results from the presence of reflectors and scatterers in the propagation channel that cause multiple versions of the transmitted signal to arrive at the receiver, each distorted in amplitude, phase and angle of arrival. Due to the increased time required to receive the baseband portion of the signal, intersymbol interference (ISI) can occur resulting in signal smearing. ISI is a disturbance caused by extraneous energy from the signal in one or more keying intervals that interferes with the reception of the signal in another keying interval.

b) Speed of the mobile receivers and transmitters

The relative motion between a base transceiver station and a mobile receiver results in random frequency modulation due to the different Doppler shifts on each of the multipath components (waves arriving at the receiver). The Doppler shifts can be either negative or positive depending on whether the mobile receiver is moving towards or away from the base transceiver station. In the case of D2D communication, the speed of mobile transmitter is also considered, since it can either be fixed at a point or in motion. The Doppler shifts varies depending if the D2D pair is moving towards each other or moving away from each other.

c) Speed of the surrounding objects

This phenomenon occurs if the objects surrounding a mobile receiver are moving much faster in relation to the mobile receiver. For example, if a mobile receiver is adjacent to a highway, the speed and multitude of the vehicles near the mobile receiver will induce a Doppler shift upon the signals being received.

d) Signal transmission bandwidth

This physical factor is concerned with the transmitted signal bandwidth compared to the “bandwidth” of the multipath channel. If the transmitted signal bandwidth is much greater than the “bandwidth” of the multipath channel, then the received signal strength will not decrease by much over the local area because of small-scale fading factors. Otherwise, if the transmitted signal bandwidth is narrow relative to the "bandwidth" of the multipath channel, then the signal amplitude can change rapidly while the signal structure is not itself distorted in time.

So far, only the classifications and effects of multipath have been discussed. Statistical models for small-scale fading for various scenarios exist. For mobile communication over multipath channels, the models for Rayleigh and Rice fading are commonly used. In our research work, we will use the Rayleigh fading model.

Rayleigh fading

In non-line of site (NLOS) mobile radio channels, the Rayleigh distribution is often used to describe the statistical time-varying nature of a flat fading channel, or of the envelope of an individual multipath component. In a multipath environment, the received envelope of either path experiences Rayleigh fading. Depending on the relative speed, i.e. the Doppler spread, the rate of change is increased or decreased accordingly. The amplitude, or envelope, of each reflected component can be represented in terms of its in-phase and quadrature component. Because of the wave cancellation effect and random movement, both the in-phase and quadrature components are Gaussian distributed with zero-mean. The envelope of a complex Gaussian distributed variable is Rayleigh distributed. The individual paths of a multipath channel suffer Rayleigh fading in a NLOS environment. The received signal, r_i in a multipath channel is modeled as:

$$r_i = \sqrt{\varepsilon_i} s_i h_i + n_i , \tag{2.1}$$

where s_i is the transmitted signal, h_i is the Rayleigh channel coefficient, $\sqrt{\varepsilon_i}$ is the energy coefficient due to the corresponding path loss and n_i is the additive white Gaussian noise (AWGN) with one-sided power spectral density (PSD), σ_n^2.

2.2.2 Shadowing

In wireless communication, fading that represents the average signal power attenuation or path loss due to motion over large areas and is commonly known as shadowing because it generates a radio electrical shadow effect produced by prominent objects, mainly terrain contours (e.g. hills, forests, and buildings) in the context of mobile cellular networks. This effect can be realistically modelled by a log-normally distributed variation about the mean path loss attenuation, this last term being due to the distance between transmitter and receiver. In our model, we introduce different shadowing components as a Gaussian distribution which are explained later in Chapter 3.

2.2.3 Path loss

Path loss is the attenuation in power density of an electromagnetic wave as it propagates through space. Path loss models describe the signal attenuation between a transmit and a receive antenna as a function of the propagation distance, frequency, the height of BS antenna, the height of user equipment antenna and other parameters. Path loss for a non-free space wireless environment, such as a path with obstructions consisting of buildings and trees, can be difficult to model. Different models have been developed to describe the propagation behavior in different conditions. Some models just consider carrier frequency and distance travelled by the signal whereas others include many details of the terrain profile to estimate the signal attenuation.

Research on propagation models is an academic field of its own. For our research we have chosen to use Okumura-Hata model for urban areas [32], [33], [34]. The Okumura-Hata model is a radio propagation model that predicts the behavior of cellular transmissions in built up areas. This model adds up the effects of diffraction, reflection and scattering caused by city structures. This model is widely used in literature because of its detailed calculation, while still providing a realistic description of the overall signal degradation. With the chosen model, we can calculate the path loss for urban wireless environments as follows:

$$PL_i = 69.55 + 26.16 \log f - 13.82 \log h_b + (44.9 - 6.55 \log h_b) \log d - C_H , \quad \textbf{(2.2)}$$

where f is the frequency of transmission in MHz. d is the distance between two points in kilometers, h_b is the height of base station antenna in meters, and C_H is the Antenna heigh correction factor.

$$C_H = 0.8 + ((1.1 \log f - 0.7) h_M) - 1.56 \log f , \quad \textbf{(2.3)}$$

where h_M, which is the height of mobile station antenna in meters and f which is the frequency of transmission in MHz.

For different D2D links, path loss is calculated for that particular link according to the parameters of the link.

2.3 D2D Mode Descriptions

Where ever the devices are located, either within the proximity region or outside the proximity region, BS should assign a mode to that particular link. Assigning a mode, would increase the performance of the network allowing the load to be reduced from the network. In our research, we consider different modes which are:

- Direct mode
- Indirect mode

In Figure 2.3, the modes are shown. The left hand shows direct mode, whereas the right hand picture shows the indirect mode.

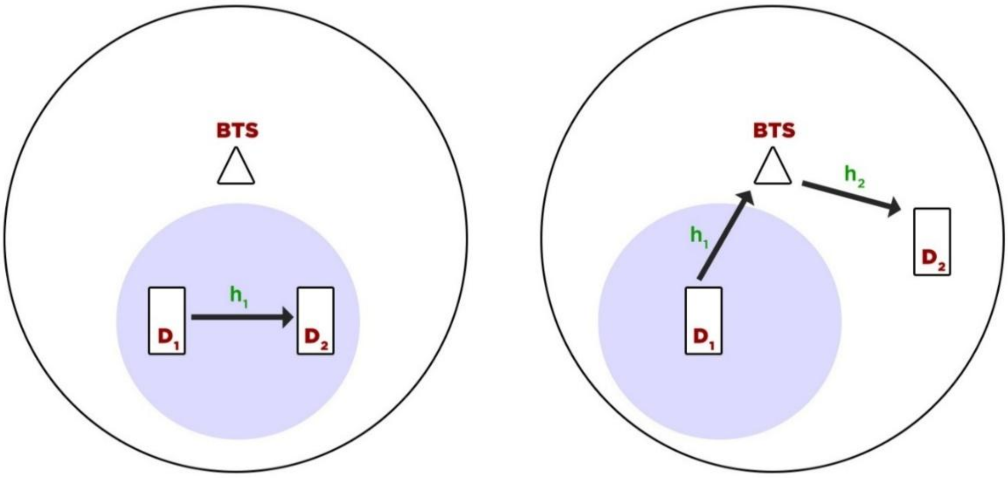

Figure 2.3 : D2D communication modes

2.3.1 Direct mode

When the devices are in close proximity, the mode for D2D communication would be direct, where the devices will directly communicate with each other. For direct mode, the received signal at D_2 is defined as:

$$r_d = \sqrt{\varepsilon_d} s_1 h_d + n_d \, , \tag{2.4}$$

where s_1 is the transmitted signal from D_1, h_d is the channel coefficient between the two terminals D_1 and D_2, $\sqrt{\varepsilon_d}$ is the energy coefficient and n_d is an AWGN with one sided PSD of N_0.

2.3.2 Indirect mode

When the devices are out of the proximity region, D2D communication is done through the BTS which acts as a relay for indirect mode. In our research, D_1 is communicating with D_2 through BTS which amplifies and acts as a relay. Assume that D_1 is transmitting a signal s_1. The received signal at BTS can be defined as:

$$r_1 = \sqrt{\varepsilon_1} s_1 h_1 + n_1 , \qquad \textbf{(2.5)}$$

where s_1 is the transmitted signal from D_1, h_1 is the channel coefficient between the two terminals D_1 and BTS, n_1 is an AWGN with one sided power spectral density (PSD) of N_0. The received signal is then multiplied by the gain of the relay, and then retransmitted to D_2. The received signal at D_2 can be defined as:

$$r_2 = \sqrt{\varepsilon_2} G r_1 h_2 + n_2 , \qquad \textbf{(2.6)}$$

where h_2 is the channel coefficient between BTS and D_2, and n_2 is an AWGN signal with one sided PSD N_0.

For both of the D2D modes, we calculate the system parameters for every link. These parameters are described as below.

2.4 System Parameters

In D2D communication, radio path of the D2D link can be either between the devices directly or it can be either through the BTS, which serves as a relay. For every link, different system parameters have to be taken into account separately. For example if the battery life of the wireless devices is the parameter of interest, we want to compare the transmitting power of a device when communication. But, if the channel capacity needs to be taken into account, than a comparison is made of the links based on the length of the links (i.e. the distance between the communicating nodes either direct or through BTS). To increase the overall performance of the link interference-to-signal ratio (ISR) is taken into account. The system parameters that are taken into account are:

- Distance,
- Signal to noise ratio (SNR)
- Interference to signal ratio (ISR)
- Received signal strength indicator (RSSI)
- Capacity

The system parameters are further explained as below.

2.4.1 Distance

In mobile communication, to calculate path loss, SNR, RSSI, the very basic parameter used is distance between the two nodes. In our research for D2D communications we define a distance threshold in which direct mode of communication can take place. This distance threshold notifies whether the devices are inside the proximity region or not. When the devices are inside the proximity region than the devices could have a direct D2D communication. If the devices are outside the proximity region, indirect D2D communication can take place. Distance of the links, either between devices or either between the device and BTS is calculated to be compared and used for further reasons, being selection of mode for every link.

2.4.2 Signal to noise ratio (SNR)

The signal to noise ratio (SNR) is the ratio between the signal strength that a wireless connection can achieve and the noise present in the connection. The SNR of a network needs to be as high as possible. The higher the value of SNR, the better will be the signal strength and the quality of transmission. This value can decrease due to various reasons. At the time of rain or fog, the air is denser than usual, so the signals may get attenuated (i.e., get reduced in strength). In these cases the value of SNR will be lowered to some extent. Also, the presence of any strong electrical field in the path of signal, like high tension electrical wiring, can reduce the value of SNR substantially. Interference with the signal can reduce the signal strength to quite an extent. SNR of direct mode is defined as:

$$\gamma_{direct} = \frac{\varepsilon_d |h_d|^2}{N_0}, \tag{2.7}$$

where h_d is the channel coefficient between the two terminals D_1 and D_2, ε_d is the energy coefficient and N_0 is the variance of AWGN. For indirect mode, since BTS is acting as a relay the overall SNR for indirect mode at the receiving end is defined as [35]:

$$\gamma_{indirect} = \frac{|h_2 G h_1|^2}{\left(|h_2 G|^2 + 1\right) N_0} = \frac{\frac{\varepsilon_1 |h_1|^2}{N_0} \frac{\varepsilon_2 |h_2|^2}{N_0}}{\frac{\varepsilon_2 |h_2|^2}{N_0} + \frac{1}{G^2 N_0}} . \quad \textbf{(2.8)}$$

The relay receives the signal from source, amplifies it with amplification factor G and forwards it to the destination. The amplification factor G of relay to maximize the end-to-end SNR in the 2 hop system from [36] is defined as:

$$G^2 = \frac{1}{\varepsilon_1 |h_1|^2 + N_0} . \quad \textbf{(2.9)}$$

Substituting (2.9) in (2.8) leads to the overall SNR for indirect mode as:

$$\gamma_{indirect} = \frac{\gamma_1 \gamma_2}{\gamma_1 + \gamma_2 + 1} , \quad \textbf{(2.10)}$$

where $\gamma_1 = \varepsilon_1 |h_1|^2 / N_0$ is SNR between D_1 and BTS, and $\gamma_2 = \varepsilon_2 |h_2|^2 / N_0$ is SNR between BTS and D_2. γ_{direct} is SNR between D_1 and D_2.

