Measurement Results for Cooperative Device-to-Device Communication in Cellular Networks

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Certificate

This is to certify that the thesis titled **"Measurement Results for Cooperative Device-to-Device Communication in Cellular Networks"** submitted by **Vibhutesh Kumar Singh** for the partial fulfillment of the requirements for the degree of *Master of Technology* in *Electronics & Communication Engineering* is a record of the bonafide work carried out by him under my guidance and supervision at Indraprastha Institute of Information Technology, Delhi. This work has not been submitted anywhere else for the reward of any other degree.

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Abstract

Device-to-Device communication is expected to be a part of future 5G networks. Many researchers have provided solid theoretical concepts to implement it, but a real practical solution is still in dearth. In this work, first the design and development of a proof-of-concept testbed for single carrier Device-to-Device (D2D) communication have been done. The results obtained from this testbed can be used to evaluate the subtle design issues associated with the real world deployment of single carrier D2D communication protocols. These issues are often overlooked in a theoretical or simulation framework. The performance of this light-weight, readily deployable testbed has been validated by emulating a cellular scenario in which a base station (BTS) and many D2D enabled devices coordinate and communicate with each other to select an optimum communication range, transmit parameters, intracellular localization and mode of communication. Through the experimental results it has been shown that D2D communication can significantly reduce the power consumption of a conventional cellular network. After this, another testbed (Multi-carrier) was developed using Software Defined radio which incorporates the concept of Spectrum Sharing through static sub-carrier allocation to D2D user by cellular system which will eventually enhance the performance of cellular as well as D2D communication system. Our purposed and deployed protocol have shown significant improvement (10% to 30%) on Symbol Error Rate (SER) and Signal to Noise Ratio (SNR) as compared with conventional direct transmission schemes.

Acknowledgments

Towards the end of my Master degree, I would like to pay my gratitude to several individuals who contributed in many ways. First of all, I would like to express my deep gratitude to my thesis supervisor, Dr. Vivek Ashok Bohara for his support, guidance and motivation all along the way round. I feel extremely fortunate to work with him. Also this would not been possible with the support and Guidance of my family, my Father Dr. Bijay Kumar Singh have induced in me a scholar over the years. My mother Beena Singh who, whenever I felt misguided was a source of love and inspiration. My grandfather Dr. Vishwanath Prashad Sinha, whom I always followed, to be like him, and my little sister Dr. Abhilasha Singh. Last but not the least, I want to thank my friends especially Ms. Nidhi Upadhyay for all the thoughtful intellectual discussion throughout the thesis.

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List of Abbreviation

AF/DF	Amplify and Forward/Decode and Forward
AWGN	Additive White Gaussian Noise
BTS	Base Station
CU	Cellular Equipment
D2D	Device-to-Device
DRUE	D2D Receiver User Equipment
DSP	Digital Signal Processing
DTN	Delay Disruptive Tolerant
DTUE	D2D Transmitter User Equipment
eNB	Evolved Node-B
FDMA	Frequency Division Multiple Access
FPGA	Field Programmable Gate Array
HDTV	High Definition Television
ICI	Inter Carrier Interference
IEEE	Institute of Electrical and Electronics Engineers
ISI	Inter Symbol Interference
ISM	Industrial, Scientific and Medical
LAN	Local Area Network
MANET	Mobile Adhoc Network
MRC	Maximal Ratio Combining Networking
OFDM	Orthogonal Frequency Division Multiplexing
PAPR	Peak to Average Power Ratio
QoS	Quality of Service
RSSI	Received signal strength indication
SC/EGC	Selection/Equal Gain Combining
SDR	Software Defined Radio
SER	Symbol Error Rate
SNR	Signal to Noise Ratio
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
UE	User Equipment
USRP	Universal Software Radio Peripheral
WARP	Wireless Open-Access Research Platform

Chapter 1

Introduction

1.1 Research Motivation and Objective

Contemporary cellular communication is resource intensive and heavily dependent on infrastructure. It is restricted in terms of coverage and limited in terms of capacity since the number of simultaneous access it can support is often constrained by the design and specifications of the particular cellular area and base station respectively. Additionally, contemporary cellular communication often gets paralyzed during natural disasters [33] which leads to destruction of cellular infrastructure and hampering of cellular services. The above motivates the use of a cellular service that is minimally dependent on network infrastructure as well as enhances coverage and capacity of deployed networks.

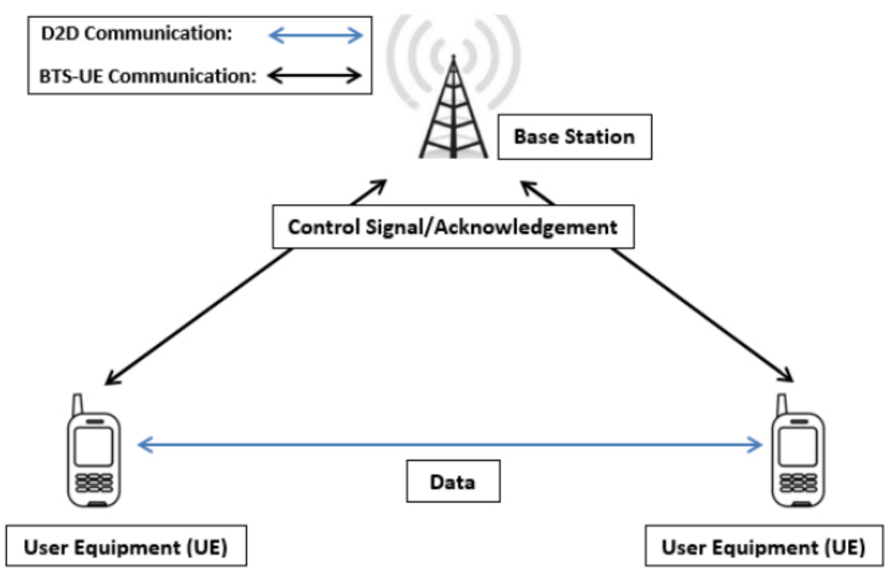

Figure 1.1: A Typical D2D Communication Scenario, Without Relay

Device-to-device (D2D) communication is one such service in which devices have minimal dependency on the network infrastructure [2]. In a typical D2D communication scenario, the users who are within the D2D range in a cellular network set up a direct radio link instead of communicating through the base station. D2D communication is generally opaque to the Base Station and it can occur either in the in-band i.e., the data and control signals are transmitted in the same channel which is also allocated to cellular users, or out-of-band wherein the control signals and data are transmitted within a channel separate from the channel reserved for cellular users.

Since, the user equipment (UE) exchange data directly through the D2D link circumventing the Base Station, it can achieve high data rate, and low latency as compared to conventional cellular services. D2D reduces the load on the network and provides the robustness against infrastructure failures [38]. Further, it is also low power consuming and spectrally more efficient, since transmit power and required spectrum for a given coverage area is reduced considerably [7]. The spectral and energy efficiency of D2D communication can be further increased by taking advantage of proximity to other devices by using a relay mode of communication. Inclusion of mobile relays and relay assisted D2D communications can enhance the achievable transmission capacity, and also improve the coverage of networks.

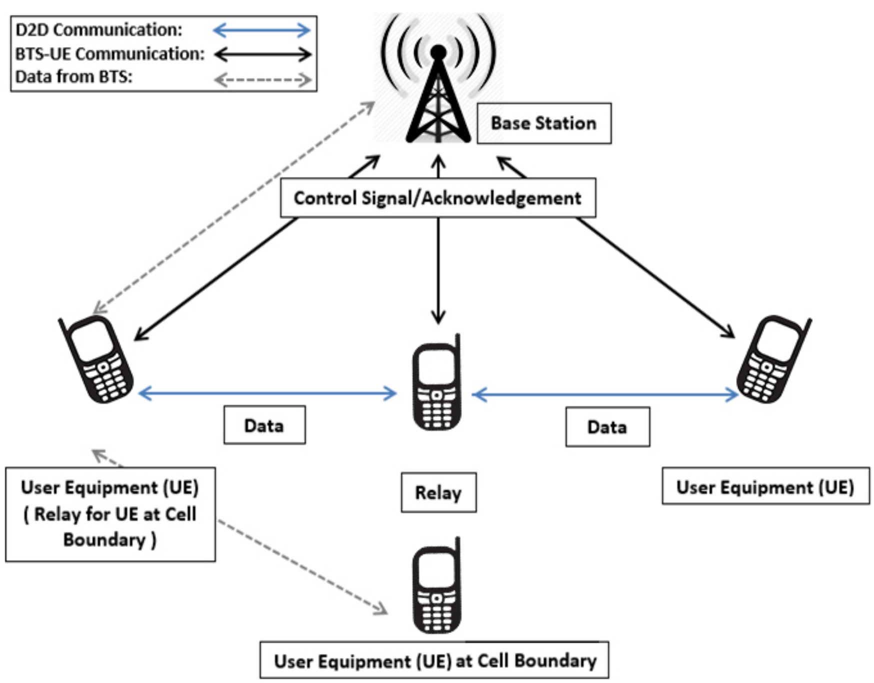

Figure 1.2: A Typical D2D Communication Scenarios, With a Relay

In case of emergency scenarios, one of the primary concerns is to get the message to a faraway destination. Here, the relay transmission is useful as it can enhance the coverage area manifold. In this work we have designed and developed a, low cost, readily deployable D2D communication prototype testbed. The implemented D2D testbed emulates a portable BTS [38] and duplex transceivers which are capable of acting as relays, as and when required. The portability of this system enables it to be readily deployed in any emergency scenario in order to have immediate access to communication services. The devices are battery powered and their low power consumption facilitates the use of light portable batteries. This proof-ofconcept wireless network has been implemented using embedded IEEE802.15.4 standard device [42] and 2.4 GHz RF Transceivers (CC2500) [24] which are battery powered, and known for their sparse energy consumption.

Fig 1.1 and Fig 1.2 represent two general D2D scenarios. As in the case of cellular infrastructure, in the proposed illustration as well, we assume that the control signals responsible for connection establishment, synchronization, resource allocation and resource release, are assigned by the BTS. In a typical D2D scenario, control signaling is usually routed through BTS, whereas subsequent voice/data communication happens between two UEs. Fig 1.1 depicts a cellular environment in which there are two UEs and one BTS. Since the two users are in close proximity to each other they can be designated as a D2D pair. A D2D pair, inside a cell will be allocated channel resource on request, by the BTS, which can be used by the users for D2D communication.

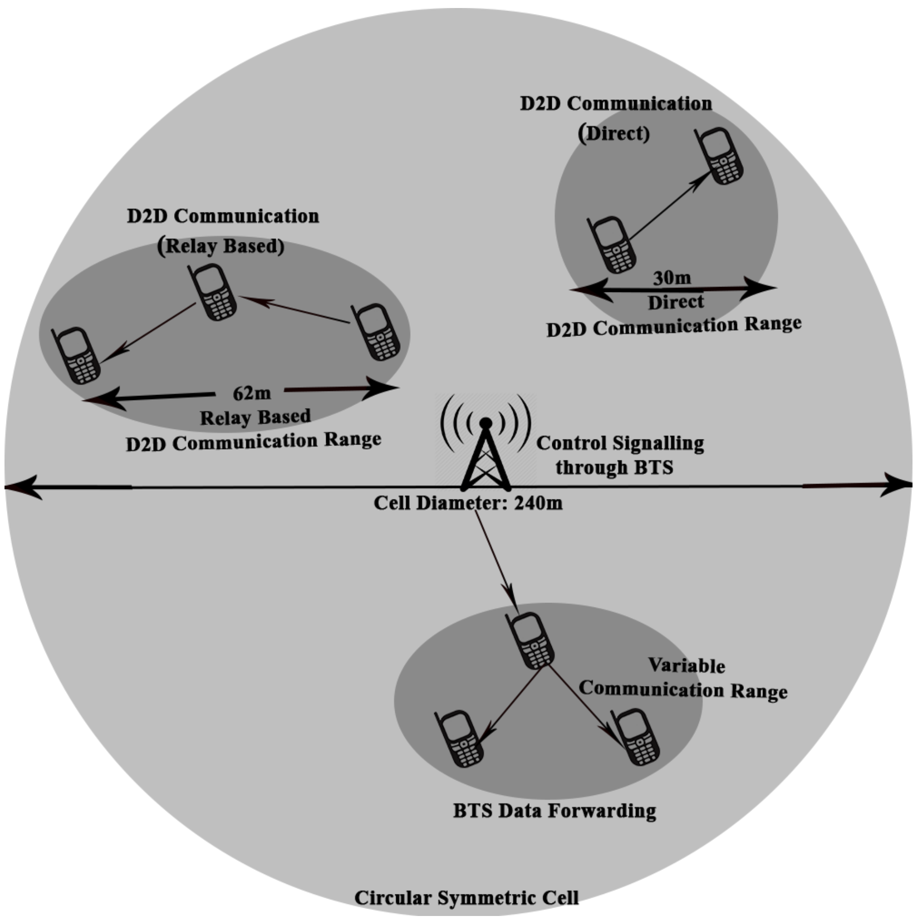

Figure 1.3: Our D2D testbed Measurement set-up

Fig 1.2 illustrates the scenario when two D2D enabled devices are inside a cell but cannot directly communicate as a D2D pair (due to distance or unfavorable channel conditions). In this case the BTS will request some other node/nodes to act as a relay, which will relay the data from one device to another. It also shows the test case in which BTS decides to serve a UE near the edge of cell boundary, which has low SNR, through the relay device which is in proximity to both the

BTS and UE. The benefit of using this technique is that the UE at the cell boundary gets the required SNR, and the BTS does not need to transmit with high power in order to serve this user, which helps in efficient BTS power management. Fig 1.3 tries to depict the measurement set-up, in which we have tested the scenario mentioned in Fig 1.1 and Fig 1.2.

