Online Relay Switching in the presence of Dynamic Obstacles in millimeter wave D2D communication

Ravi Shukla

Online Relay Switching in the presence of Dynamic Obstacles in millimeter wave D2D communication.

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Ravi Shukla
[Roll No: CS-1812]

under the guidance of

Dr. Sasthi Charan Ghosh
Associate Professor
Advanced Computing and Microelectronics Unit

Indian Statistical Institute
Kolkata-700108, India

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To my family and my guide

CERTIFICATE

This is to certify that the dissertation entitled **"Online Relay Switching in the presence of Dynamic Obstacles in millimeter wave D2D communication"** submitted by **Ravi Shukla** to Indian Statistical Institute, Kolkata, in partial fulfillment for the award of the degree of **Master of Technology in Computer Science** is a bonafide record of work carried out by him under my supervision and guidance. The dissertation has fulfilled all the requirements as per the regulations of this institute and, in my opinion, has reached the standard needed for submission.

Dr. Sasthi Charan Ghosh
Associate Professor,
Advanced Computing and Microelectronics Unit,
Indian Statistical Institute,
Kolkata-700108, INDIA.

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Ravi Shukla
Indian Statistical Institute
Kolkata - 700108 , India.

Abstract

With the ever-increasing number of diverse user-equipments (UEs) and their requirement of high data rate several modifications have been done on previous wireless technologies leading to the evolution of 5G device to device (D2D) communication. The use of millimeter wave (mmWave) channels is gaining popularity for short-range D2D communication due to its high available bandwidth. But due to the excessive penetration loss suffered by mmWave, it is necessary to facilitate D2D communication along the line of sight (LOS) path. In the D2D communication, UEs also acts as relays to forward the data packet transmitted by the source to receiver. In the presence of dynamic Obstacles as well as due to the motion of UEs, blockage of LOS is highly probable which makes relay selection quite challenging. We are proposing the unique strategies based on the geometric approach to find the priority of the relays for a given D2D pair. In case of blockage of LOS by dynamic or static obstacles, the respective D2D pair might switch to the other high priority relay. We are modeling the entire problem as a game-theoretic auction framework with the goal of increasing the overall throughput of the system as well as prevention of starvation of any D2D pair. We perform centralized relay selection using the global information but found that this might not be sufficient to reduce packet loss adequately. Motivated by this, we develop an online relay switching (ORS) algorithm, where we perform pre-emptive distributed switching using the local information of the UEs to reduce any further packet loss due to the blockages. Through simulation we show that in the presence of large number of dynamic obstacles, ORS not only gives a significant improvement in the average throughput and packet loss but also the lower starvation of D2D pairs than the traditional approaches which does not take into account the pre-emptive switching of the relays in case of blockage.

Contents

1 Introduction **6**

1.1 Introduction to 5G 6

1.1.1 Device-to Device (D2D) Communication 6

1.1.2 Millimeter Wave Band 7

1.2 Motivation for Relay Switching 8

1.3 Why Game Theory? 8

1.4 Our Contribution 9

1.5 Thesis Outline 10

2 Related Work **11**

2.1 Relay Assisted D2D communication 11

2.2 Relay Selection in the presence of Dynamic Obstacle 12

2.3 Game Theory in D2D communication 12

2.3.1 Game Theory in Resource Allocation 12

2.3.2 Game Theory in Relay Selection 13

3 System Model **15**

3.1 Directional Beamforming 16

3.2 Pathloss Model 17

4 Relay Priority Formulation 18

4.1 Analysing LOS Probability 19

4.1.1 Case 1:- Both S and R are static 19

4.1.2 Case 2:- W.L.O.G. S is static and R is Dynamic 20

4.1.3 Case 3:- Both S and R are in motion 23

4.2 Priority List 26

5 Centralized Relay Selection 28

5.1 Auction Framework 30

6 Distributed Relay Switching 33

6.1 Detection of blockage of LOS of a D2D pair 33

6.1.1 Case 1:- D2D pair was communicating directly 33

6.1.2 Case 1:- D2D pair was communicating via Relay 34

6.2 Detection of a better alternative relay 34

6.3 Online Relay Switching 34

6.3.1 Action Profile 35

6.3.2 Online Relay Switching Steps 36

7 EXPERIMENTAL RESULTS 39

7.1 Simulation Setup 39

7.2 Simulation Results and Analysis 41

7.2.1 Hyper-Parameter Tuning 41

7.2.2 Comparison with State of the Art 45

8 Conclusion and Future Works 51

List of Figures

3.1 Network-assisted device-tier architecture for D2D communication . . 16

4.1 Position, orientation and representation of path of movement for UEs and dynamic obstacle 21

7.1 System Capacity vs β 41

7.2 Avg. Throughput vs β 42

7.3 Blockage Fraction vs β 43

7.4 System Capacity vs β 44

7.5 Avg. Throughput vs β 45

7.6 Blockage Fraction vs β 46

7.7 System Capacity vs β 47

7.8 Avg. Throughput vs β 48

7.9 Blockage Fraction vs β 49

7.10 Avg. Throughput vs dObs 49

7.11 PacketLoss vs dObs 50

7.12 Blockage Fraction vs dObs 50

Chapter 1

Introduction

1.1 Introduction to 5G

With the explosion in the number of smart mobile devices/user equipments (UEs), advanced technological development and the ever-increasing need of high data rate, there has been various major breakthroughs in terms of transition from 3G to 4G long-term evolution (LTE) to LTE advanced (LTE-A) and now to fifth generation (5G) in mobile telecommunication [1]–[3]. 5G promises to deliver improved end user experience by offering new applications and services through seamless coverage, high data rate, low latency, and significantly improved performance and reliable communications. It will increase energy efficiency, spectrum efficiency, network efficiency as well as efficiency of other systems. 5G enhances the variety and scope of use cases like virtual reality, autonomous driving, blockchain etc, that LTE is able to minimally address today, and brings new revenue streams to operators by leveraging new solutions that LTE was not able to serve. Some of the key-enabler of 5G communication are as follows:-

1.1.1 Device-to Device (D2D) Communication

Generally, D2D communications provide the connection between two wireless devices either directly or by hopping. Specifically, when one wireless device needs to communicate with the base station; then the base station conveys the data to another wireless device directly or via backbone networks. Motivated by the increasingly high-rate local services, such as distributing large files among the wireless devices in the same cell, local D2D communications have recently been studied as an underlay to LTE-A 4G cellular networks [4]. It can significantly enhance the network capacity by establishing a path between two wireless devices in the same cell without an infrastructure of a base station. In 5G cellular networks, local D2D communications can be formed to relieve the back-bone network from humongous traffic due to the increasing bandwidth hungry applications, thus supporting more simultaneous users[5]. Meanwhile, global D2D communications can be formed with multihop wireless transmissions via base stations between two wireless devices associated with different cells.

1.1.2 Millimeter Wave Band

Millimeter wave (mmWave) band has gained popularity for the short-range D2D communication over the traditional microwave [6]. There are some major advantages in moving to the mmWave spectrum for cellular.

1. The channel bandwidth available is likely to be much larger than today's microwave systems.

2. The small wavelength at mmWave frequencies makes it possible to pack a large number of antennas into the mmWave transceivers. With these large antenna arrays at both the base stations and mobile stations, mmWave systems can employ directional beamforming to boost the received signal power and reduce the impact of out-of-cell interference.

But the downside of mmWave is the high propagation and penetration loss which makes their deployment quite challenging. Because of the smaller wavelength of mmWave, propagation loss can be dealt by the use of large number antennas and enhance the signal power as mentioned above. The multi-input multi-output (MIMO) antennas make the directional communication possible using beam-forming techniques [7]. But mmWave are very much affected by penetration loss. For example, penetration losses of about 40 dB for outdoor tinted glass at 28 GHz mmWave and 178 dB from a 10 cm brick wall at 40 GHz are mentioned in [8], [9] respectively. Due to this, almost a line of sight (LOS) path is required for a communicating D2D pair. To deal with the high penetration loss suffered by mmWave, devices can act as relays to provide LOS to the other devices. In [10], authors have shown that in the presence of obstacles, relay assisted D2D communication provides significant improvement in terms of coverage over direct D2D communication and hence mitigate the effect of obstacles.

1.2 Motivation for Relay Switching

In today's world, there are various situations where users are present in a particular region in a very high density continuously demanding a high data rate. In such scenarios, there are lot of devices which may communicate or relay the devices. But, there are also a lot of dynamic obstacles, in terms of humans and vehicles, in the area which could cause huge penetration losses. To worsen the situation, static obstacles such as buildings and trees might also act as dynamic obstacles since users are also in motion. Hence, frequent switching of relay devices to get new LOS path for the D2D pair is required to prevent or mitigate the blockage. Moreover, the D2D pair which are starving (waiting for very long time) for communication should be given higher priority while switching relays.

1.3 Why Game Theory?

Game theory is a very powerful and novel framework to model strategic interactions between multiple agents having conflicting interests. It provides a mathematical way of capturing the behavior of such conflicting agents so as to arrive at strategic decisions to meet a desired objective.

In this thesis, we have developed an auction based game theoretic approach to not only find the best relays for D2D pairs but also to switch them in case of any blockage so as to increase the total throughput and also reduce the starvation of the D2D pairs. We have compared our approach with the existing approaches to demonstrate the effectiveness of the relay switching of our game theoretic approach.

1.4 Our Contribution

The main contributions of this thesis are:-

- We first find the priority of the relays for a D2D pair according to the expected signal to noise ratio (SNR) offered by the relay to them by capturing the effect of the both static and dynamic obstacles as well as the mobility of UEs.

- We then develop an auction based framework for assignment of relays to the D2D pairs by performing centralized relay selection based on global information. The goal is to increase the overall throughput of the system as well as prevention of starvation of any D2D pair.

- Next, based on the D2D pair specific local auction, we propose an online relay switching (ORS) algorithm to switch the relays locally when the LOS is blocked by the obstacles or the priority of the current relay falls below the other relay by a hysteresis(significant) margin.

- Considering low, medium and heavy blockage scenarios, we show through simulation that ORS provides significant improvement in terms of average throughput, packet loss and starvation of devices in comparison with the other state of the art relay selection algorithms which does not take into account the local switching of relays.

1.5 Thesis Outline

The rest of the thesis is organized as follows. In Chapter 2, we discuss some of the recent works in D2D relay assisted communication and state of the art game theoretic resource allocation and relay selection approaches. Chapter 3 deals with the system model and directional beamforming assumptions as well as the pathloss model. In Chapter 4, we describe the relay priority list formulation by D2D pairs. In Chapter 5, we propose the auction framework for our central relay selection algorithm. Next, in Chapter 6, we describe our online relay selection(ORS) approach. Later, in Chapter 7, we discuss our simulation setup and the results obtained. Finally conclusions and future works are presented in Chapter 8.

Chapter 2

Related Work

2.1 Relay Assisted D2D communication

D2D communication is evolving as one of the major driving force behind 5G LTE-A communication in addition to 4G cellular communication thereby immensely improving the system capacity, resource utilization and energy efficiency [11]. Relay selection is an important aspect of D2D communication as it is not always possible to provide LOS path from source to destination directly. But due to the presence of both static and dynamic obstacles as well as the motion of UEs, relays are also prone to blockages. Besides, poor relay selection may even worsen the situation. In [12], [13], authors discussed several ways to deal with the adverse effect's of obstacles. Relay assisted D2D communication is discussed in [13], [14]. Performance of D2D 2-hop relays to overcome blockages using stochastic geometry was studied in [15] and a matching based relay selection policy was studied in [16]. In [17], authors proposed an approach to perform multi-hop relay selection in the urban environment where they prove that their relay selection schedule provides the maximum throughput. In [18], authors have given a reinforcement learning based approach to find the relays for D2D devices and showed that their approach provided comparable performances from the other non-learning based approaches without complex calculations. But all of these approaches considered only the obstacles to be static which might not be the valid assumption in the modern mobile telecommunication.