2.4.3 Interference to signal ratio (ISR)

The interference to signal ratio (ISR) is the quotient between the average received interference co-channel interference power and the average received modulated carrier power. In our research work, ISR is defined as the interference from cellular user equipment (CUE) to D_1 (which is source of D2D communication). To calculate the ISR, we need to define a δ_D-*Interference limited area (ILA)* control. In Figure 2.4, the δ_D-*ILA* control scheme is defined as the area in which the ISR from CUE to D_2 is greater than a threshold δ_D.

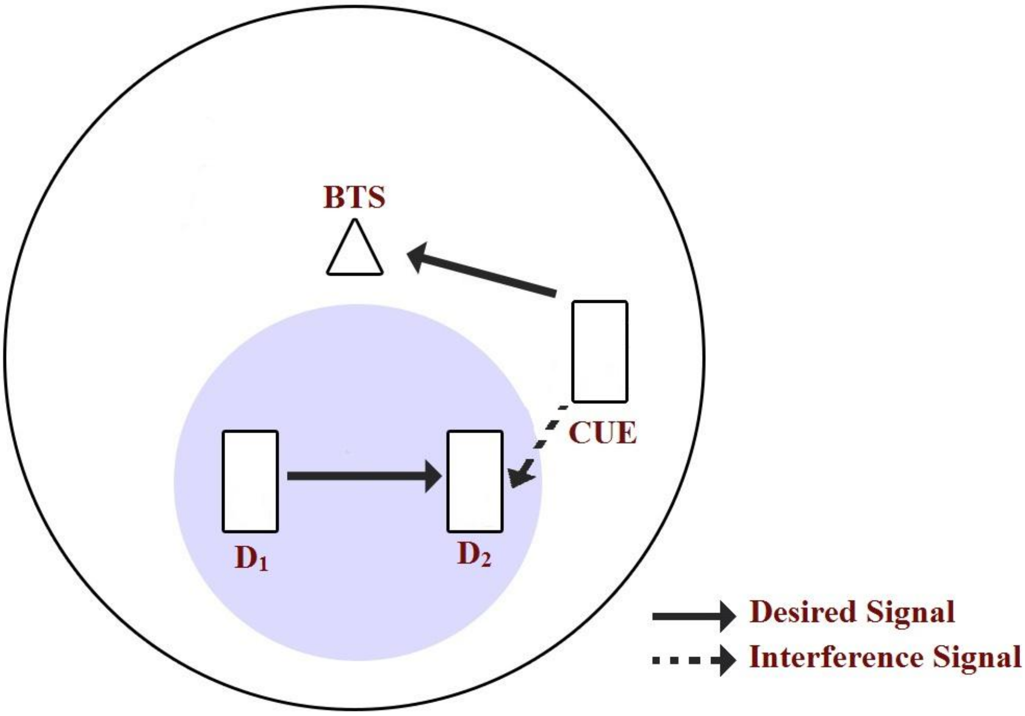

Figure 2.4 : δ_D-*ILA* control scheme.

The constraint for δ_D-*ILA* is expressed as:

$$I_R = \frac{P_{I,C_{UE}D_2}}{P_{S,D_1D_2}} > \delta_D, \tag{2.11}$$

where I_R is the ISR from CUE to D_R. δ_D is calculated by the BTS since it knows the location of the D2D pair and CUE. From [28], [29], [38] it could be shown that:

$$P_{S,D_1D_2} = \left(\frac{d_{D_1B}}{d_{D_1D_2}}\right)^{\alpha} P_{ID_1B},$$

$$P_{ID_1B} = (\delta_B) P_{I,C_{UE}D_2}.$$

Replacing the above in (2.11), δ_D with a path-loss component α is defined as:

$$\delta_D = \left(\frac{d_{D_1D_2}}{d_{D_1BTS}}\right)^{\alpha} \frac{1}{\delta_B}. \tag{2.12}$$

Let us assume that the maximum acceptable ISR at BTS is δ_B. The approximate SINR at D_1 using δ_D-*ILA* control scheme can be written as:

$$\gamma_{\delta_D} = \frac{\left|h_{D_1D_2}\right|^2}{I_R\left|h_{C_{UE}D_2}\right|^2 + \frac{N_O}{P_{S,D_1D_2}}} \approx \frac{\left|h_{D_1D_2}\right|^2}{I_R\left|h_{C_{UE}D_2}\right|^2} \approx \frac{1}{\delta_D}\gamma \ . \tag{2.13}$$

Hence it shows that the maximum ISR is limited to δ_D.

2.4.4 Received signal strength indicator (RSSI)

Received signal strength indicator (RSSI) is the received signal strength at the receiver. Depending on the channel model and fading model, RSSI tends to vary for every link due to different physical and radio properties of the link. The RSSI at node *j* from node k due to path loss PL_i is given by:

$$P_{R_j} = P_{T_k} - PL_i \, , \tag{2.14}$$

where P_{T_k} is the transmitted power from node *k*. The transmission power in the research work of BTS is kept different than to the transmission power of the devices.

2.4.5 Capacity

Capacity is the rate at which information can be reliably transmitted over a communication channel. The capacity for the direct and indirect mode are derived from the Shannon Capacity formula [30], [31]. Although Capacity for indirect mode is given as an *I*-hop transmission system [36]. They can be defined as:

$$C_{direct} = \log_2(1+\gamma_{direct}) \, . \tag{2.15}$$

From [36], the formula for *I*-hop capacity is defined as:

$$C_{indirect} = \frac{1}{I}\log_2(1+\gamma_{eq}) \, , \tag{2.16}$$

where γ_{eq} is defined as [36]:

$$\gamma_{eq} = \frac{1}{2}\log_2(1+\frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2+1}) \, . \tag{2.17}$$

Substituting (2.17) in (2.16), indirect capacity is defined as:

$$C_{indirect} = \frac{1}{2}\log_2(1+\frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2+1}) \, , \tag{2.18}$$

where I is the number of hops, in this case $I = 2$.

3. MODE SELECTION FRAMEWORK

In this chapter we propose a framework for mode selection that is composed of various selection rules and associated performance metrics. Mode selection rules are based on the ergodic channel capacity, signal to noise ratio (SNR), received signal strength indication (RSSI), interference to signal ratio (ISR) and distance comparisons. In addition, the detection problem for mode selection is modeled as a hypothesis test, and analytical expressions for correct detection, false alarm, and missed detection are derived.

3.1 Maximum Detection Rule

There are many situations in which we are required to choose among several possibilities. For example, choosing which mode to select from different performance metrics, such as RSSI. If RSSI of direct mode is greater than that of indirect mode, direct mode is chosen. In this case, the selection involves making a decision among different choices. Such decision are made through hypothesis testing. In a typical hypothesis testing, given an observation or a set of observations, a decision has to be made regarding the source of the observations. We can think of a hypothesis as a statement of a possible source of observations. If the set of hypotheses is only two, we consider is as a binary hypotheses. If there are M hypotheses with $M > 2$, it is a multiple hypothesis testing. For example, the hypotheses for the RSSI can be written as "RSSI for direct mode being higher than for the indirect mode" and "RSSI for direct mode being lower than for the indirect mode". We can label these choices as H_1 and H_0. H_0 is called the *null hypothesis* which refers to indirect mode being selected and H_1 refers to *alternative hypothesis* which refers to direct mode.

Suppose that corresponding to each hypothesis we have an *observation*, a random variable that is generated according to some probabilistic law. The hypothesis testing decides which hypothesis is the correct one, based on a single measurement, z, of the random variable. The range of values that z takes constitutes the *observation space*. The decision problem in case of two hypotheses thus essentially consists in partitioning this one-dimensional space into two regions, Z_0 and Z_1, such that whenever z lies in Z_0, we decide that H_0 was the correct hypothesis, and whenever z lies in Z_1, we decide that H_1 was the correct hypothesis [39], [40]. The problem of deciding between two hypotheses is essentially one of partitioning the observation space into two appropriate regions. Let us consider a simple versus simple hypotheses testing. If $P(H_i \mid z)$, $i = 0,1$, denotes the probability that H_i was the true hypothesis given a particular value of the observation, we decide that the correct hypothesis is the one corresponding to the larger of the two probabilities. The decision rule can be written as:

$$P(H_1 \mid z) \gtrless P(H_0 \mid z)\,. \qquad \textbf{(3.1)}$$

The criterion we have used above is known as the *maximum* criterion, since we are choosing the hypothesis that corresponds to the maximum of the two posterior probabilities.

3.2 Mode Selection Rules

In this section, we explain the mode selection rules, and the design criteria are derived where the selection of proposed mode through various selection rules is modeled as a hypothesis test [39], [40]. For a given activity area by the devices, the problem of determining the mode can be modeled as hypothesis test where the devices are located within the area for direct mode or in the area for indirect mode. Let H_m represent the hypothesis that the devices will either have direct or indirect mode for communication. H_0 is the null hypothesis, representing indirect mode and the alternative hypothesis H_1 represents the direct mode.

The hypothesis H_m that maximizes the probability of correct detection can be chosen according to maximum detection rule. The maximum detection rule is used for the given metrics such as capacity, SNR, ISR, RSSI and distance. The mode selection rules for different metrics are defined below.

3.2.1 Capacity

In this subsection, we analyze the capacity of direct, indirect and proposed mode. In order to evaluate the proposed mode through the maximum detection rule, a decision rule is be defined as:

$$z_c = C_{indirect} - C_{direct}, \tag{3.2}$$

where z_c is the difference of the simulated indirect and direct capacities. The hypothesis is defined as:

$$\begin{matrix} H_0 : z_c > 0 \\ H_1 : z_c \le 0 \end{matrix}, \tag{3.3}$$

where null hypothesis, H_0 is for indirect mode and alternative hypothesis, H_1 is for direct mode. Based on the simulation, the value of z_c is calculated and a decision is made to define the proposed mode of communication. Proposed mode would have the maximum value from either capacity of direct mode or capacity of indirect mode which would be chosen by the maximum detection rule.

When at the point where direct capacity is same as indirect capacity then the difference z_c is equal to 0, the equation below is encountered:

$$C_{direct} = C_{indirect},$$

$$\log_2(1+\gamma_{direct}) = \frac{1}{2}\log_2(1+\frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2+1}),$$

$$(1+\gamma_{direct})^2 = (1+\frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2+1}),$$

$$\gamma_{direct}^2 + 2\gamma_{direct} = \frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2+1}. \tag{3.4}$$

More detailed parameters are required by the BTS for a selection rule. Since channel capacity is dependent on the SNR for direct and indirect mode, hence we define a mode selection rule w.r.t the SNR of both the modes to obtain a more feasible rule for choosing a higher value of SNR.

3.2.2 Signal to noise ratio (SNR)

In this subsection, we analyze the SNR of direct, indirect, and proposed mode. From Chapter 2, the SNR for direct and indirect mode can be used to define a maximum detection rule. While D_2 is placed randomly across R, γ_{direct} and $\gamma_{indirect}$ are calculated for every link. A decision rule is defined as:

$$z_s = \gamma_{indirect} - \gamma_{direct}, \tag{3.5}$$

where z_s is the difference of the simulated indirect and direct SNR. The hypothesis is defined as:

$$\begin{aligned} H_0 &: z_s > 0 \\ H_1 &: z_s \leq 0 \end{aligned}, \tag{3.6}$$

where null hypothesis, H_0 is for indirect mode and alternative hypothesis, H_1 is for direct mode. Based on the simulation, the value of z is calculated and a decision is made to define the proposed mode of communication.

Proposed mode would be the maximum of the mode selection rule for SNR. The rule shows that γ_{direct} would have a greater value than $\gamma_{indirect}$ whenever the devices are further away from the BTS. In the same scenario, C_{direct} would have a maximum value through the mode selection rule for capacity, although being not so close to each other. Hence we need to define a mode selection rule w.r.t a region, in which the devices should be close to each other to obtain the maximum capacity.