1.2 Thesis Outline

The remaining thesis is organized as below:

Chapter 2 deals with the design and implementation of a prrof-of-concept Single Carrier Device-to-Device Communication testbed. In this various cellular scenarios in which Device-to-Device communication is deployed is emulated. This chapter further discusses the hardware setup and results.

Chapter 3 states the design and implementation of a Multi-Carrier Device-to-Device Communication testbed using Software Defined Radio (SDR). In this prototype using the results and conclusion made through single carrier Device-to-Device Communication, various modes has been introduced which a single carrier system is not able to perform. Spectrum sharing is introduced, to Improve the Cellular User Symbol Error Rate as well to increase the efficiency of the spectrum use.

Chapter 4 This chapter concludes the thesis and suggests the possible directions for future work.

Chapter 2

A proof-of-concept Single Carrier Device-to-Device Testbed Design

This chapter discuss in detail about the design and implementation of a proof-of-concept Single Carrier Device-to-Device Testbed, using embedded devices which follows a pre-built communication protocol. After the incorporation of prototype testbed we collect the data which provide various valuable results, which helped us to model the cellular communication scenario of real world. We will first discuss, related work in context of Device-to-Device communication testbeds and present a comparison with our testbed to them. Then a discussion on experimental setup, parameters and results will conclude this chapter.

2.1 Background and Related Work

In this section, we briefly summarize the previous hardware implementations of D2D communication. Although there has been significant research on simulation and theoretical concepts of D2D related problems of device discovery [12] [36], device association [40], synchronization [29], mode selection [21], power control [14], interference [18], resource allocation [46], and optimization [44] [39], but there are very few practical implementations. One of the foremost implementations was the FlashLinQ by [41], which utilizes the licensed spectrum. The system was implemented on the FPGA board (Vertex-4), alongside a DSP Chip, TMSC64x. Through the experimental results, various concepts of D2D communication were demonstrated. By using the licensed spectrum, it [41] successfully avoided the overcrowded scenario of ISM bands, which automatically reduced the interference from unlicensed frequency bands. Our implementation works in ISM bands, but selection of channel of operation was done, to avoid interference with nearby operating devices. Other existing implementations include [25], in which a testbed was developed using a DSP development board, based on TMS320C6670/6678. Using this board they have implemented the user equipment (UE) and evolved-NodeB (eNB). Additionally, they have incorporated three D2D services, i.e., Open Discovery, Restricted discovery and Communication capability, which our developed prototype is also capable of.

Another D2D test-bed implementation and testing was made by [25], utilizing testbed of iMinds in Zwijnaarde, where each of their nodes was powered by Intel Atom D510 and 4Gb RAM. They used WiFi to transmit the data. Our hardware implementation is rather lightweight, portable and compact, by using Arduino UNO [11] for UE and a Serial communication capable Mini Computer. Another FPGA implementation includes [34] which uses Wireless Open-Access Research Platform (WARP) Board, and uses IEEE802.15.4 protocol for communication. Similar WARP board implementations are described in [25] and [6]. [9] uses WiFi in adhoc mode to interconnect the devices. In [32], hybrid Mobile Adhoc Network and Delay Disruptive Tolerant Networking (MANET/DTN) routing techniques were incorporated and tested on more than 30 smartphones.

In [1] WiFi direct links of Android devices were used to emulate a D2D scenario. However, this increases the power consumption. Similar WiFi based implementation is used in [43], using Nokia N800 Internet Tablets. They have tuned the transmission power to 10mW, which restricts the range of the communication till 35m.

A SDR (Software Defined Radio) based implementation includes [30]. In this a baseband processing Application was developed in C++, and running on Ubuntu. Our later implementation of Multi-carrier Device-to-device communication also based on Software Defined Radio, which is NI LabVIEW [13] powered.

2.2 Hardware and Software Information

This section discusses about various hardware and software components used in our Single Carrier Device-to-Device Communication testbed [38].

2.2.1 CC2500 Based Wireless Transceiver

We have used different transceivers for base-station and D2D communication. The transceiver responsible for D2D communication is based on CC2500 chip [24], a transceiver working in the ISM band of 2.4GHz, commonly used for short range communication. Due to its Wake-On-Radio functionality [24] it consumes much less power than its counterparts. Channel bandwidth is also user programmable. For our testbed we have used a data rate of 57.6k Baud with Minimum Shift Keying, and 540 kHz channel bandwidth. Forward Error Correction Coding is enabled to reduce the packet errors.

2.2.2 Zigbee Protocol Based Wireless Transceiver

In our testbed, Zigbee protocol based Wireless Transceivers have been used which are configured to work in the ISM band of 2.4GHz. The communication range of this device is more than CC2500 based transceivers which makes it suitable for BTS to UE communications. Its inherent capability to address the device in the network helped to perform point-to-point message/instruction, communication from BTS to UE and vice versa easily.

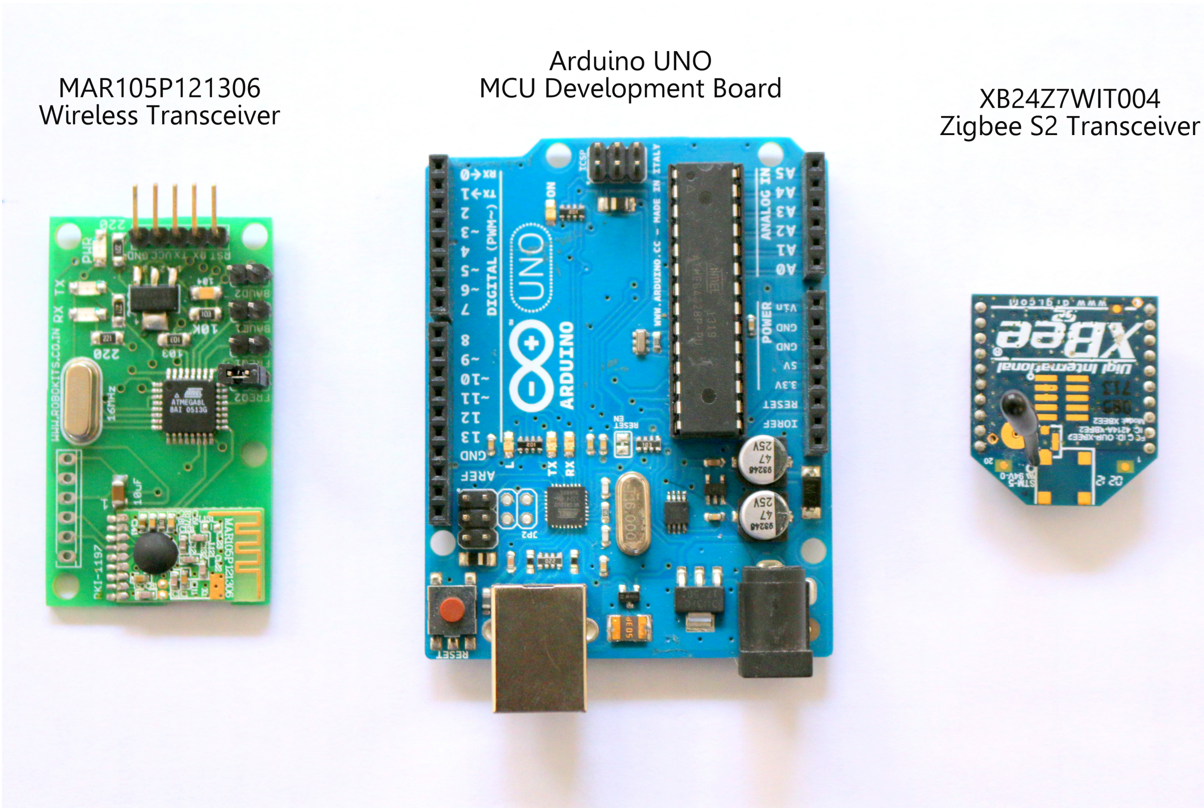

Figure 2.1: Major Components used in Single Carrier D2D testbed set-up

2.2.3 Atmega328p (Arduino) Based Microcontroller Development Board

The Arduino UNO [11] which is a microcontroller board based on the ATmega328 [10] is used in our testbed for developing D2D devices. For our implementation, it supports enough features.

2.2.4 Software for Connection Setup and Device Control

BTS is modelled using a Serial Communication Enabled Software [8] and hyperterminal. The BTSs configuration requires baud rate, number of data, parity and stop bits in a packet. The connection setup and communication parameters instructed by the BTS have to be adhered by D2D and relay devices in order to communicate. Ensuring this also automatically incorporates the concept of network authorization in our network.

2.2.5 Software for Network Testing, Configuration and Control

Fig 2.2 shows the software, that has been used for configuring the Zigbee modules [42]. This software is also used for cellular range test analysis, through received signal strength indicator (RSSI) and packet drop count. If there is a difference between the transmitted packet, and the corresponding received packet, we conclude it to be a packet transmission failure.

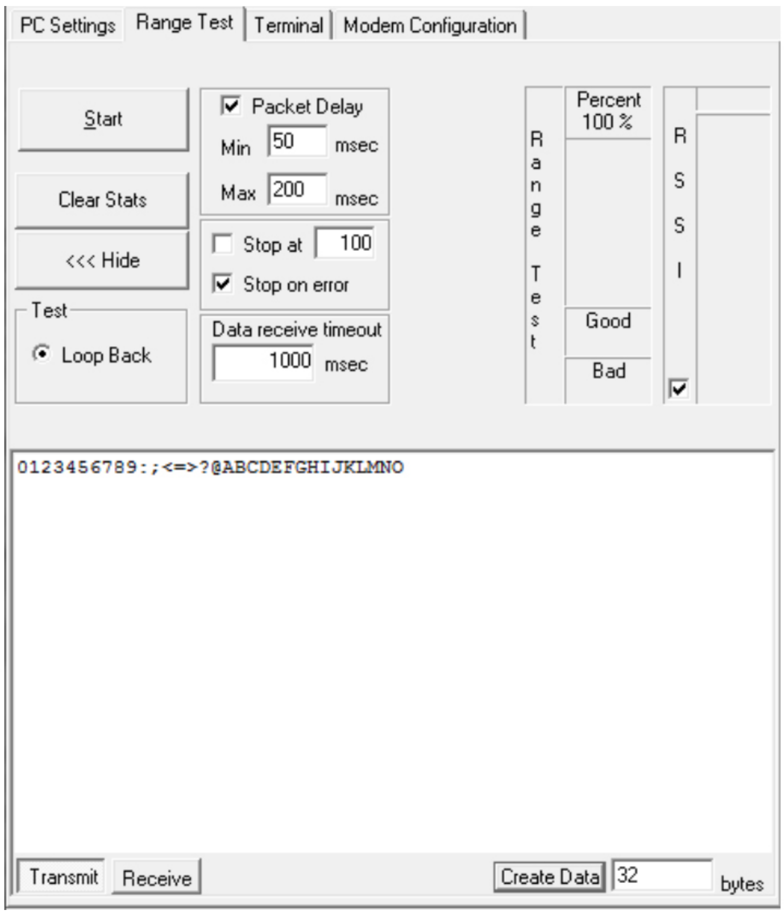

Figure 2.2: Software for Network Testing, Configuration and Control

2.3 Packet Drop Count Calculation Process

Many of the results in Single Carrier Device-to-Device Communication depends directly upon Packet Drop Count per experiment. While collecting the data for analysis, transmission of 50 packets at each distance was done. Packets followed a cycle transmission from the transmitter and re-transmission by receiver towards the transmitter (i.e., a loopback path). While receiving those 50 packets we concluded a packet being dropped when any of the original content is altered when compared to original transmitted one.