2.2 Relay Selection in the presence of Dynamic Obstacle

The problem of dynamic obstacle is much more challenging than static obstacles and it is further more complex when the UEs participating in the D2D communication are also in motion [19]. In [20], authors have suggested a geometric approach to find the relay path with maximum expected capacity. But they assumed to have complete knowledge of the location and motion of the dynamic obstacles owing to the wireless radars that leverages doppler's shift to gain such information. But this approach is completely centralized and using such sophisticated radars might not always be feasible. Further, due to the volatile environment, frequent local relay switching might be required to prevent any packet loss due to blockage of LOS. Moreover, it is also necessary to ensure that while increasing the system capacity, none of the device is getting starved.

2.3 Game Theory in D2D communication

Game theory is a useful tool to understand the complex interactions among various rational independent players in the game and model their strategic decision making. Game theoretic approaches can be classified into *cooperative* and *non-cooperative* games. Game-theory has found its various useful applications in D2D communication.

2.3.1 Game Theory in Resource Allocation

Recently game theory has found its application in improving power efficiency, optimal spectrum utilization, ensuring proper channel quality before allocating the resources[21]–[25]. In [21], authors have studied the problem of unknown channel quality (UCQ) using game theoretic approach where they proposed a contract based approach which removes the incentive of D2D devices with designed service contract. Due to this, false reporting of results about their channel quality so as to get undue advantages in resource allocation is eliminated. In [22], authors have analyzed the resource allocation problem as a non-cooperative game in which D2D UEs are viewed as players competing for channel resources. In [23], authors have studied the problem of resource allocation in D2D communication as auction games. Authors in [24] have addressed the joint resource allocation and scheduling problem using a stackelberg game theoretic approach where cellular users and D2D user followed a leader-follower pair. Authors in [25] proposes a cooperative game theoretic model in which each user not only aims to maximize its own utility but also has an incentive to cooperate with other users in order to form a strong user group. This increases the opportunity of each users to win the preferable spectrum resources. Authors in [26] addressed the problem of resource sharing among 5G D2D users and legacy 4G users. They proposed a game theoretic approach to ensure that no legacy cellular users are compromised heavily while encouraging the modern D2D users.

2.3.2 Game Theory in Relay Selection

Various game theoretic approaches for relay selection have also been proposed. Authors in [27] modeled the problem of relay selection in mobile social networks (MSNs) into a bargain game and proposed to provide incentives to the other nodes to relay the communication in terms of virtual currency. They used a sub-game nash perfect equilibrium to calculate the agreement price. In [28], authors have modelled the relaying problem into the auction market and used the game-theoretic approach to find relays for the mobile terminals with the aim of not only increasing the system capacity but also to prolong the battery lifetime for relay devices. But the major drawback with all the above resource allocation and relay selection approaches is that they did not address the presence of dynamic obstacles and mobility of UEs. Further in case of blockage of LOS, appropriate relay switching might also be required. Motivated by this, we devise a game theoretic auction framework to assign and switch relays to mitigate the effect of blockage by obstacles.

Chapter 3

System Model

We have considered downlink communication and specifically the operator-controlled (network-assisted) scenario of device-tier 5G D2D architecture mentioned in [5] and shown in figure 3.1. For simplicity, we have done our analysis for 2 dimensional area. UEs can be classified into D2D pairs and relays depending upon their intention to communicate. There are N D2D pairs which are willing to communicate for the next ΔT time duration. These N D2D pairs can not relay any other D2D pairs. Further, there are M relays which can provide the relaying service to the D2D pairs. These relays does not intend to initiate any communication of their own. Half duplex communication is assumed.

Since UEs are connected to the BS, they can be tracked quite easily. UEs can find their position and velocity by the Global Positioning System(GPS) and intimate this to BS via control signals. Further, the location, size and the shape of the static obstacle are also known through satellite imagery. We further assume that the service area is discretized into square grids of 1×1. In our analysis, we have assumed static obstacle to be a collection of points in the grid. If there is a static obstacle of dimension 10×10, then we can assume it to be 100 point static obstacles clustered as a square. Since tracking of dynamic obstacles is expensive and infeasible, we assumed them to be distributed uniformly with the density Γ throughout the simulation area following the random walk mobility model. We are considering one hop relaying in this thesis.

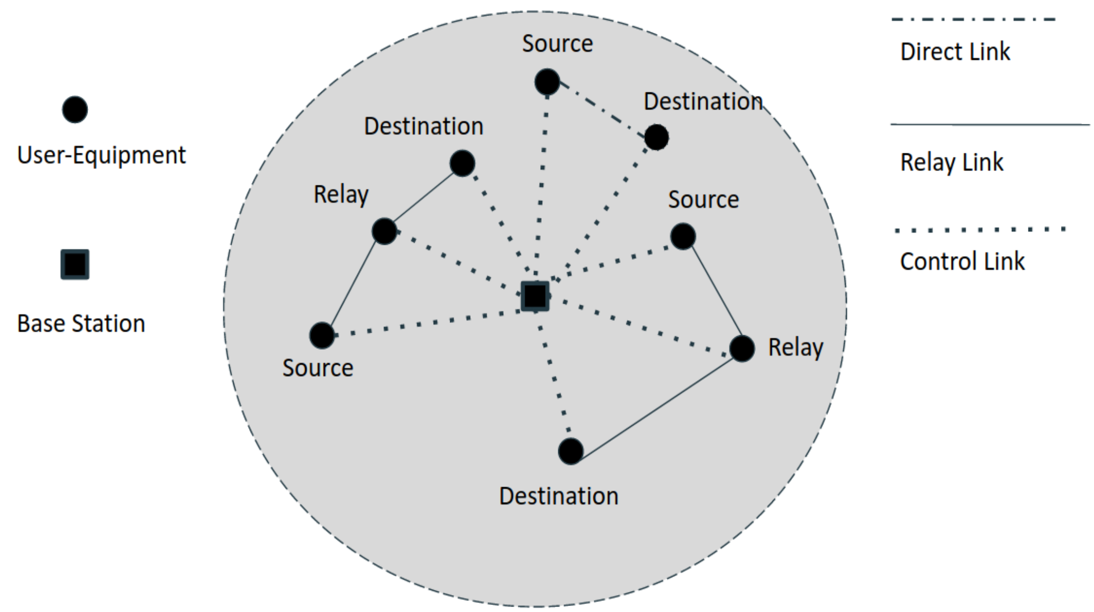

Figure 3.1: Network-assisted device-tier architecture for D2D communication

Time is discretized as T, T+1, T+2 and so on for the BS and difference between T+1 and T is ΔT. That is, ΔT is the duration between two consecutive global decisions by the BS. Similarly, for the D2D devices, time is discretized as t, t+1, t+2 and so on and difference between t+1 and t is Δt ($< \Delta$T). Here Δt is the duration between two consecutive local decisions by the devices. Every node is maintaining the priority list of possible relays every Δt time which is discussed in the later chapters.

3.1 Directional Beamforming

We are considering a simple sectored antenna array model for both transmitters and receivers as mentioned in [20]. Antenna gains for an M $\times$ M uniform planar square antenna array can be written as [10]

$$G_x = \begin{cases} G_{ml} & if\, \theta \leqslant \phi/2 \\ G_{sl} & otherwise \end{cases}$$

where x = $\{t, r\}$ is subscript for transmitter and receiver, $G_{ml} = M^2$, G_{sl} and ϕ are main-lobe gain, side-lobe gain and beam-width respectively. Here $\theta \in$ [-π, π] is the angle off the bore-sight direction. We are assuming that the transmitter-receiver pairs are perfectly aligned to obtain the maximum power gain [7]. Alignment overhead is in order of hundreds of micro seconds even for extremely narrow beams of width=1°. As described in [29], this overhead, with respect to the communication time in order of seconds, can be neglected.

3.2 Pathloss Model

The pathloss in dB for a LOS link with length r can be modeled as [30]

$$PL_{LOS}[dB](r) = 20log_{10}\left(\frac{4\pi}{\lambda}\right) + 10\alpha_L log_{10}(r) + \chi_{\sigma_L} \tag{3.1}$$

where λ is the wavelength, α_L is the pathloss exponent of a LOS link, and χ_{σ_L} is LOS shadowing, which is a normal distribution in dB (lognormal distribution in linear scale) with zero mean (dB) and standard deviation σ_L(dB). For a LOS link, σ_L is usually small and has a small effect on the pathloss.

Similarly, the pathloss in dB for a Non-LOS (NLOS) link can be expressed with different pathloss exponent and shadowing standard deviation as

$$PL_{NLOS}[dB](r) = 20log_{10}\left(\frac{4\pi}{\lambda}\right) + 10\alpha_N log_{10}(r) + \chi_{\sigma_N} \tag{3.2}$$

where α_N is the pathloss exponent for a NLOS link, and σ_N is the standard deviation of shadowing for a NLOS link. σ_N is usually big and has a big effect on the pathloss.

Chapter 4

Relay Priority Formulation

BS will store the location of moving UEs as shown in figure 4.1(i) and mentioned in [20]. BS is located at (0,0) and the UEs i and j are located at (x_i^t,y_i^t) and (x_j^t,y_j^t) at time t respectively. Positions of static obstacles are known to us through satellite imagery. After the positions of UEs are known, we need to analyze the probability of blockage of links, formed at time t, by any obstacle for Δt time duration till the time instance t+1. For this, we need to analyze the path of the moving UE for Δt time as: a moving UE i present at $\overrightarrow{L_i^t}$ at time t will move with velocity V_i^t for duration of Δt to arrive at new location $\overrightarrow{L_i^{t+1}}$ at time t+1. For a short time duration Δt, the movement can be assumed to be a straight line as shown in figure 4.1(ii). The equation of this line segment is:

$$\delta \cdot \overrightarrow{L_i}^{t+1} + (1-\delta) \cdot \overrightarrow{L_i}^{t} = \overrightarrow{L_i}^{\Delta t} \tag{4.1}$$

where $\delta \in (0,\ 1)$. Static obstacle o $\in \mathbb{O}$ is assumed to be present as $\overrightarrow{L_o}$ which is stationary throughout the experiment. The number of dynamic obstacles k is assumed to be known while their position is uniformly distributed throughout the simulation area and their movement is modelled as random walk mobility model with V_{max} assumed to be known. Given the position,velocity and direction of the dynamic obstacle j, we can find the motion path as equation (4.1) as shown in the figure 4.1(iii) :

$$\delta \cdot \overrightarrow{L_j}^{t+1} + (1-\delta) \cdot \overrightarrow{L_j}^{t} = \overrightarrow{L_j}^{\Delta t} \tag{4.2}$$

But, since we don't know the positions and velocities of dynamic obstacles, we have done a different analysis for them based on their mobility model assumed. In the next section, we will compute the LOS probability of the link.

