ALGORITHM ON DEVICE TO DEVICE COMMUNICATION

A Thesis submitted in partial fulfillment of the Requirements for the degree of

Master of Technology
In
Electronics and Communication Engineering
Specialization: signal and image processing

By

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Rourkela, Odisha, 769 008, India

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DEPT.OF ELECTRONICS AND COMMUNICATION ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY,
ROURKELA – 769008, ODISHA, INDIA

Certificate

This is to certify that the work in the thesis entitled **Algorithm on device to device communication** by **Rahul Kumar Singh** is a record of an original research work carried out by him during 2014 - 2015 under my supervision and guidance in partial fulfillment of the requirements for the award of the degree of Master of Technology in Electronics and Communication Engineering (signal and image processing), National Institute of Technology, Rourkela. Neither this thesis nor any part of it, to the best of my knowledge, has been submitted for any degree or diploma elsewhere.

Place: NIT Rourkela

Dated- May 27, 2015

Dr. Sarat Kumar Patra

Professor

DEPT. OF ELECTRONICS AND COMMUNICATION ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY,
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Declaration

I certify that

a) The work contained in the thesis is original and has been done by myself under the general supervision of my supervisor.
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Dated-May 27, 2015

Rahul Kumar Singh

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ALGORITHM ON DEVICE TO DEVICE COMMUNICATION

ABSTRACT

Mobile communication services is already assumed very important in many ways, like mobile data, video and TV services now becomes the part of the everyday of human life. In view growing demand of the data for these services is increasing day by day. For this we need to increase our capacity in order to give these services to the end user. For this we going to introduce an application of device to device communication in which device are communicate with each other with the help of cellular networks. D2D communication decreases the load on the mobile network and increase in spectral efficiency.

In this thesis we going to evolved a method in which D2D communication will controlled by the cellar networks. For the achievement of the given minimum SINR we derived a minimum distance relation between two D2D links which is operating simultaneously. For the fulfillment of these minimum requirement we develop an idea for the grouping and scheduling of the links so that they can operate simultaneously. Finally we perform the simulation in different situation to see the effect of how the cell is populated with the varying the links and also we see that how we achieve the minimum required SINR in different situation.

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NOMECLATURE

PL(d)	Path loss at distance d
n	Path loss exponent
SINRi	Signal to interference noise ratio receiving node i
P_{Rij}	Power received by i from j
P_{Rik}	Interference power of k received at node i
P_{Tj}	Transmitted power by node j
P_{Tk}	Transmitted power by node k
P_{Tmax}	Maximum transmit power
d_{min}	Minimum distance
r	Radius of the cell
N	No of interference node
I_{max}	Maximum interference
I_R	Received interference
d_{margin}	Distance between a interferer and a receiver minus the length of D2D links of the interferer
L_{max}	Maximum amount of links

ABBREVIATIONS

3GPP	3rd Generation Partnership Project
AMPS	Advanced Mobile Phone System
AR	Augmented Reality
BS	Base Station
CDMA	Code Division Multiple Access
CSD	Circuit-Switched Data
D2D	Device-to-Device
EDGE	Enhanced Data rates for GSM Evolution
ETSI	European Telecommunications Standards Institute
EV-DO	Evolution-Data Optimized
FDMA	Frequency Division Multiple Access
FDD	Frequency-Division Duplexing
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HSCSD	High-Speed Circuit-Switched Data
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSUPA	High Speed Uplink Packet Access
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
ITU	International Telecommunication Union
LTE	Long Term Evolution
M2M	Machine-to-Machine
MS	Mobile Station
QoS	Quality of Service
RAN	Radio Access Network
RBS	Radio Base Station
SDM	Space Division Multiplexing
SINR	Signal-to-Noise plus Interference Ratio

TDD	Time-Division Duplexing
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telecommunications System
WAP	Wireless Access Protocol
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network

Chapter 1

INTRODUCTION

1

INTRODUCTION

One of the schemes that is being researched and considered for 4G LTE Advanced is the concept of Device to Device communications. This form of communication using the LTE system is used where direct communications are needed within a small area. LTE D2D communications is a peer to peer link which does not use the cellular network infrastructure, but enables LTE based devices to communicate directly with one another when they are in close proximity.LTE device to device communication is also being investigated for applications where peer discovery is required for commercial applications in the presence of network support.

1.1 Era of the Mobile Internet

The mobile Internet has been a long time coming It found its beginnings around 1998 with the Wireless Access Protocol which was designed to assume short, handheld wireless communication devices connect to the Internet. Since the introduction of WAP a lot has happened, and after a slow start, the mobile Internet is now finally booming. Increasingly more people want to have access to the Internet anytime and anywhere with their mobile phones and laptops. Facebook - the most popular social networking website | has more than 400 million active users, of which more than 25% access Facebook through their mobile devices [14]. Facebook also reports that people that use Facebook on their mobile devices are twice more active on Facebook than non-mobile users. Video on mobile is likely to grow just like it did on the desktop and stimulate explosive growth of mobile data usage. An example is YouTube Mobile, which is expected to grow much more the coming years. VoIP leader Skype already has more registered users than any global carrier, while the network effects from Apple's iPhone are immense [16]. More objects are gaining the ability to communicate, giving shape to the concept of Internet of things" [5]. All these improvements clearly shows that we are in the early stages of an Era of the Mobile Internet.

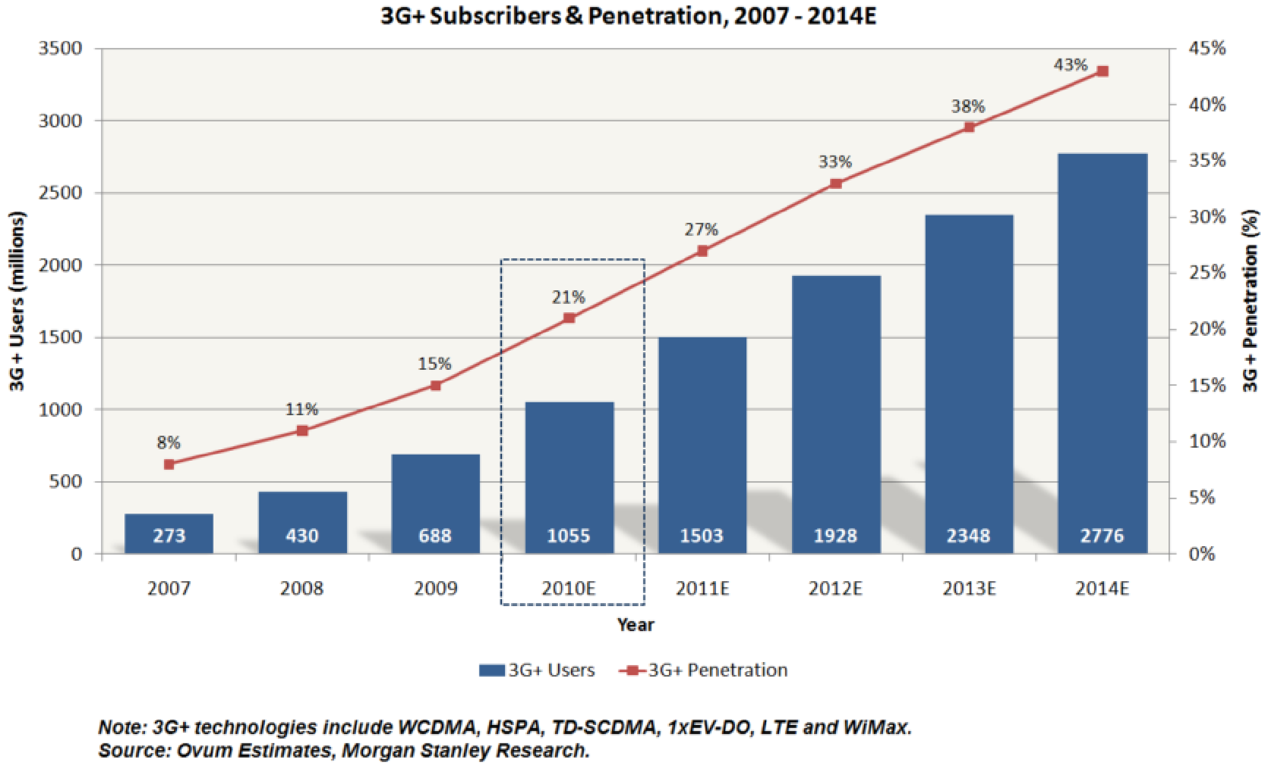

Figure (1.1)-Expected rising trajectory of the global 3G+ penetration

1.2 Implications for Mobile Operators

For the wireless service suppliers the increasing quality of mobile communications is nice news. The enlargement of wireless omnipresence can result in a rise of customers World Health Organization access and place confidence in mobile networks. However, whereas the traffic load on mobile networks is predicted to grow exponentially throughout the approaching years, the financial gain is sadly not essentially directly coupled to the present growth. The overwhelming majority of mobile operators charge a monthly expected value for broadband mobile access to the web. The most important value objection covering wireless service suppliers these days is that the backhaul network [7]. This infrastructure is incredibly dearly-won to take care of and hard to measure. The surge of knowledge traffic is pushing several mobile networks to their capability limit. A lot of antennas area unit needed to accommodate all users and succeed acceptable signal coverage. Mobile operator's area unit seeking innovative solutions to address the rising demand of mobile traffic whereas minimizing in operation prices.