3.2.3 Distance

A proximity region needs to be defined for the devices in which direct mode can be achieved if the devices have distance d_{dir}, less than a given threshold, λ. If any of the devices is out of the proximity region, indirect mode should be chosen as the mode for D2D communication. A decision rule is defined as:

$$z_d = d_{dir} - \lambda, \tag{3.7}$$

where z_d is the difference of the simulated direct distance and λ. Here $\lambda = \alpha R$, where α is a constant between 0 and 1, which determines how much area is covered by the proximity region w.r.t. the cellular radius, R.

The hypothesis can be defined as:

$$H_0 : z_d > 0$$
$$H_1 : z_d \leq 0, \quad \textbf{(3.8)}$$

where null hypothesis is for indirect mode and alternative hypothesis is for direct mode. The performance of the selection of correct mode for communication is mainly affected by the correct decision. In some cases false alarm and missed detection can occur when either wrong detection is made or either when a detection is made but the corresponding action is not taken.

3.2.4 Interference to signal ratio (ISR)

In this subsection, we need to define which mode should be chosen when ISR for the CUE to receiving device is analyzed. To evaluate the proposed mode through the maximum detection rule, a decision rule is defined as:

$$z_i = \gamma_{\delta_D\_indirect} - \gamma_{\delta_D\_direct}, \quad \textbf{(3.9)}$$

where z_i is the difference of the simulated indirect and direct ISR. The hypothesis is defined as:

$$H_0 : z_i > 0$$
$$H_1 : z_i \leq 0, \quad \textbf{(3.10)}$$

where null hypothesis, H_0 is for indirect mode and alternative hypothesis, H_1 is for direct mode. Based on the simulation, the value of z_i is calculated and a decision is made to define the proposed mode of communication.

Proposed mode would be the maximum of the mode selection rule for ISR. The rule proves that depending on the values of δ_D the ISR would be different for both direct and indirect mode. The maximum ISR from the direct and indirect mode is chosen to be the proposed mode.

3.2.5 Received signal strength indicator (RSSI)

A proximity region would need to be defined by how much is the received signal strength at the receiver. From Chapter 2, the RSSI for direct and indirect mode can be used to define a maximum detection rule. P_{R_j} is calculated for every link, and a decision rule is defined as:

$$z_r = P_{R\_indirect} - P_{R\_direct}, \quad \textbf{(3.11)}$$

where z_r is the difference of the simulated indirect and direct RSSI. The hypothesis is defined as:

$$\begin{aligned} H_0 &: z_r > 0 \\ H_1 &: z_r \leq 0 \end{aligned}, \qquad \textbf{(3.12)}$$

where null hypothesis, H_0 is for indirect mode and alternative hypothesis, H_1 is for direct mode. Based on the simulation, the value of z_r is calculated and a decision is made to define the proposed mode of communication.

Proposed mode would be the maximum of the mode selection rule for RSSI. The rule shows that P_{R_direct} would have a higher value than $P_{R\_indirect}$ whenever the devices are near to each other compared to them being further away from the BTS. For instance when P_R is -40 dB for direct and -60 dB for indirect, direct mode is chosen due to a higher level of RSSI.

The summary of the mode selection rules is shown in Table 3.1. For every mode selection rule, decision rule was formulated. Depending on the hypothesis, and the system parameters for the mode selection rules, a mode was selected to enhance the performance of the D2D communication.

Table 3.1 : Summary of mode selection rules

Mode Selection Rule	Decision Rule	Hypothesis
Capacity	$z_c = C_{indirect} - C_{direct}$	$H_0 : z_c > 0$ $H_1 : z_c \leq 0$
SNR	$z_s = \gamma_{indirect} - \gamma_{direct}$	$H_0 : z_s > 0$ $H_1 : z_s \leq 0$
Distance	$z_d = d_{dir} - \lambda$	$H_0 : z_d > 0$ $H_1 : z_d \leq 0$
ISR	$z_i = \gamma_{\delta_D\_indirect} - \gamma_{\delta_D\_direct}$	$H_0 : z_i > 0$ $H_1 : z_i \leq 0$
RSSI	$z_r = P_{R\_indirect} - P_{R\_direct}$	$H_0 : z_r > 0$ $H_1 : z_r \leq 0$

3.3 Performance Metrics

We introduce different shadowing components as a Gaussian distribution with zero mean and variance σ_i^2 to the mode selection rules defined in section 3.2. The direct and indirect links for these rules are than estimated. Using the estimates we calculate the probabilities of correct detection, false alarm and missed detection for the rules.

The performance of the mode selection rules is mainly affected by the selection of the correct hypothesis under different metrics. For this purpose, we divide the observation space into regions, in order to decide which hypothesis was true. It is clear, that irrespective of where this point of division is chosen to be, we will occasionally make a wrong decision. Let us denote by D_i, our choice of H_i as the outcome of the mode selection rules. The decision regions are shown in Figure 3.1.

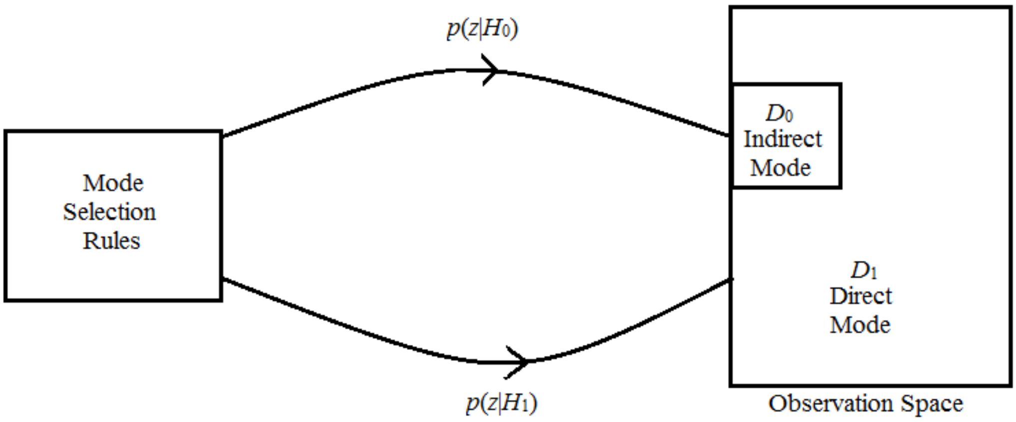

Figure 3.1 : Decision regions

In making a decision in binary hypothesis testing, we will have four possibilities to consider:

- H_0 is the true hypothesis, we decide D_0;
- H_1 is the true hypothesis, we decide D_1;
- H_0 is the true hypothesis, we decide D_1. This means that a false decision has been made.
- H_1 is the true hypothesis, we decide D_0. This means that a miss decision has been made.

The performance of the mode selection rules is determined by evaluating the probability of false alarm, missed detection and correct detection. The probability for correct detection is defined as [39], [40]:

$$P_C = P(D_1 \mid H_1) = \int_{z \in H_1} P(z \mid H_1) dz \,. \quad \textbf{(3.13)}$$

The probability for missed detection corresponds to deciding H_0 when H_1 is true, is defined as [39], [40]:

$$P_{MD} = P(D_0 \mid H_1) = \int_{z \in H_0} P(z \mid H_1) dz \,. \quad \textbf{(3.14)}$$

The probability for false alarm corresponds to deciding H_1 when H_0 is true, is defined as [39], [40]:

$$P_{FD} = P(D_1 \mid H_0) = \int_{z \in H_1} P(z \mid H_0) dz . \quad \textbf{(3.15)}$$

We model the hypothesis H_i as a Gaussian distribution with mean m_i and variance σ_i^2 [38], [39], [40], which is defined as:

$$P(z \mid H_i) = \frac{1}{\sqrt{2\pi}\sigma_i} \exp\left(\frac{-(z - m_i)^2}{2\sigma_i^2} \right). \quad \textbf{(3.16)}$$

From the previous section, we can calculate the probability of false alarm, miss detection and correct detection for every metric.

3.3.1 Capacity

Capacity is calculated for every link irrespective of where the devices are. Depending upon the values of indirect capacity and direct capacity, proposed mode is selected. For a device D_1, located near other device, the direct capacity would be more than the indirect capacity, the probability of correct detection for direct capacity to be chosen is defined as:

$$P_C = P(H_1 \mid H_1) = \int_{z \in H_1} P(\hat{z}_c \mid H_1) dz , \quad \textbf{(3.17)}$$

where the devices should be within the region H_1, where the direct capacity is more than the indirect capacity. For a device with higher direct capacity, but indirect mode is chosen, the probability of missed detection would be defined as:

$$P_{MD} = P(H_0 \mid H_1) = \int_{z \in H_0} P(\hat{z}_c \mid H_1) dz . \quad \textbf{(3.18)}$$

False alarm represent when direct mode is chosen as proposed mode, although indirect capacity had a greater value. The probability of false alarm can be calculated as:

$$P_{FD} = P(H_1 \mid H_0) = \int_{z \in H_1} P(\hat{z}_c \mid H_0) dz . \quad \textbf{(3.19)}$$

The performance of the capacity mode selection rule can be determined by using the probability of false alarm, the probability of missed detection.

3.3.2 Signal to noise ratio (SNR)

SNR is is calculated for every link irrespective of where the devices are. Depending upon the values of indirect SNR and direct SNR, proposed mode is selected. For a device D_1, located near other device, the direct SNR would be more than the indirect SNR, the probability of correct detection for direct SNR to be chosen is defined as:

$$P_C = P(H_1 \mid H_1) = \int_{z \in H_1} P(\hat{z}_s \mid H_1) dz \,, \qquad \textbf{(3.20)}$$

where the devices should be within the region H_1, where the direct SNR is more than the indirect SNR. For a device with higher direct SNR, but indirect mode is chosen, the probability of missed detection would be defined as:

$$P_{MD} = P(H_0 \mid H_1) = \int_{z \in H_0} P(\hat{z}_s \mid H_1) dz \,. \qquad \textbf{(3.21)}$$

False alarm represent when direct mode is chosen as proposed mode, although indirect SNR had a greater value. The probability of false alarm can be calculated as:

$$P_{FD} = P(H_1 \mid H_0) = \int_{z \in H_1} P(\hat{z}_s \mid H_0) dz \,. \qquad \textbf{(3.22)}$$

The performance of the SNR mode selection rule can be determined by using the probability of false alarm, the probability of missed detection.

3.3.3 Distance

A proximity region is defined in which the mode is selected depending upon how far the devices are. While the devices are in the proximity region, direct mode is chosen, which is the correct detection. But when D_2 lies outside the proximity region and direct mode is chosen, this would result in a false alarm. While the devices are outside the proximity region, indirect mode is chosen that is the correct detection. But when D_2 lies within the proximity region and indirect mode is chosen, this would result in missed detection.

For a device D_1, located within the proximity region, the probability of correct detection for D_2 to be located within the proximity region can be obtained as:

$$P_C(x_2, y_2) = P(H_1 \mid H_1) = \int_0^{\lambda} p(\hat{z}_d \mid H_1) dz \,, \qquad \textbf{(3.23)}$$

where the devices should be within the threshold λ, as defined from previous section. For a device located within the proximity region, the probability of missed detection is:

$$P_{MD}(x_2, y_2) = P(H_0 \mid H_1) = \int_0^{\lambda} p(\hat{z}_d \mid H_1) dz . \qquad \textbf{(3.24)}$$

False alarm represent when D_2 outside the proximity region is detected to be within λ, and mode is chosen to be direct mode. The probability of false alarm can be calculated as:

$$P_{FD}(x_2, y_2) = P(H_1 \mid H_0) = \int_{\lambda}^{R} p(\hat{z}_d \mid H_0) dz . \qquad \textbf{(3.25)}$$

The performance of the proximity region can be determined by using the probability of false alarm, the probability of missed detection.