4.1 Analysing LOS Probability

The LOS path between two UEs say S and R might be blocked by static as well as dynamic obstacles. The probability of LOS for the UEs S and R from time t to t+1 can determined as:

$$P(LOS_{SR}^{t+1}) = P(Nblock_{dynamic}|S,R) \cdot \prod_{o \in \mathbb{O}} P(Nblock_{static}^{o}) \tag{4.3}$$

where $P(Nblock_{dynamic}|S,R)$ is the probability that the link under consideration is not blocked by any of the dynamic obstacle while $P(Nblock_{static}^{o})$ is the probability that the link is not blocked by the static obstacle $o \in \mathbb{O}$. In the above equation all terms in RHS are in product because if any one of them is 0, then the entire LOS probability is 0. This is because the pathloss model we described in chapter 3 assumes that even a single blockage is sufficient to block the LOS. Depending upon the mobility of UEs, we might model the LOS probability into three cases :-

4.1.1 Case 1:- Both S and R are static

When both of the UEs are static, then for S and R, $\overrightarrow{L_S}^{t+1} = \overrightarrow{L_S}^{t}$ and $\overrightarrow{L_R}^{t+1} = \overrightarrow{L_R}^{t}$. Thus, the equation of line segment connecting them can be expressed as:

$$\delta \cdot \overrightarrow{L_S}^{t} + (1-\delta) \cdot \overrightarrow{L_R}^{t} = \overrightarrow{L_{SR}} \tag{4.4}$$

Now we need to determine whether the line segment $\overrightarrow{L_{SR}}$ is prone to blockage by obstacles. It can be easily determined whether static obstacles block the LOS by checking that any of the $o \in \mathbb{O}$ satisfies the equation (4.4) then $P(Nblock_{static}^{o}) = 0$ otherwise $P(Nblock_{static}^{o}) = 1$. For a dynamic obstacle j with the location (x,y), the absolute direction of motion θ and the velocity magnitude V , we determine its motion path $\overrightarrow{L_j^{\Delta t}}$ (equation(4.2)) and check whether it intersects with the line segment $\overrightarrow{L_{SR}}$ (equation(4.4)). Thus, the probability that the dynamic obstacle j does not block the LOS of SR is given by:

$$P(NBlock_{SR}^{j}|x, y, \theta, V) = \begin{cases} 0, & if\ \overrightarrow{L_j^{\Delta t}}\ intersect\ \overrightarrow{L_{SR}} \\ 1, & otherwise \end{cases}$$

Since we don't know the exact positions and velocities of dynamic obstacles and are assuming them to be distributed in the entire simulation area uniformly and following the random walk mobility model with V_{max} known, we are checking blockage for all the possible locations, directions and velocities of dynamic obstacles. Hence, we can find the probability that the LOS path of UE S and R is not blocked by any of the dynamic obstacle by the following joint uniform probability distribution function:-

$$P(Nblock_{dynamic}|S, R) = \int_x \int_y \int_0^{2\pi} \int_0^{V_{max}} \frac{1}{C} P(NBlock_{SR}^{j}|x, y, \theta, V) dV d\theta dy dx \tag{4.5}$$

where $P(Nblock_{dynamic}|S, R)$ is the probability that the LOS path of UE S and R is not blocked by dynamic obstacles, C is product $\Gamma * 2\pi * V_{max} * A$ which is the normalizing constant, Γ is the density of dynamic obstacles while A is the total simulation area in m^2, (x,y) is the location of dynamic obstacle which is uniformly distributed in the entire simulation area, absolute angle of motion θ uniformly distributed in [0, 2π] and velocity V uniformly distributed in [0, V_{max}]. We are approximating the integral in the equation 4.5 depending on the mentioned cases in this section using trapezoidal rule of numerical integration method.

4.1.2 Case 2:- W.L.O.G. S is static and R is Dynamic

We can divide this case into further two sub-cases[20] :- first, when the UE R is moving towards or away the static UE S i.e., the angle of motion path of UE R is $0°$ or $180°$ respectively with respect to line $\overrightarrow{L_S}^t\overrightarrow{L_R}^t$. In this case, UE R's movement forms a straight line with respect to the stationary UE S for duration Δt denoted as

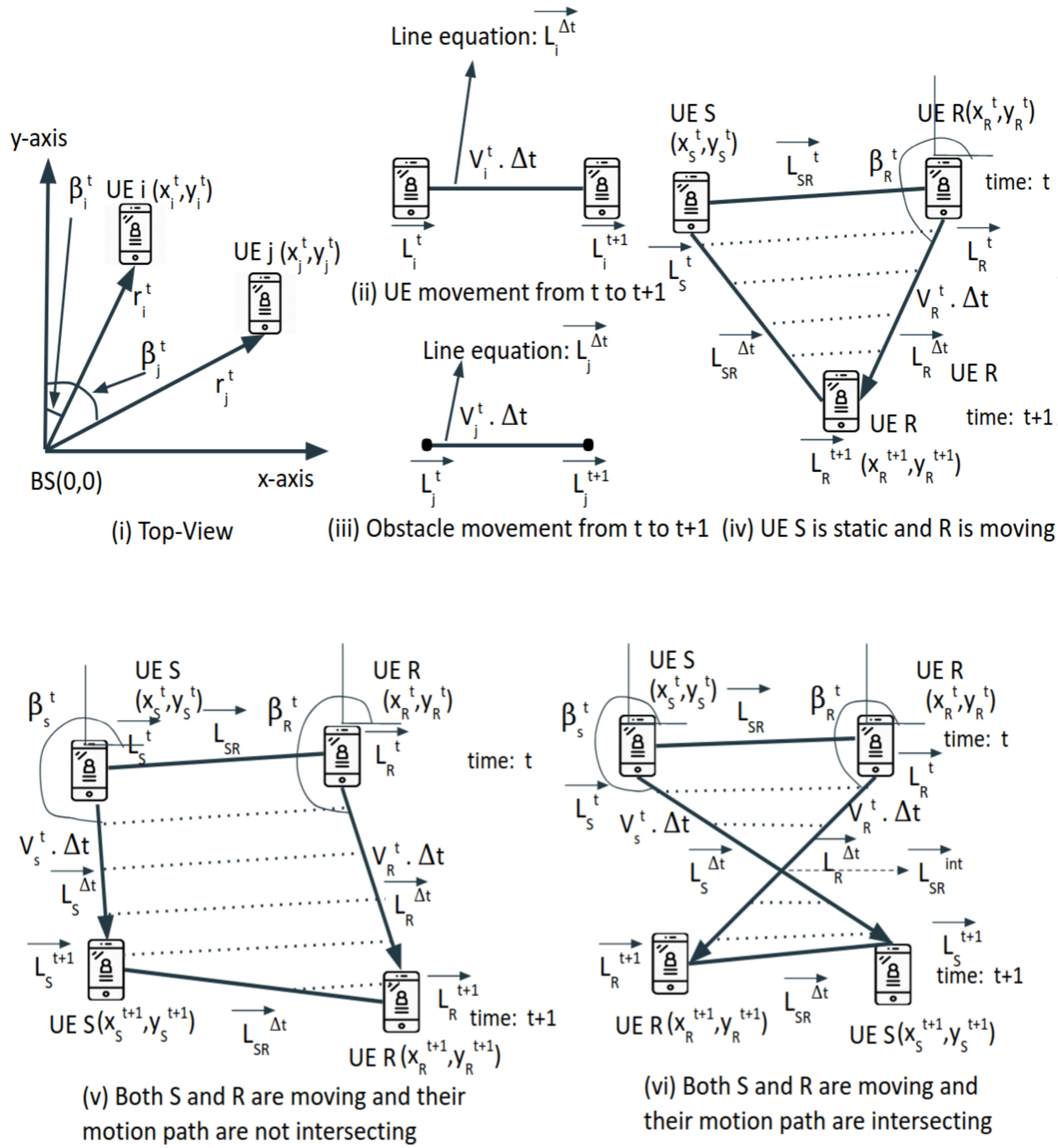

Figure 4.1: Position, orientation and representation of path of movement for UEs and dynamic obstacle

$\overrightarrow{L_{SR}^{\Delta t}}$ which is given by the following equation :-

$$\delta \cdot \overrightarrow{L_S}^t + (1-\delta) \cdot \overrightarrow{L_R}^{t+1} = \overrightarrow{L_{SR}^{\Delta t}} \tag{4.6}$$

For static obstacles if $o \in \mathbb{O}$ satisfy line $\overrightarrow{L_{SR}^{\Delta t}}$, then $P(NBlock_{static}^{o}) = 0$, otherwise $P(NBlock_{static}^{o}) = 1$. For dynamic obstacles, we need to find out the probability of blocking of the communication between UE S and R. Given the position (x,y), direction(θ) and velocity(V) of dynamic obstacle j, it can be checked if its motion path $\overrightarrow{L_j^{\Delta t}}$(equation(4.2) intersects $\overrightarrow{L_{SR}^{\Delta t}}$ or not. Hence the probability that the LOS between SR is not blocked by dynamic obstacle is given by

$$P(NBlock_{SR}^{j}|x,y,\theta,V) = \begin{cases} 0, & if\ \overrightarrow{L_j^{\Delta t}}\ intersect\ \overrightarrow{L_{SR}^{\Delta t}} \\ 1, & otherwise \end{cases}$$

The second case is when the angle of motion of UE R relative to the UE S is other than that of $\{0^\circ, 180^\circ\}$. This case is described in figure4.1(iv). Initially at time t, UE R is at $\overrightarrow{L_R^t}$, in next Δt time, R follows a straight line path with velocity V_R^t and covers the distance $V_R^t * \Delta t$ to reach $\overrightarrow{L_R^{t+1}}$. Since, UE S is stationary in this case, hence $\overrightarrow{L_S^{t+1}} = \overrightarrow{L_S^t}$. So, there is a triangle under consideration with vertices at $\overrightarrow{L_S^t}$, $\overrightarrow{L_R^t}$, $\overrightarrow{L_R^{t+1}}$ and the three line segments as $\overrightarrow{L_{SR}}$(equation(4.4), $\overrightarrow{L_R^{\Delta t}}$(equation(4.1)) and $\overrightarrow{L_{SR}^{\Delta t}}$(equation(4.6)) as shown in the figure4.1(iv). For static obstacles, there can be the two sub-cases,

1. the obstacle can be intersecting any of the side of the triangle $\overrightarrow{L_S^t}\overrightarrow{L_R^t}\overrightarrow{L_R^{t+1}}$
2. the static obstacle can be completely inside the triangle $\overrightarrow{L_S^t}\overrightarrow{L_R^t}\overrightarrow{L_R^{t+1}}$.

For the obstacle $o \in \mathbb{O}$, if it satisfies any of the two sub-cases, then $P(NBlock_{static}^{o}) = 0$, otherwise $P(NBlock_{static}^{o}) = 1$. Sub-case (i) can be checked if the obstacle o satisfies any of the line segment $\overrightarrow{L_{SR}}$, $\overrightarrow{L_R^{\Delta t}}$ and $\overrightarrow{L_{SR}^{\Delta t}}$. For the sub-case (ii), if the position of the static obstacle o is $\overrightarrow{L_o}$, it can be checked if all of the vector cross products $(\overrightarrow{L_S^t} - \overrightarrow{L_o}) \times (\overrightarrow{L_R^t} - \overrightarrow{L_S^t})$, $(\overrightarrow{L_R^t} - \overrightarrow{L_o}) \times (\overrightarrow{L_R^{t+1}} - \overrightarrow{L_R^t})$ and $(\overrightarrow{L_R^{t+1}} - \overrightarrow{L_o}) \times (\overrightarrow{L_S^t} - \overrightarrow{L_R^{t+1}})$, have the same sign, then the obstacle o is present inside the triangle and satisfies the sub-case(ii), otherwise not.

For a dynamic obstacle j, given its position (x,y), direction(θ) and velocity(V), its motion path could be determined as $\overrightarrow{L_j^{\Delta t}}$(equation (4.2)). Dynamic obstacle j can block the UE S and R in the two sub-cases:-

1. the obstacle line segment $\overrightarrow{L_j^{\Delta t}}$ can be intersecting any of the side of the triangle $\overrightarrow{L_S^t}\overrightarrow{L_R^t}\overrightarrow{L_R^{t+1}}$

2. the obstacle line segment $\overrightarrow{L_j^{\Delta t}}$ can be completely inside the triangle $\overrightarrow{L_S^t}\overrightarrow{L_R^t}\overrightarrow{L_R^{t+1}}$.

For the dynamic obstacle j, if it satisfies any of the two sub-cases, then $P(NBlock_{SR}^j|x, y, \theta, V) = 0$, otherwise $P(NBlock_{SR}^j|x, y, \theta, V) = 1$. For sub-case(i), it can be checked if $\overrightarrow{L_j^{\Delta t}}$ intersects any of the line segment $\overrightarrow{L_{SR}}$, $\overrightarrow{L_R^{\Delta t}}$ and $\overrightarrow{L_{SR}^{\Delta t}}$. For the sub-case(ii), the initial position vector can be represented as $\overrightarrow{L_j}$ and it can be checked whether $\overrightarrow{L_j}$ lies inside the triangle formed by the line segments, $\overrightarrow{L_{SR}}$, $\overrightarrow{L_R^{\Delta t}}$ and $\overrightarrow{L_{SR}^{\Delta t}}$ just as done in case for static obstacle. Now, we can find the probability $P(Nblock_{dynamic}|S, R)$ by plugging $P(NBlock_{SR}^j|x, y, \theta, V)$ determined in this case in the equation(4.5).

4.1.3 Case 3:- Both S and R are in motion

In this case, both the UEs, S and R are moving from time t to $t + 1$. Based on their relative angle of motion, we can further classify them into two cases, first when both of them are moving towards or away from each other i.e., their relative angle of motion $\in \{0° , 180°\}$. This case is similar to that of the previous subsection except here UE S is also moving. But here too, both UEs will form a straight line and hence we just need to check if any of the obstacle is intersecting it. Hence this is solved in similar way as mentioned in the previous subsection.