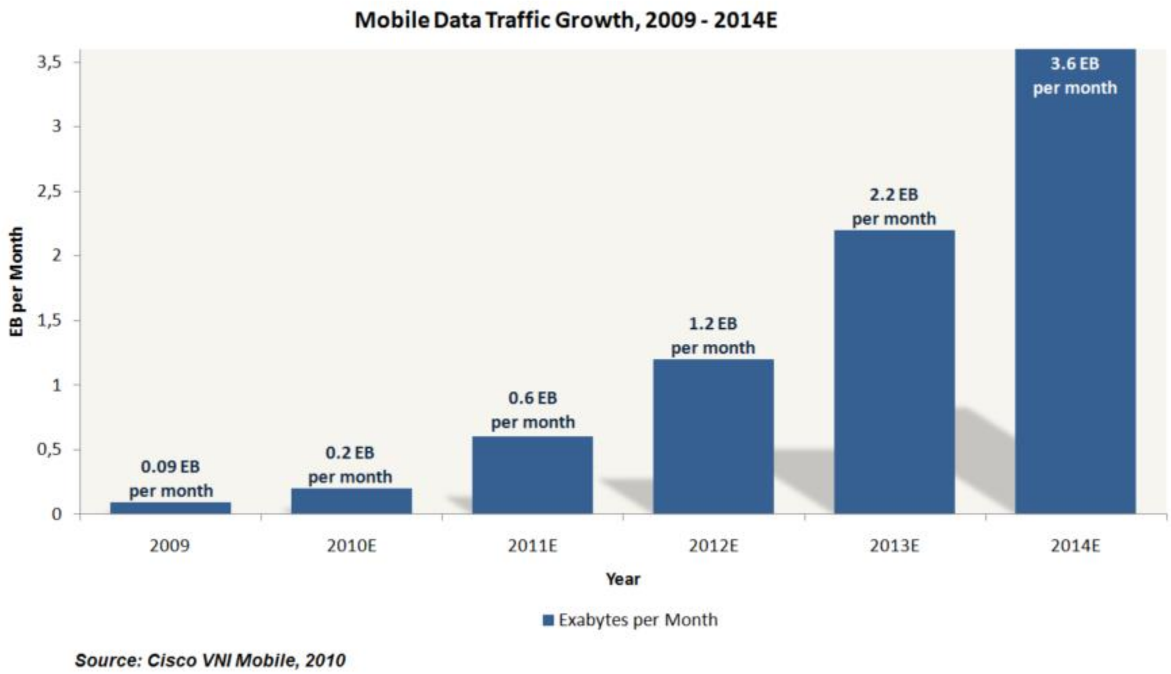

Figure (1.2) - Projected Mobile Data Traffic Growth.

1.3 D2D Communications

In order to solve the issues mentioned in the previous paragraph, to enhance the communication capacity and capabilities and to introduce new area, research is performed on many subjects. A recent research topic is D2D communications as an underlay to cellular networks [17]. A D2D link is a direct connection between two communicating Devices, in spectrum managed by the cellular network. The goal of using D2D links is to: (a) increase the spectral efficiency, (b) reduce the load on the network and (c) introduce and facilitate new services.

As the range of human action devices increasing, the spectrum during which the signals area unit present becomes jam-pawncked. In mobile access networks, if the backhaul and backbone portions of the network area unit dimensioned properly, the limiting issue (the bottleneck) is the air interface.

As the name of this work proposes, the D2D correspondence happens under the umbrella of a cell system. This shows that the D2D sessions happen inside the same waveband on the grounds that the cell correspondence. Hence, the sessions happen underneath the superintendence of the cell system. In apply this shows that the baccalaureate covering square measurement amid which the gadgets are blessing is in control, provisioning and dealing with the correspondence joins. This administration common sense is basic if the D2D correspondence happens inside the approved waveband, as a consequence of the obstruction created by D2D interfaces on the traditional cell correspondence ought to be contained. At no time D2D correspondence could hinder cell correspondence. To boot, D2D interfaces conjointly meddle with each other. These obstruction issues ar the most test once encouraging D2D correspondence fundamentally

1.4 Scope of the Research

The purpose of this thesis is to present a strategy for the application of D2D communication in a cellular network. The research consists of four parts: (a) we analytically derive equations describing what the minimum distance between simultaneously operating links should be to achieve a minimum required SINR at all receivers. For the derivation of the equations we propose a method to and an upper bound on the interference between D2D links. (b) We propose a method to use the derived equations in a practical way. (c) The derived analytical equations give minimum distance requirements in the worst case scenario. It is possible to relax this stringent minimum distance requirement while still being able to achieve a given minimum SINR by using optimization mathematics.

1.5 Literature Review

D2D correspondence underlying cell correspondence frameworks has been under the consideration of investigative scientists for a brief while and subsequently is another range to be investigated. Most research has been performed in Finland, at the Helsinki University of Technology with the collaboration of Nokia Research Center.

In [17], the creators propose to encourage neighborhood shared correspondence by a D2D radio that works as an underlay system to an IMT-Advanced cell system in light of Orthogonal Frequency Division Multiple Access (OFDMA) innovation. A force control. Plan for the D2D connections is recommended that impart uplink assets to a cell system. The force control plan is assessed in an indoor impedance constrained situation. The outcomes demonstrate that D2D correspondence can occur with a decent D2D connection Signal-to-Noise Ratio (SINR). It is likewise demonstrated that indoor D2D correspondence causes insignificant obstruction to open air cell clients in the downlink of a metropolitan region system.

In [4], D2D correspondence in a solitary cell environment is dissected in which one cell client and two D2D clients impart the accessible radio assets. The investigation concentrates on enhancing the entirety rate by force control for different methods of asset imparting. It is demonstrated that with advanced force control, noteworthy upgrades for the entirety rate can be attained to in the given situation.

The relevant issues regarding the feasibility of D2D communications as an underlay to the LTE Advanced network are discussed in [9]. In this paper, solutions are sketched in how the interference of D2D communications to the cellular network can be controlled. Results are given for an indoor scenario and an outdoor scenario with many eNBs distributed in a Manhattan grid5. The results demonstrate that underlay D2D communications by reusing cellular resources is possible for both scenarios. It is seen that LTE-Advanced, if any system, overs opportunities for D2D communications due to its time-frequency edibility in allocation.

In [8], it is illustrated how D2D communication can be established in an LTE-Advanced network having an SAE (System Architecture Evolution) architecture. The main contribution of this article is to draft the functionality and messaging required to set up a D2D connection inside the SAE architecture, and also if the session setup takes place as an application layer signaling to the Internet beyond the cellular network.

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1.6 Structure of thesis

In chapter 2 we will introduce and compare the technologies which are using in the device to device communication. The principles' of the some technologies are explained briefly. In the next chapter we our main focus on the how D2D communication works and we derived equation for the minimum distance criteria which for which we achieve the minimum SINR requirement in worst condition. For this we introduce two distance model.in first one only one device to device are operating and in our second model two device to device operating simultaneously.in the chapter 4 we explain the two grouping algorithm for these two distance model given in chapter 3. And in chapter 5 we show all our simulation result and see the effect of the varying links on the cell and on the SINR also. In final and last chapter there is conclusion, final remarks and future work suggestion are given.

Chapter 2

WIRELESS COMMUNICATION SYSTEM

2

WIRELESS COMMUNICATION SYSTEM

Cellular network

2.1.1 Cellular network concepts

Every transmitter, generally known as a base station (BS), covers a particular space. The bottom station includes a radio reference to the mobile station (MS), and this base station ought to be capable of act with the mobile station inside a particular coverage space. A mechanism is employed that transfers the affiliation of users from cell to cell, once the MS moves out of vary of the first BS and into the vary of successive.

In cellular networks, mobile stations could not communicate directly with each other. Communications are continually relayed via the bottom station(s) covering the area unit(s) during which the mobile stations area section placed. To be ready to accommodate enough mobile stations whereas maintaining the decision quality standards, the radio network ought to be ready to offer sufficient capability and coverage.

2.1.2 Cell

The shape of a cell is often modeled as a regular hexagon (Fig.2.1 (a)). By using the hexagonal shape, cells can graphically be displayed next to each other without having overlapping areas of coverage. The ideal shape of a cell, which represents the ideal coverage of the power transmitted by the base station antenna, is a perfect circle (Fig.2.1 (b)) with a fixed radius R. Cell radii can vary from tens of meters in buildings, and hundreds of meters in cities, up to tens of kilometers in large open areas. In reality, the shape of cells are never perfect hexagons or circles (Figure 2.1(c)), but depend on the environment (buildings, mountains, valleys etc.), on weather conditions and in some systems even on system load. Hence the real shape of a cell is not a fixed figure; it fluctuates over time and depends on a multitude of parameters.

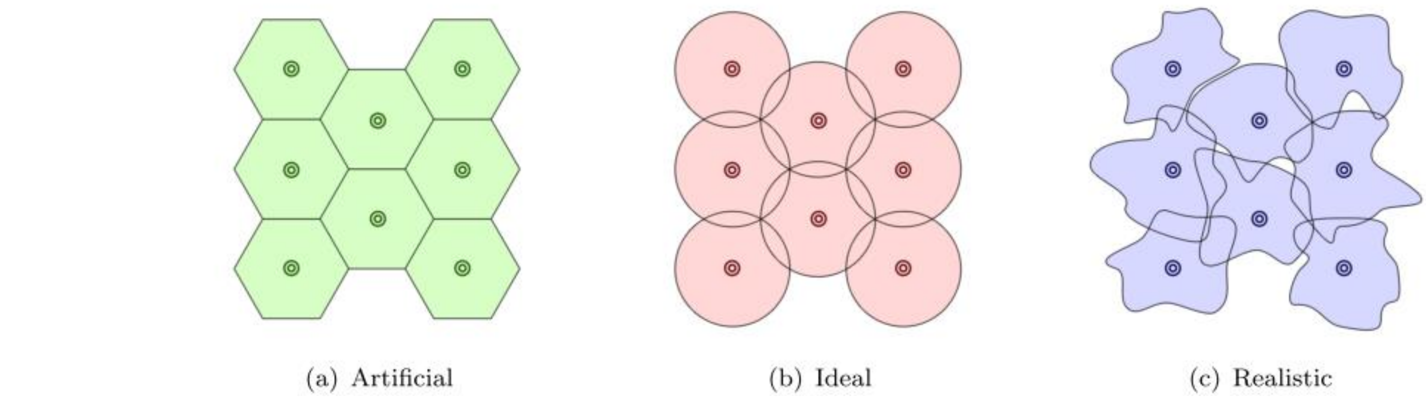


Figure (2.1) - Cell Shapes

In cell versatile correspondence, recurrence range is a valuable, restricted asset. The recurrence band utilized by a versatile administrator is situated in the authorized band. The versatile administrator wishes to use the accessible range as efficiently as would be prudent.

2.2 WLAN

There are numerous conventions and advancements for remote correspondence inside a certain geographic range. As of now, Bluetooth and Wi-Fi are the most mainstream and generally utilized ones, having numerous applications. Bluetooth and Wi-Fi both work in the unlicensed ISM (modern, scientific and restorative) recurrence groups, implying that no hard QoS insurances can be given on the grounds that the impedance is not controlled.

D2D correspondence offers an option on the off chance that hard QoS insurances are fundamental or longed for, or when no Wi-Fi hotspots are open to- or inside the scope of a portable gadget. Since D2D correspondence is controlled by the BS and uses the authorized recurrence band, a dependable correspondence channel can be offered. D2D correspondence has the focal point that the cell system identifies the clients, so that no physical matching system is important to shape joins (as with Bluetooth) and no keys need to be traded to make an association (as with WiFi).