3.3.4 Interference to signal ratio (ISR)

ISR is calculated for every link irrespective of where the devices and CUE are. The interference from CUE to D_2 is kept to a minimal so D2D communication can have a better performance. Depending upon the values of indirect ISR and direct ISR, proposed mode is selected. For a device D_2, located near other CUE, the direct ISR would be less than the indirect ISR, the probability of correct detection for direct ISR to be chosen is defined as:

$$P_C = P(H_1 \mid H_1) = \int_{z \in H_1} P(\hat{z}_{isr} \mid H_1) dz , \qquad \textbf{(3.26)}$$

where the devices should be within the region H_1, where the direct ISR is less than the indirect ISR. For a device with lower direct ISR, but indirect mode is chosen, the probability of missed detection would be defined as:

$$P_{MD} = P(H_0 \mid H_1) = \int_{z \in H_0} P(\hat{z}_{isr} \mid H_1) dz . \qquad \textbf{(3.27)}$$

False alarm represent when direct mode is chosen as proposed mode, although indirect ISR had a lower value. The probability of false alarm can be calculated as:

$$P_{FD} = P(H_1 \mid H_0) = \int_{z \in H_1} P(\hat{z}_{isr} \mid H_0) dz . \qquad \textbf{(3.28)}$$

The performance of the ISR mode selection rule can be determined by using the probability of false alarm, the probability of missed detection.

3.3.5 Received signal strength indicator (RSSI)

Depending on the location of the devices, RSSI is calculated for every link. Depending upon the values of indirect RSSI and direct RSSI, proposed mode is selected. For a device D_1, located near other device, the direct RSSI would be more than the indirect RSSI, the probability of correct detection for direct RSSI to be chosen is defined as:

$$P_C = P(H_1 \mid H_1) = \int_{z \in H_1} P(\hat{z}_r \mid H_1) dz \,, \qquad \textbf{(3.29)}$$

where the devices should be within the region H_1, where the direct RSSI is more than the indirect RSSI. For a device with higher direct RSSI, but indirect mode is chosen, the probability of missed detection would be defined as:

$$P_{MD} = P(H_0 \mid H_1) = \int_{z \in H_0} P(\hat{z}_r \mid H_1) dz \,. \qquad \textbf{(3.30)}$$

False alarm represent when direct mode is chosen as proposed mode, although indirect RSSI had a greater value. The probability of false alarm can be calculated as:

$$P_{FD} = P(H_1 \mid H_0) = \int_{z \in H_1} P(\hat{z}_r \mid H_0) dz \,. \qquad \textbf{(3.31)}$$

The performance of the RSSI mode selection rule can be determined by using the probability of false alarm, the probability of missed detection.

4. SIMULATION RESULTS

In this chapter we present our simulation results. By varying the parameters of our topology we populate a cell with many devices. D2D communication is implemented with the direct and indirect mode algorithms. We simulate different scenarios and the mode selection rules metioned in Chapter 2 are calculated and compared. Along with the rules, from Chapter 3, performance metrics are calculated and plotted to show the performance of the D2D communication.

4.1 Simulation Setup

Firstly we need to determine the simulation environment. A single cell environment, where the base transceiver station is placed in the center of the cell is considered. The environment takes into account that, signal strength decays around the base transceiver station. Once the simulation area is created, devices are placed accordingly. The main parameters used in the simulation are defined in Table 1.

Table 4.1 : Simulation parameters

Parameters	**Value**
Coverage Area, R	700 m
Carrier Frequency	800 MHz
BTS Transmission (Tx) Power	43 dBm
D2D Tx Power	27 dBm
Noise Power	-116.4 dBm
δ_B	0.01

The device D_1, is placed at a fixed place in every simulation, where as the device D_2 is placed randomly across the radius R. Additionally, D_1 and D_2 cannot be at the same location at the same time. To evaluate the performance of D2D modes, we consider a large number of simulations. In every simulation, all the possible D2D communication modes are calculated and analyzed. Figure 4.1, shows a random snap shot of the simulation setup where the device D_2, are randomly being placed across the radius R, although there are 200,000 D2D pairs considered for our simulation.

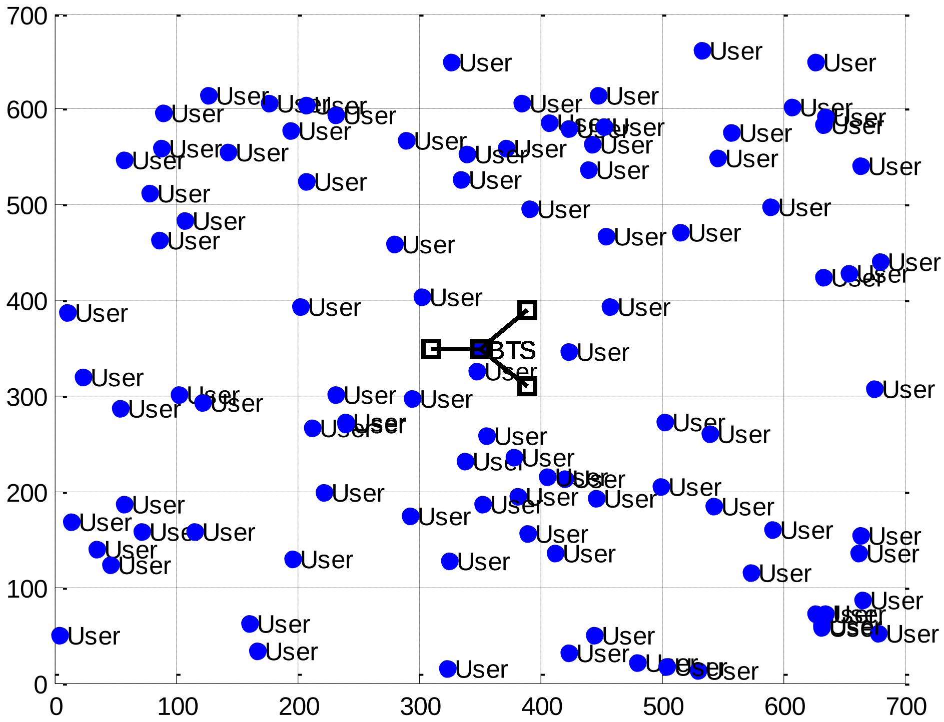

Figure 4.1 : Devices being randomly placed around the BTS.

4.2 Simulation Results

In this section, we show the performance analysis for our simulation setup. As seen from section 2.2, the signal after being transmitted from the BTS undergoes fading, which we consider as Rayleigh fading. We calculate the theoratical bit error rate (BER) for Rayleigh fading, and the simulated BER of the Rayleigh fading model as used in the simulation setup. This shows the number of bits that did not reach the destination, due to multipath propagation or the surrounding objects or the signal bandwidth or the speed of the user. Figure 4.2, shows the BER in Rayleigh channel. It is seen, that the simulated and the theoretical values of BER are the same. The BER decreases as the SNR is increased.

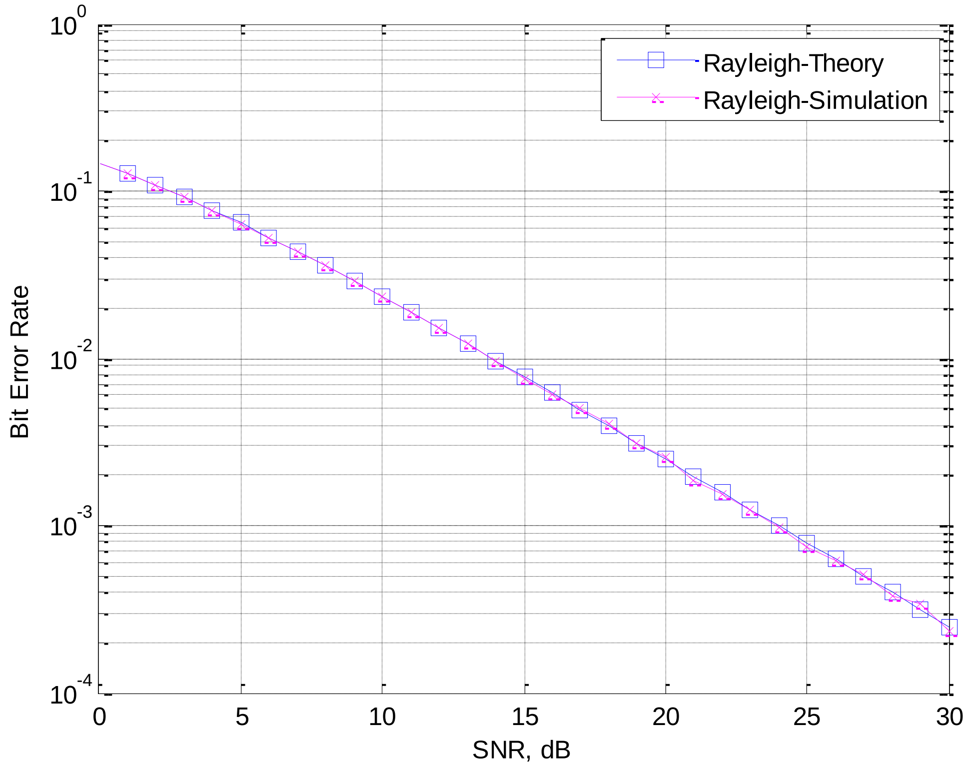

Figure 4.2 : BER for BPSK in a Rayleigh channel

We compare average capacity for different mode selection rules which is shown in Figure 4.3. It is shown that, ISR rule has the highest average capacity. This is because the interference is minimized in the interference limited area, increasing the capacity. At an instant when ISR has a value of 20.1 bps/Hz. The capacity rule has has an average capacity of 14.2 bps/Hz, at the same instant. SNR rule follows the capacity rule, with an average capacity of 14.1 bps/Hz. RSSI rule at the same instant has an average capacity of 6.4 bps/Hz and distance rule has the lowest average capacity with a value of 6.1 bps/Hz due to the defined proximity region. If the devices are not in the proximity region, indirect mode would be chosen. As seen from the figure it is shown that the average capacity varies with the different mode selection rules.

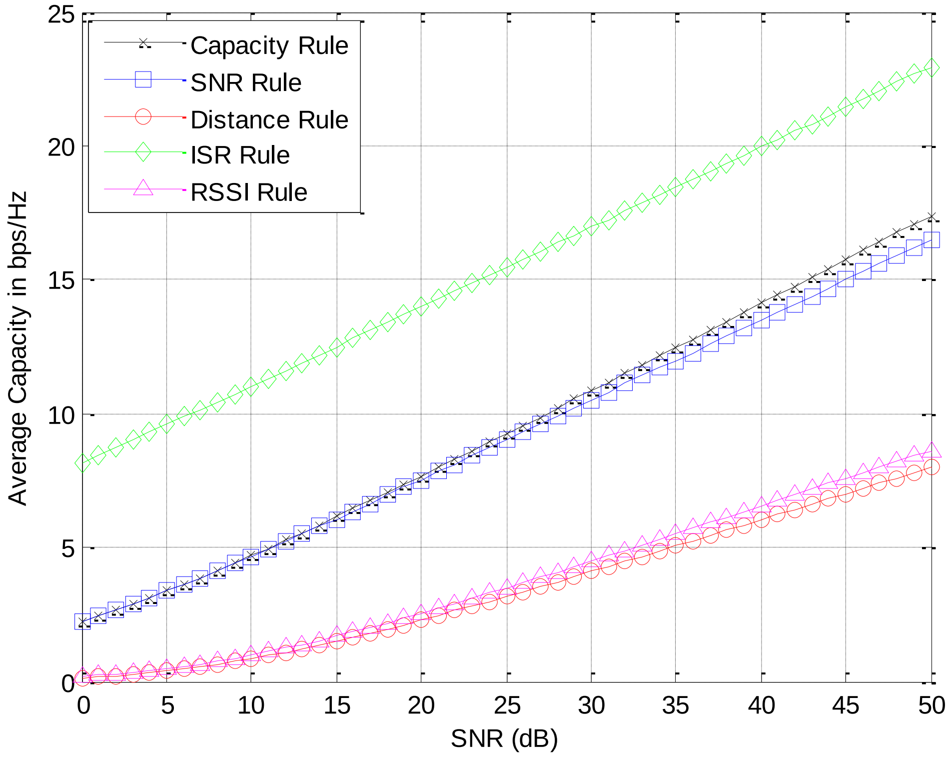

Figure 4.3 : Average capacities for different rules.