In the second case, when their relative angle of motion $\notin \{0° , 180°\}$, they may or may not intersect their motion. Depending on this, there can be further two sub-cases, first when the motion path of UE S and R does not intersect, and second when they intersect.

(a) When line segments $\overrightarrow{L_S^{\Delta t}}$ and $\overrightarrow{L_R^{\Delta t}}$ does not intersects, then there would be a quadrilateral in consideration with vertices $\overrightarrow{L_S^t}$, $\overrightarrow{L_S^{t+1}}$, $\overrightarrow{L_R^{t+1}}$, $\overrightarrow{L_R^t}$ and the four line segments as $\overrightarrow{L_S^{\Delta t}}$, $\overrightarrow{L_{SR}}$, $\overrightarrow{L_R^{\Delta t}}$ $\overrightarrow{L_{SR}}^{\Delta t}$ as shown in the figure4.1(v). For static obstacles, there can be any two sub-cases:-

   (i) the static obstacle can be intersecting any of the side of the quadrilateral $\overrightarrow{L_S^t}\overrightarrow{L_S^{t+1}}\overrightarrow{L_R^{t+1}}\overrightarrow{L_R^t}$.

   (ii) the static obstacle can be completely inside the quadrilateral $\overrightarrow{L_S^t}\overrightarrow{L_S^{t+1}}\overrightarrow{L_R^{t+1}}\overrightarrow{L_R^t}$.

   For the obstacle $o \in \mathbb{O}$, if it satisfies any of the two sub-cases, then $P(NBlock_{static}^o) = 0$, otherwise $P(NBlock_{static}^o) = 1$. Sub-case (i) can be checked if the obstacle o lies on any of the line segment $\overrightarrow{L_S^{\Delta t}}$, $\overrightarrow{L_{SR}}$, $\overrightarrow{L_R^{\Delta t}}$ $\overrightarrow{L_{SR}}^{\Delta t}$. For the sub-case (ii), if the position of the static obstacle o is $\overrightarrow{L_o}$, it can be checked if all of the vector cross products $(\overrightarrow{L_S^t} - \overrightarrow{L_o}) \times (\overrightarrow{L_R^t} - \overrightarrow{L_S^t})$, $(\overrightarrow{L_R^t} - \overrightarrow{L_o}) \times (\overrightarrow{L_R^{t+1}} - \overrightarrow{L_R^t})$, $(\overrightarrow{L_R^{t+1}} - \overrightarrow{L_o}) \times (\overrightarrow{L_S^{t+1}} - \overrightarrow{L_R^{t+1}})$ and $(\overrightarrow{L_S^{t+1}} - \overrightarrow{L_o}) \times (\overrightarrow{L_S^t} - \overrightarrow{L_S^{t+1}})$ have the same sign, then the obstacle o is present inside the quadrilateral and satisfies the sub-case(ii), otherwise not.

   For a dynamic obstacle j, given its position (x,y), direction(θ) and velocity(V), its motion path could be determined as $\overrightarrow{L_j^{\Delta t}}$(equation 4.2). Dynamic obstacle j can block the UE S and R in the two sub-cases:-

   (i) the obstacle line segment $\overrightarrow{L_j^{\Delta t}}$ can be intersecting any of the side of the quadrilateral $\overrightarrow{L_S^t}\overrightarrow{L_S^{t+1}}\overrightarrow{L_R^{t+1}}\overrightarrow{L_R^t}$

   (ii) the obstacle line segment $\overrightarrow{L_j^{\Delta t}}$ can be completely inside the quadrilateral $\overrightarrow{L_S^t}\overrightarrow{L_S^{t+1}}\overrightarrow{L_R^{t+1}}\overrightarrow{L_R^t}$.

For the dynamic obstacle j, if it satisfies any of the two sub-cases, then $P(NBlock^{j}_{SR}|x,y,\theta,V) = 0$, otherwise $P(NBlock^{j}_{SR}|x,y,\theta,V) = 1$. For sub-case(i), it can be checked if the line segment $\overrightarrow{L_j^{\Delta t}}$ intersects with any of the line segment $\overrightarrow{L_S^{\Delta t}}$, $\overrightarrow{L_{SR}}$, $\overrightarrow{L_R^{\Delta t}}$, $\overrightarrow{L_{SR}}^{\Delta t}$. For the sub-case(ii), the initial position vector of the dynamic obstacle j can be represented as $\overrightarrow{L_j}$ and it can be checked whether $\overrightarrow{L_j}$ lies inside the quadrilateral formed by the line segments, $\overrightarrow{L_S^{\Delta t}}$, $\overrightarrow{L_{SR}}$, $\overrightarrow{L_R^{\Delta t}}$, $\overrightarrow{L_{SR}}^{\Delta t}$ just as done in case for static obstacle. Now, we can find the probability $P(Nblock_{dynamic}|S,R)$ by plugging $P(NBlock^{j}_{SR}|x,y,\theta,V)$ determined in this case in the equation (4.5).

(b) When line segments $\overrightarrow{L_S^{\Delta t}}$ and $\overrightarrow{L_R^{\Delta t}}$ intersects with each other, then there would be two triangles in consideration with vertices $\overrightarrow{L_S^t}$, $\overrightarrow{L_R^t}$, $\overrightarrow{L_{SR}^{int}}$ and $\overrightarrow{L_S^{t+1}}$, $\overrightarrow{L_R^{t+1}}$, $\overrightarrow{L_{SR}^{int}}$ where $\overrightarrow{L_{SR}^{int}}$ is the point(position vector) of intersection of line segments $\overrightarrow{L_S^{\Delta t}}$ and $\overrightarrow{L_R^{\Delta t}}$ as shown in the figure4.1(vi).

For static obstacles, there can be any two sub-cases:-

(i) the static obstacle can be intersecting any of the side of the triangles $\overrightarrow{L_S^t}\overrightarrow{L_R^t}\overrightarrow{L_{SR}^{int}}$ and $\overrightarrow{L_S^{t+1}}\overrightarrow{L_R^{t+1}}\overrightarrow{L_{SR}^{int}}$

(ii) the static obstacle can be completely inside any of the two triangle $\overrightarrow{L_S^t}\overrightarrow{L_R^t}\overrightarrow{L_{SR}^{int}}$ and $\overrightarrow{L_S^{t+1}}\overrightarrow{L_R^{t+1}}\overrightarrow{L_{SR}^{int}}$.

For the obstacle $o \in \mathbb{O}$, if it satisfies any of the two sub-cases, then $P(NBlock^{o}_{static}) = 0$, otherwise $P(NBlock^{o}_{static}) = 1$. Sub-case (i) can be checked if the obstacle o lies on any of the line segment of any of the triangles $\overrightarrow{L_S^t}\overrightarrow{L_R^t}\overrightarrow{L_{SR}^{int}}$ or $\overrightarrow{L_S^{t+1}}\overrightarrow{L_R^{t+1}}\overrightarrow{L_{SR}^{int}}$ as in previous cases . For the sub-case (ii), if the position of the static obstacle o is $\overrightarrow{L_o}$, it can be checked if the obstacle is inside any of the two triangles $\overrightarrow{L_S^t}\overrightarrow{L_R^t}\overrightarrow{L_{SR}^{int}}$ or $\overrightarrow{L_S^{t+1}}\overrightarrow{L_R^{t+1}}\overrightarrow{L_{SR}^{int}}$ by checking the sign of the vector cross product as done in previous cases.

For a dynamic obstacle j, given its position (x,y), direction(θ) and velocity(V), its motion path could be determined as the motion path equation $\overrightarrow{L_j^{\Delta t}}$ (equation 4.2). Dynamic obstacle j can block the UE S and R in the two sub-cases:-

(i) the dynamic obstacle can be intersecting any of the side of the triangles $\overrightarrow{L_S^t}\overrightarrow{L_R^t}\overrightarrow{L_{SR}^{int}}$ and $\overrightarrow{L_S^{t+1}}\overrightarrow{L_R^{t+1}}\overrightarrow{L_{SR}^{int}}$

(ii) the dynamic obstacle can be completely inside any of the two triangle $\overrightarrow{L_S^t}\overrightarrow{L_R^t}\overrightarrow{L_{SR}^{int}}$ and $\overrightarrow{L_S^{t+1}}\overrightarrow{L_R^{t+1}}\overrightarrow{L_{SR}^{int}}$.

For the dynamic obstacle j, if it satisfies any of the two sub-cases, then $P(NBlock_{SR}^j|x, y, \theta, V) = 0$, otherwise $P(NBlock_{SR}^j|x, y, \theta, V) = 1$. For sub-case(i), it can be checked if $\overrightarrow{L_j^{\Delta t}}$ intersects any of the line segment of any of the two triangle $\overrightarrow{L_S^t}\overrightarrow{L_R^t}\overrightarrow{L_{SR}^{int}}$ or $\overrightarrow{L_S^{t+1}}\overrightarrow{L_R^{t+1}}\overrightarrow{L_{SR}^{int}}$ as done in previous cases. For the sub-case(ii), the initial position vector of the dynamic obstacle j can be represented as $\overrightarrow{L_j}$ and it can be checked whether $\overrightarrow{L_j}$ lies inside any of the two triangle $\overrightarrow{L_S^t}\overrightarrow{L_R^t}\overrightarrow{L_{SR}^{int}}$ or $\overrightarrow{L_S^{t+1}}\overrightarrow{L_R^{t+1}}\overrightarrow{L_{SR}^{int}}$ just as done in previous sub-cases.

Now, we can find the probability $P(Nblock_{dynamic}|S, R)$ by plugging $P(NBlock_{SR}^j|x, y, \theta, V)$ determined in this case in the equation (4.5).

4.2 Priority List

There are N D2D pairs, i^{th} D2D pair comprising of UEs S^i and D^i is represented as $P^i = (S^i, D^i)$. There are M relays which could assist the D2D communication and the j^{th} relay is represented as R^j. At the start of Δt time, each D2D pairs ranks the available relays according to their priority score. Priority score of the relay for a D2D pair is the expected SNR offered by the relay to the D2D pair in the next Δt time interval. So, for the $P^i = (S^i, D^i)$, the SNR offered by the S^i node to the relay R^j is given by:-

$$\gamma_{R^j}^{S^i} = \frac{P_{S^i} G_{S^i} G_{R^j} g_{S^i R^j} PL_{d_{S^i R^j}}^{-1}}{N_o} \tag{4.7}$$

where P_{S^i} is the transmit power of the S^i node, $G_{S^i}G_{R^j}$ are the combined antenna gains between node S^i and the relay R^j, $g_{S^iR^j}$ is the rayleigh fading, $PL_{d_{S^iR^j}}$ is the pathloss which is equal to $PL_{LOS}(d_{S^iR^j})$(equation 3.1) in case of LOS and $PL_{NLOS}(d_{S^iR^j})$(equation 3.2) in case of NLOS, $d_{S^iR^j}$ is the distance between S^i node and relay R^j and N_o is the power of additive white gaussian noise in the channel.

Similarly, the SNR offered by the relay R^j to the D^i node is given by

$$\gamma_{D^i}^{R^j} = \frac{P_{R^j}G_{R^j}G_{D^i}g_{R^jD^i}PL_{d_{R^jD^i}}^{-1}}{N_o} \tag{4.8}$$

According to the equation (4.3), we can calculate the probability of LOS from S^i node to the relay R^j in the next Δt time as $P(LOS_{S^iR^j}^{t+1})$ and that of relay R^j to the D^i node as $P(LOS_{R^jD^i}^{t+1})$.

The priority score of the relay R^j for $P^i = (S^i,\ D^i)$ is given by:-

$$Score_{R^j}^{P^i} = \arg\min(P(LOS_{S^iR^j}^{t+1}) * \gamma_{R^j}^{S^i}, P(LOS_{R^jD^i}^{t+1}) * \gamma_{D^i}^{R^j}) \tag{4.9}$$

The above priority score is the minimum expected SNR provided by the particular relay to a D2D pair. For a D2D pair $P^i = (S^i,\ D^i)$, we can rank all the relays according to their priority score which ensures that the relays which provide higher expected SNR in the next Δt time are ranked higher.