2.3 Ad-Hoc-network

A wireless ad-hoc network is a decentralized, self-configuring wireless network. The network is ad hoc because it does not rely on a preexisting infrastructure, such as routers wired networks or access points in managed (infrastructure) wireless networks. Instead, each node participates in routing by forwarding data for other nodes, and so the determination of which nodes forward data is made dynamically based on the network connectivity. An ad-hoc multichip network could be constructed out of D2D links underlying a cellular network, provided that a cellular network is present. By utilizing the knowledge of the BS regarding the (estimated) position and activity of nodes and the overall network load distribution, the performance of such ad-hoc networks could be increased by routing data more efficiently.

Chapter 3

D2D LINK DISTANCE STUDY

3

D2D LINK DISTANCE STUDY

3.1 Basic model

In cellular network, the base station is a relay. The radio path of a cellular link containing of 2 parts: the trail from the transmitter to the bottom station and therefore the path from the bottom station to the receiver. A D2D link may be a single direct path from transmitter to receiver. Once examination the 2 links, we tend to might not merely assume that the length of a D2D link is adequate the summation of the 2 ways of a cellular link. The two parts of the cellular link need to be taken into consideration individually. As an example if the battery lifetime of the wireless devices is that the parameter of interest, we would like to match the transmitting power of a tool once human action via D2D versus cellular links. In this case the trail from the bottom station to the receiving device in a very cellular link will not need to be taken into consideration. The trail from the transmitter to the bottom station can be compared on to the D2D path. For the general cell performance in terms of interference and capability, each elements of the cellular link would need to be taken into account.

In the elementary analysis, a comparison is made between D2D- and cellular links based on the length of the links (i.e. the distance between the two communicating nodes).

Elementary analysis-Ina circular cell with radius R we uniformly distribute N nodes over the area in the cell. If N the average distance from a node to the base station can be determined by weighting all radii and dividing the sum of all weighted radii by the sum of the weights.

The most easy and intuitive thanks to decide whether or not to use a cellular link or a D2D link, is to settle on the one with the shortest distance. This suggests that the utmost .D2D link distance equals the circle radius R, as a result of if the space of a D2D link is larger than R, a cellular link are going to be chosen. The chance density operates f_x of the distance x between 2 random points in a very circle of radius R is given by [2]

3.2 Path Loss

Path loss is that the reduction (attenuation) in power density of a non-particulate radiation as it propagates through house. Path loss models describe the signal attenuation between a transmit and a receive antenna as a perform of the propagation distance and alternative parameters. Path loss for a non-free house wireless atmosphere, like a path with obstructions consisting of buildings and trees, could very tough to design. Different models have been developed to explain the propagation behavior in dissimilar situation. Some models embody several details of the piece of land profile to estimate the signal attenuation, whereas others simply take into account carrier frequency and distance traveled by the signal.

We can calculate the pass loss model as follows [22]-

$$PL_{dB} = PL_{FSdB}(d_O)+10n\ log10(\frac{d}{d0})+X_{dB} \quad (3.1)$$

Where

$$PL_{FSdB}(d_O) = 20\ log_{10}(\frac{4\pi dof}{c}) \quad (3.2)$$

$PL_{FSdB}(d_O)$ is the free space loss for a distance d_o that is close to the transmitter but in the far field and $d > d_{o.}$ n is the path loss exponent .

Typically d_o is taken to be 1 km for large area 100 m for microcell system and 1 m for indoor wireless system. We take for n as a free space 2.when barrier are present in the path of the signal we take n more than 2.tapically we take n in the range of 2 to 4 usually its valve is 4 for ground-reflection model.

After fixing the system parameters we have the modified equation as

$$PL_{dB}(d) = 10n\ log_{10}(d)+C \quad (3.3)$$

Where c is the constant which is depends on which system parameter we have chosen. We use this path loss model in our remaining of this work.

-

3.3 Study of Optimum Distance between Two D2D Links

In the following figure (4) we see the relation of the D2D link and the length of the D2D is explained. According to the fig when two D2D links are communicating with each other are keep separate with each other with distance d_{link} and when the separation of two D2D are extended the distance between two D2D links are also increased accordingly. This is because of to get better SINR.

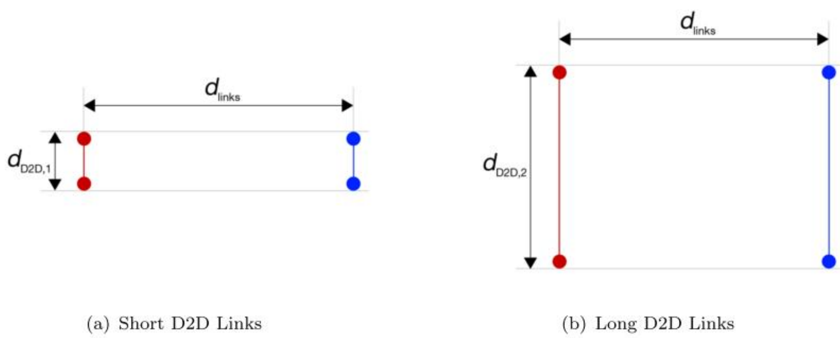


Figure-(3.1) Two D2D links of length dD2D;1 are separated from each other by a distance of dlinks (a). If the D2D link is larger, while the separation remains the same, more interference will be experienced at the receivers in (b).

Now we are interested a case in which two D2D links are operated simultaneously. In the fig given below we assume the two nodes of D2D links namely i and j operated simultaneously in which node i is receiving the data from node j which is works as a transmitter . at the same time k transmits the data to the l node. SINR at receiving node I is given by the following relation

$$SINR_i = \frac{P_{Rij}}{(P_{Rik}+N)} \quad (3.4)$$

Where P_{Rij} is the received power of signal which is received by I from j .interference power of k received at node i. we consider that there is noise present. Now we rewrite the above equation in decibels for simplicity

$$SINR_{i,dB} = PR_{ij,dB} - PR_{ik,dB}, \quad (3.5)$$

Where

$$P_{Rij,dB} = P_{Tj,dB} - PL_{dB}(dij) \quad (3.6)$$

And

$$P_{Rik,dB} = P_{Tk,dB} + PL_{dB}(d_{ik}), \quad (3.7)$$

in which P_{Tj} and P_{Tk} is transmitted power by node j and k . $PL_{dB}(d)$ is the propagation is of the signal traveling in the distance d. propagation loss can be calculated by the combining the above equation we get

$$SINRi_{,dB} = P_{Tj,dB} - PL_{dB}(d_{ij}) - P_{Tk},dB + PL_{dB}(d_{ik}) \quad (3.8)$$

Now we consider a d2d has a maximum length of D2Ddmax and all devices had the maximum transmission power P_{Tmax}..

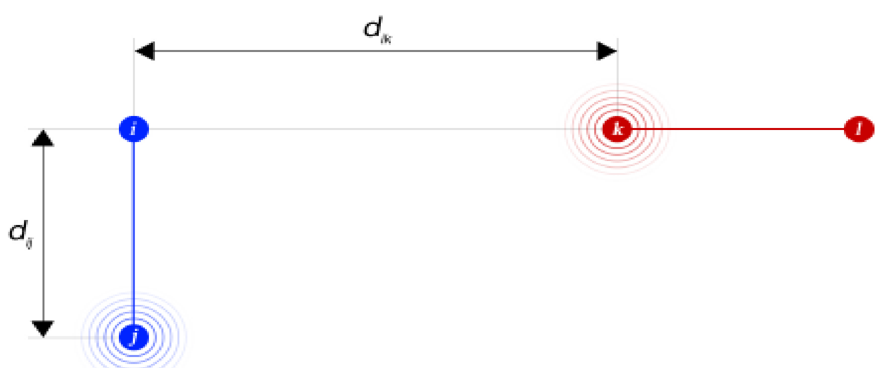


Figure-(3.2)- Node j is the transmitting a signal to node I .node k is the interfering node to guarantee an optimum SINR at the node I, the minimum distance between l and k is can be calculated

Assume that optimum SINR requirement is stated as $SINRi_{,dB} \geq \emptyset$ (dB). If the interference node is very much close to the receiver node I then we can achieve the required SINR even after node j transmits the power of its full capacity that is $P_{Tj}=P_{Tmax}$. Here we are mainly interested about determined the optimum distance d_{min} between the receiver end I and interferer end k .at which requirement of SINR can be still fulfilled that is $\{d_{ik}=d_{min}\}$ or @<$SINR_{i,dB}$.then above equation can be written as

$$\emptyset \leq SINR_{i,dB} = P_{Tmax,dB} - PL_{dB}(d_{ij}) - P_{Tk,,dB} + PL_{dB}(dmin). \quad (3.9)$$

In worst condition the interference node transmit power with full length that is *PTk = PTmax.*

In this situation we find that ∅=SINRi;dB .putting these values in above equation we have

$$\emptyset = P_{Tmax,dB} - PL_{dB}(d_{ij}) - P_{Tk,,dB} + PL_{dB}(dmin). \quad (3.10)$$

$$= PL_{dB}(d_{min}) - PL_{dB}(d_{ij}). \quad (3.11)$$

Using equation (3.9) in above equation to evaluate the path loss. We have

$$\emptyset = 10n\log_{10}(d_{min}) + C - (10n\log_{10}(d_{ij}) + C). \quad (3.12)$$

Finally we have the following eq after simplification

$$d_{min} = \left[10^{\frac{\emptyset}{10n}}\right] d_{ij}. \quad (3.13)$$

Now we got the desired equation for the min distance .now we generalize our equation for system or link. By putting at the place of d_{ij} as d2d

$$d_{min}(d_{D2D}) = \left[10^{\frac{\emptyset}{10n}}\right] d_{D2D}. \quad (3.14)$$

Now we conclude this by saying that if two d2d links with node i-j and k-l working simultaneously the following relation always holds

$$\{min\,(d_{ik}, d_{il}, d_{jk}, d_{jl}) \geq d_{min}(max(d_{ij}, d_{kl}))\} \rightarrow \{SINR_m \geq \emptyset\},$$

3.4 Minimum Distance between Two D2D Links: First Assumption

In this we are going to explain the model which we have to derived an equation which explains a direct relation between the desired distance d_{min} between all other d2d links working simultaneously and the max length of d2d max of a d2d link.