The standard packet content in this case was, ”0123456789:;¡=¿?@ABCDEFGHIJKLMNO”, (Fig 2.2 shows the packet formation and other components of the test) about 32 Bytes in size.

Whenever the packet received has some characters different from the original one, we conclude it to be a packet transmission failure. Fig 2.3 further shows the whole process of calculating the packet drop.

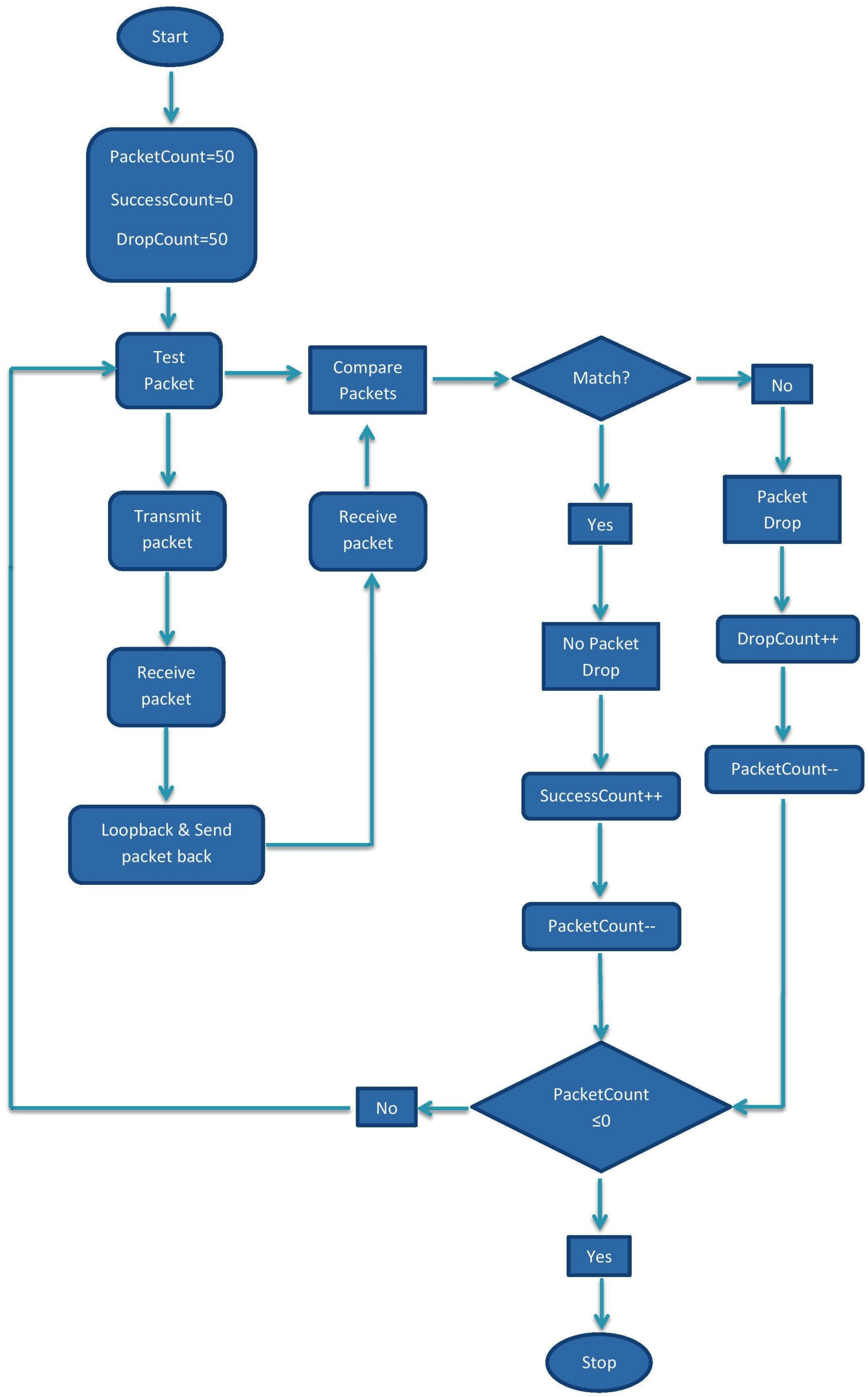

Figure 2.3: Flowgraph, illustrating the packet drop count is obtained from 50 transmitted packets

2.4 Packet Specifications

Fig 2.4 shows a data frame for D2D communication in our testbed. In the proposed scheme the frame will be transmitted in two time slots. The first time slot of the frame is explicitly reserved for addressing the devices as sender and receiver. The second time slot is reserved for data transmission. Due to this topology the effective data rate gets halved. However, as the baud rate is high (57.6k Baud), the impact is less severe. This addressing scheme will also be useful in case of relay communication as it aids in routing the data efficiently. For additional error checking we have also enabled the parity bit. Due to 4-bit addressing scheme, it limits the system capacity to a maximum of 16 (2^4) devices in a cell.

Time Slot 1	Start	To	From	Parity	Stop
(Address Frame)	1 bit	4 bits	4 bits	1 bit	2 bits
Time Slot 2	Start	Data		Parity	Stop
(Data Frame)	1 bit	8 bits		1 bit	2 bits

Figure 2.4: Representation of Data frame for D2D Communication

2.5 Experimental Setup

This section discusses the experimental setup used for performance analysis. Our proposed D2D prototype was tested in an open environment at IIIT-Delhi campus. D2D devices are based on Arduino [11] connected with Zigbee and CC2500 based transceiver. The experimental set-up has been shown in Fig 2.5 BTS is emulated using a PC connected with a Zigbee transceiver. Signaling and synchronization between all the nodes is done through the BTS.

Devices use CC2500 based transceiver to communicate with each other and Zigbee based transceiver for communicating with Base Station. Experiments were conducted using three devices which were also capable of acting as a relay, and a base station. The base station decides one of the following on the basis of RSSI:
(a.) Whether D2D communication is feasible.
(b.) If (a) is true, then whether it should take place through a direct link or through a relay.

To test the Base Station-Device link we have transmitted 50 packets from various distances and we have recorded the RSSI for each packet received. Device-to-Device link was tested by transmitting 20 packets at various possible distances and the packet drop count was measured to determine the threshold distance for communication.

Figure 2.5: Device-to-Device (D2D) Communication testbed

2.5.1 Setup 1: D2D Communication, Without Relay Device

Setup 1 has also been depicted in Fig 1.1 and illustrated through the flow graph in Fig 2.6 In this setup, BTS through the RSSI value of the last received packet, estimates the distance between itself and the nodes, and thus is aware of the radial distance between the devices. To initiate the process, one of the devices will request the base station to allow a connection to another device which is in the same cell.

The base station based on the localization information of the devices in the cell will decide whether its going to be a normal cellular communication (data being relayed through base station) or a D2D communication. Once acknowledged for D2D communication, receiving device will be instructed by the Base Station to be in receiving mode and transmitting device will be instructed to start the transmission. At the end, both will send a data transfer success notification to base station. The connection will be closed and allocated resources are released.

2.5.2 Setup 2: D2D Communication, With Relay Device

Setup 2 has been depicted in Fig 1.2 and illustrated through the flow graph in Fig 2.7 In this setup, we have deployed a BTS, two duplex and one relay device. Also, all the devices are capable of acting as a relay. The base station, through RSSI values of packets received from devices, can estimate their location inside the cell. Now to initiate the process, one of the devices will request base station to allow a connection to another device, within the cell.

The base station based on RSSI information, infers that the requesting devices are out of range

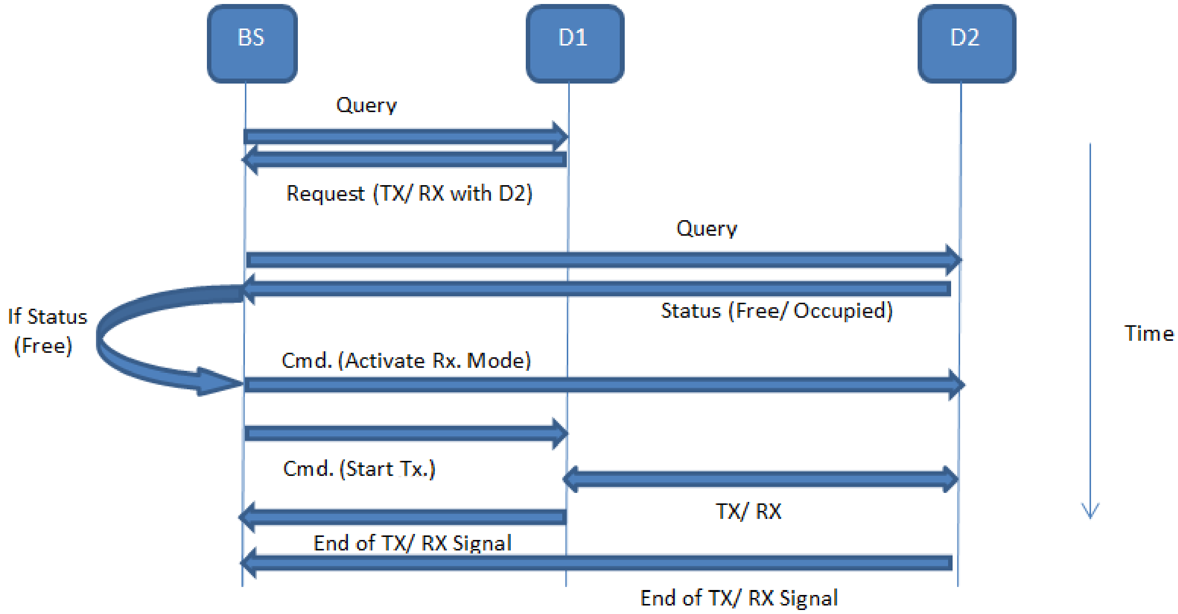

Figure 2.6: Intercommunication between devices in Setup 1 mode (When a Relay Device is not Present)

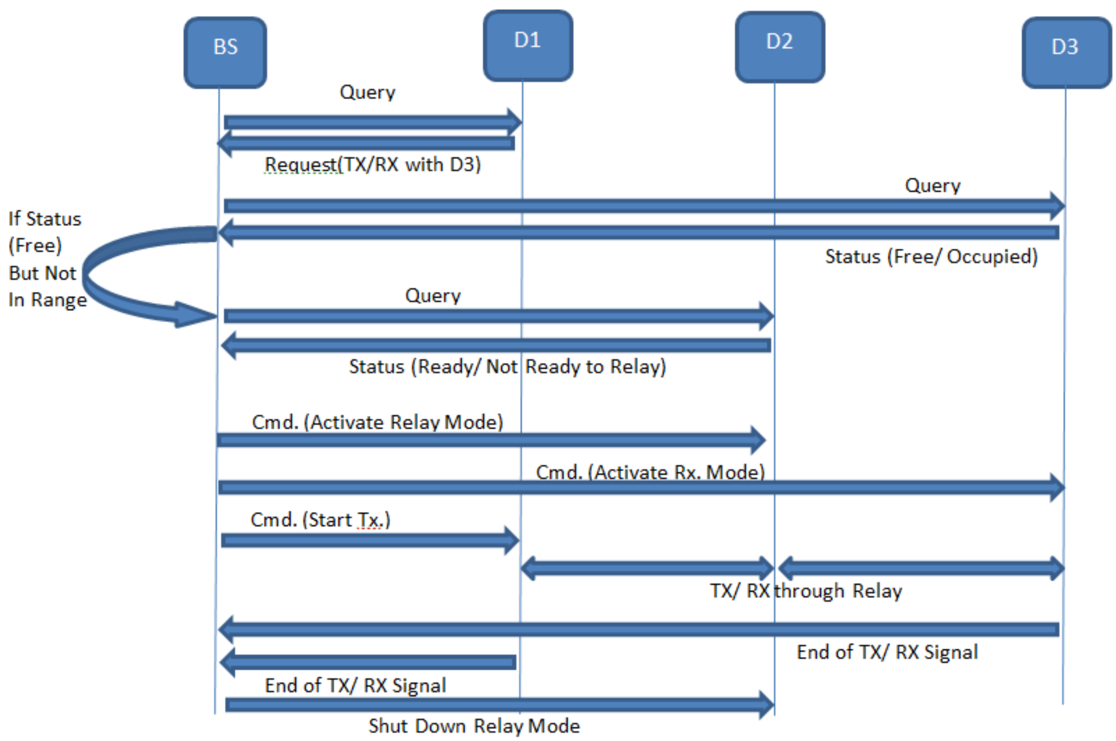

Figure 2.7: Intercommunication between devices in Setup 2 mode (When a Relay Device is Present)

for a practical D2D communication. Apart from this, the base station also knows that there is another device in proximity, capable of acting as a relay to both the devices which want to communicate. The base station will check the state of relay device. If the relay is in busy state, the communication will happen through the base station, otherwise it will be through relay device. The data packets will first arrive at the relay and then forwarded to the destination. Both transmitting and receiving devices send a data transfer success notification to base station and the connection will be closed.