Chapter 5

Centralized Relay Selection

Every ΔT time, centralized relay selection is performed so as to assign relays to the D2D pairs such that it not only provides a high total capacity in the system but also ensure prevention of starvation of any D2D device. The double-auction theory is often used in the multi-buyer and multi-seller scenario. The *bid* of buyer and the *ask* of seller is a mapping of its payment. In economics, *bid* is defined as the price which buyer is willing to pay to get the service from seller and *ask* is defined as the minimum bid which the seller will agree with to give the service to buyer. We model the entire problem into a double auction where the N D2D pairs are the buyers and the M relays acts as sellers while the base station(BS) is the auctioneer. The D2D pair would prefer to assign the relay which increases its capacity the most while relays would prefer to provide the service to those D2D pairs that would get the maximum benefit from them. Thus, the conflicting preferences of sellers and buyers in this scenario encourages us to model the whole problem into a stable matching problem. We define capacity or data rate as follows:-

$$C_{A,B} = Wlog_2(1 + \gamma_B^A) \tag{5.1}$$

where $C_{A,B}$ is the data rate received at the node B transmitted by the node A which is determined by the shannon's capacity theorem, W is the bandwidth and γ_B^A is the SNR offered by the node A to the node B. If a D2D pair comprising of nodes S^i and

D^i which is represented as $P^i = (S^i,\ D^i)$ communicates via relay R^j, it will get the benefit on channel capacity:

$$G_{P^i,R^j} = (\arg\min(C_{S^i,R^j}, C_{R^j,D^i}) - C_{S^i,D^i}) * (1 + \beta * t^{P^i}_{waiting}) \tag{5.2}$$

where G_{P^i,R^j} is increase in the capacity for the D2D pair $P^i = (S^i,\ D^i)$ when it uses the relay R^j instead of direct communication, C_{S^i,R^j} is the data rate at the the R^j relay by S^i node, C_{R^j,D^i} is is the data rate at the the D^i node by using the R^j relay and C_{S^i,D^i} is the data rate at the D^i node transmitted by the S^i node(i.e., direct communication capacity). G_{P^i,R^j} is the bid of the D2D pair P^i for the relay R^j which is multiplied by the ageing weight($1{+}\beta * t^{P^i}_{waiting}$) to increase the bid for starving(waiting for very long time) D2D pairs. $t^{P^i}_{waiting}$ is the waiting time of the D2D pair P^i and β is the weightage given to the waiting time in the bid which is required to be tuned.

Game theoretic auction approach is most suitable for our problem as it emphasizes on strategic decision making. The auction framework here is basically a double auction as described in section 5.1 below, consists of five main parts namely the players,the action profile, the utility function, the preference relation and the payoff matrix. Here players are the D2D pairs and the relay devices. D2D pairs requires the relay service from the available relay devices and relay devices wishes to provide the service to the D2D pairs such that the capacity of the system increases and starvation is prevented. The action profile decides the action configurations that need to be considered in the game. Specifically, each D2D pairs bids for the available relays and the relays gives their ask. Then comes the utility function which consists of the primary validation, which ensures that the bid is reasonable, and the global objective which is to increase the throughput gain along with the starvation prevention. Next comes the preference relation which indicates which relay is preferred more by a D2D pair and which D2D pair is preferred more by the relay. Finally comes the payoff matrix based on which the actual decision making is done. The payoff matrix influences the final outcome of the game and decides which action suits best for the benefit of the global objective.

5.1 Auction Framework

The game theoretic double auction framework consists of the 5 main parts: (1) Players, (2) Action Profile, (3) Utility function, (4) Preference Relation and (5) Payoff matrix

1. *Players*:- Let $\mathbb{P}$ be the set of M D2D pairs and $\mathbb{R}$ be the set of N Relays. D2D pairs and relays are the two types of player in this game.

2. *Action Profile* :- Each D2D pair $P^i \in \mathbb{P}$ bids G_{P^i,R^j} for the relay $R^j \in \mathbb{R}$ as defined in equation(5.2). Since we have assumed that relays are not intending to initiate any communication for themselves, hence the relays submits their ask as 0.

3. *Utility function* :- Utility function has two main parts:
   Primary Validation :- The primary validation is performed as
   $$G_{P^i,R^j} \;>\; G_{thresh} \tag{5.3}$$
   where G_{P^i,R^j} is the bid of the D2D pair P^i for the relay R^j and G_{thresh} is the capacity threshold. This check ensures that the bid is reasonable.
   Throughput gain: The throughput gain G_{P^i,R^j} as computed in equation (5.2) which is to be maximized.

4. *Preference Relation*: The preference relation indicates which D2D pair is preferred more by the relay R^j and which relay is preferred more by the D2D pair P^i. Since this is a double auction framework, the relay will prefer the D2D pair P^i over P^j only if P^i bids higher than P^j. Similarly the D2D pair P^i will prefer the relay R^j over R^k only if the ask of R^j is lower than that of R^k. Due to such preference relation of D2D pairs and relays we can model the overall problem into a stable matching problem.

5. *Payoff Matrix*: The payoff matrix is based on the amount of benefit the system will get not only in terms of capacity but also in terms of starvation reduction(since we have added ageing factor in the bid) if a particular relay provides the service to a particular D2D pair.

Based on the game-theoretic double auction framework described above, we can model it into a stable matching problem with both D2D pairs and relays as the nodes. We prepare the graph with nodes as D2D pairs and relays. D2D pair $P^i = (S^i, D^i)$ has an edge with the relay R^j with edge weight $-G_{P^i,R^j}$ only if $G_{P^i,R^j} > G_{thresh}$. We add the threshold constraint as only the relays which provides the sufficient data rate should take part in the auction, moreover this limit the complexity of the matching. We can now solve this matching problem via Hungarian matching algorithm which originally finds the minimum weighted matching in $O(n^3)$, where n is the total number of nodes.

After solving the matching, D2D pairs can communicate via their matched relays and the D2D pair $P^i = (S^i, D^i)$ left without any relay can communicate directly with each other if C_{S^i,D^i} is above a threshold C_{thresh}. In this way, we assure that relays are provided to D2D pairs such that it increases the capacity of the system and also prevents starvation. Algorithm 1 shows the pseudocode for our centralized relay selection algorithm which assigns the relays to the D2D pairs based on the approach mentioned above.

Algorithm 1 Centralized Relay Selection Algorithm

Input: the relay set and the D2D pair set
Output: relay selection result
At the beginning of each ΔT time slot
Construct D2D pair vertex set $\mathbb{P}$ and the relay vertex set $\mathbb{R}$

```
for all vertex P ∈ ℙ do
    for all vertex R ∈ ℝ do
        if G_{P,R} > G_{thresh} then
            Construct an edge between P and R
            and set its weight as −G_{P,R}
        end if
    end for
end for
Apply Hungarian matching on the graph obtained
RETURN a matching result among D2D pairs Ps and relays Rs
END
```

Chapter 6

Distributed Relay Switching

Centralized relay selection is performed in every ΔT time interval. But, due to the presence of dynamic obstacles and the motion of UEs, LOS might be blocked. So, the UEs might have to wait for the next ΔT time interval to get the relay to provide LOS. Hence, we propose to perform a distributed relay switching(online relay switching) whenever the communication of any D2D pair is interrupted.

6.1 Detection of blockage of LOS of a D2D pair

A D2D pair, might either be communicating directly or with the help of a relay. So, there might be two cases to detect the blockage.

6.1.1 Case 1:- D2D pair was communicating directly

If a D2D pair $P^i = (S^i, D^i)$ is communicating directly, then we can detect the blockage by sensing the received SNR at the node D^i transmitted by S^i, i.e., if $\gamma_{D^i}^{S^i}$ falls below a threshold γ_{thresh}, this implies blockage as in the presence of obstacle, the SNR received becomes almost 0 because of the path loss model we discussed in the System Model section.

6.1.2 Case 1:- D2D pair was communicating via Relay

If a D2D pair $P^i = (S^i, D^i)$ is communicating via relay R^j, then there can be blockage either in the LOS of S^i and R^j or in the LOS of R^j and D^i. So, if $\gamma_{R^j}^{S^i}$ or $\gamma_{D^i}^{R^j}$ falls below a threshold γ_{thresh}, then there is blockage.

6.2 Detection of a better alternative relay

Since in every Δt time, the priority list of D2D pairs are updated, hence a D2D pair $P^i = (S^i, D^i)$ communicating directly or via relay R^j might find another relay offering the higher data rate. If the priority of any other relay R^k rise above that of the current relay R^j by the significant amount(*hysteresis margin* $\mathfrak{H}$), then the relay R^k is the candidate replacement relay over the current relay R^j.

6.3 Online Relay Switching

The LOS of the current relayed or direct link might get blocked or a new alternative relay might be detected. Moreover, the current relay of a D2D pair might also be snatched by some other D2D pair. In all the three cases, a new relay may have to be allocated for the D2D pair. The primary task is to find the *candidate relays*. A D2D pair $P^i = (S^i, D^i)$ who wants a new relay for communication, forms the list of top priority candidate relays as mentioned in the chapter 4. We are now modeling another distributed D2D pair specific local double auction where the D2D pair bids for the new relay among the candidate relays. This local auction is slightly different from the auction framework discussed in the centralized relay selection(chapter 5) in terms of the action profile of players. Further, here only one D2D pair participates at a time. Action profile of player in this local auction can be described as:-

6.3.1 Action Profile

The D2D pair P^i bids for only the candidate relays $\subseteq \mathbb{R}$ and the candidate relays submits their ask and in this case, the ask of relays might not be 0 as it was in case of centralized relay selection. Bids of D2D pairs and asks of relays can be found depending upon the following 2 cases:-

1. When the link is blocked or the current relay is snatched:- Since the current communication for D2D pair is interrupted, so we assume its initial data rate as 0. Hence, the D2D pair $P^i = (S^i,\, D^i)$ bids for the R^j relay as

$$G_{P^i,R^j} = \arg\min(C_{S^i,R^j}, C_{R^j,D^i}) * (1 + \beta * t_{waiting}^{P^i}) \tag{6.1}$$

   where G_{P^i,R^j} is the capacity increase for the D2D pair multiplied by ageing weight$(1 + \beta * t_{waiting}^{P^i})$, β is the weightage given to the waiting time, $t_{waiting}^{P^i}$ is the total waiting time of the D2D pair P^i. If the relay is currently not utilised by any other D2D pair, then its ask is 0. If the relay R^j is currently used by a D2D pair $P^k = (S^k,\, D^k)$, then its ask is given as

$$G_{P^k,R^j} = \arg\min(C_{S^k,R^j}, C_{R^j,D^k}) * (1 + \beta * t_{waiting}^{P^k}) \tag{6.2}$$

   G_{P^k,R^k} is the loss in the capacity of D2D pair $P^k = (S^k,\, D^k)$(with ageing weight factor) if the relay R^j is snatched away from it, $t_{waiting}^{P^k}$ is the total waiting time of the D2D pair P^k. If the node D^i has the SNR $\gamma_{D^j}^{S^i}$ above the threshold γ_{thresh}, then it is also a candidate relay(direct communication or no relaying) with ask surely 0 as it is the receiver node and is not intending to relay any other D2D communication.

2. When another alternative relay with higher priority is found:- Since, every Δt time, the priority list of D2D pairs are updated, hence at the start of the time slot, it is checked whether any other relay with significantly higher priority(*hysteresis margin* $\mathfrak{H}$) than the current relay is present. If another relay

devices say R^k with higher priority is detected for the device P^i whose current relay is R^j, then the D2D pair might switch for the relay R^k only if

$$Score_{R^k}^{P^i} > Score_{R^j}^{P^i} + \mathfrak{H} \tag{6.3}$$

where $Score_{R^k}^{P^i}$, $Score_{R^j}^{P^i}$ are the priority score of relay R^k and R^j for the D2D pair P^i respectively and $\mathfrak{H}$ is the hysteresis margin. If this condition is satisfied, then the bid of the D2D pair P^i for relay R^k would be G_{P^i,R^k} which is given as:-

$$G_{P^i,R^k} = (\arg\min(C_{S^i,R^k}, C_{R^k,D^i}) - \arg\min(C_{S^i,R^j}, C_{R^j,D^i})) * (1 + \beta * t_{waiting}^{P^k}) \tag{6.4}$$

where G_{P^i,R^k} is the total gain in the capacity of the system(with ageing factor) if D2D pair P^i switches to the relay R^k from the relay R^j. In case the D2D pair P^i had a direct connection and a better relay is discovered, then its bid for the relays can be given by equation(5.2).