In the following figure have clearly seen that when all nodes are separated by at least d_{min} a hexagonal grid is formed.in the worst case when all other nodes accept green are interfere and center node that is green node is receiving node

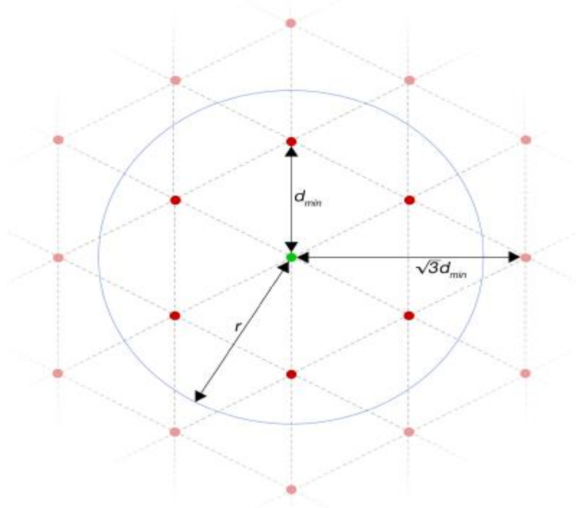


Figure-(3.3)- The center node is the receiver node that is green and red nodes are transmitter nodes. All nodes are at least d_{min} to each other

Now we are very interested to know how many nodes interfere on the cell center .this the all nodes presents in the cell subtracted by center node of the cell.in every hexagon six interferer are placed .therefore it is clear that the no of cell depends upon no of hexagon fits in the cell. Now starts from the shortest hexagon, length v_h of the edges of the h^{th} hexagon is

$$v_h = \begin{cases} \frac{h+1}{2} dmin, & if\ h\ is\ odd \\ \frac{h}{2}\sqrt{3}dmin, & if\ h\ is\ even \end{cases}$$

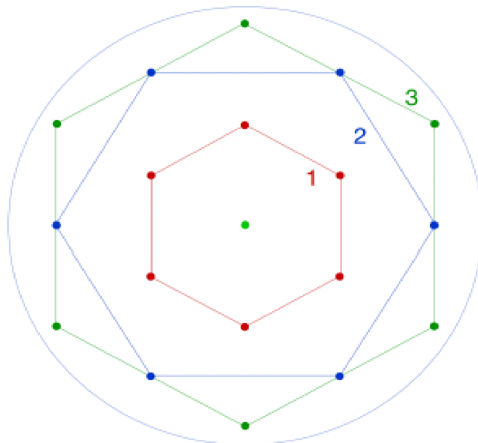


Figure (3.4) - The model from the figure (3.3)

The number of hexagon that is fit for a cell is function of radius of the cell and the optimum distance b/w nodes. We can fit maximum $\left\lfloor\frac{r}{dmin}\right\rfloor$ odd hexagon and $\left\lfloor\frac{r}{\sqrt{3}dmin}\right\rfloor$even hexagon in a cell with radius hence the maximum no of interfering nodes according to the model given in above figure

$$N = 6\left\lfloor\frac{r}{dmin}\right\rfloor+6\left\lfloor\frac{r}{\sqrt{3}dmin}\right\rfloor \qquad (3.15)$$

When all interference nodes transmits with the maximum power P_{Tmax} , an upper bound on the interference received by the node in the center of the cell can be calculated and is given by:

$$I_{max}= \sum_{i=1}^{A}\frac{P_{T_{max}}}{PL(d_{A,i})} +\sum_{i=1}^{B}\frac{P_{T_{max}}}{PL(d_{B,i})} \qquad (3.16)$$

In the above equation A and B are the odd and even nodes of the hexagon

$$A=6\left\lfloor\frac{r}{dmin}\right\rfloor+ \text{ and } \quad B=6\left\lfloor\frac{r}{\sqrt{3}dmin}\right\rfloor , \qquad (3.17)$$

And path loss is given by PL(d) with the distance travelled by the signal is given by d.

The distance given in above equation (3.16) is given as follows

$$d_{A,i}=\left\lceil\frac{i}{6}\right\rceil d_{min} \text{ and } d_{B,i}=\left\lceil\frac{i}{6}\right\rceil \sqrt{3}\, d_{min} \qquad (3.18)$$

We simplify equation in the term of only taking that the first hexagon ring is interfering node that is A=6 and B =0.the model is given in the figure and we finally get an equation from (3.18)

$$d_{A,}i=d_{min} \qquad (3.19)$$

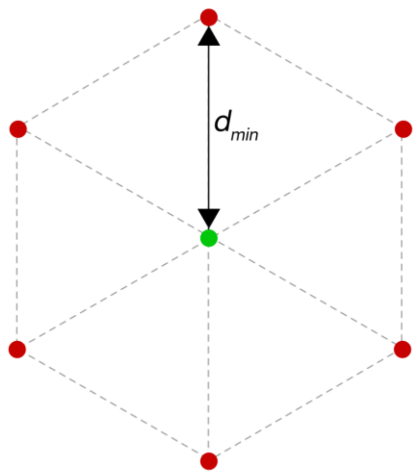
from the (3.17) and (3.19) we get the following equation

$$I_{max}(d_{min}) = \sum_{i=1}^{6} \frac{P_{T_{max}}}{PL(d_{min})} = 6\frac{P_{T_{max}}}{PL(d_{min})} \quad (3.20)$$

In decibels we can express the above equation as following

$$I_{max}(d_{min}) = 10\ log_{10}\left(6\frac{P_{T_{max}}}{PL(d_{min})}\right) \quad (3.21)$$

$$= P_{T_{max},dB} - PL_{dB}(d_{min}) + 10log_{10}(6) \quad (3.22)$$



Figure(3.5)The green node is the receiver, while red nodes are transmitters. All nodes fulfill the requirement of being at least d_{min} apart from each other

For the calculation of the path loss we use the following equation

$$PL_{dB}(d) = 10log_{10}(d) + C \quad (3.23)$$

In the above equation we take C=35.5 then the SINR at the receiving end is given by

$$SINR = \frac{P_R}{I_R + N} \quad (3.24)$$

In decibels we can express as

$$SINR_{dB} = P_{R,dB} - I_{R,dB} - N_{dB} \quad (3.25)$$

We assume that minimum SINR requirement is given by $\emptyset \geq SINR_{dB}$. When the maximum interference is achieved at the receiver node that is $(I_R = I_{max})$. However our goal still is find to minimum SINR hence

$$\emptyset \leq SINR_{dB} = P_{R,dB} - I_{max,dB} \quad (3.26)$$

in this case our goal is find to minimum distance for which the required SINR is always fulfilled. in the given worst case $\emptyset$ =SINR .the transmitter transmits maximum power P_{Tmax} . Therefore power at the receiver is given by

$$P_{R,dB} = P_{T,dB} - PL_{dB}(d_{D2D})$$

$$= P_{Tmax,dB} - PL_{dB}(d_{D2Dmax}) \tag{3.27}$$

From equation (3.26) and (3.27) we can get the following

$$\emptyset = P_{Tmax,dB} - PL_{dB}(d_{D2Dmax}) - I_{max,dB}(d_{min}) \tag{3.28}$$

Simplifying above equation we can get

$$I_{max,dB}(d_{min}) = P_{Tmax,dB} - PL_{dB}(d_{D2Dmax}) - \emptyset \tag{3.29}$$

from (3.22) and (3.29) we get

$$P_{Tmax,dB} - PL_{dB}(d_{min}) + 10log_{10}(6) = P_{Tmax,dB} - PL_{dB}(d_{D2Dmax}) - \emptyset \tag{3.30}$$

Above equation can be rewritten as

$$PL_{dB}(d_{min}) = \emptyset + PL_{dB}(d_{D2Dmax}) + 10log_{10}(6) \tag{3.31}$$

Now we combine equation (3.23) and (3.31) for the path loss calculation and is given by

$$10n\ log_{10}(d_{min}) + C = \emptyset + 10n\ log_{10}(d_{D2Dmax}) + C + 10\ log_{10}(6) \tag{3.32}$$

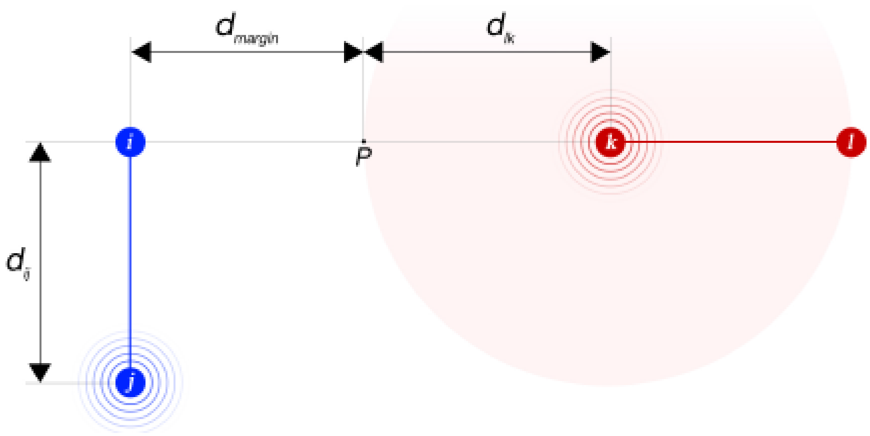
After simplifying we get the following equation

$$d_{min} = \left[10^{\left(\frac{\emptyset + 10\ log10(6)}{10n}\right)}\right] d_{D2Dmax} \tag{3.33}$$

This is our desired equation

3.5 Minimum Distance between D2D Links in a Cell: A Second Approach

In the previous paragraph we get an upper limit of the interference and use this equation to calculate the minimum distances between receiving and interfering nodes. The upper limit was given with the assuming that all interfering nodes transmit with maximum power and are put on a hexagon grid. But in reality we well know that D2D links all not of the equal length. In this section we take care the fact that different ideas for the estimating of the interference that is found at the receiver and explain a new way to define the 'contention zone' of a D2D links.



Figure(3.6)Illustrative explanation of dmargin; it is the distance between a interferer and a receiver minus the length of the D2D link of the interferer

As we can see in above figure we define a distance called margin distance which is the distance between the interferer and receiver subtracted by the length of the D2D links of the interferer therefore

$$d_{margin} = d_{ik} - d_{lk} \quad (3.34)$$

The interference power of P_{Rlk} is given by

$$P_{Rik,dB} = P_{Rlk,dB} - PL_{\Delta,dB}\,(d_{lk},d_{margin}) \quad (3.35)$$

In the above equation $PL_{\Delta,dB}\,(d_{lk},d_{margin})$ is the path loss of the signal which is traveling node P to i.