2.5.3 Setup 3: Data Forwarding To User Near Cell Boundary

Setup 3 has also been depicted in Fig 1.2 and can be illustrated through the flow graph in Fig 2.8 In this setup. This setup shows a benefit of D2D relaying for a cellular network. In this base station will pass the control signal to the device as well as to relay. Through RSSI value of the devices, Base Station knows that data requesting device is nearby the cellular boundary, thus to maintain a certain QoS, it has to transmit with considerably higher power, which in turn will also increase the interference to the non-orthogonal communication bands.

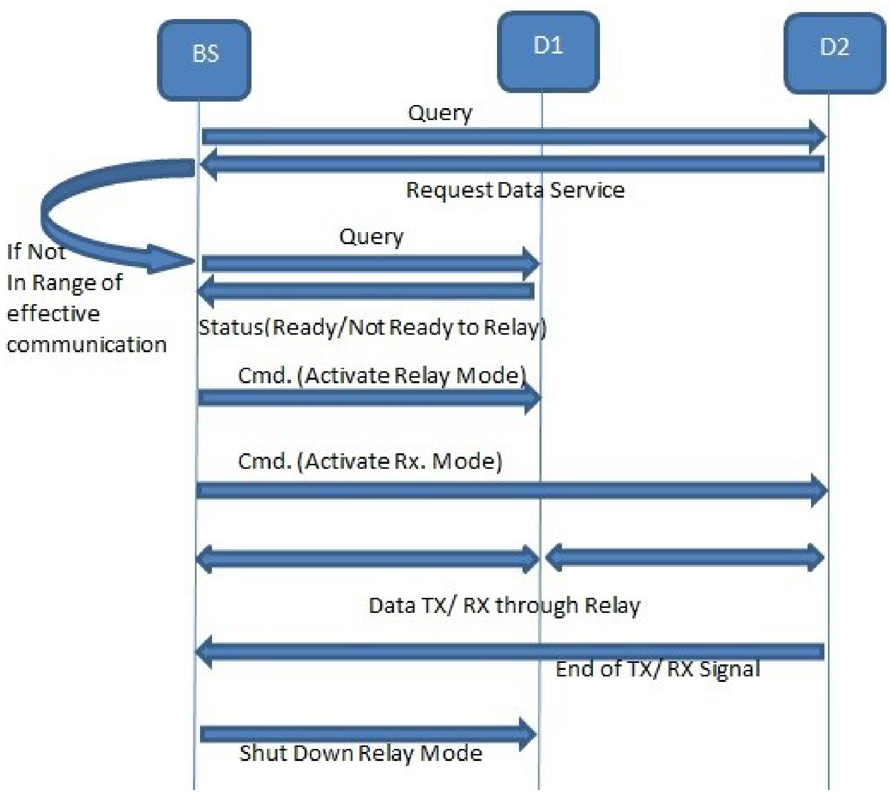

Figure 2.8: Intercommunication between devices in Setup 3 mode (Data Forwarding To User Near Cell Boundary)

This problem can be suitably solved, by identifying a relay in proximity to that device, to which base station will send at low power which in the next step will forward to the end device, thus maintaining a reasonable QoS.

2.5.4 Setup 4: Data Multi-casting to Users Nearby

Setup 4 has also been depicted in Fig 1.3 and illustrated through the flow graph in Fig 2.9 in this setup. Another benefit of D2D relaying for a cellular network. In this mode base station will do control signaling to all the device. Through the RSSI value of the devices, Base Station could predict, that a group of devices is in proximity and requesting same data e.g., streaming the same video/ audio content. In this scenario, a normal cellular communication approach would be to dedicate a separate data channel for each device. However, by applying D2D, it can dedicate only one channel resource to one of the devices in that group, and that device will multi-cast that data to other devices in its proximity. This mode is most suitable for offloading in network and particularly helpful in avoiding congestion. Above process starts with multiple

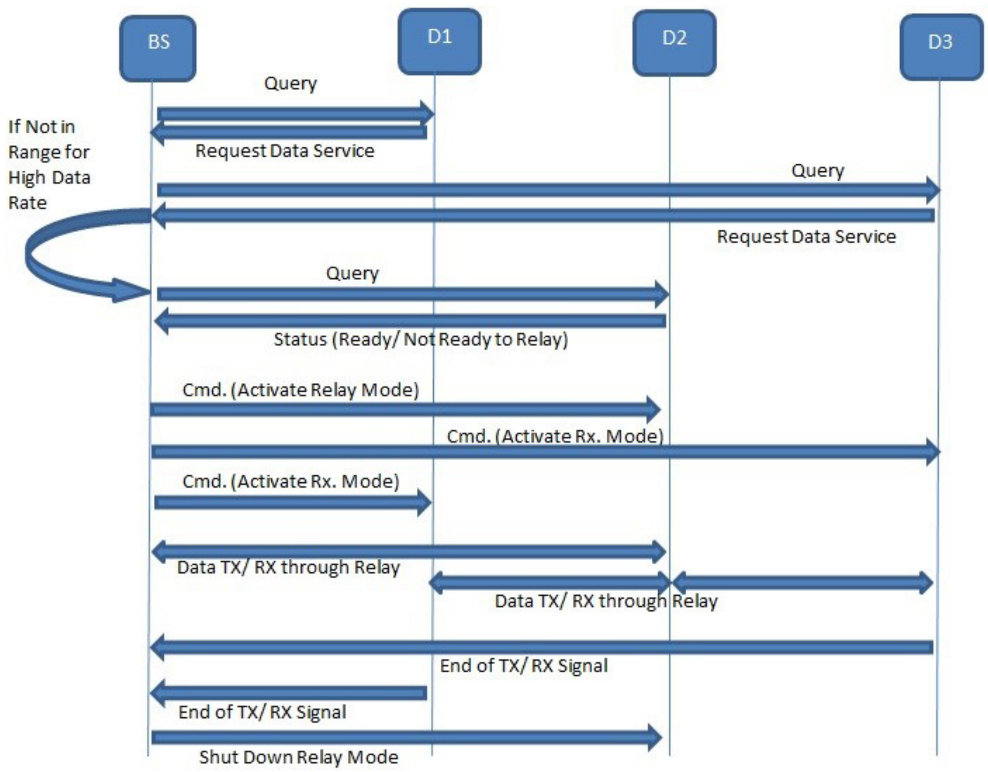

Figure 2.9: Intercommunication between devices in Setup 3 mode (Data Multi-casing using D2D Communication)

devices requesting a certain data from the network. The base station may not have enough resources to each device, instead it has channels to allocate to the group of device so that they could multi-cast the data within their group. So, in place of a direct data delivery to every device the base station will choose a device, which will multi-cast the data to every other device in proximity which requests that data.

2.6 Experimental Results and Analysis

This section describes the experimental results and analyses of our D2D testbed. To test the Base Station-Device link, we have transmitted 50 packets from different distances and have accounted the RSSI value of each packet, which gives us an estimate of the communication range and efficiency of the link.

2.6.1 RSSI vs Distance Plot

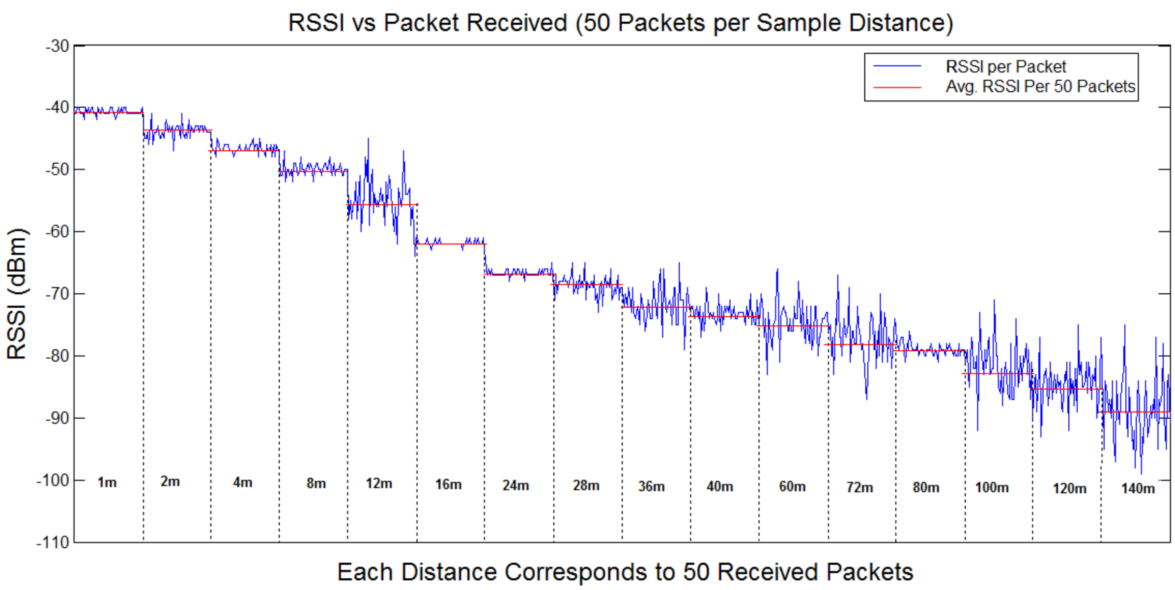

Figure 2.10: Variation of Packet Efficiency with RSSI for base station

Here we have transmitted 50 data packets from base station to device at various distances. The average RSSI of 50 packets at each distance was also calculated and plotted (Fig 2.10). The data rate was maintained at 57.6kbps, which is sufficient for message and coded voice data. Following observation can be made from Fig 2.10:

(a) As the distance between the base station and the device increases, the RSSI value decreases, both in terms of absolute value as well as in average. It is due to the path loss in the wireless channel.

(b) The variance of the RSSI of received packets, also increases with the increase of the distance between the Base station and the device, this could be attributed to the fact that as the distance increasing the SNR value is decreasing (as the received signal power value is also decreasing leading to more fluctuations due to noise). The RSSI value is used to estimate the approximate distance between the base station and a device within the cell. Based on this model, the base station is also able to predict the possibility of D2D communication between different devices by setting a threshold RSSI value. RSSI based localization is an established method to localize various objects within a locality and could be accurately used to estimate the radial distances.