For the direct and indirect modes, we calculate the SNR and the SNR after δ_D-*ILA* control scheme was introduced. In Figure 4.4, SNR is shown for the direct and indirect mode of communication. SNR with δ_D-*ILA* control scheme would be higher than the normal SNR, since the interference was calculated for an area where interference was minimum, resulting in a higher SNR being achieved. From the graph, it is seen that SNR direct if at an instant has value of 31.2 dB, after introduction of δ_D-*ILA*, the value of SNR-ILA direct at the same instant was 57.4 dB. The similar values for indirect mode of communication are calculated and shown. From the graph, it is seen that SNR indirect if at an instant has value of 20.2 dB, after introduction of δ_D-*ILA*, the value of SNR-ILA indirect at the same instant was 44.3 dB.

It should be noted, that SNR for direct mode of communication is higher than the indirect mode of communication. For direct mode of communication, gain in SNR after introduction of δ_D-*ILA* control scheme was 26.2 dB and the gain in SNR for indirect mode of communication was 24.1 dB.

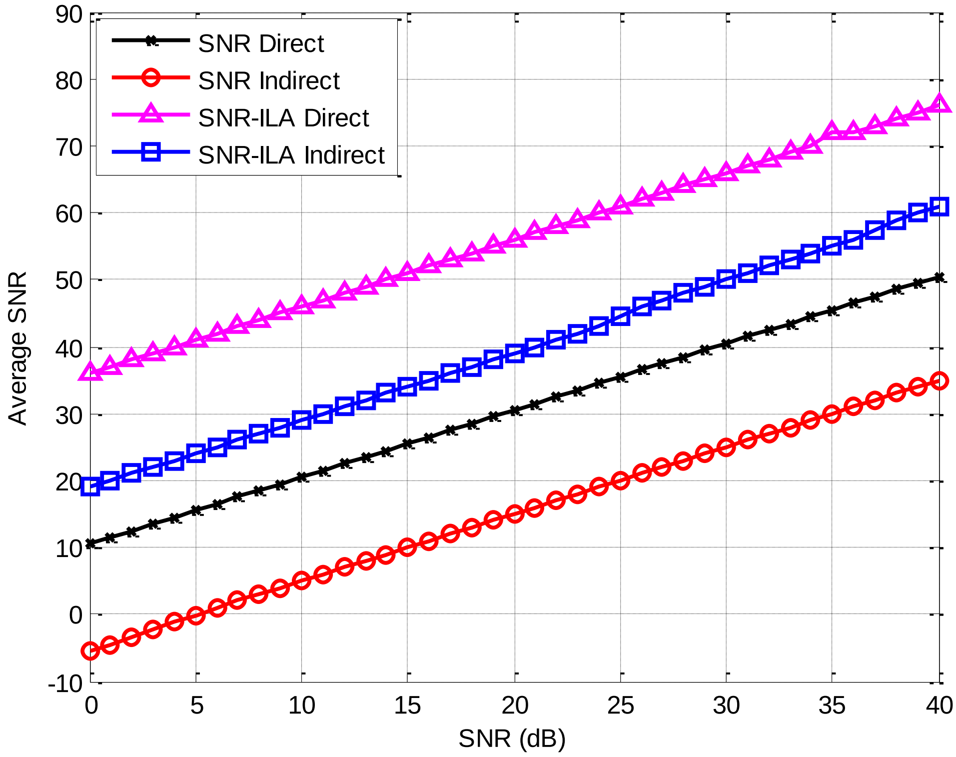

Figure 4.4 : Average SNR for direct and indirect mode of communications.

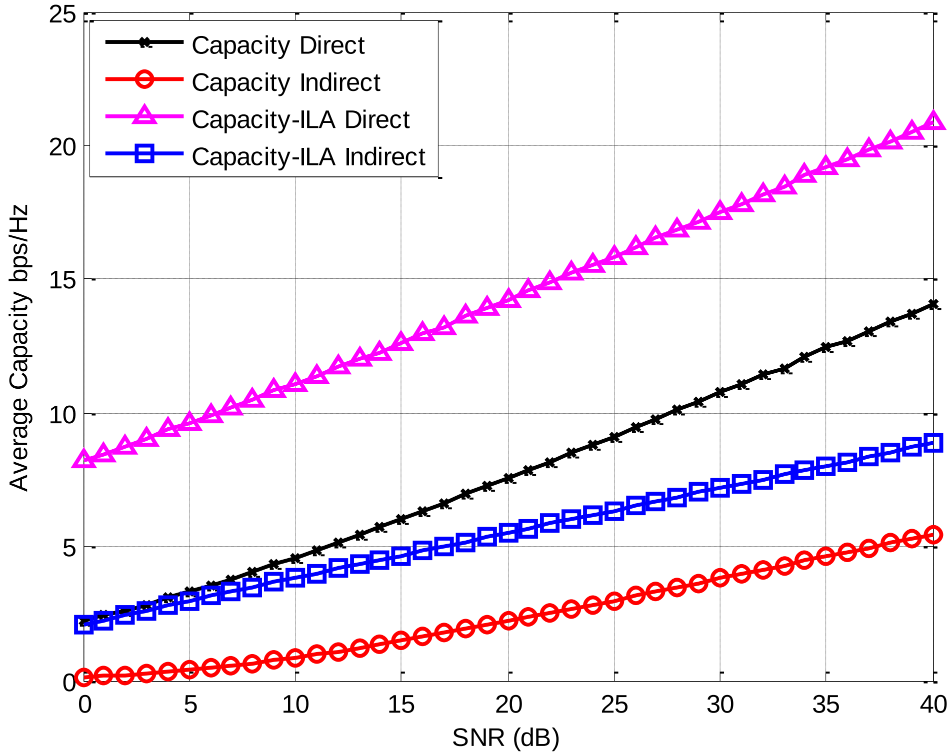

Figure 4.5 : Average capacity for direct and indirect mode of communications.

Similarly to SNR, for the direct and indirect modes, we calculate the channel capacity for both the modes and the channel capacity after δ_D-*ILA* control scheme was introduced. In Figure 4.5, for the direct and indirect modes of communication, graph for various capacities is shown. Capacity with δ_D-*ILA* would be higher than the normal capacity, since the interference was calculated for an area where interference was minimum, resulting in a higher capacity being achieved. From the graph, it is seen that capacity direct if at an instant has value of 7.3 bps/Hz, after introduction of δ_D-*ILA* control scheme, the value of capacity-ILA direct at the same instant was 13.8 bps/Hz. The similar values for indirect mode of communication are calculated and shown in the figure. From the graph, it is seen that capacity indirect if at an instant has value of 3.4 bps/Hz, after introduction of δ_D-*ILA* control scheme, the value of capacity-ILA indirect at the same instant was 6.1 bps/Hz.

Similarly, capacity for direct mode of communication is higher than the indirect mode of communication. For direct mode of communication, gain in capacity after introduction of δ_D-*ILA* was 6.5 bps/Hz and the gain in capacity for indirect mode of communication was 2.7 bps/Hz.

In Figure 4.6, normalized frequency histogram for modes of communication for different performance metrics is shown. It is seen that capacity rule selects direct mode of communication for a greater number of times then the rest of the mode selection rules, since the capacities are being measured and compared. Maximum of the capacities is selected, irrespective of the location of the devices, either they are near by or either they are far apart. The same result is seen for the SNR and ISR mode selection rule. Interestingly, since the distance is limited for a better performance of D2D communication, a higher probablity distribution is shown for indirect mode of communication being selected. Whenever the devices are in a proximity region then direct mode is selected as the mode of communication making the D2D communication more effective. Since received power decreases as distance increases, RSSI rule also shows a similar pattern to distance rule where indirect mode of communication is selected more based on the hypothesis defined in the previous chapter.

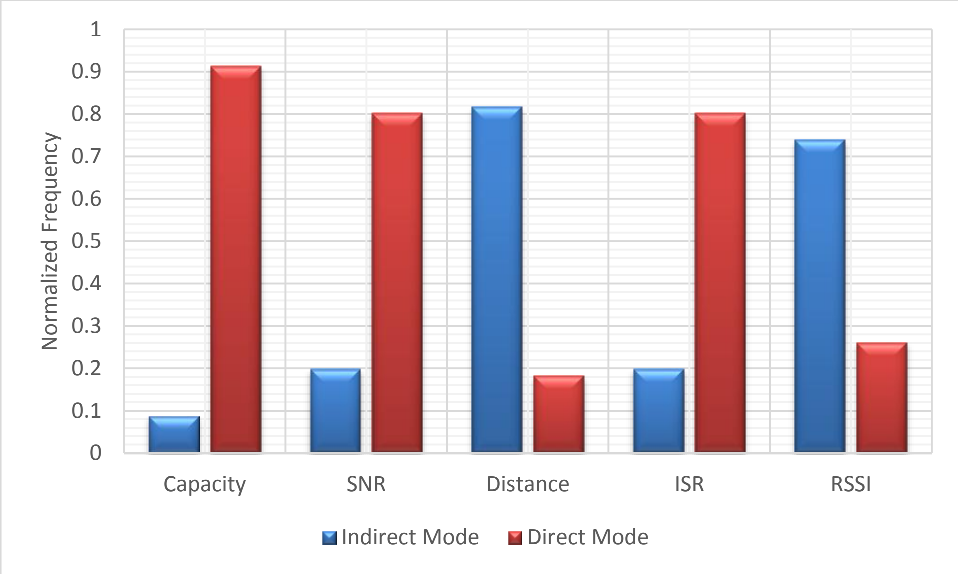

Figure 4.6 : Normalized frequency histogram for modes of communication

In Figure 4.7, 4.8, 4.9, 4.10 and 4.11, the normalized frequency histograms are shown for the mode selection rules. It is seen that depending on where D_2 is placed in the cellular coverage of the BTS, for every link the system parameters are calculated and are distributed in different ranges. These ranges are defined and the probability of each range is calculated.

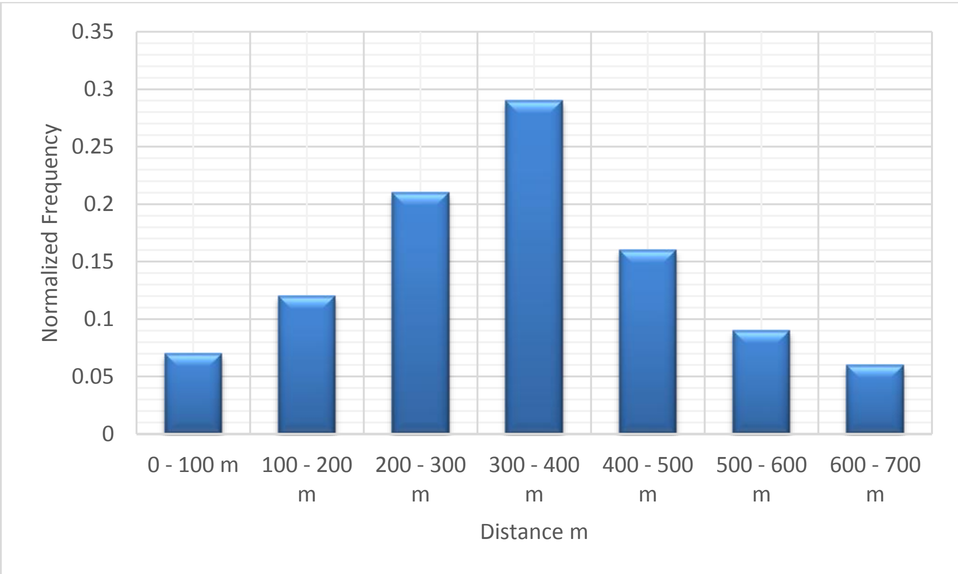

Figure 4.7 : Normalized frequency histogram for distance rule.