The path loss function which is given in equation (3.3) is not linear therefore we have

$$PL_{\Delta,dB}\,(d_{lk},d_{margin}) = PL_{dB}\,(d_{lk},d_{margin}) - PL_{,dB}\,(d_{lk}) \quad (3.36)$$

$$= 10n\, log_{10}(d_{lk} + d_{margin}) - 10n\, log_{10}(d_{lk} \quad (3.37)$$

$$=10n\, log_{10}\left(\frac{d_{lk}+d_{margin}}{d_{lk}}\right) \quad (3.38)$$

For the achievement of the required SINR which is presented by the $\emptyset \geq SINR_{dB}$, the necessity is keep to the limit of the interference . This is achieved by keeping d_{margin}g minimum. If the $d_{marging}$ between the interfare and receiver node is very small, they cannot operate simultaneously. So we want keep $d_{marging}$ just like our previous paragraph as d_{min}. In the cell if L active links are present at the same time, there will be L-1 interferer nodes for every receiver. Now we consider that all receiver nodes receive the same power of signal P_R from which they are paired transmitter, analogous to the way we deriver equation (3.35) the maximum interference power we receive at the receiver is given by

$$I_{max,d} = P_{R,dB} - PL_{\Delta,dB}\,(d_{D2Dmax}, d_{margin,min}) + 10\log_{10}(L-1)$$

$$= P_{R,dB} - 10n\log_{10}\left(\frac{d_{D2Dmax}+d_{margin,min}}{d_{D2Dmaxx}}\right) + 10\log_{10}(L-1) \qquad (3.39)$$

In the above equation d_{D2Dmax} largest D2D allowed link length. Then minimum SINR is given by

$$SINR_{min,dB} = P_{R,dB} - I_{max,dB} \qquad (3.40)$$

And we know that in the worst case this is equal to $\emptyset$ then we combine both the above equation we get

$$\emptyset = 10n\log_{10}\left(\frac{d_{D2Dmax}+d_{margin,min}}{d_{D2Dmax}}\right) + 10\log_{10}(L-1) \qquad (3.41)$$

After simplifying the above we get

$$d_{margin,min} = \left[10^{\left(\frac{\emptyset+10\,log10(L-1)}{10n}\right)} - 1\right] d_{D2Dmax} \qquad (3.42)$$

Now we apply the method same as in previous section, to argued is accepted to the amount of interfere links to 6, so that L_{max} =7 . it can be seen that when there are only two interfering links that is L=2 then the equation (3.42) compressed as

$$d_{margin,min} = \left[10^{\left(\frac{\emptyset}{10n}\right)} - 1\right] d_{D2Dmax} \qquad (3.43)$$

So the minimum distance between two links will becomes

$$d_{min} = d_{D2Dmax} + d_{margin,min} \qquad (3.44)$$

$$= \left[10^{\left(\frac{\emptyset}{10n}\right)}\right] d_{D2Dmax} \qquad (3.45)$$

3.6 Chapter Summary

In this chapter we have performed an elementary analysis on the distances between two random points in a circle and the distances between a random point in a circle to the center of the cell, representing D2D and cellular links respectively. A comparison is made in terms of the average link lengths in a cell when the choice of the BS to make use of a D2D link instead of using cellular links relies solely on link lengths. We have used a simple path loss model to derive an upper bound on the interference coming from devices separated from each other by a distance of at least d_{min}. We used this upper bound to analytically derive an equation with which we can find the minimum separation requirement between nodes as a function of the path loss exponent, the minimum SINR and the maximum D2D link length. To guarantee a minimum SINR at every node without the need of adjusting the initial transmit powers, the d_{min} from the derived equation can be used. We also presented a second method to derive a minimum distance requirement, with the use of a margin distance d_{margin}. With this second method we can take it into account that not every link is of equal length and assuming power control on D2D links give a less stringent distance requirement while still guaranteeing a minimum SINR at every node.

In the next chapter we give a purpose to the derived minimum distances in this chapter by introducing the idea of grouping links.

Chapter 4

SCHEDULING OF D2D LINKS

4

SCHEDULING OF D2D LINKS

In D2D communication many criteria have been used to measure the effect of communication system for the verifying its nature that is perfect or ideal. As we explained earlier in chapter 2 wireless communication is affected by the interference .for the limiting the bit error rate and use the signal bandwidth as much as possible, we want to reduce the interference in the wireless communication links.in the previous chapter we explained that the minimum distance is always maintained in any D2D communicating between active links. If we maintained the given minimum distance at any cast we much closer to the desired output at the receiver end without any interface with guarantee SINR.

In this chapter we going to introduce two grouping algorithm. First we explain the concept of grouping and in later part of this chapter we introduce with two grouping algorithm.

4.1 Groping of D2D Links

In previous chapter we explains the two distance equation which is specify that we achieve guarantee a given SINR with maintaining the minimum distance. In next paragraphs we want to form a group of links to filling all the distance model calculated in previous chapter which is working simultaneously belongings to the same group when achieve the minimum SINR.

The links which formed a group is by distance criteria, only links which is separated by Δ keep in the same group. This is given in the following figure. In the figure there are three links are given. now we assume that $d<\Delta<2d$, in this way that is the distance between the nodes of links 1 and 2 is less than @.so the links 1 and 2 cannot keep in the same group because of the distance criteria. Same procedure is follows for the links node 1 and 3 and they can form a group according to the distance criteria.

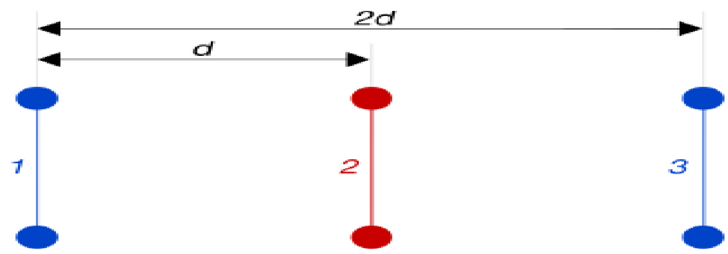


Figure (4.1)- Grouping of D2D links with a distance criterium

Now we can take =d_{min}, where d_{min} is given in the distance model in previous paragraph. If we do this this means that all links which belongs to the same group satisfied the minimum distance requirement.

In reality it is only enough that a distance d_{min} is always maintained between receiver and interferers.

4.2 Assumption and Consideration

Spectrum sharing- most of the cellular system including UMTS/WCDMA frequency division multiplexing mode and the CDMA2000 system, we use frequency division multiplexing to separate the uplinks from downlinks. This can only be achieved by the sharing of resource or dedicated resource in up or down link .this is detailed explained in the following figure

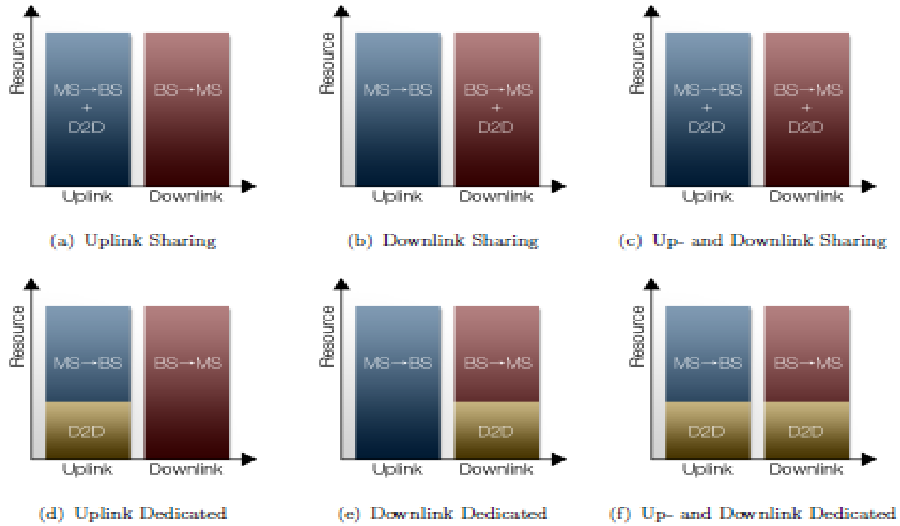


Figure (4.2)-Spectrum Sharing Strategies

The cellular uplink spectrum sharing is shown in fig (a). in uplink sharing only which devices take part in cellular communication transmit signal to the BS. By sharing the of the uplink spectrum which D2D links are not allowed which very close to BS, as if we allow them they cause more interference on the BS. Meanwhile D2D receiver will-to a lesser or greater extent – suffer from the interference caused by the cellular system.

In this (b) conation the lines may not cause disturbance to the devices which is receiving data from the BS. The base station is caused interference at the receiving end of the device to device links. Particularly when the base station is transmits to a node closer the edges of the cell while the device to device receiver is locates closer to the base station.

Fig (c) is the combination of the both two given above. Sharing of spectrum is more advantageously especially when short cellular links are working. That is when the devices are present near the base station communicating with each other over a cellular links with the base station.

The fig shown above from d-f assumes dedicated resource allocation for device to device communication. This is very advantageous over the sharing resources with the cellular communication. There is no interference in device to device communication with the cellular communication and the opposite can also happened. The disadvantage of it is that D2D devices will have tune to the correct band .however the portion that is used for D2D communication can be calculated dynamically .therefore no resource are wasted in case there is no device to device session.

4.3 Multiplexing

The algorithm present in this chapter, group some links in such a way that all links in a same group can operate simultaneously using the same resource. In the analysis we can use any of the multiplexing methods which is used before but the choice of the selection of the multiplexing is very much depend upon the energy consumption, Qos etc.

Here we consider that which nodes wants to be able to transmitting and receiving data is independent of other d2d links. The mutual independence make d2d2 communication more flexible. Another advantage is that less coordination is required from the base station.

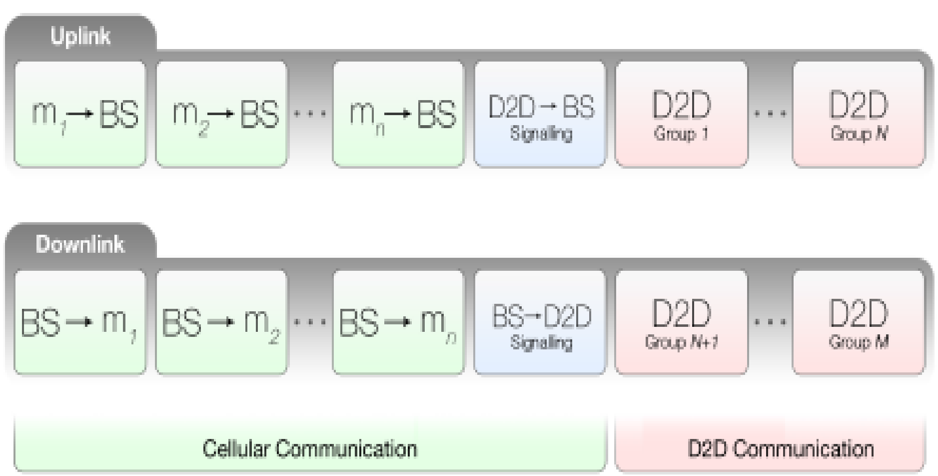


Figure (4.3) In the figure dedicated slots are allocated for D2D communication, both In the uplink as in the downlink frequency bands

4.4 Grouping Algorithm

We consider that the base station is responsible for the setting up and allocated of time slots for device to device links. So we explained in this chapter recently every group has its own time slots. Our aim to minimize the time slots to achieve the maximum capacity in the form of time slots. For this reason we want to create some gropes because we want to keep the maximum links in every group. For this we going to present two grouping algorithm for the two distance model exploded earlier.