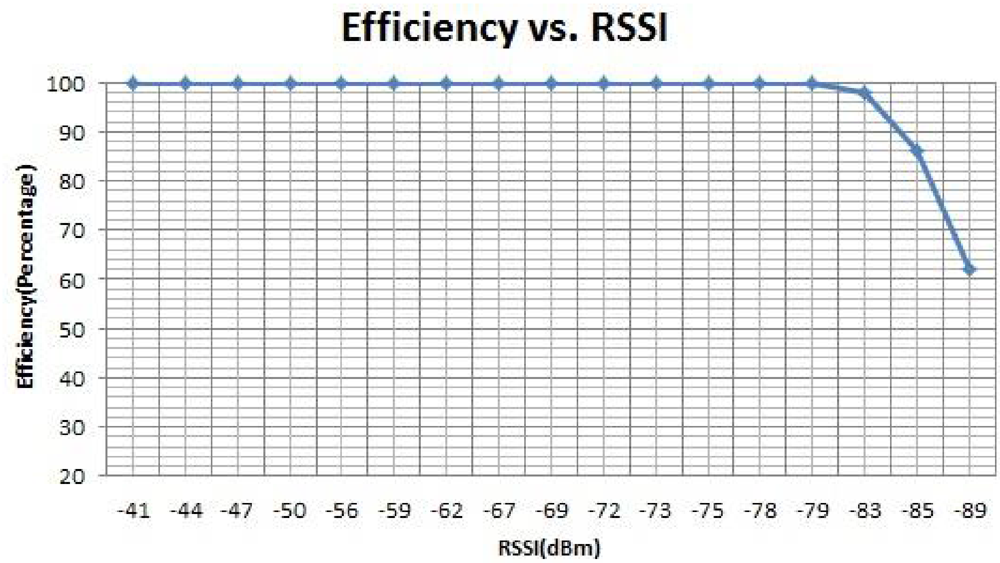

Figure 2.11: Variation of Packet Efficiency with RSSI for base station

2.6.2 Estimating the Cellular Radius and Other Cellular Parameters

The results from Fig 2.11 and Fig 2.12 leads to the decision that what cellular radius for effective communication range between Base Station and the device. From Fig 2.11 above, is conclusive of us that if the received average RSSI of the packets is above a particular threshold then there would be virtually no packet drop and the packet efficiency of the communication will be nearly 100%. But as the average RSSI value decreases, there increase the chance of packet drop, this is in corollary of the Distance vs Efficiency data plot in Fig 2.12.

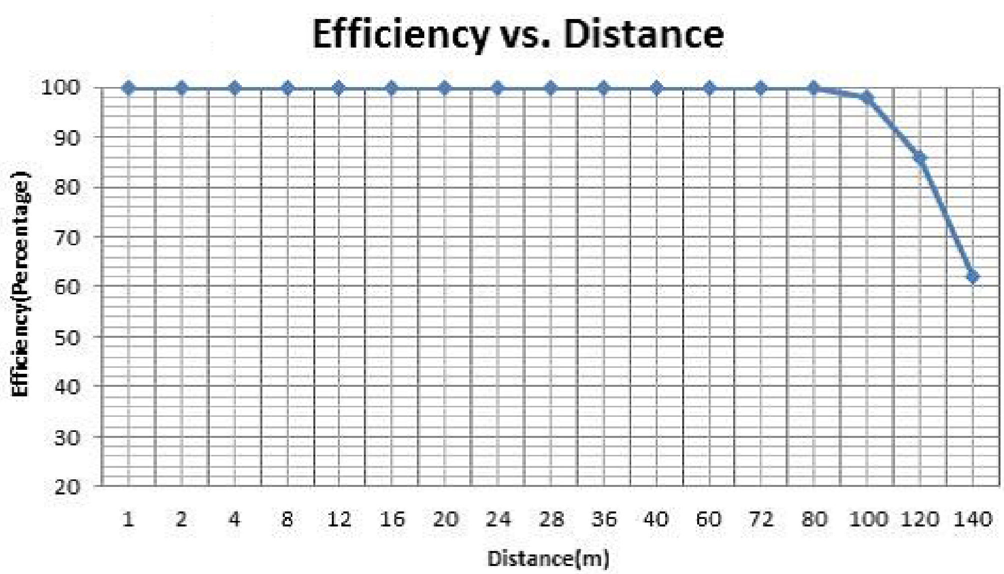

Figure 2.12: Variation of Packet Efficiency with Distance from the base station

From Fig 2.11 and Fig 2.12, it is quite obvious, that if the average RSSI of the packets is above a threshold, then there would be virtually no packet drop (less than 15%) out of 50 packets transmitted and the efficiency of the communication will be nearly greater than 85%. With this efficiency threshold we conclude our cellular radius to be 120m. Since the Zigbee Module antenna which we are using in our prototype testbed is of whip type [35]. Its radiation pattern comes to be circular. Thus, through Fig 2.13, a sample experiment setup is represented, since we have considered RSSI only, as a distance measurement parameter, it will lead only to measurement of radial distance from base station(Assuming BTS as the center of the cell).

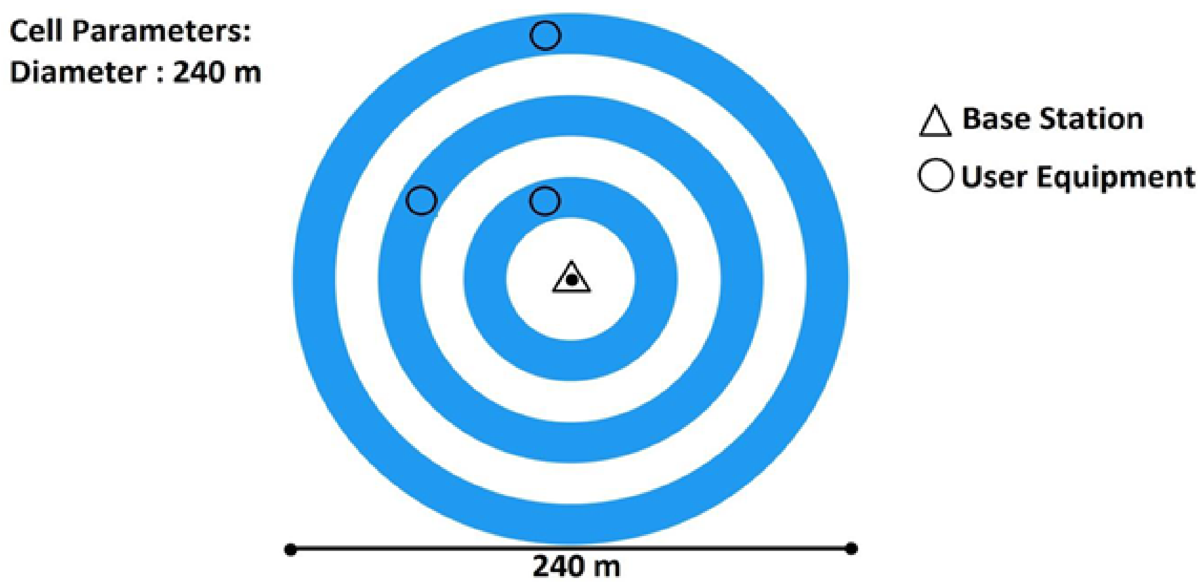

Figure 2.13: A Model Cell representation on the basis of above experimental results

2.6.3 Estimating the D2D Communication Range (With and Without Relay UE)

The range for direct D2D communication which was determined by the Packet Efficiency[1], as we have did in Section 2.6.2 for cellular parameters estimation. The threshold for Efficiency was set to be 90% and was used to define the D2D communication range, which comes out to be 30m, as shown in Fig 2.14.

In the next stage, a relay incorporated between two end devices. The distance was varied for both the devices, taking the reference point as relay and it was found that the range was extended slightly more than twice of the range in previous case i.e., without relay. We also observed that there is a steeper drop in packet efficiency in the test case without relay as compared to the case in which the relay was used. By the plot of Efficiency of packet vs Distance we conclude that the D2D maximum range with a relay device is 62 m, with the efficiency threshold being set to 90% as shown in Fig 2.15.

[1] *Here Percent Efficiency is 100*(Number of packets received correctly/Number of packets transmitted)*

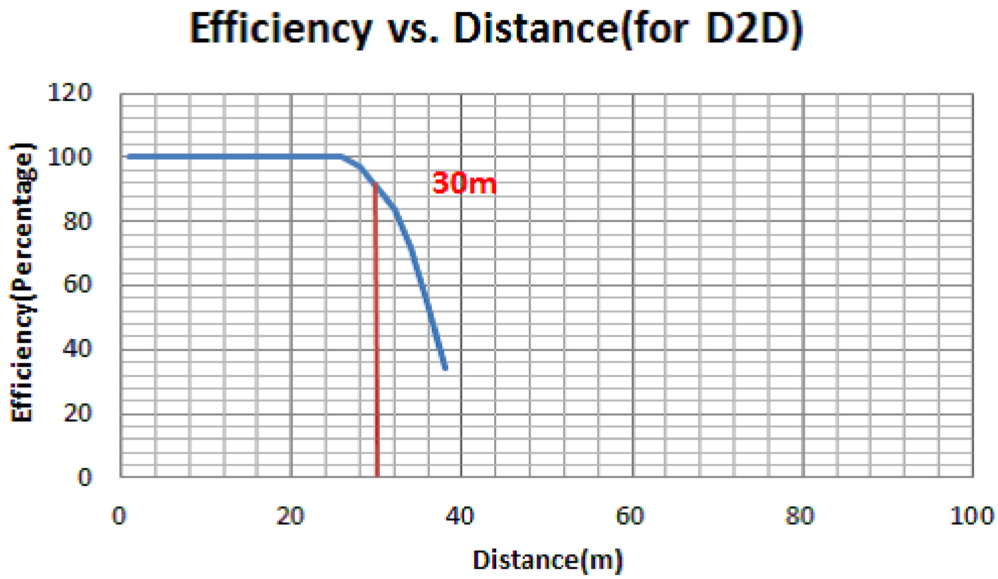

Figure 2.14: Graph showing variation of Efficiency with Distance for D2D Communication when relay is not present

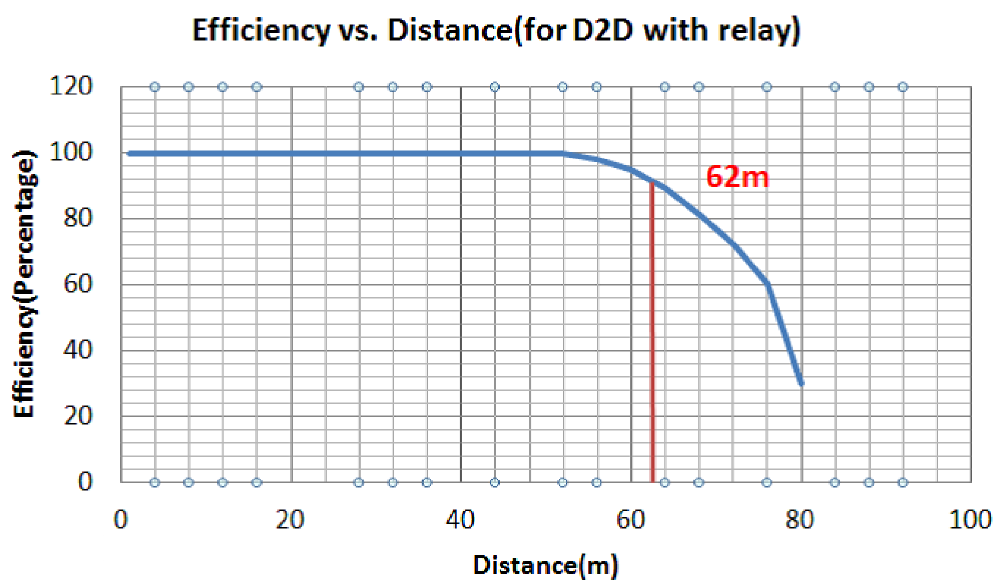

Figure 2.15: Graph showing variation of Efficiency with Distance for D2D Communication when relay is present

2.6.4 D2D Device (UEs) Specific, Power Rating Analysis

Table 1, shows the current and power consumption of the various modules used for building our D2D devices also, the combined current and power consumption of the D2D device in active and inactive mode.

* Active mode is the mode when the device is communicating through D2D link.

Table 2.1: Power consumption in various operation modes: Individual components and for whole device.

	Arduino	**XBee**	**RFLinks**	**Total**
Current Consumption (Per Component)	34 mA	31 mA	42 mA	107 mA
Current Consumption (D2D Feature Off)	34 mA	31 mA	OFF	65 mA
Power Consumption (D2D Feature ON)	122.4 mW	111.6 mW	151.2 mW	385.2 mW
Power Consumption (D2D Feature OFF)	122.4 mW	111.6 mW	OFF	234 mW
Active time (D2D Feature ON)	-	-	-	13.75hr (With 5.3Wh 3.6V Battery)
Stand by-time (D2D Feature Off)	-	-	-	22.64hr (With 5.3Wh 3.6V Battery)

* Inactive mode is when the device is not communicating but is paired with the Base Station.

All the currents rating are measured through a high resolution Multimeter. The power consumption rating is obtained by multiplying the current consumption rating with the operating voltage of the device, which is 3.7 Volts. The active time and standby time have been calculated by taking a standard 5.3Wh battery as reference.

2.7 Applications and Further Developments

Applications of D2D communication are many, but this prototype have been developed by keeping in view the disaster mitigation, as well as a proof-of-concept model for various scenarios in which D2D communication could be used. This implementation is an effective emulation for that scenario and in which D2D communication effectively offloads the network and preserve resources for intracellular communication to happen.