The ask of the relay R^k can be determined just as the case 1.

The bids and asks of D2D pairs and relays are multiplied by the ageing factor in terms of waiting time so as to enhance them for starving devices.

6.3.2 Online Relay Switching Steps

The D2D pair whose LOS is blocked or other better alternative relay is detected or its current relay is snatched by some other D2D pair performs a local auction to switch its relay by the following steps:-

1. The D2D pair sends the control signals to the top K candidate relays in its priority list and measures the received capacity. The D2D pair calculates its bids for the candidate relays based on the received capacity and its waiting time as mentioned in the above subsection and sends this information to the BS via control signals.

2. BS, then sends control signals to the candidate relays and request them to announce their asks.

3. Relays based on the current D2D served, calculate and announce their asks to the BS through control signals.

4. Based on the bids of the D2D pair for relays and the asks revealed by relays, BS performs a local auction for the D2D pair. Since the preference relation in this local auction is exactly the same as described in the centralized relay selection(chapter 5), the relay with the maximum profit(difference of the bid and ask) is chosen as the new relay for the D2D pair.

5. BS sends the control signals to D2D pair and the chosen relay and informs them to initiate the communication. If the chosen relay is the receiver node of the D2D pair, then its direct connection is restored. A relay which was used by a D2D pair might be taken from them and used by some other D2D pair only if by doing so, the system capacity is increased or starvation of latter D2D device is avoided.

The number of control signals transmitted is $\mathcal{O}(K)$ where K is the number of top candidate relays to be considered in the priority list. Usually, K is very less than the total number of relays M in the system. Algorithm 2 shows the pseudocode for the online relay switching algorithm described above.

Algorithm 2 Online Relay Switching Algorithm

Input: the needy D2D pair and the candidate relay set
Output: relay selection result
When the LOS of a D2D pair is blocked by the obstacle or the priority of the current relay falls below the other relay by hysteresis margin or when the current relay is snatched by some other D2D pair
Construct candidate relay set $\mathbb{R}$ and the D2D pair P
  for all relay R $\in \mathbb{R}$ **do**
    Calculate the bid_R of P for R
    Calculate the ask_R of R
    $Profit_R = bid_R - ask_R$
  end for
RETURN the relay R which provides the maximum profit
END

Chapter 7

EXPERIMENTAL RESULTS

7.1 Simulation Setup

We uniformly distributed 5 D2D pairs and 20 relay devices in 200m $\times$ 200m square area and assumed that these devices remains within the service region throughout the experiment. Depending upon the mobility of UEs and the number of obstacles, we have devised three scenarios:-

1. Low Blockage Scenario:- In this case, we uniformly distributed 5 static Obstacles of size 12m $\times$ 12m and 10 dynamic obstacles of size 1m $\times$ 1m. In this scenario, all the D2D pairs are static and only relays are in motion. Due to the less number of obstacles and no mobility of D2D pairs, the chances of blockage is low.

2. Medium Blockage Scenario:- In this case, we uniformly distributed 7 static Obstacles of size 20m $\times$ 20m and 10 dynamic obstacles of size 1m $\times$ 1m. In this scenario, one of the UE in every D2D pair is static and the other is in motion. All the relays are also in motion.

3. Heavy Blockage Scenario:- In this case, we uniformly distributed 7 static Obstacles of size 20m $\times$ 20m and dynamic obstacles of size 1m $\times$ 1m. The number of dynamic obstacles varies in the set $\{0, 10, 20, 30, 40\}$. In this scenario, both

the UEs in every D2D pair as well as all the relays are in motion. Due to the higher number of obstacles and mobility of D2D pairs, the chances of blockage is higher.

Table 7.1: Simulation Parameters[13], [20]

Bandwidth	20MHz
Total number of D2D pairs	5
Total number of Relay Devices	20
Transmit Power P_i	18dBm
Antenna Gain G_i	6dBi
α_{LOS}	2.1
α_{NLOS}	3.4
σ_{LOS}	3.6dB
σ_{NLOS}	9.7dB
Thermal Noise density	-174dB per Hz
Noise Figure	7dB
Packet Length	65535 bytes
Load	200 packets
ΔT	20 seconds
Δt	5 seconds
Rayleigh Fading	Rayleigh distribution with mean 0 and standard deviation 1
Hysteresis Margin $\mathfrak{H}$	10
SNR Threshold γ_{thresh}	10 dB

The UE's and dynamic obstacles are following the random walk mobility model with their speed distributed uniformly in the range [0, V_{max}]m/s, for $V_{max}\in\{5, 10, 15, 20\}$ and angle in range $[-\pi, \pi]$. *Load* i.e., the total number of packets to be transferred between D2D devices every second, is set as 200 and is assumed to be uniform for all D2D pairs. Most of the other simulation parameters are taken from [13], [20] as mentioned in the table(7.1). We have calculated the priority of relays as mentioned in chapter 4 by approximating the integral in the equation 4.5 depending on the mentioned cases in section 4.1 using trapezoidal rule of numerical integration method.

7.2 Simulation Results and Analysis

The simulation code is iterated 1000 times for each scenario based on the simulation environment mentioned in the above section. The average of 1000 iterations is presented to reduce the effect of randomization.

7.2.1 Hyper-Parameter Tuning

As mentioned in the section 5 and the equation 5.2, β is the parameter which controls the weightage given to the waiting time in the bid and asks of D2D pairs and relays respectively. Since, β is a hyper-parameter, it is needed to be tuned to obtain the optimum results.

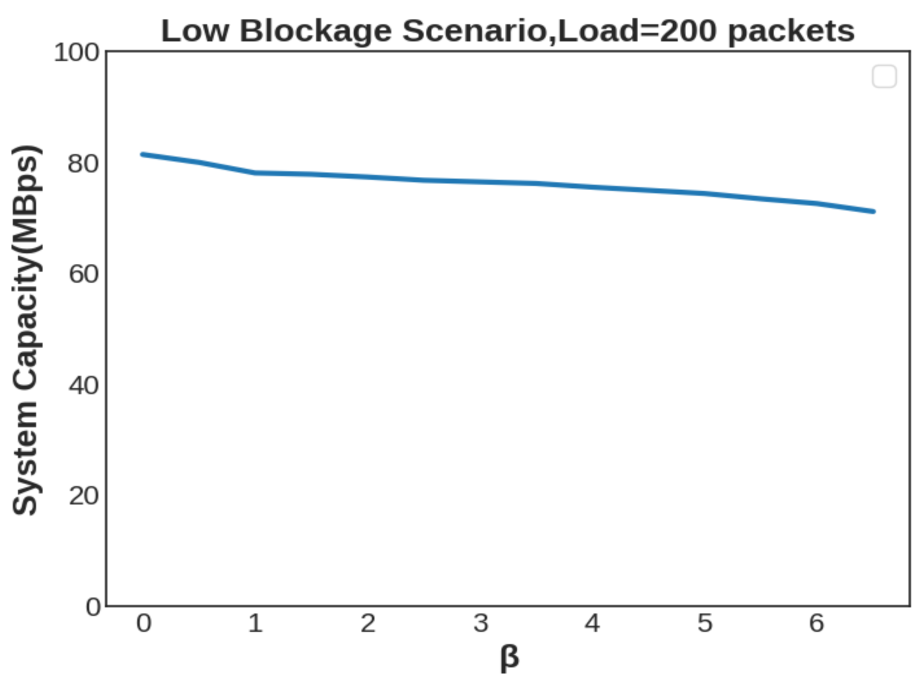

Figure 7.1: System Capacity vs β

Figures 7.1−7.9 shows the variation of the *system capacity*, *average throughput* and *blockage fraction* with respect to the β parameter in lower blockage, medium blockage

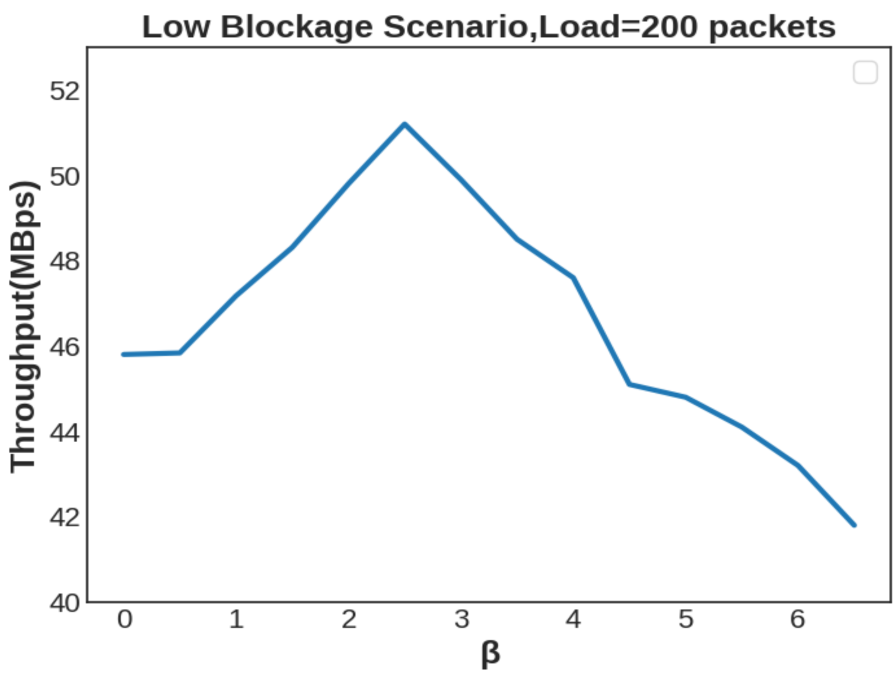

Figure 7.2: Avg. Throughput vs β

as well as heavy blockage scenarios. *System capacity* is the maximum achievable data rate given by Shannon's capacity formula, *average throughput* is the total data transferred successfully by all the D2D pair every second under a given load, *packet loss* is the average number of packets lost per second by every D2D pair under a given load and *blockage fraction* is total average fraction of time the devices were blocked and were waiting for D2D communication to restore. Since β is the trade-off parameter for the capacity and waiting time in the bid as well as asks of UEs, with increase in β, the system capacity decreases. In spite of the decrease in the system capacity, the average throughput and packet loss initially improves with increase in β and becomes optimum when β is 0.25 in lower blockage as well as medium blockage scenario and 0.2 in heavy blockage scenario. This is because of the three main reasons:-

1. As from the figures 7.1, 7.4 and 7.7, it is evident that the rate of decrement in the system capacity with increase in β is quite low.

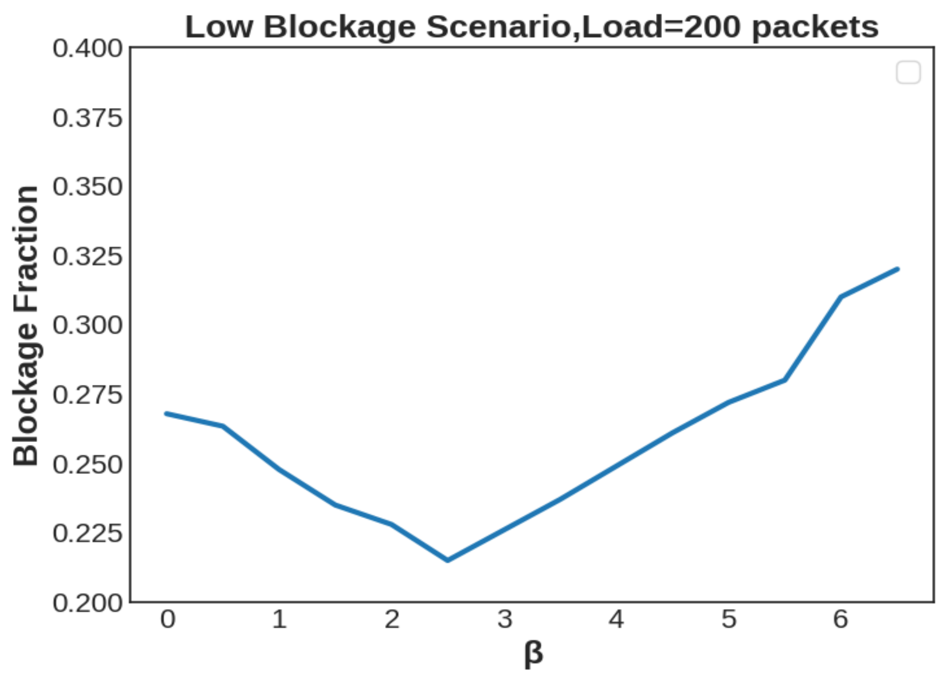

Figure 7.3: Blockage Fraction vs β

2. Since the load is fixed, even if the capacity for D2D pairs is very high, they can't transfer more than their need(load).