4.5 First Grouping Algorithm

In this paragraph we written and implement an algorithm that is very much similar to the wales-Powell coloring algorithm in mat lab. This algorithm is very much simple and speedy. For the drawing of the edges of the graph first we to give the minimum distance criteria as an input. And from the graph we construct an adjacency matrix. Following we give the code for the algorithm.

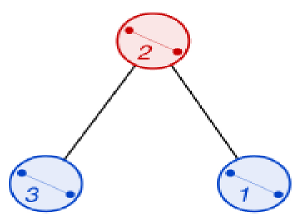


Figure-(4.4) The links shown in figure are mapped to the graph shown above, where every vertex represents a D2D link. An edge between vertices is present if the links represented by the vertices do not fulfill the distance requirement with respect to each other

1: First of all we make a list of all the vertices, in ascending order

2: After that create a new group and place the first vertex in it

3: WHILE not all vertices are put in the same group

4: Try to put the next vertex in the in an existing group

5: Starting at the first group, the n second so on.

6: If this is not possible, then create a new group for the vertex

7: END while

Now we take a simple example and understand that what groups formed in ten links with links length of 300 meter, randomly placed in the cell which radius is 1000 meter. From the equation of second distance model we calculate that SINR of 6 dB and path loss exponent n=4 the required minimum distance is 663.2 meter. In the fig every color belongs to the same group of the links.

The histogram of the figure shows that in every group how many links we have placed.

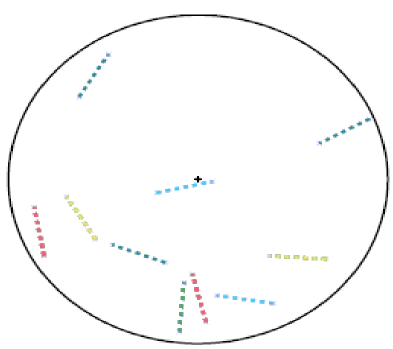


Figure-(4.5) Ten links grouped with the greedy grouping algorithm. Links of the same color belong to the same group

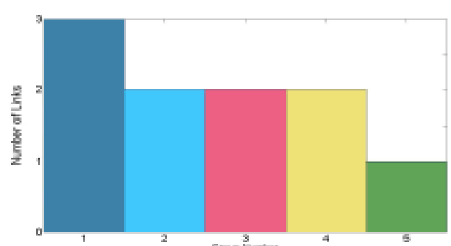


Figure (4.6) Histogram showing the number of links per group resulting from the greedy grouping algorithm of the links shown in figure. The bar colors correspond with the group colors shown in figure

This algorithm is best suited for our first distance model .where the distance criteria is given by the equation (3.33). In first distance model a minimum SINR is guaranteed if we fulfill the required distance which is anyway the case where links in the group formed the first grouping algorithm.

This algorithm is not suited for our second distance model. Now we going to introduce a new algorithm on the basis of the first one.

4.6 Second Grouping Algorithm

When we use second model of distance as described earlier we cannot use this algorithm because in this model we take the distances which is unequal this creates an issue in the first grouping algorithm. The reason behind it that in the second model of distance we consider that we know in advance the number of interfering links that is L-1.we cannot predict with the first grouping algorithm that how many interfering links are present in every group, till we have not create a group.in second distance model the required distance can only be known after we know the L.

If we want to use the second distance model, then the links distributed over the groups become less or more equal, so we have to estimate L as

$$L = \frac{L_t}{M} \qquad (4.1)$$

In the above equation L_t represent the total no of links present in the given cell and M the no groups. To find this relation we introduce an adapted version of the previous algorithm. This algorithm is referred to as a second groping algorithm. The code for this algorithm is given below

1: First off all make list of all vertices, by descending order,

2: Now crate a group and place the first vertex in it

3: While not all vertex placed in group

4: Check in which of the existing group the vertex can fits

5: If it is not possible create a new group

6: END while

Chapter 5

Simulation Result

5

Simulation Result

In this paragraph we are going to introduce the situation which simulation is given in the next paragraph. in the following fig we explain with the example that how the cell is consisted in every situation. All situations are simulated with different SINR. For both the first and second grouping algorithm. In our simulation we use the table 2 with the path loss exponent n=4 the radius of the cell is taken as 1000 meters.

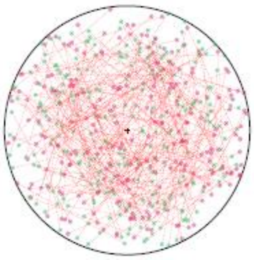
In the first situation the cell is consisted with 250 randomly distributed links of equal length we start our simulation with a fixed links length to 500, 250, 100, and 50. We repeat this for second situation also but this time 50 randomly distributed links. For the reason behind the choosing this situation is to see the effect of the length on the links. In the third situation we chose the variable length. 250 links are arbitrary placed in the cell.in the figure6.3d-f the same was done but now in this we chose the 50 randomly placed links of variable length. This situation tell us what the effect is made on the differing the link length.

In the following table we summarize the entire situation given above as follows.

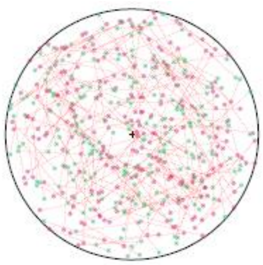
Table 1

situation	Situation example cell figure	Cell radius	Total no of links L_{total}	Number of cluster K	Cluster radius (meter)	Number of D2D links per cluster	Link length (meter)	Average link length
1	5.1	1000	250	1	1000	250	1000 500 250 100 50 10	1000 500 250 100 50 10
2	5.2	1000	50	1	1000	50	1000 500 250 100 50 10	1000 500 250 100 50 10
3	5.3	1000	250 50	1	1000	250 50	10-1000 10-500 10-100	505 255 55

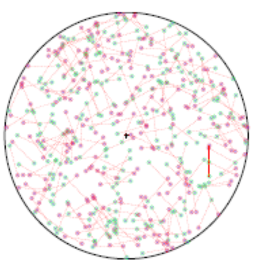
All situations



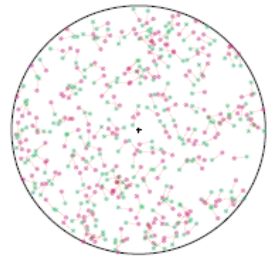
(a) 500 nodes, 1000 meter links



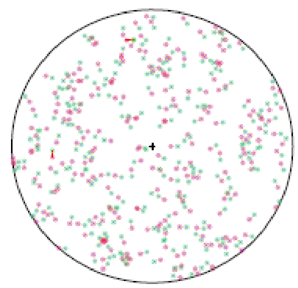
(b) 500 nodes, 500 meter links



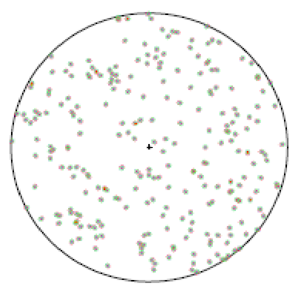
(c) 500 nodes, 250 meter links



(d) 500 nodes, 100 meter links

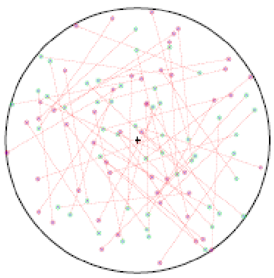


(e) 500 nodes, 50 meter links

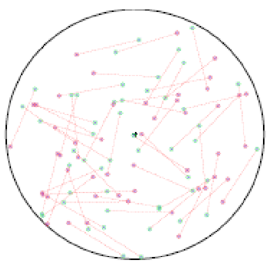


(f) 500 nodes, 10 meter links

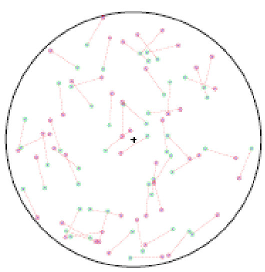
Figure (5.1) Examples of cell scenarios with fixed D2D link lengths (500 nodes)



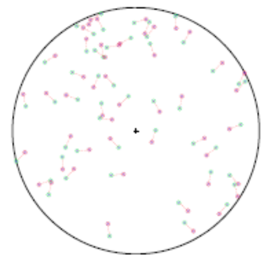
(a) 100 nodes, 1000 meter links



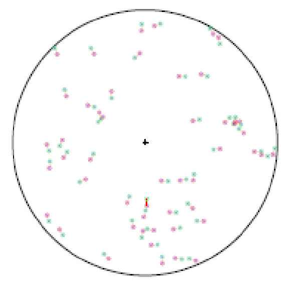
(b) 100 nodes, 500 meter links



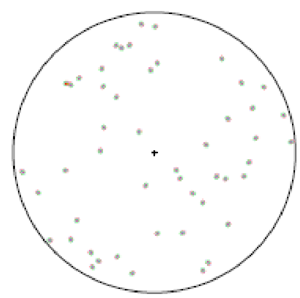
(c) 100 nodes 250 meter links



(d) 100 nodes, 100 meter links

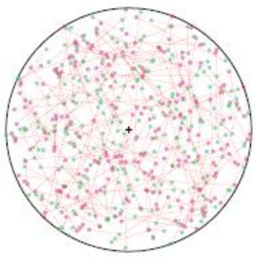


(e) 100 nodes, 50 meter links

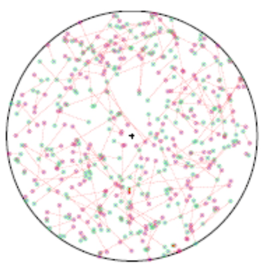


(f) 100 nodes, 10 meter links

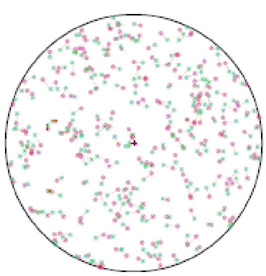
Figure (5.2) Examples of cell scenarios with fixed D2D link lengths (100 nodes)



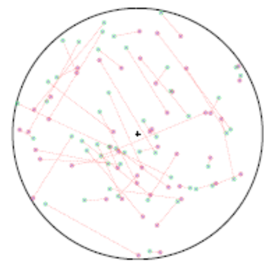
(a) 500 nodes, 10 to 1000 meter links



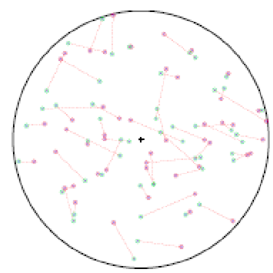
(b) 500 nodes, 10 to 500 meter links



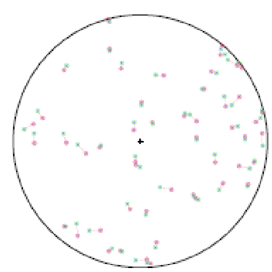
(c) 500 nodes, 10 to 100 meter links



(d) 100 nodes, 10 to 1000 meter links



(e) 100 nodes, 10 to 500 meter links



(f) 100 nodes, 10 to 100 meter links

Figure (5.3) Examples of cell scenarios with variable D2D link lengths

5.1 Simulation Results

In this paragraph we perform the simulation of all situations given above with our distance model. We mainly focus in the number of groups are created that gives a guarantee SINR. In the first situation we take the fixed length of the links. In the given situation tells us the total number of d2d links and the size of every d2d links. In every simulation M groups are created. When we performed the simulation we observed that there is three type of M called small, medium and maximum which is denoted by min (M), average M and max (M) respectively. Besides it we can also calculate worst SINR which is found in every situation.