Apart from it, we have done range estimations through RSSI estimations which is a proven and much studied concept for localization at radial distances. This could be improved imposing some advanced method of localization and would increase practicability of the testbed in discussion.

Chapter 3

Multi-carrier D2D Communication Testbed with Opportunistic Spectrum Sharing

In this work, we have designed a Multi-carrier Device-to-Device Communication Testbed based on Software Defined Radio (SDR). This testbed utilizes Orthogonal Frequency Division Multiplexing (OFDM) making it a multi-carrier system. OFDM enables us to perform Opportunistic Spectrum Sharing between the Cellular User (CU) and User Equipments (UE) for enabling D2D communication. One of the UE (say DTUE), who needed to perform D2D Communication with another UE (say DRUE) will act as a relay for the CU, which will help it sending the requested information to the Base Station (BTS), with required Symbol Error Rate (SER) and Signal to Noise Ratio (SNR) level.

DTUE acts as a relay for the BTS, which Decode and Forward (AF) the cellular data/information by allocating some of its sub-carriers to boost the performance of Cellular transmission whereas remaining sub-carriers are used for its D2D transmission. Results demonstrate the Symbol Error Rate with respect to Signal to Noise Ratio (SNR) of up-link transmission for different distanced of in both direct and cooperation mode of communication. Through the developed testbed it is proved that the Symbol Error Rate for the cellular transmission in improved when there is a Co-operation between CU and UE for data transmission, likewise there is a net increase in SNR for the up-link transmission.

The generalization of the results is, as distance between CU and DTUE increases the symbol error rate for the transmission increases, but there is a trend that followed with each set of experiments which shows significant improvements in Error Rate when DTUE is introduced, as compared to a direct transmission between BTS and CU. A much detailed theoretical interpretations of the Co-Operative relaying is given in [19] and [20].

3.1 Background and Related Work

Bandwidth requirement for the wireless communication services have increased manifold during the last couple of decades and created a spectrum scarcity. Also, with the advent of cheaply available wireless devices, this problem is further intensified [26], as more will be the users, more will be the demand for the spectrum usage. But after all there would be a practical limitation upon what extent the spectrum could be allocated. Under current scenario almost all frequencies bands are allocated to different wireless standards throughout the world in order to limit the interference from neighboring band, consequently resulting in poor spectrum utilization.

In the recent time Device-to-Device Communication through co-operative relay, has emerged out as a promising spectrum sharing technology which allows spectrum reuse in space, frequency and time to solve spectrum scarcity problem as stated in [3] and [4]. This technology allows unlicensed (UE) user to acquired the premium frequency band which is allocated to the CU without providing any hazardous interference to the Cellular transmission. In recent times, cooperative relaying has been conceived in D2D Communication for sensing and sharing. In cooperative relaying, a relay can be used as a virtual radio for primary system and a secondary transmitter can be considered as a relay. Cooperative relaying for two-hop cognitive environment is considered in [45]. Coo-perative system where subset of relay is used to create transmission opportunities via sensing the radio is considered in [15].

Distributed protocols in reference to cooperative Amplify and Forward (AF) and Decode and Forward (DF) relay has been described in [27], [22]. Cooperative relaying via two way has been considered in [23], [17] for spectrum sharing. Some existing work on Co-operative communication is based on the scenario when primary system is having much capacity to handle interference from secondary system while capable to support its QoS [5]. This create a favorable circumstances for a D2D UE to occupy CU spectrum altogether with CU system with low power level not affecting BTS-CU transmission. But all this work based on the single carrier systems like [38], [36], [37] and [28].

This work illustrates the SER and SNR analysis of the Cellular User for different sets of distances between BTS and CU. Here, implementing a protocol for opportunistic spectrum sharing which is based on the fact that when the primary system is unable to support its target transmission rate because of various channel impairment factors like shadowing, interference etc., then DTUE helps the BTS by way of OFDM based two phase co-operative relaying. DTUE acts as an Decode and Forward relay by allocating half of its sub-carriers to boost up Cellular Data transmission while remaining sub-carriers can be used for its own D2D transmission with DRUE. Here DTUE is getting opportunistic spectrum access as an exchange of improving the performance of the CU-BTS link.

In cooperation mode the DRUE transmits only half of its sub-carriers to Base Station (BTS) while remaining sub-carriers can be used for its own D2D transmission. Testbed results also validate the advantages of this spectrum access protocol to both the Cellular User (CU) and D2D Users.

3.2 Terminologies Used in this Chapter

3.2.1 Diversity

The three important features of fading channels i.e. time correlation, frequency correlation and space correlation, give birth to notation called diversity. Conceptually, if one radio path undergoes deep fade at a particular point, another independent (or almost no correlation) path may have a strong signal at that input. Thus, it increases the chance of correctly decoding a signal at receiver. For example, if probability of a deep fade happening in one channel is p, then the probability for N channels is p^N. Three main diversity types are:

1. **Spatial Diversity:** The different communication branches are spatially different and hence have different property. This can be achieved by providing a significant antenna spacing.

2. **Temporal Diversity:** Here communication branches are uncorrelated on the basis of time property of the channel.

3. **Spectral Diversity:** Here communication branches are uncorrelated on the basis of frequency selective property of channel.

The experimental implementation in discussion provides Temporal Diversity and Spectral Diversity.

3.2.2 Combining

After getting multiple uncorrelated replicas of a same signal, it can be combined by:

1. **Selection Combining (SC):** In this the strongest signal is selected having maximum SNR.

2. **Maximum Ratio Combining (MRC):** A Weight based methods for different communication branches, thus getting maximum SNR.

3. **Equal gain combining (EGC):** Coherently combining of all the branches with equal gain.

The experimental implementation in discussion uses Maximum Ratio Combining (MRC).

3.2.3 Relay

A relay in is a device which forwards the information from source node to another node, that may be destination node. Depending on how the relay forwards the source information to the next node, relay can be classified mainly as:

1. **Amplify and forward (AF) relay:** In AF, relay just amplifies and retransmits the source data to next node. As there is no error correction coding in relay, the error from source propagates to the destination.

2. **Decode and forward (DF) relay:** In DF, relay decodes and forwards the source data to the next node, therefore due to regeneration of sources signal at relay, there is almost nil error

propagation from source-relay channel. However, this increases the complexity of implementation.

Our implementation of relay is based on Decode and Forward technique.

3.2.4 Software Defined Radio

A software defined radio, also known as SDR, is a radio frequency enabled communication device where the typical device components like modulators, filters, gain amplifiers and mappers etc. are implemented by the means of a software code. A typical example of software defined radio is a Universal Software Radio Peripheral which is built for the research and analysis purpose to support various types of interfaces. SDR intends to solve the commercial wireless industry problems like interoperability of the standards, spectrum shortage and device-to-device communication etc.

Our multi-carrier D2D implementation is fully developed in Software Defined Radio.

3.2.5 Orthogonal Frequency Division Multiplexing

The Orthogonal Frequency Division Multiplexing (OFDM) is a multiple access technique in which the high rate digital data stream is divided into sub stream and each sub-stream is transmitted using number of sub carriers.

Advantages of Orthogonal Frequency Division Multiplexing (OFDM) [31]:

1. The major advantage of OFDM in multi-carrier system is robustness against ISI(Inter Symbol Interference) and ICI(Inter Carrier Interference) by adding the cyclic prefix.

2. Increase in the spectrum efficiency by allowing orthogonal carriers to overlap.

3. The transmitted data-stream is divided in to many sub-streams and each sub-stream is send using different sub-channels (sub-carrier) such that they experiences flat fading and thus eliminates the use of equalizers as used in single carrier systems.

4. Error Correction Channel coding can be used to recover the data bits lost due to channel effects.

Disadvantages of Orthogonal Frequency Division Multiplexing (OFDM) [31]:

1. PEAK TO AVERAGE POWER RATIO (PAPR) [31]- The OFDM signal uses many sub-carriers which when added gives large PAPR which causes nonlinear distortion in OFDM signal.

2. It is sensitive to frequency synchronization [31] problems.

3. Frequency offset and timing mismatch affects the orthogonality of sub-carriers.

Applications of Orthogonal Frequency Division Multiplexing (OFDM) [31]:

4. In Wired Medium- Asymmetric digital Subscriber line and Very High bit rate digital subscriber line for broadband access using Plain Old Telephone System and Power Line Communi-

cation.

5. In Wireless Medium-Broadband Wireless Access System, Universal Mobile Communication System, Long Term Evolution, Wireless LAN, etc.

Difference from Frequency and Time Division Multiple Access: The Frequency Division Multiple Access is a channel access technique in which each user is allocated one or many frequency bands. Used in 1G telecommunication systems such as Advanced Mobile Phone Service. They suffered from low capacity and, security problems.

In Time Division Multiple Access many users uses the same frequency channel by dividing the channel access into number of time slots. They are generally used in 2G network Communication.

There are some disadvantages with TDMA. Firstly, the overhead is associated with the changeover between users due to time slotting on the channel limits the number of users. Secondly, the high symbol rate of each channel causing problems with multi-path delay spread.

OFDM eliminates the problems associated with above two schemes as it has higher spectrum efficiency and no overhead is required.

3.3 Model Test Scenerio

Here we have taken a D2D Communication scenario within a Cell which both primary and secondary signals are OFDM modulated (IEEE802.11a) over N sub-carriers as shown in the Fig 3.1.

Primary system consist of Base Station (BTS) and Cellular User (CU). Similarly secondary system consist of Relay Device-to-Device Communication User Equipment (DTUE) and Device-to-Device Communication User Equipment (DRUE). Primary system backing the cooperative relaying functionality and has authority to operate in some band of frequency which lies in ISM band. We are assuming that CU continuously keeps the track of BTS-CU link. Secondary system can only do opportunistic communication by taking the advantage of scenario when BTS is unable to achieve the target rate of transmission due to channel impairments. If the target rate is already achieved their will not be any secondary transmission.

3.4 Deploying the Proposed D2D Communication Protocol

3.4.1 Proposed Protocol

In the proposed and deployed, D2D communication protocol the data transmission is done in two time slots.

Time Slot 1: In this transmission, CU broadcast the signal to BTS (uplink transmission). But this signal is overheard by DTUE as well as by DRUE.

Time Slot 2: In this transmission the DRUE Demodulates the data, received from CU. And

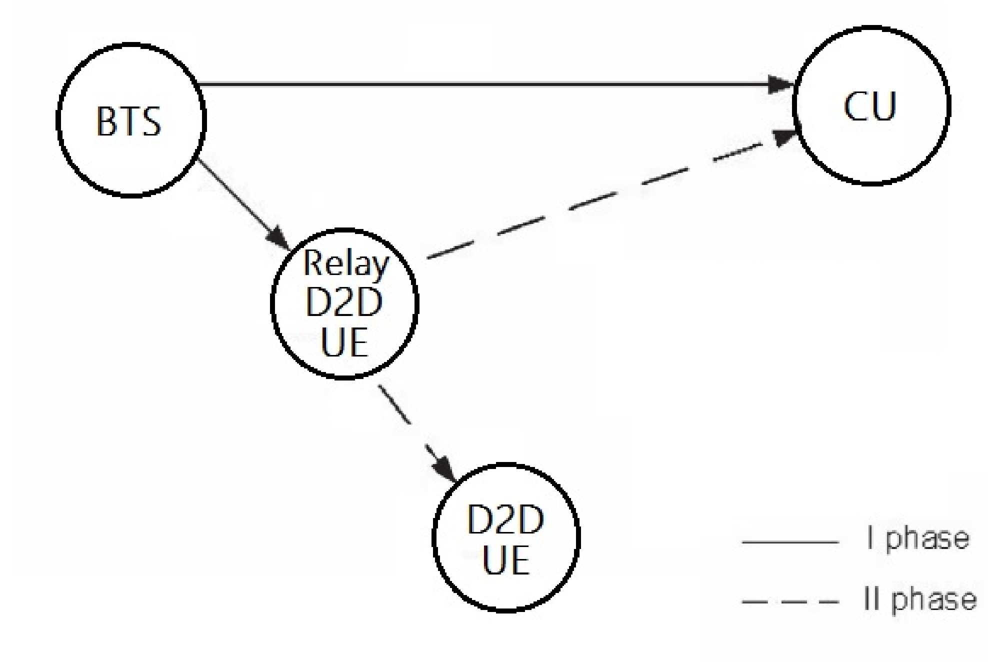

Figure 3.1: Representing our Model Test Scenario, Here CU is Cellular User, UE is User Equipment which are D2D Communication Enabled and BTS is Base Station which has data for the Cellular User

uses 50% of the OFDM sub-carriers (N/2) for its own D2D transmission. And the remaining 50% of the OFDM sub-carriers for the demodulated data as received from CU. At the end, DRUE, combines the two data then decode and forwards the data, which is to be listened by DRUE and BTS.