3. With increase in β, the starving devices, due to their enhanced bid, are getting the relays from other D2D pairs which in turn have to switch to other alternative relays.

All the above mentioned reasons are responsible for the increase in the throughput of the system with initial increase in β. But when β becomes more than 0.25, it adds too much weightage of the waiting time in the bids and ask which deteriorates the performance of the system.

Figures 7.3, 7.6 and 7.9 shows the variation of average blockage fraction of D2D pairs with β in lower blockage, medium blockage and heavy blockage scenarios. Since, β is the parameter which adds the weightage of the waiting time in the bid as well as asks of UEs, with the initial increase in the value of β, blockage fraction of D2D

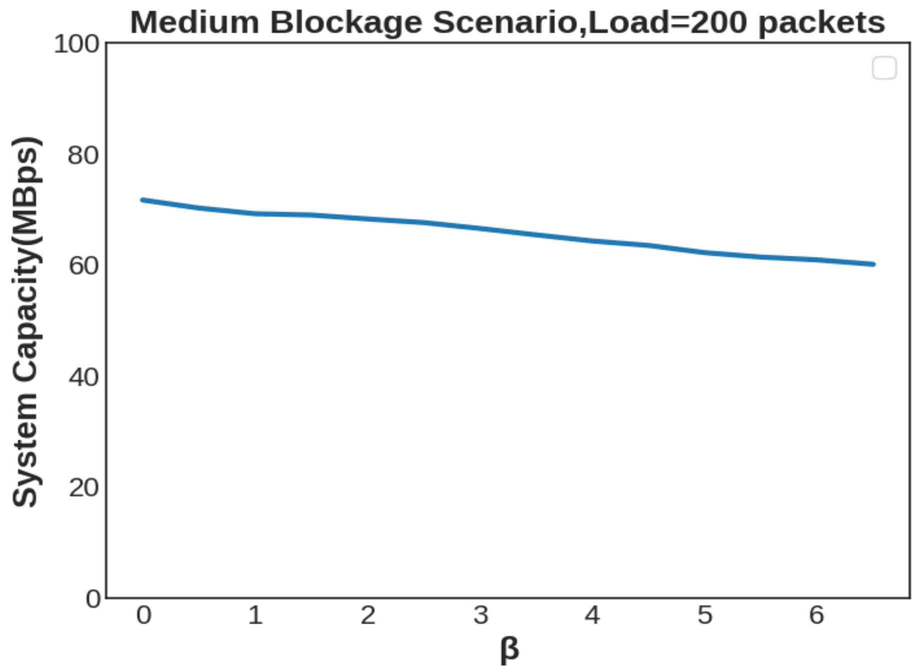

Figure 7.4: System Capacity vs β

pairs decreases and it reaches the minimum when $\beta = 0.25$ for lower blockage and medium blockage scenario and $\beta = 0.2$ for heavy blockage scenario. Hence, even smaller value of β enables the waiting device to get relays via local switching leading to the reduction in the starvation of devices in the system. But, higher values of β causes large enhancements in the bids of devices even with small waiting time which leads to the following impact on the system performance:-

1. For higher values of β, the capacity of the system reduces to an extent which can no longer be ignored(figures 7.1, 7.4 and 7.7).

2. For higher values of β, the large enhancement in the bids of the D2D pairs by their waiting time results in frequent and unnecessary switching of relays.

Pre-emptive switching of relays have some overheads because of the control signals transmission as mentioned in the online relay switching section of the chapter 6.

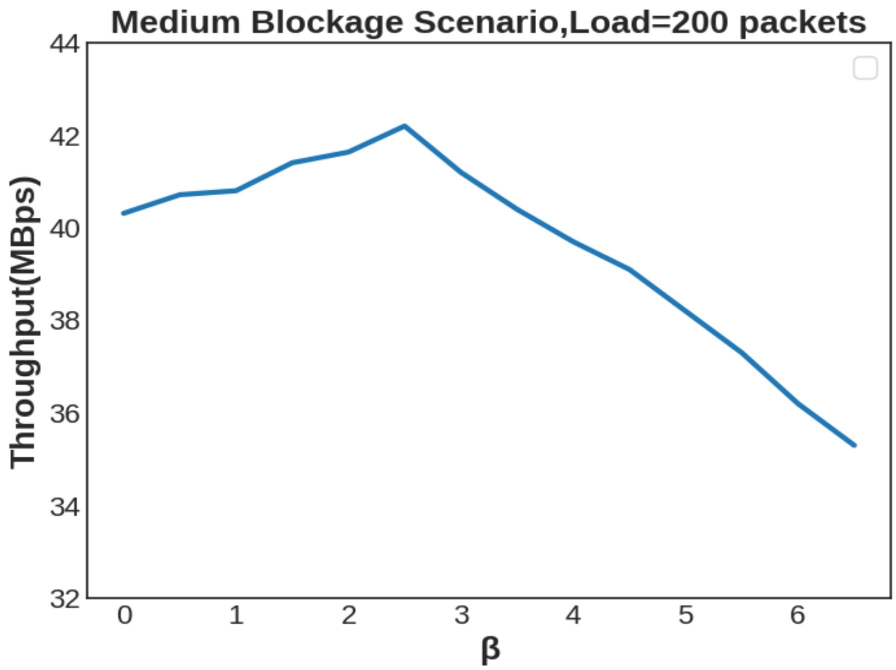

Figure 7.5: Avg. Throughput vs β

Moreover, the communication of the switching D2D pair is also interrupted for some time. Hence, if the switching is frequent, then there is too much overhead which in turn causes higher blockage fraction. Moreover, the quality of relay assigned to the D2D pairs might also become very poor due to the unrealistic bids. Because of the above reasons, the average throughput and packet loss also become worse.

7.2.2 Comparison with State of the Art

We are analyzing the effect of dynamic obstacles on the average throughput of the system, *starvation* of devices and the packet loss. *Starvation* of devices can be determined by the blockage fraction as higher blockage fraction signifies higher starvation of devices in the system and vice versa. We are comparing the results of our algorithm with the relay selection algorithms mentioned in [17], [20] in the heavy blockage scenario with 40 dynamic obstacles. In [20], authors have used the knowledge of the

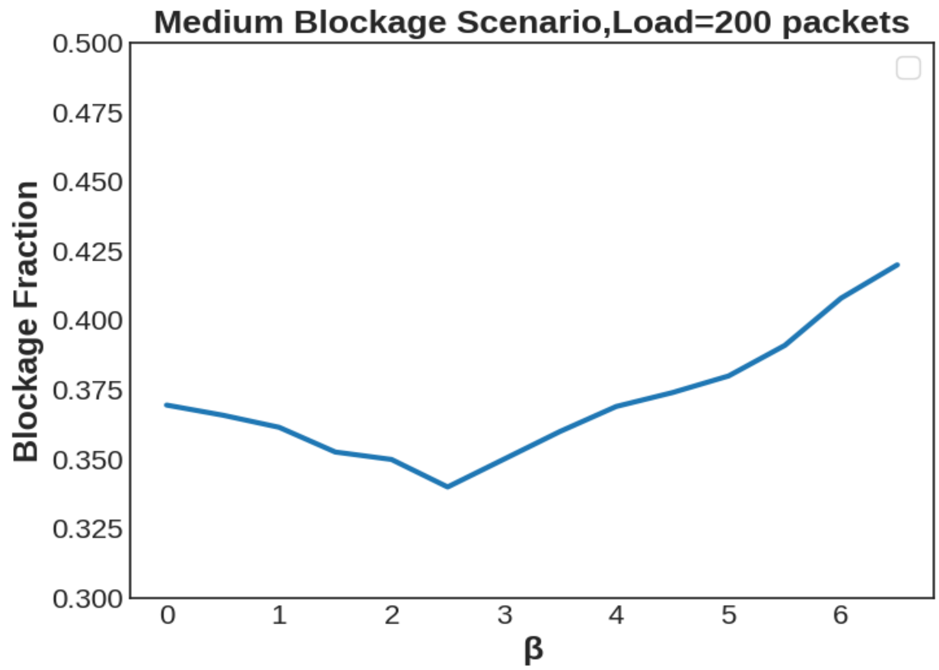

Figure 7.6: Blockage Fraction vs β

motion of dynamic obstacles from sophisticated sensors and chose the relay which would maximize the expected capacity of the system. In [17], author proposed the maximum capacity multi-hop relay selection algorithm. Since, we have only considered only single hop relaying in our analysis, we perform both of these algorithms for single hop.

Figures 7.10,7.11 and 7.12 shows the variation of average throughput, packet loss and blockage fraction with respect to the number of dynamic obstacles in the heavy blockage scenario keeping other parameters fixed. Approach given in [20] is clearly better than the approach in [17] because in [17], relays are chosen solely on the basis of the data rate provided and mobility of UEs and obstacles are not taken into account. Thus its performance degrades due to blockage of LOS by obstacles. While in [20], the relay which provides the highest expected capacity and is less prone to blockage is chosen. When the number of dynamic obstacles is low, the algorithm in [20] is

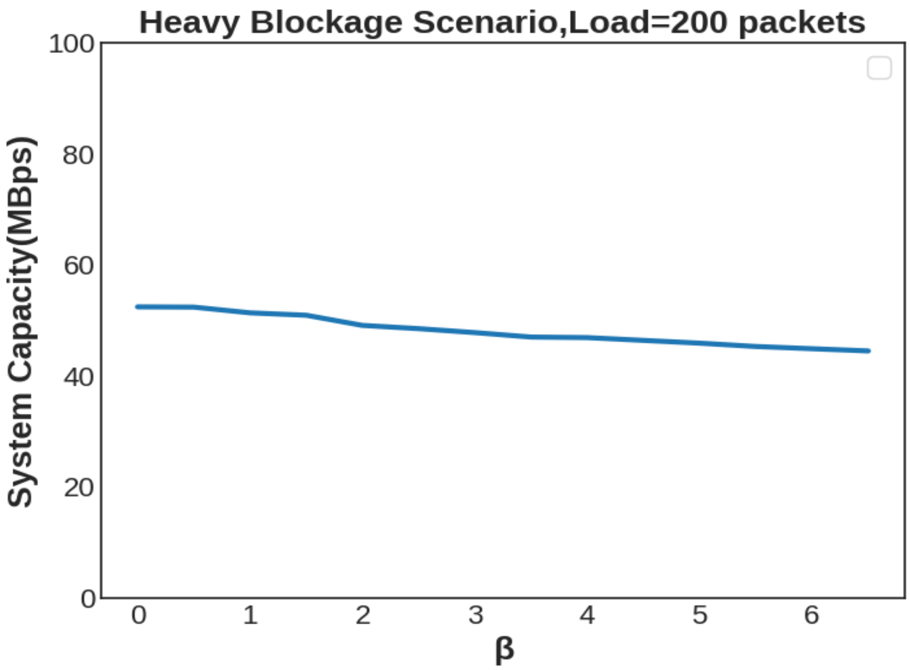

Figure 7.7: System Capacity vs β

slightly better than the online relay switching(ORS) approach. This is because in ORS algorithm, there is local switching of relays even when there is no blockage(when better alternative relay is detected). Due to the overhead in local switching in terms of the control signals to be transmitted and interruption in the communication of D2D pair for a while, there is some loss of packets and reduction in throughput. This signifies that when the dynamic obstacles are low, there is not much need of switching relays.