5.2 First Distance Model with the First Grouping Algorithm

in the following given figure we plot the number of required groups related to the total number of the links for all simulated situation and SINR requirement.in other way we can say that the height of the bar, corresponds to the fraction of groups that are needed in the number of the links. Therefore the lower the bar height, highest in the efficiency in accordance with the number of the groups that are used related to the number of groups that will be required if every link would be given its own group. With the help of bar graph we can easily understand what happened when some parameters are changed and this gives us a better idea to compare every situation in easy way.

In the first situation where we take 250 links that is 500 nodes fixed nodes. In very long links no links can be combined in the group. In the second situation there are there are only 50 randomly distributed links. Comparing with these two simulation results we can see that when the density of the links is high, the deferent simulation we performed is similar as compare to the low density.

In our third situation the links of the length varies uniformly in the given values. The simulation is performed for the both situation as 250 and 50 links. The fourth situation we performed the simulation of 50 and 5 links per cluster and in this we varying our cluster. And in the final situation where 100 cluster are used with the varying link length.

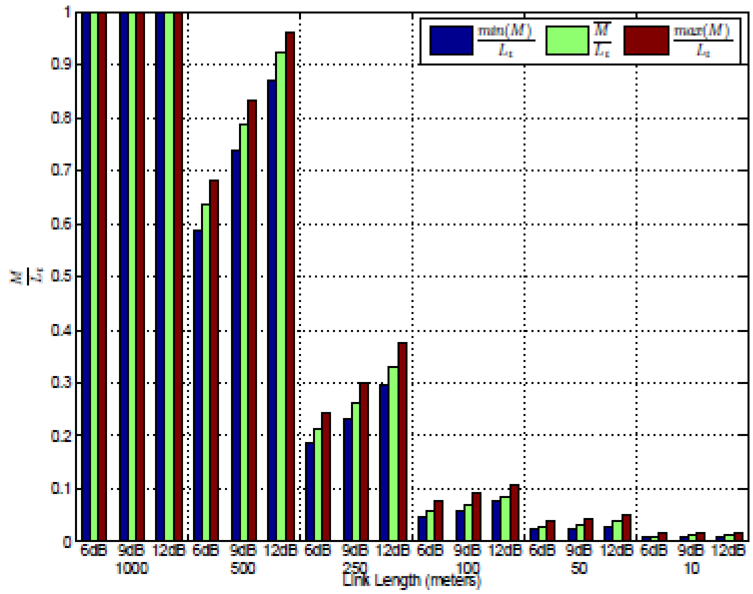


Figure (5.4)Plot of the number of groups formed with scenario 1, with 250 links and fixed link lengths, using the first distance model with the first grouping algorithm

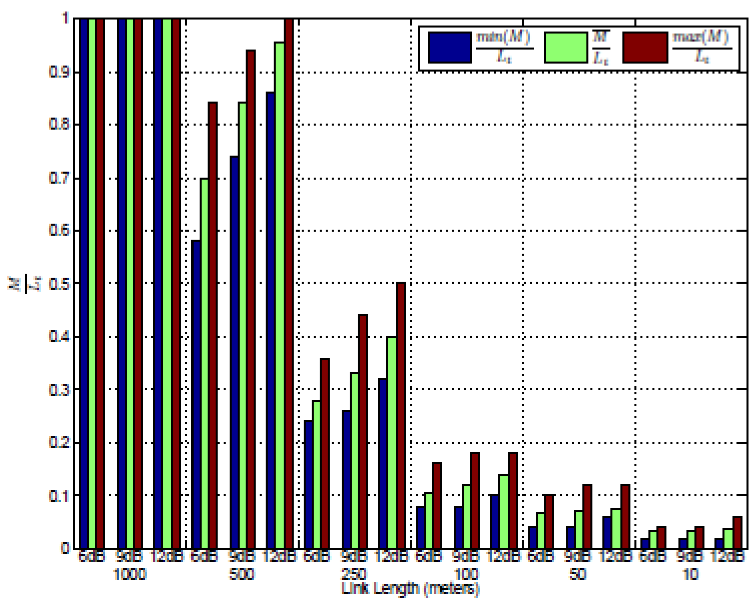
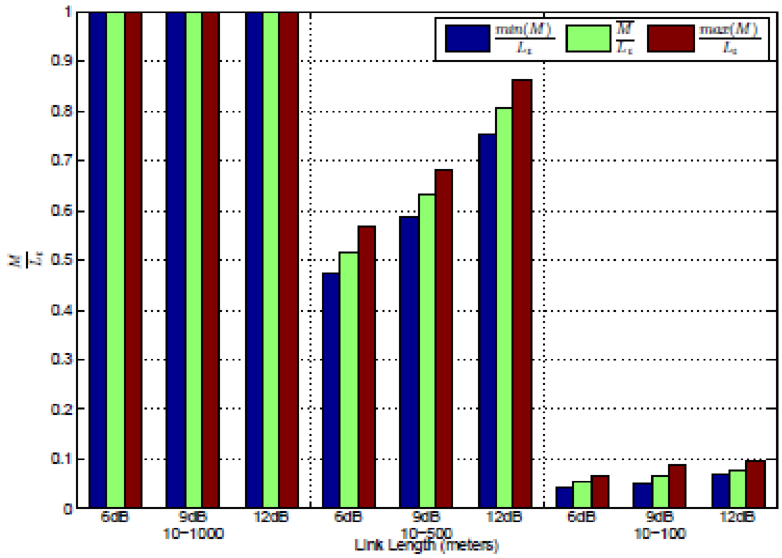
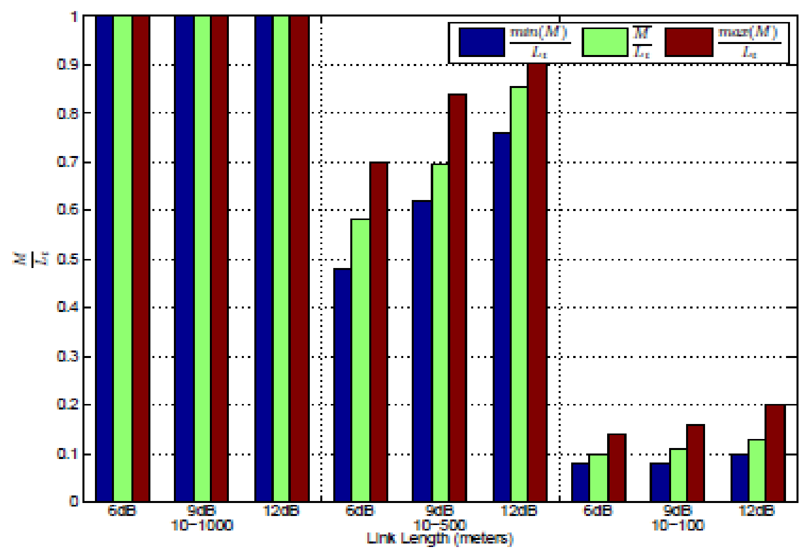


Figure (5.5)Plot of the number of groups formed with scenario 2, with 50 links and fixed link lengths, using the first distance model with the first grouping algorithm



(a)

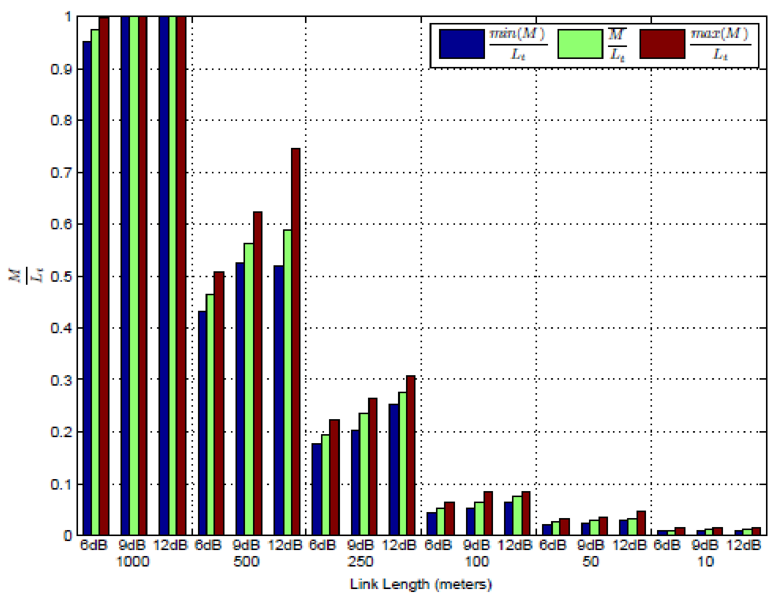


(b)

Figure (5.6)Plot of the number of groups formed with scenario 3, with 250 links (a) and 50 links (b) and varying link lengths, using the first distance model with the first Grouping algorithm

5.3 Second Distance Model with Second Grouping Algorithm

Simulate same situation with the second grouping algorithm and second distance model. And compare the result of both the algorithms with each other. The expiation is almost the same as the first case only the results are differ which is shown in the given table . In the first situation we use the 250 links with fix link length. In the second situation we use the 50 links and fix link length. Remaining situation are as explained in previous paragraph is also follow in this. The simulation results of every situation are given in the following figures.