After these transmission is complete, DR will recover its data by dropping the half of the data received which was meant for BTS. The BTS on the other hand will drop the data meant for DR, and apply Maximal Ratio Combining (MRC) with the data received in Time Slot 1 with that of remaining data in Time Slot 2.

With a 0dB gain transmission power of 1mW the transmission is done for additional gains, viz., -10dB, -5dB, 5dB, 10dB, 15dB and 20dB. In both the time slots of transmissions, the transmitted power is kept constant, i.e., if the BTS-CU link transmission is done with a gain of 5dB the DRUE - BTS link transmission will also be done with the same power.

Fig 3.2 shows the actual experimental setup used for the deployment of above 2 time slot protocol. This setup includes 4 Universal Software Radio Peripheral (USRPs) along with a master controller computer connected with a switch. The role of 4 USRPs are to provide user defined Radio capability, as a Cellular User (CU), Base Station (BTS), D2D Communication Relay (DTUE), and a simple D2D user (DRUE).

The testbed consists of 4 radio nodes, namely CU, BTS, DTUE and DRUE. Each of these nodes is implemented on the software programmable National Instruments (NI) USRP platform. The

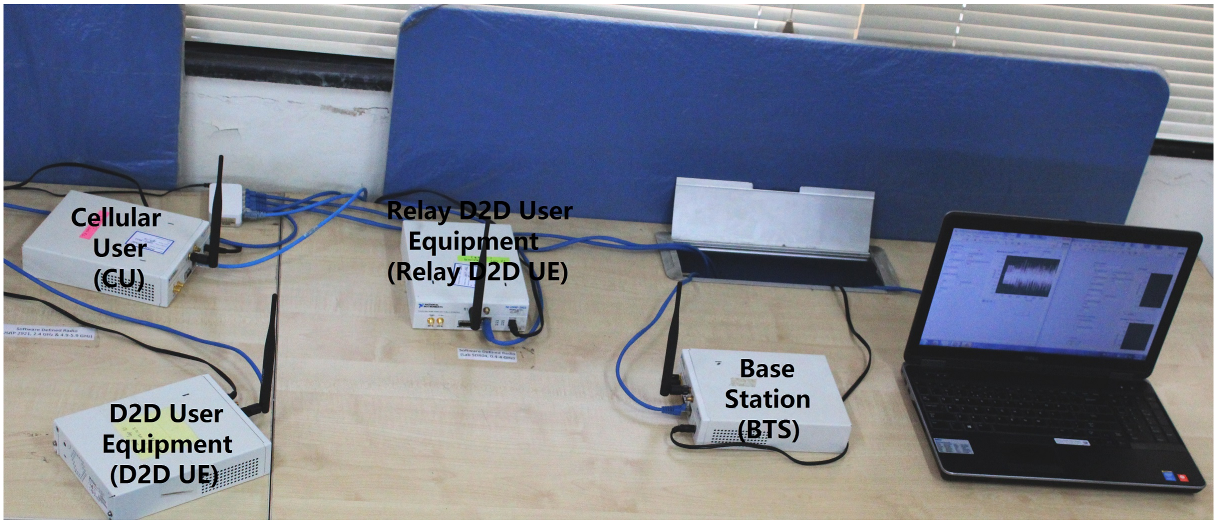

Figure 3.2: Representing our Actual Experimental Setup

Table 3.1: Distance Metrics of the Setup

BTS-CU Radial Distance (m)	BTS-Relay D2D UE Radial Distance (m)	Relay D2D UE-D2D UE Radial Distance (m)	Relay D2D UE-CU Radial Distance (m)
0.5m	0.25m	0.25m	0.25m
1.0m	0.50m	0.50m	0.50m
1.5m	0.75m	0.75m	0.75m
2.0m	1.00m	1.00m	1.00m
3.0m	1.50m	1.50m	1.50m

physical layer modem is programmed to follow the OFDM standards in IEEE 802.11a. All the nodes are transceivers operating in time division duplex (TDD) mode, except for DRUE, and BTS which only needs to receive data. The nodes are time synchronized through Zigbee interrupts. This time synchronization is necessary for the execution of the two-phase cooperative relaying protocol.

3.5 Distance Metrics of the Setup

Table 3.1 shows the distance metric of the experiment of the performed experiment. At each distance where the experiment was performed the BTS-Relay D2D UE(DRUE) link, Relay D2D UE(DRUE)-D2D UE(DTUE) link and Relay D2D UE(DRUE)-CU link distance is half of BTS-CU link distance. For Example, from above Table 3.1, we say that for a BTS-CU distance of 3.0m the BTS-Relay D2D UE(DRUE) link, Relay D2D UE(DRUE)-D2D UE(DTUE) link and Relay D2D UE(DRUE)-CU link distance is 1.50m.

3.6 Mathematical Modeling

The above protocol could be understood by some mathematical expressions.

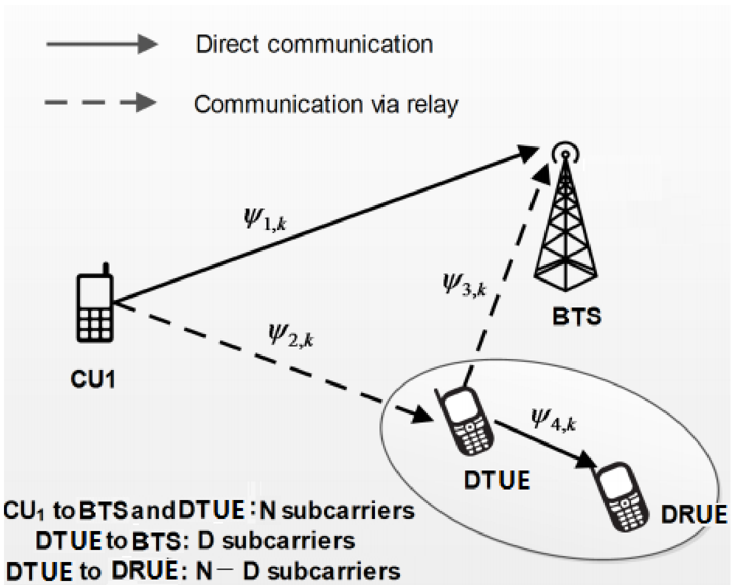

Figure 3.3: Representation of proposed Protocol in terms of a cellular scenario, here D=N/2.

In the first time slot, CU broadcast signal $x_{CU,k}$ over k^{th} sub-carrier to BTS. Since this is a broadcast it will be listened by DTUE as well. Here DTUE will act as a secondary system (relay), for BTS-CU transmission link.

Signal $x_{p,k}$ is transmitted by CU1, received by BTS. The received signal at BTS over OFDM sub-carrier k is denoted as ϕ_k^{BTS} which is equal to,

$$\phi_k^{BTS} = (p_{CU,k})^{1/2}\ \xi_{1,k}\ x_{CU,k} + \eta_{1,k}\ ;\ 1 \leq k \leq N\ ......\ (1)$$

where $p_{CU,k}$ denotes cellular signal power for k^{th} OFDM sub-carrier.

Here $\xi_{1,k}$ is the channel factor of BTS-CU communication link, $\xi_{2,k}$ is the channel factor of DTUE-CU communication link, $\xi_{3,k}$ is the channel factor of DRUE-BTS communication link, and $\xi_{4,k}$ is the channel factor of DTUE-DRUE communication link.

In the second time slot of the transmission CU remains silent and DTUE forwards $N/2$ sub-carriers to BTS and remaining $N/2$ sub-carriers to DRUE for its own communication. There will be no interference since the sub-carriers are orthogonal to each other.

3.7 Results

3.7.1 Signal to Noise Ratio

The proposed two time slot transmission D2D Communication protocol shows significant improvement in SER (Symbol Error Rate), is a direct implication that there is a increase in the SNR of the transmission after applying MRC. For notation clarification according to experiment refer Fig 3.3.

This relationship between SNR and Probability of Error is given by Goldsmith [16] as:

$$P_b(E) = (\frac{1-\mu}{2}) \sum_{l=0}^{n} (\frac{1+l}{l})(\frac{1-\mu}{2})^l ......(2)$$

Here, l=Number of path and lies between 0 to n.

$\mu = \sqrt{\frac{\gamma}{1+\gamma}}$, where, γ is the combined SNR after applying MRC.

It is clear by equation (2) that if there is an improvement in BER (in our case take it as SER) there is a net increase in SNR too, vice versa is also true.

For BTS-CU link the SNR could be expressed as $\Gamma_{BTS,CU}$, which is expressed in (3),

$$\Gamma_{BTS,CU} = \frac{1}{2} \sum_{k=1}^{N} (\frac{p_{CU,k}\gamma_{1,k}}{\sigma_1^2}) ......(3)$$

Here, k varies from 1 to N, as CU has transmitted with full sub-carriers (N) to BTS.

σ_1 is the AWGN noise of the BTS-CU transmission link.

$p_{CU,k}$ is the transmit power of the link, over k^{th} sub-carrier.

$\gamma_{1,k}$ is the channel constant, of BTS-CU transmission link.

According to the proposed and implemented protocol, in the second time slot 2 transmission are happening. CU being silent, DTUE transmits to DRUE as well as BTS.

The information meant for DRUE lies in half of the sub-carriers (i.e., total N/2). Thus, the SNR of the DTUE-DRUE link could be given as $\Gamma_{DRUE,DTUE}$ in (4),

$$\Gamma_{DRUE,DTUE} = \frac{1}{2} \sum_{k=\frac{N}{2}+1}^{N} (\frac{p_{DTUE,k}\gamma_{4,k}}{\sigma_2^2}) ......(4)$$

Here, k varies from $N/2+1$ to N, as DTUE has transmitted with half sub-carriers N/2 to DRUE.

σ_2 is the AWGN noise of the DRUE-DTUE transmission link.

$p_{DTUE,k}$ is the transmit power of the link, over k^{th} sub-carrier.

$\gamma_{4,k}$ is the channel constant of DRUE-DTUE transmission link.

Finally after applying MRC at the BTS end, with the data receiver over N sub-carriers in time slot 1 with the data received from N/2 sub-carriers in time slot 2. The net SNR will be given as $\Gamma_{BTS,CU,DTUE}$ in (5)

$$\Gamma_{BTS,CU,DTUE} = \frac{1}{2}(\sum_{k=\frac{N}{2}+1}^{N}(\frac{p_{CU,k}\gamma_{1,k}}{\sigma_1^2}) + \sum_{k=1}^{N}(\frac{p_{CU,k}\gamma_{1,k}}{\sigma_1^2} + \frac{p_{DTUE,k}\gamma_{3,k}}{\sigma_1^2}))......(5)$$

Here, k varies from $N/2+1$ to N for second time slot transmission, and k varies from 1 to N for the first time slot transmission.

σ_1 is the AWGN noise of the transmission link.

$p_{DTUE,k}$ and $p_{DTUE,k}$ is the transmit power of the link, over k^{th} sub-carrier.

$\gamma_{1,k}$ and $\gamma_{3,k}$ is the channel constant of BTS-CU and DTUE-BTS transmission link.

It is clear form the above equation (5) that there is a general increase in the SNR value when combined with the other received transmission using MRC. This phenomenon was being validated by our developed protocol experimentally.

In Fig 3.4 shows a comparison between the SNR value when the transmission happens in BTS-CU link with the SNR value which is after applying MRC. It is clearly visible that applying MRC is having an incrementing effect on SNR. The Received SNR vs Transmitter Power curves is constructed on the values taken at 3 BTS-CU distances, viz, 0.5m, 2.0m, and 3.0m. At each point on the plot, the SNR after MRC is greater than or in worst case, is equal to the SNR in direct BTS-CU transmission. The SNR values are calculated by taking reference of 10000 data packets being transmitted and their channel coefficient.