But as the number of dynamic obstacle increases, the performance degrades rapidly for the algorithms given in [17], [20] as compared to the ORS approach. This is because both of these approaches are centralized and does not perform any local switching of relays when the LOS is blocked. Due to the high blockage fraction for algorithms in [17], [20] in figure 7.12, it is evident that in both the algorithms, as the number of dynamic obstacles increases, the devices are blocked often and are waiting

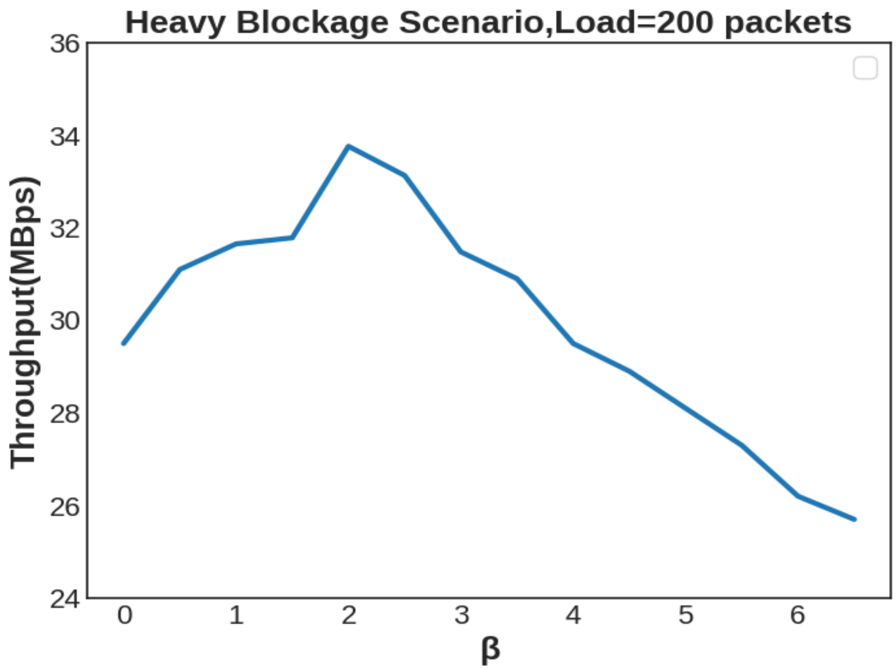

Figure 7.8: Avg. Throughput vs β

for D2D communication to restore most of the time. Whereas, in ORS, due to pre-emptive online switching of relays, D2D communication gets restored more frequently and hence have lower blockage fraction, which in turn provides better performance in terms of average throughput as well as packet loss. Further, the lower blockage fraction for ORS depicts the lower waiting time of UEs in this approach. Thus, we can infer that the starvation of UEs is lesser in our ORS approach.

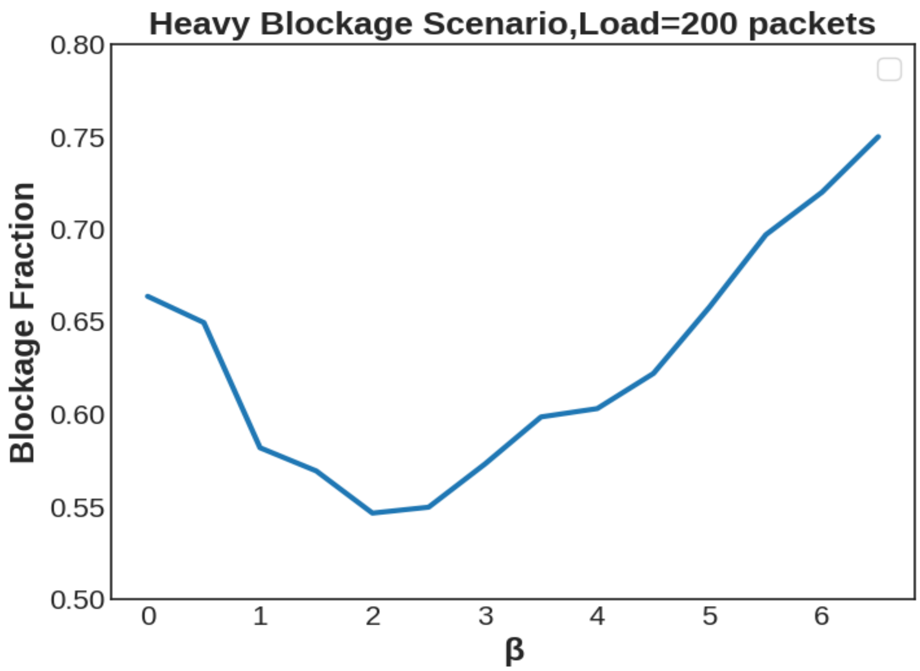

Figure 7.9: Blockage Fraction vs β

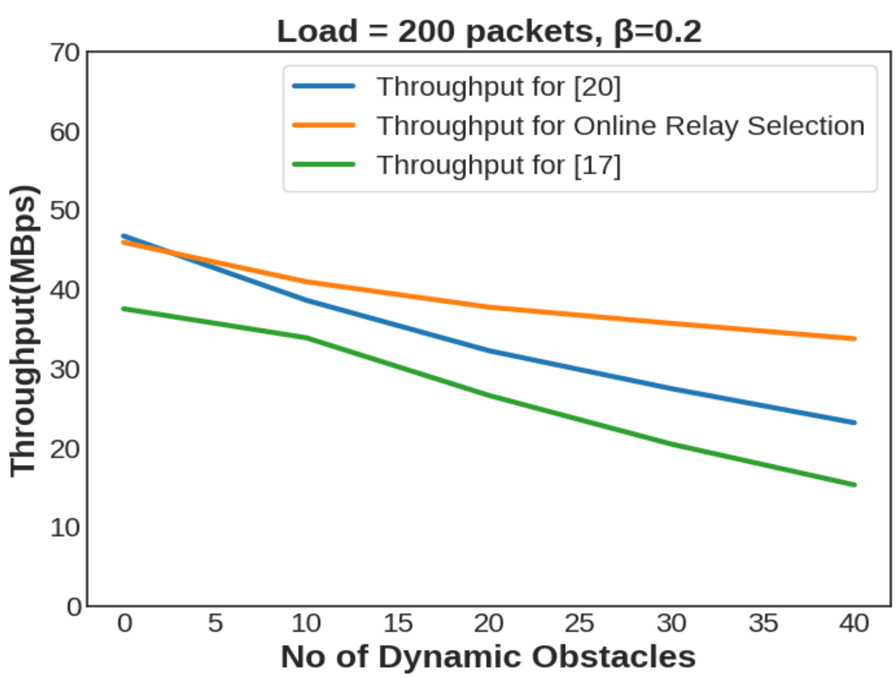

Figure 7.10: Avg. Throughput vs dObs

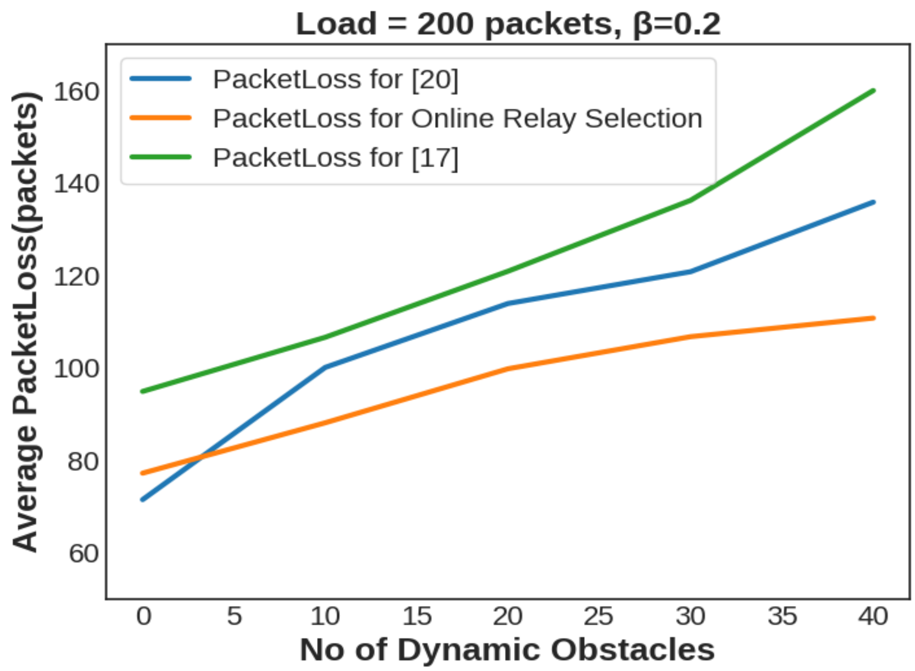

Figure 7.11: PacketLoss vs dObs

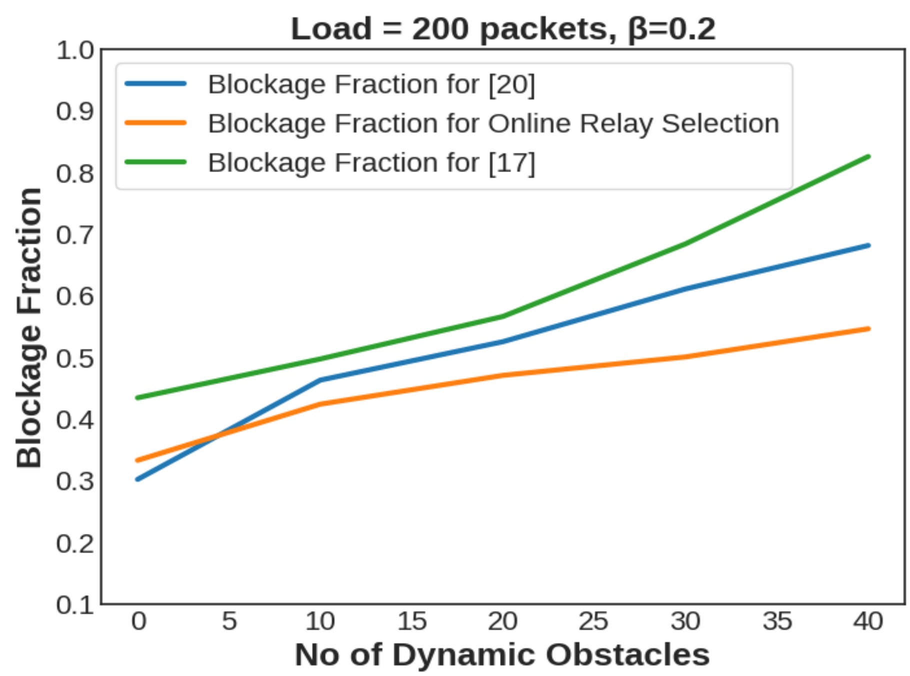

Figure 7.12: Blockage Fraction vs dObs

Chapter 8

Conclusion and Future Works

In this thesis, we formulated the problem of selecting and switching the relays by capturing the effect of the both static and dynamic obstacles as well as the mobility of UEs. We used geometrical analysis to derive the priority of relays for D2D pairs. We then modeled the entire problem into a game theoretic auction and proposed the centralized relay selection to assign the relays to the D2D pairs such that the throughput of the system is maximized. Later, we proposed the online relay switching(ORS) approach to switch the relays locally when the LOS is blocked and hence, further reduce any packet loss. In simulations we have shown the hyper-parameter tuning to obtain the optimal results in low, medium and heavy blockage scenarios. Further, we have also shown through the simulation results that our ORS approach provided significant improvement in terms of average throughput and packet loss in comparison with the other state of the art relay selection algorithms which does not take into account the local switching of relays. Besides, due to the lower blockage fraction provided by our ORS approach in the simulation result, we claim to have dealt with the problem of starvation of D2D pairs also.

We have done our analysis for 2 dimensional area and have considered only single hop relaying. Hence, similar analysis for 3 dimensional area with multi-hop relaying remains author's future work.

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