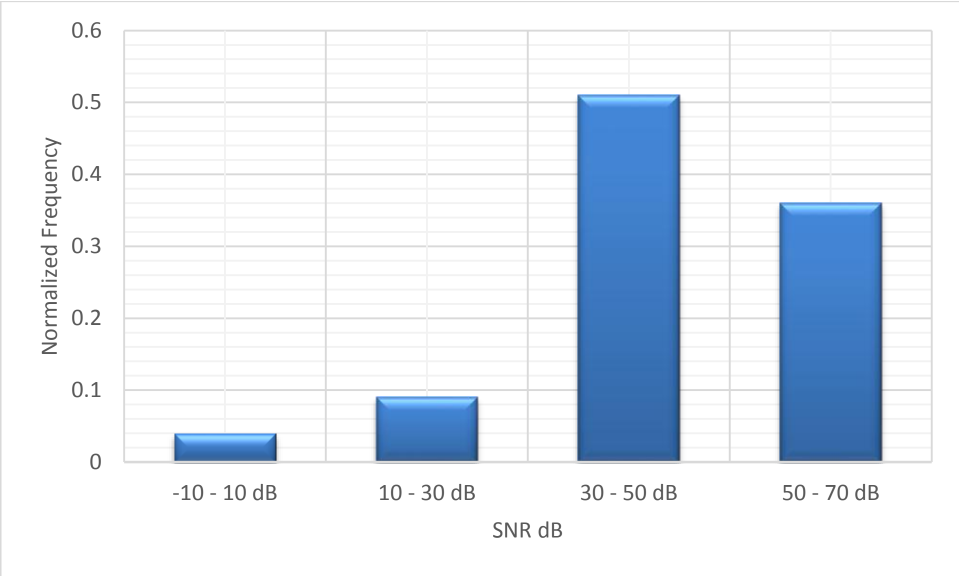

Figure 4.8 : Normalized frequency histogram for SNR rule.

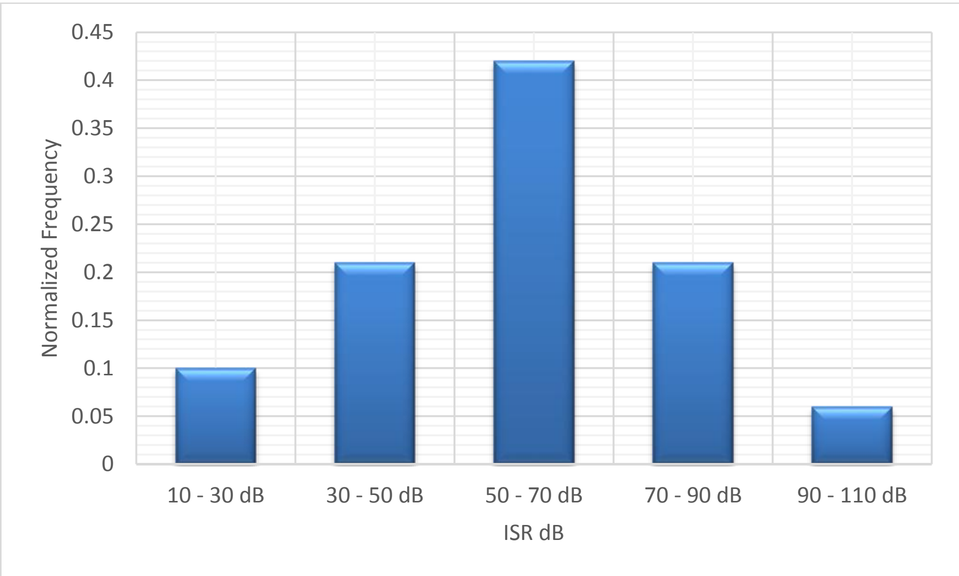

Figure 4.9 : Normalized frequency histogram for ISR rule.

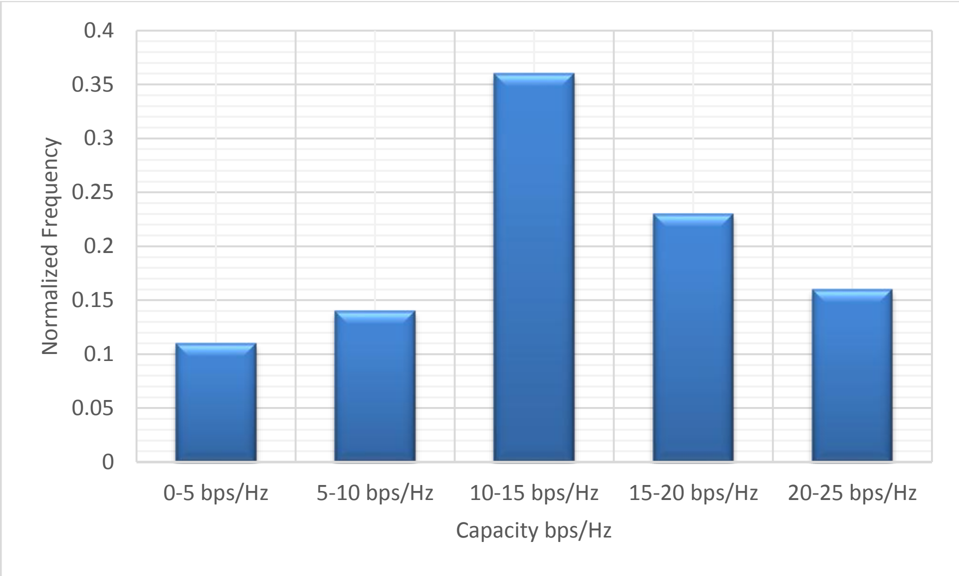

Figure 4.10 : Normalized frequency histogram for capacity rule.

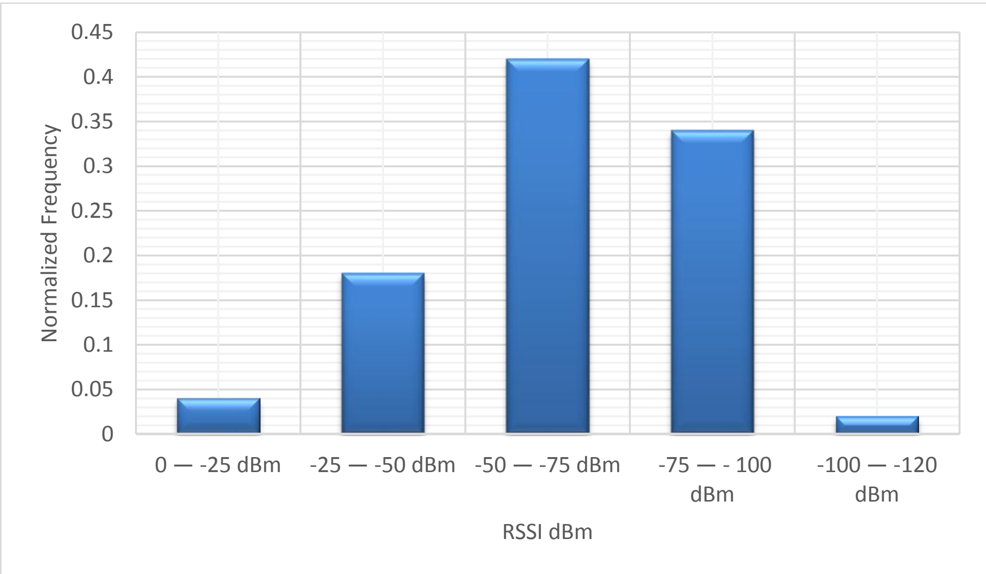

Figure 4.11 : Normalized frequency histogram for RSSI rule.

Depending on the mode selection rules from section 3.2, modes are selected. After the introduction of shadowing to the mode selection rules, the modes are reselected. Based on the comparison of modes selection before and after introduction of shadowing, certain performance metrics are calculated. These performance metrics are probability of correct detection and probability of false alarm and probability of missed detection which are shown in Figures 4.12, 4.13, 4.14, 4.17 and 4.18 respectively.

In Figure 4.12, the probability of correct detection for different mode selection rules is shown. It is seen that probability of correct detection decreases for every rule as the variance is increased. From the graph it is seen that when at an instant, probability of correct detection for capacity rule is 0.976, at the same instant the vale for SNR rule is 0.964, for ISR rule is 0.9615 and for RSSI rule is 0.96.

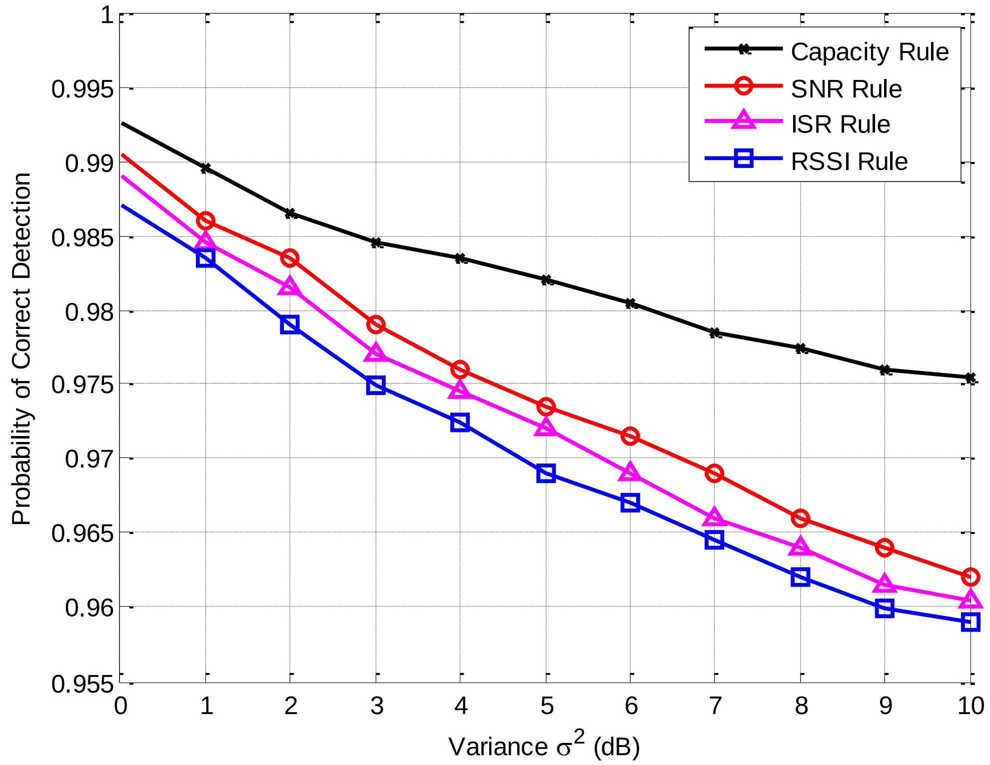

Figure 4.12 : Performance results for probability of correct detection.

As the variance is increased, wrong decision is made which increases probability of false alarm, as shown in Figure 4.13. From the figure it is seen that at the same instant, probability of false alarm for capacity rule is 0.0047, for SNR rule is 0.0056, for ISR rule is 0.0062 and for RSSI rule is 0.0115. It is shown that, when the probability of correct detection for a mode selection is higher than the probability of correct detection for other mode selection rules, the probability of false alarm for that mode selection rule would be lower than the probability of false alarm for other mode selection rules. For example, capacity rule has the highest probability of correct detection, hence it will also have the lowest probability of false alarm.

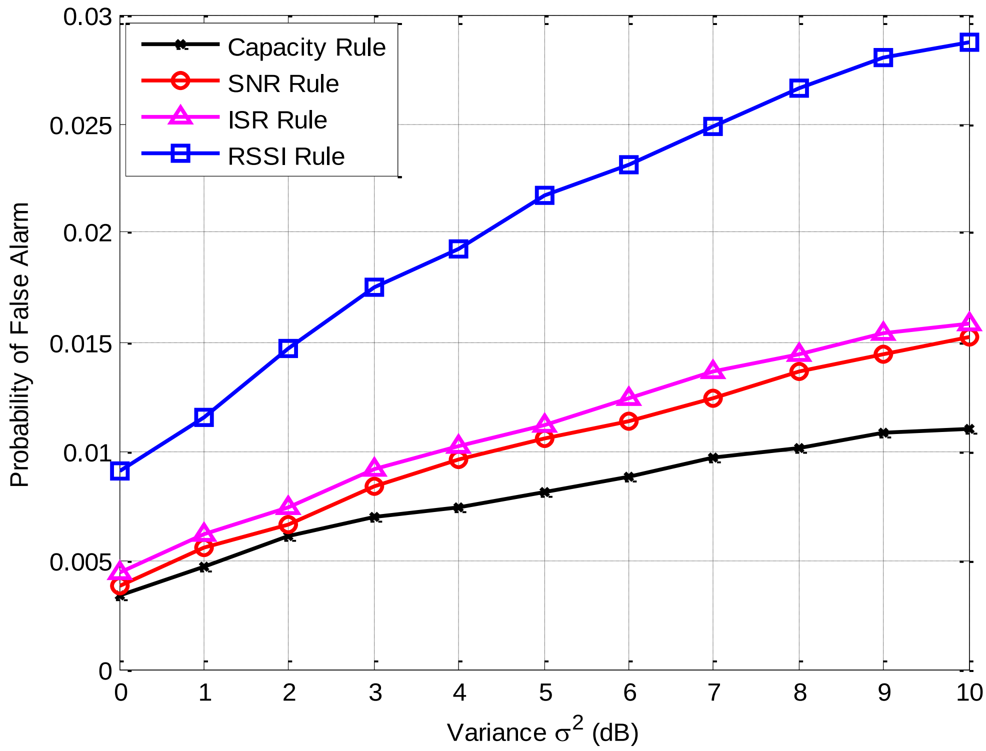

Figure 4.13 : Performance results for probability of false alarm.