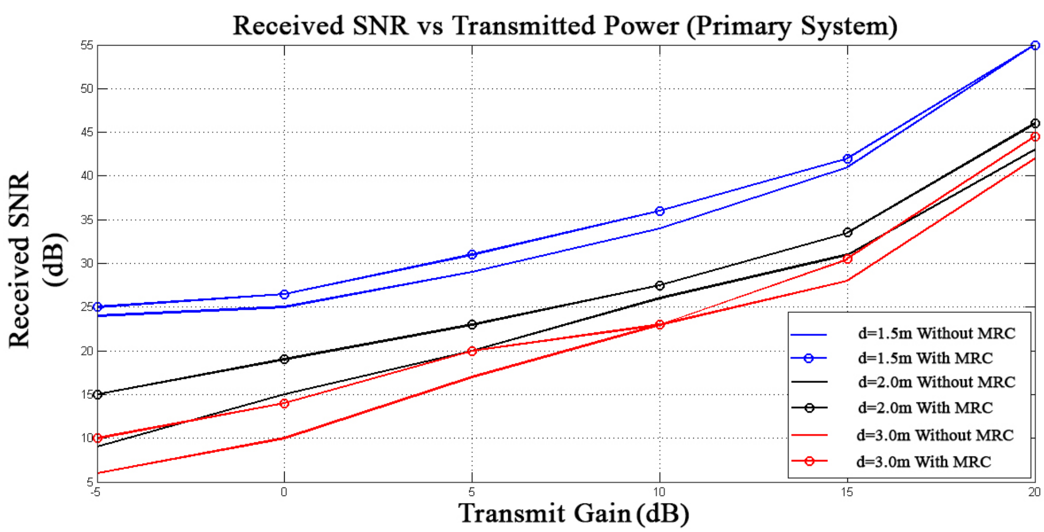

Figure 3.4: Comparison of SNR at Different Gains of Transmitter for BTS-CU transmission link, and After applying MRC with the data received from DTUE.

The emphasis was not only laid upon the SNR value improvement in BTS-UE Transmission Link but also to get a sufficient SNR value for DTUE-DRUE link i.e., secondary system. Fig 3.5 shows the SNR values at different transmitted power level of DTUE at three different distances of DTUE-DRUE, viz, 0.25m, 1.00m, and 1.50m.

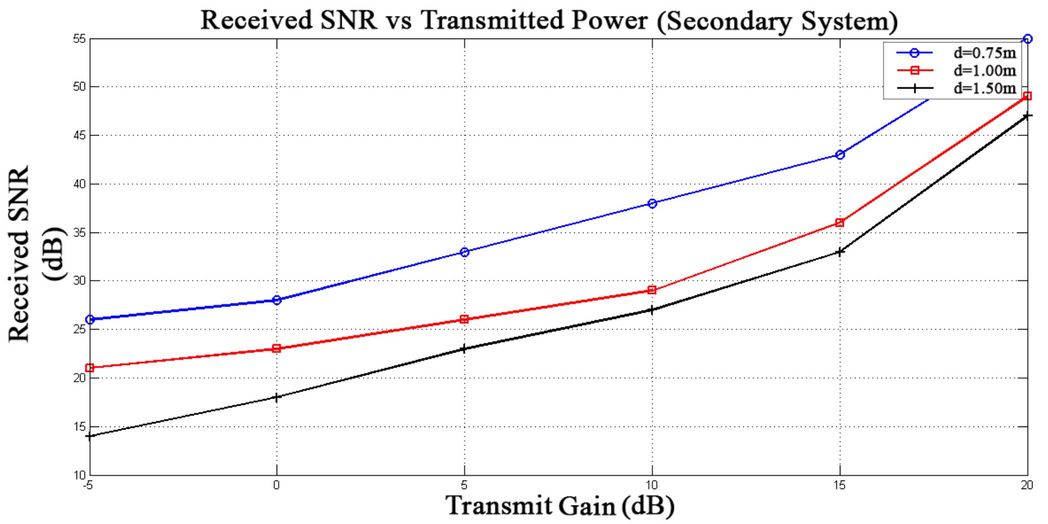

Figure 3.5: Comparison of SNR at Different distances of DTUE-DRUE transmission link

3.7.2 Symbol Error Rate

At each experimental step a total of 10000 packets were transmitted from CU towards BTS and which is also listened by DTUE. This happens in time slot 1. In the next time slot, the 10000 packets which was listened by DTUE is demodulated and embedded with the data that needed to be transmitted by DTUE to DRUE for D2D Communication, along with the cellular data.

The data received in time slot 1, is then compared at the Base Station with the original data transmitted for the errors in symbol received. Thus the symbol error rate is calculated, by dividing the total number of symbol which is having error to the total symbols being transmitted.

Data received in time slot 2, gets extracted after being applied with MRC. Then the same process of comparing the resultant data with the original set of data is done to calculate the SER. Fig 3.6, shows the comparison of Symbol Error Rate which is being calculated for BTS-CU (time slot 1) link, and after applying the MRC with respect to the proposed scheme.

Likewise the SER of DTUE-DRUE at different distance link is presented by the plot in Fig 3.7.

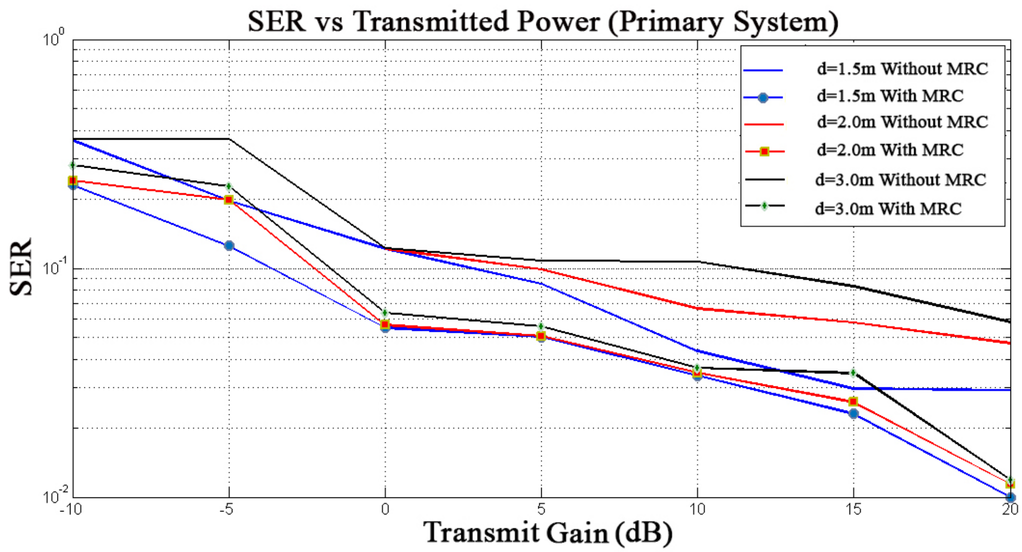

Figure 3.6: Comparison of SER (Symbol Error Rate) at Different distances of BTS-UE transmission link, with and without MRC

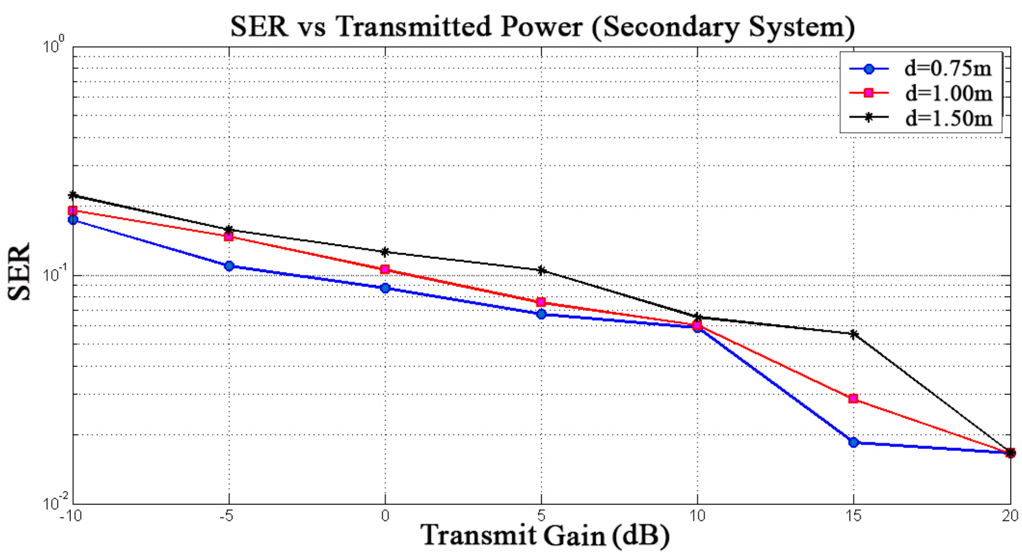

Figure 3.7: Comparison of SER (Symbol Error Rate) at Different distances of BTS-UE transmission link, with and without MRC

Chapter 4

Conclusion and Future Work

This chapter concludes the results which the proposed and implemented testbeds have produced. With a slight glimpse on future work which to be taken.

4.1 Conclusion From Single Carrier D2D Communication Testbed

An experimental testbed for D2D communication was designed and implemented using embedded IEEE802.15.4 standard device and 2.4 GHz CC2500 Transceivers. The results and analysis indicate that the testbed is highly scalable and can be implemented for a real world scenario. The portable architecture of this testbed enables it to be readily deployed in a disaster area to provide immediate emergency communication services. The single carrier testbed has many limitation but serves well for solving various wireless problems like localization within a cell, outage detection, mode selection etc. The range of the testbed can be further extended by incorporating power amplifiers and high gain antennas. By using sophisticated algorithms and Software Defined Radio platforms the concepts of network coding and cognitive radio networks can be utilized in this tesbed to make it adaptable and more spectrally efficient.

4.2 Conclusion From Multi-Carrier D2D Communication Testbed

In this work, secondary system gains opportunistic spectrum access by assisting the primary system to achieve its required SNR and SNR level. Secondary transmitter acts as a DF relay to help the primary system by relaying few sub-carriers to primary receiver to fulfill the SNR and SER requirement of primary system while remaining sub-carriers can be used for secondary transmission. A multi-carrier system gives more robustness than a single carrier system from various impairing channel condition. One can also, selectively prefer one of the channel in the multi-carrier system that has the better performance over the another. This multi-carrier system which uses OFDM, was developed to deploy the two time slot protocol which have a positive effect on the net SNR and SER on direct communication link after applying combining technique like MRC or selection combining. Overall result says that there is an overall improvement on SER level, which in general 10-30% higher than that in direct transmission case, there has been sometimes observed an overlapping of SER and SNR results (e.g., in Figure 3.4 and Figure 3.6) that could be attributed to the fact that we have assumed sub-carriers in the first transmission are in bad channel condition, but in contradiction, at that particular distance sub-channel already be performing good (low loss channel).

The primary and secondary system were in coordination by using Zigbee device data interrupts. The communication range could be further increased by using power amplifiers.

4.3 Future Work

A possible future-work for the single carrier testbed would be to create more number of devices. It will create a scenario where actual cellular communication system can be modeled effectively. It would be a way to see it practically not only through simulation. For the multi-carrier testbed it would be to show the effect of opportunistic spectrum sharing further, like in this thesis the effect of a fixed number of sub-carrier sharing was shown. But in a next possible extension of the testbed a dynamic spectrum access would be given to the DTUE for the best possible effect on Cellular Transmissions. Another possible extension would be in which, modulation scheme within a sub-channel of multi-carrier system may change according to the channel condition and data rate demand.

List of Publications

(PUBLISHED):

[1]. **Singh, Vibhutesh Kumar**, Sanjeev Baghoriya, and Vivek Ashok Bohara. "Project Monitomation." 7th International Conference on Communication and Networks, (COMSNETS 2015) Demo & Exhibits Session, Bangalore, January 2015.

[2]. **Singh, Vibhutesh Kumar**, Sanjeev Baghoriya, and Vivek Ashok Bohara. "HELPER: A Home assisted and cost Effective Living system for People with disabilities and homebound Elderly." Proc. 26th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Hong Kong, China, September 2015.

[3]. Kumar, Manish, Shubham Kaul, **Vibhutesh Kumar Singh**, and Vivek Ashok Bohara. "iDART-Intruder Detection and Alert in Real Time." National Instruments (India) Engineering Impact Award 2015, Bangalore, November 2015.

[4]. **Singh, Vibhutesh Kumar**, Hardik Chawla, and Vivek Ashok Bohara. "A Proof-of-Concept D2D Communication Testbed." 8th International Conference on Communication and Networks, (COMSNETS 2016) , Bangalore, January 2016.

(UNPUBLISHED-UNDER REVIEW):

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