Figure(5.7)Plot of the number of groups formed with scenario 1, with 250 links and fixed link lengths, using the second distance model with the second grouping algorithm

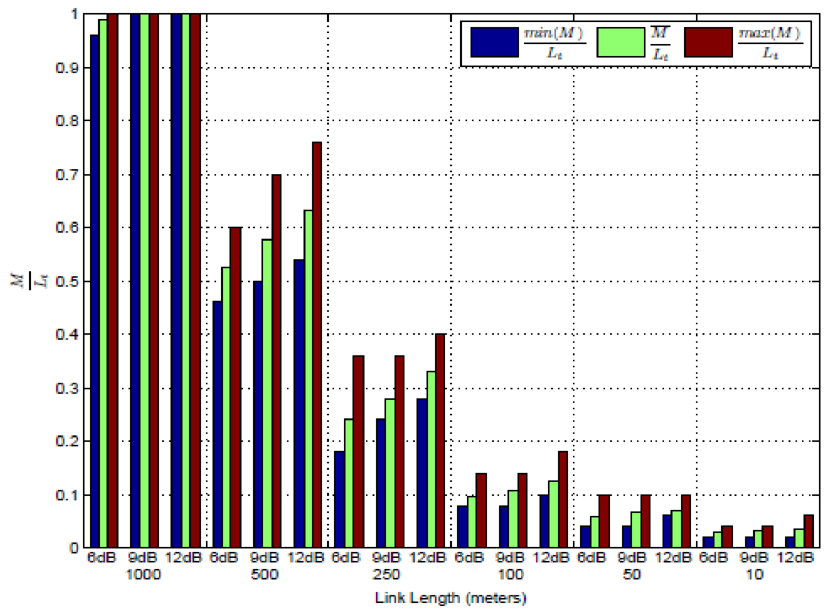
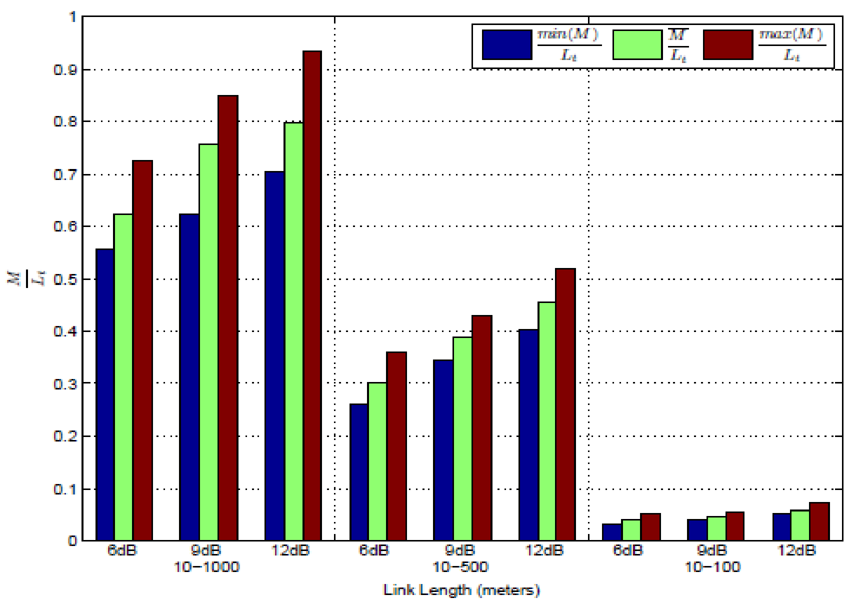
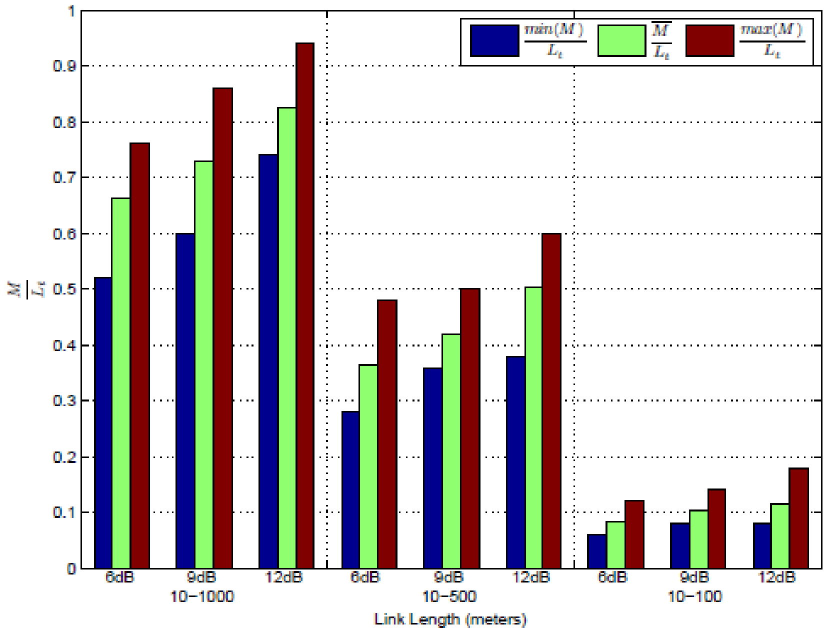


Figure (5.8)Plot of the number of groups formed with scenario 2, with 50 links and fixed link lengths, using the second distance model with the first grouping algorithm



(a)



(b)

Figure(5.9)Plot of the number of groups formed with scenario 3, with 250 links (a) and 50 links (b) and varying link lengths, using the second distance model with the second grouping algorithm

Table-2

	$SINR_{min}$(dB)	D_{min}(m)	Min(M)	$\bar{M}$	Max(M)	Min($SINR_{dB}$)	$\mu_{1/2}$($SINR_{dB}$)
1000	6	2.3105	250	2500	250	∞	∞
	9	2.6526	250	2500	250	∞	∞
	12	3.125	250	2500	250	∞	∞
500	6	1.152	149	1596	170	1125	1810
	9	1.315	181	1927	208	1665	∞
	12	1.651	213	2350	245	1976	∞
250	6	5526	48	560	65	803	1574
	9	6589	59	635	71	1102	1712
	12	7809	76	830	91	1504	2010
100	6	2212	12	152	18	845	1500
	9	2657	15	175	24	1178	1751
	12	3125	21	213	26	1354	1964
50	6	1115	6	75	9	978	1786
	9	1351	6	83	12	1185	1985
	12	1562	7	93	14	1452	2123
10	6	221	2	26	4	1152	3035
	9	262	2	25	4	1440	3032
	12	321	2	31	4	1638	3135

Table-3

250 link length (m)	$SINR_{min}$(dB)	Min(M)	$\overline{M}$	Max(M)	Achieved SINR in dB Min($SINR_{dB}$)
1000	6 9 12	238 250 250	2434 2500 2500	249 250 250	600 ∞ ∞
500	6 9 12	108 131 130	1150 1440 1475	128 156 185	601 911 1200
250	6 9 12	44 51 64	485 588 692	57 66 78	684 972 1205
100	6 9 12	11 12 15	131 157 186	15 20 20	646 914 1214
50	6 9 12	5 6 7	62 72 83	8 9 12	745 1015 1257
10	6 9 12	2 2 2	24 26 27	4 4 4	940 1190 1418

Chapter 6

Final Remark and Conclusion

6

Final Remark and Conclusion

6.1 Conclusion

The popularity of mobile communications has increased immensely the past decade. In chapter 1 we performed a survey illustrating the growth of mobile data traffic. We argued that mobile operators need innovative solutions to cope with the rising demand of mobile traffic while minimizing operating costs. A recent research topic is D2D communications as an underlay to cellular networks. A D2D link is a direct connection between two communicating devices. The goal of using D2D links as such is to: (a) increase the spectral efficiency, (b) reduce the load on the network and (c) introduce and facilitate new services. In this thesis we have presented a strategy for the application of device-to-device (D2D) communication in a cellular network.

In chapter 2 we explained the concept and evolution of cellular networks briefly and positioned D2D communication as proposed in this research in the contemporary wireless networking landscape.

In chapter 3 we derived two equations, specifying the minimum distance requirement between simultaneously operating links, given that a minimum SINR that has to be achieved. To find the first equation, we derived an upper bound on the interference in a worst case scenario. We recognized that when links vary in length, our first minimum distance model is not optimal. Hence we also devised a second minimum distance model, which assumes that there is power control in place and thus take varying link lengths into account.

In chapter 4 we applied graph link theory to form groups of links in a way that all links belonging to the same group fulfill a given minimum distance requirement with respect to each other. We applied the well-known Welsh-Powell algorithm for the grouping of links in combination with our first distance model and explained how we adapted this algorithm so it could be used with our second distance model. Throughout this thesis the grouping algorithms used with the first and the second distance models are commonly referred to as the first and the second grouping algorithm respectively. We stated all possible spectrum sharing strategies and argued that the best strategy is to allocate dedicated resources for the D2D sessions in both the cellular up- and downlink frequency bands.

In chapter 5 simulations were performed in three different situation to learn more about the grouping performance in cells with varying node densities, D2D link lengths and clustering parameters. We proved that our two grouping methods function correctly in all situation, under different minimum SINR requirements for the first distance model with the first grouping algorithm the following conclusions have been drawn:

- As the link density increases, the grouping becomes more efficient, i.e. relatively less groups can be formed.
- . Large links (around the size of the cell radius) cannot be combined into groups together; every D2D link is allocated its own group (and thus its own timeslot).
- .The first grouping method is very sensitive to variations in the link lengths. When link lengths vary, the grouping performance decreases quickly: more than two times more groups are needed when compared to scenarios with fixed link lengths, equal link densities and comparable average link lengths.

For the second distance model with the second grouping algorithm we have seen the same behavior as with the first grouping method with regard to the influence of the link density. Overall, the second grouping algorithm with the second distance model is more economic with groups when compared to the first grouping algorithm, but as the link lengths decrease, the advantage approaches zero. Furthermore, the following conclusions have been drawn:

- Large links (around the size of the cell radius) can occasionally be combined into groups together. For links with a length of around half the cell radius, the fair grouping method performs much better when compared to the first grouping method.
- The second grouping method is less sensitive to variations in the link lengths than the first grouping method. Significantly higher performance is achieved compared with the first grouping method: from 25% to 40% less groups are formed depending on the scenario. However, there is still a drop in performance when compared to scenarios with

fixed link lengths, equal link densities and comparable average link lengths: around 50% more groups are formed.

6.2 Future work

- User mobility. Our simulated scenarios in chapter 5 assume static nodes, whereas in reality nodes might be moving. The dynamics as consequence of moving nodes is a topic for further study.
- A multicellular environment. We assumed perfect separation of neighboring cells, whereas this might not always be the case. Also, by letting base stations work together, D2D links can be set-up between nodes under different base stations.

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