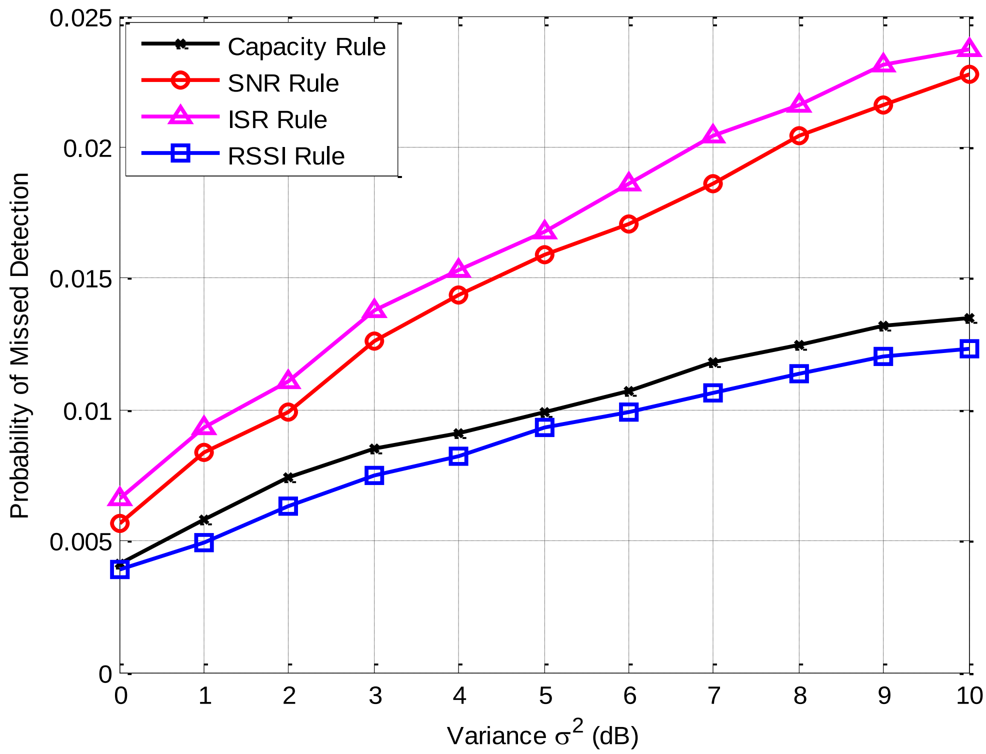

Figure 4.14 : Performance results for probability of missed detection.

Similarly probability of missed detection is shown in Figure 4.14. From the figure it is seen that if at the same instant, probability of missed detection for capacity rule is 0.0132, for SNR rule is 0.0218, for ISR rule is 0.0225 and for RSSI rule is 0.0121.

From Figure 4.6, it was seen that distance been the devices gives a better opportunity to see the benefits of having a D2D communication. We further observe the changes when distance is increased between the device. In Figure 4.15, the effect on capacities of direct, indirect and modes are shown when the D2D pair separation is increased while keeping the distance between D_1 and BTS constant, i.e. 250 m. As the D2D pair (D_1 and D_2) moves further away from each other, the SNR of direct communication decreases, which in return minimizes the capacity of direct communication. From the graph, it is seen that when separation of D_1 and D_2 is more 130 m, indirect mode is more suitable, but when the separation is less than 130 m, the capacity of direct mode is the maximum, which than becomes the proposed method of communication.

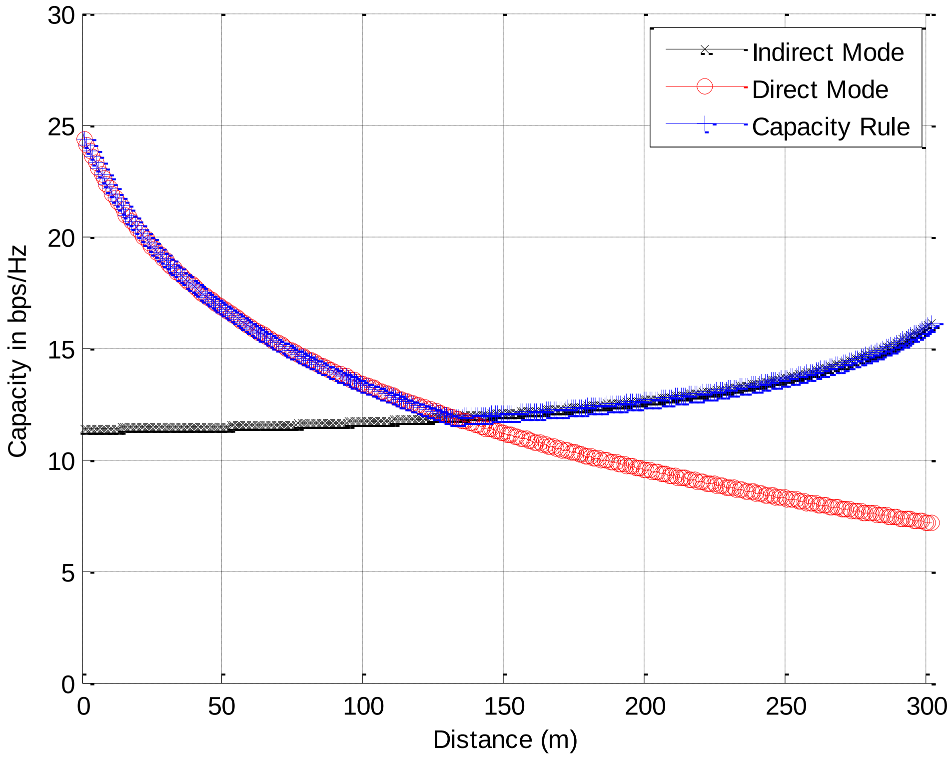

Figure 4.15 : Channel Capacity of D2D modes with respect to increasing distance between D_1 and D_2 while keeping fixed distance of D_1 and BTS

Threshold λ, could be found from (2.15) and (2.18), when the direct capacity would be equal to indirect capacity. Below this threshold, direct mode is taken as the proposed mode and after that, indirect mode is taken as the proposed mode of D2D communication. The same results could be seen from Figure 4.15 in which λ = 130 m, where indirect and direct capacities are the same. A better D2D communication is attainted if the devices are present within a proximity region. This region is defined from Figure 4.15, the point where both direct mode capacity and indirect mode capacity are equal. We randomly add some distance to the threshold to see its effects which are shown in Figure 4.16.

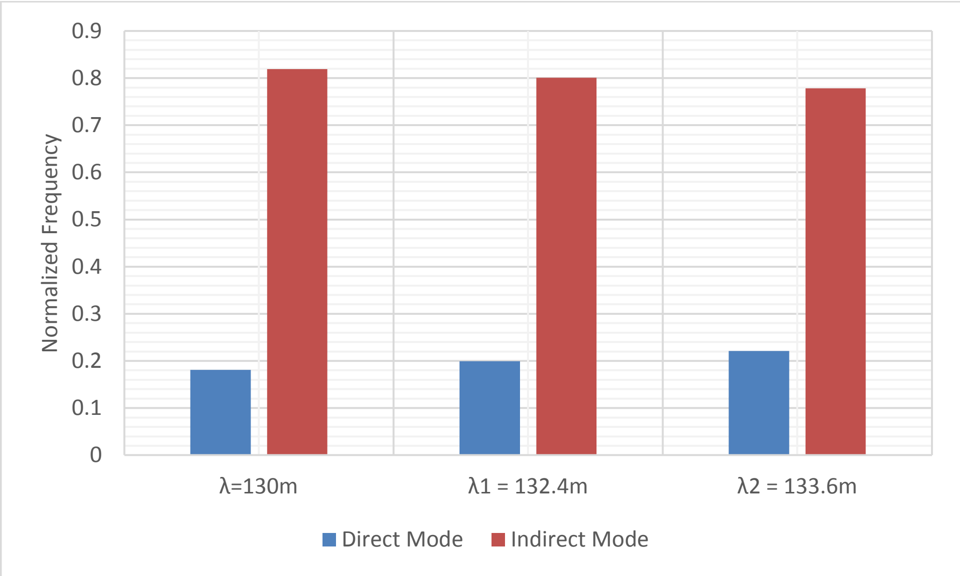

Figure 4.16 : Normalized frequency histogram for increase of distance threshold.

It is seen from the figure that when the distance threshold increases i.e. the proximity region area increases, it is more likely to have higher number of direct mode communication. Alternately it is also shown that when the threshold λ is varied, the correct detection and false alarm vary as well which is shown in Figure 4.17 and 4.18. When λ was 130m, the probability of correct detection was 0.9973 at a particular variance. At the same variance increasing λ_1 to randomly generated value of 132.4m and λ_2 to 133.6m, the probability of correct detection decreased to 0.9964 and 0.995 respectively. In Figure 4.18, probability of false alarm increases as we increase the proximity region. For λ = 130m, the probability of false alarm is 0.0027, but when λ_1 is increased to 132.4m, the probability of false alarm increases to 0.0036.

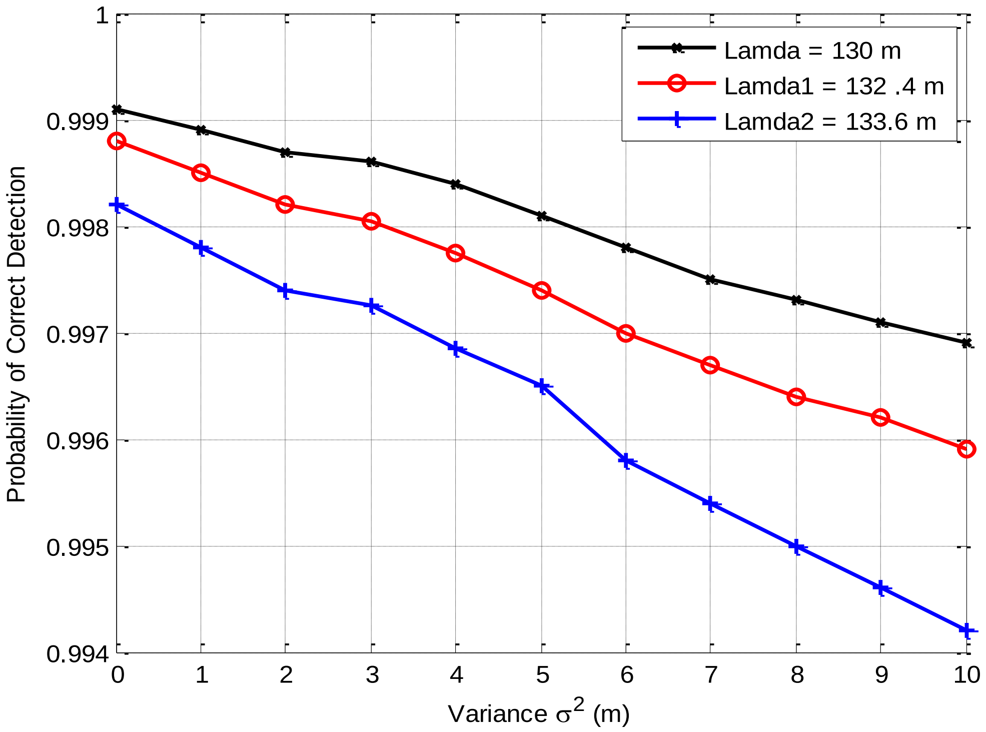

Figure 4.17 : Probability of correct detection for distance rule.

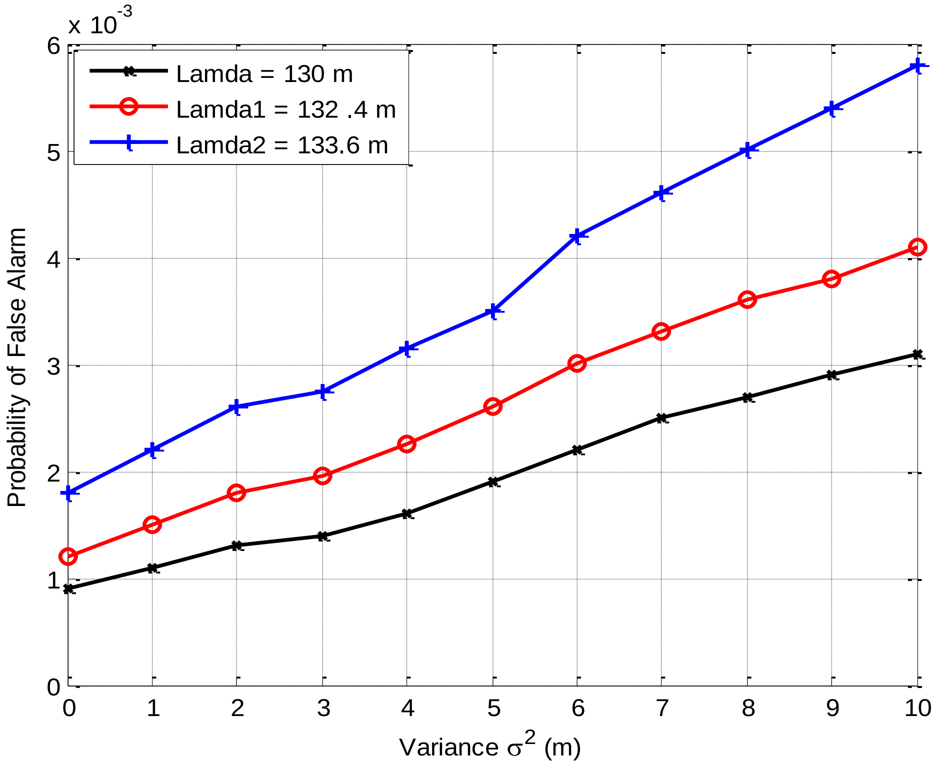

Figure 4.18 : Performance results for probability of false alarm for distance rule.

At the same point, when λ_2 is increased to 133.6m, the probability of false alarm is 0.005. Hence as the proximity region increases, the probability of correct detection decreases, increasing the probability of false alarm.

This summarizes, that the probability of correct detection for distance rule has the maximum value, making the distance rule highly efficient. But at the same point, it is seen from Figure 4.3, that distance rule has the least average capacity. Hence to increase the average capacity of a mode selection rule, the performance metrics are not to be neglected.

The receiver operating characteristics (ROC) for mode selection rules are shown in Figure 4.19 and 4.20. In Figure 4.19, correct detection is shown w.r.t false alarm based on capacity, SNR, ISR and RSSI rules. As seen, the probability of correct detection increases as the false alarm is increased. The capacity rule shows the best characteristics, since it has the highest probability of correct detection followed by SNR and than ISR. RSSI shows the worst characteristics, since shadowing causes decrease in received signal strength. SNR and ISR rules show a decent characteristics since the shadowing component of the surroundings is a key factor which makes the SNR and ISR to have a great difference in values, hence having a lower probability of correct detection.

In Figure 4.20, receiver-operating characteristics (ROC), is shown for distance rule. Probability of correct detection increases with probability of false alarm for the three curves. The three curves in the figure correspond to three different values of the threshold λ. The smaller the value of λ, the larger will be the separation of densities under the two hypothesis and hence P_C for a fixed P_{FD} would be higher. When the value of threshold λ, is increased the proximity region would have a lower probability for correct detection with respect to the probability of false alarm.

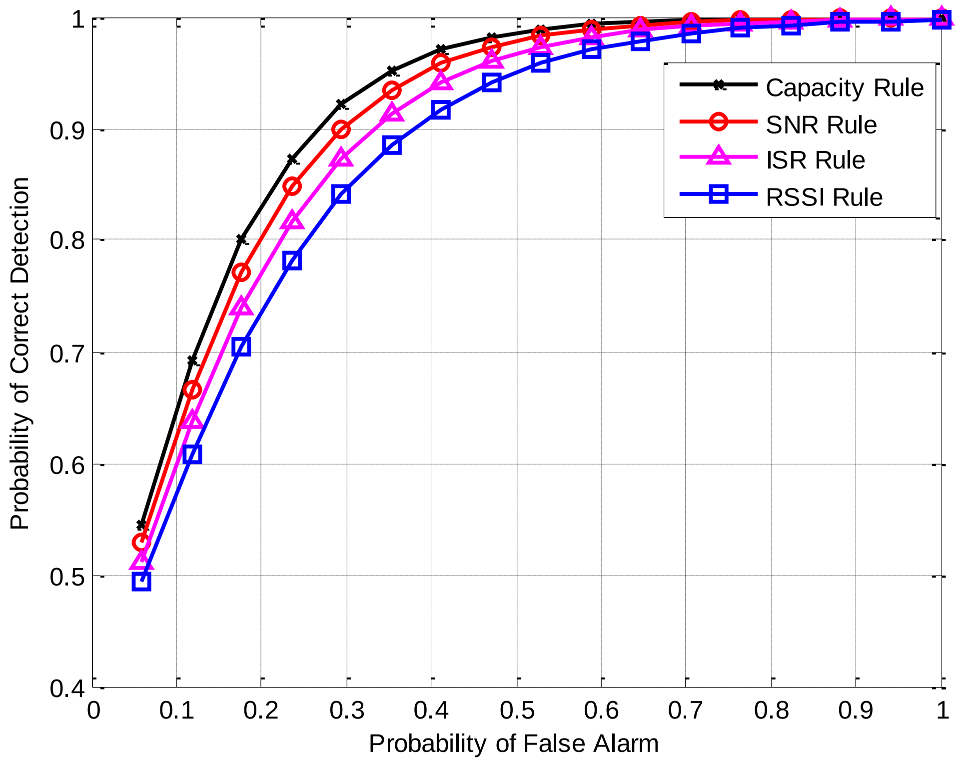

Figure 4.19 : ROC for mode selection rules.

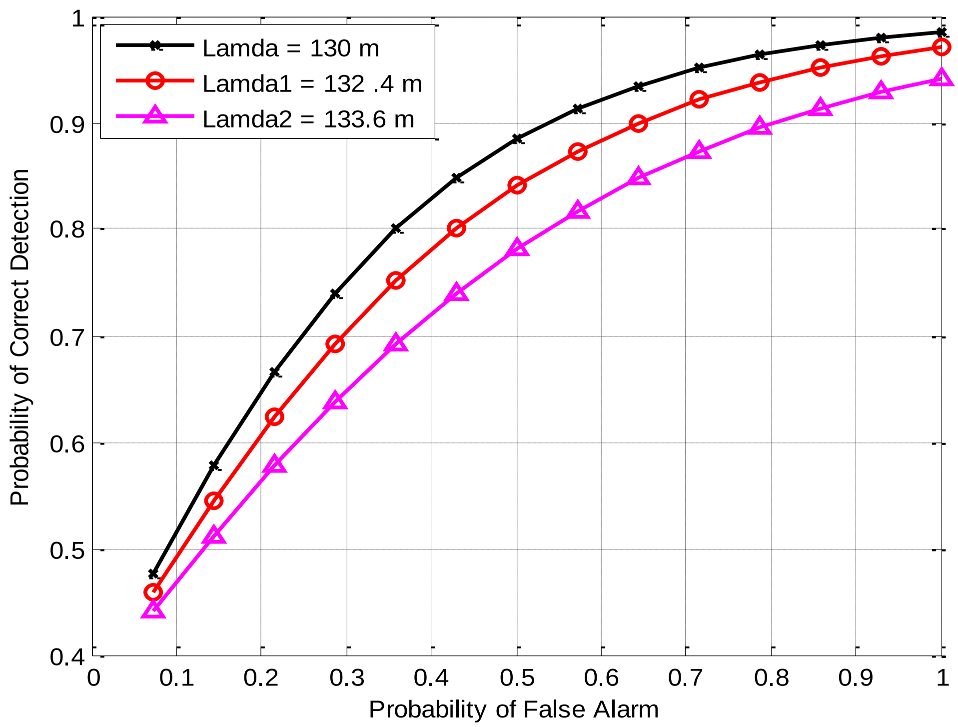

Figure 4.20 : ROC for distance rule.

5. CONCLUSION

5.1 Conclusion

The purpose of this study was to discover devices which could have a D2D communication in a cellular network and propose the mode selection rules, in which either the communication is done without the BTS, or with the BTS, which is used as a relay for communication. Apparently, the D2D session take place in the same frequency band as the cellular communication. This implies that the BTS covering the area in which the devices are present is administrating the communication links. Interference is introduced between D2D user equipments and cellular user equipments.

In Chapter 2, we explained the system model in which the devices are randomly placed within the coverage area of the BTS. The transmitted signal from the devices decays due to different propagation models, which are taken into consideration. A link is created between two communication devices, either being D2D, or device-to-BTS and from BTS-to-device. For every link the mode selection rules, i.e. capacity, RSSI, SNR, ISR and distance were calculated. We introduced two modes for D2D communication. One being direct mode of communication, where the devices communicate directly with each other, and other being indirect mode of communication, where devices communicate through the BTS, making it as a relay for amplifying and forwarding the data. The modes are selected depending on the metrics defined in the next chapter.

In Chapter 3, we introduced maximum detection rule to select the maximum of the direct mode and indirect mode to be choosen as the proposed mode for communication. Later in the chapter, we derived equations for capacity, SNR, distance, ISR and RSSI rules. Using these equations, direct and indirect mode of communication were calculated and the proposed mode was selected by the maximum detection rule and used as the mode for communication. Later we introduced shadowing to the mode selection rules and calculated the performance of the rules. The performance included probability of correct detection, probability of missed detection and probability of false alarm.

In Chapter 4, Monte Carlo simulations were performed for devices that were randomly placed within an area. The simulated scenario consisted of a single cell. Depending on the performance metrics, mode of communication is selected for every link. For both direct and indirect mode of communication, capacity, SNR, distance, ISR and RSSI is calculated and proposed mode of communication is selected using the maximum detection rule for every mode selection rule. It was shown the for a fixed ILA control scheme, where the interference was kept minimum between the devices and CUE, the SNR and capacity increased in that area. The probability distribution for the mode selection rules was shown graphically by a histogram. After addition of shadowing is done in the system, probabilities of correct detection, missed detection and false alarm are calculated, compared and summarized that which rule has the best performance. It was shown that probability of correct detection decreases for every rule depending on increasing variance. This was because the threshold for every rule was increasing hence a chance to lie within the threshold decreased. As the threshold increased the probability to generate a false alarm increase. Hence, with increasing variance, the probability of false alarm increases for every rule.

5.2 Future Work

Device to Device communication is a new area of research with several interesing and challenging problems. In this thesis, we introduced a novel methodology of choosing the mode of D2D communication. We believe this structure provides an appropriate context for understanding of D2D communication. However, the impacts of multiple antenna system on the mode selection rules requires future studyfor. The system model would be need to be changed and an optimal mode selection rules would need to be derived. Introduction of difference fading schemes can be used to get a more realistic result to benefit the reasearch on D2D communication.

Moreover, group mode for D2D is another interesting research area to consider where multiple devices in vicinity of each other could form a group and communicate using D2D links. Every group will have a group leader, by which the devices within the group could communicate with each other directly or indirectly. Group D2D communication could be enhanced with the multiple antenna system and used as an optimal mode of communication.

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