USE OF SOCIAL INFORMATION IN RELAY SELECTION SCHEMES TO IMPROVE THROUGHPUT OF DEVICE-TO-DEVICE COMMUNICATIONS

BY

MR. USHIK SHRESTHA KHWAKHALI

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF
PHILOSOPHY (ENGINEERING AND TECHNOLOGY)
SIRINDHORN INTERNATIONAL INSTITUTE OF TECHNOLOGY
THAMMASAT UNIVERSITY
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DISSERTATION

BY

MR. USHIK SHRESTHA KHWAKHALI

ENTITLED

USE OF SOCIAL INFORMATION IN RELAY SELECTION SCHEMES TO IMPROVE THROUGHPUT OF DEVICE-TO-DEVICE COMMUNICATIONS

was approved as partial fulfillment of the requirements for
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Thesis Title	USE OF SOCIAL INFORMATION IN RELAY SELECTION SCHEMES TO IMPROVE THROUGHPUT OF DEVICE-TO-DEVICE COMMUNICATIONS
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ABSTRACT

Device-to-device (D2D) communication boosts the network capacity by enabling direct communications between devices. It can be used to exchange data between devices in proximity. This technology can be used in traditional cellular networks to improve throughput and spectral efficiency, reduce delay in transmission time or extend network coverage. Additionally, a relay can be used in D2D communications to enhance the benefits.

This thesis proposes relay selection schemes for D2D communications in cooperative cellular networks. Our proposed schemes increase throughput of D2D communications using social information of users in the network, as well as their location information. The challenge of selecting a good relay is, as mobile devices are power constrained, the selected relay may not transmit at a high power, hence delivering low throughput. We assume relays are more likely to transmit at a high power if the device belongs to a user with a strong social trust with the source. Social information gathered from call history and online social networks gives an indicator of social trust between users, and in turn an indicator of a relay willing to transmit at a high power. We designed a set of relay selection schemes that differ by how much social trust information is available to mobile devices and base stations. All our relay selection schemes probe devices around the midpoint of the distance between the source and the destination. However, the filtering of devices before probing for relay selection vary for each of the schemes. Our proposed schemes perform significantly better than other schemes including the Hybrid Relay Selection (HRS) scheme proposed by Pan and Wang in all the network scenarios under consideration. Our newly developed scheme increases network throughput by upto 29% compared to HRS.

Keywords: Wireless communication systems, Wireless networks, Cellular networks, Mobile communications, Device-to-device (D2D) communications, Relay aided D2D, Routing mechanism, Relay selection scheme, Quality of Service (QoS), Distribution model, Node distribution model, Social information, Social relationships, Social interaction, Social network, Pareto distribution, Cooperative transmission, Performance, Network throughput

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TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviations	**Terms**
Adaptive-MRS	Adaptive Midpoint Relay Selection
AODV	Ad-hoc On-demand Distance Vector
AP	Access Point
BS	Base Station
DF	Decode and forward
D2D	Device-to-device
GPS	Global positioning system
LTE-A	Long-Term Evolution-Advanced
MRS	Midpoint Relay Selection
MRS-SA	Midpoint Relay Selection with Social Awareness
MRS-SD	Midpoint Relay Selection with Social Distance
MRS-ST	Midpoint Relay Selection with Social Trust
OFDMA	Orthogonal Frequency Division Multiple Access
3GPP	3^{rd} Generation Partnership Project

CHAPTER 1

INTRODUCTION

1.1 Device-to-device communications

Device-to-device (D2D) communication allows devices in proximity to directly communicate with each other. Traditional mobile cellular networks use base stations for communications between mobile devices. Mobile devices in proximity cannot communicate directly. A mobile device needs to first send the information to the base station and the base station sends the information back to the destination. The use of frequency spectrum and energy becomes significantly inefficient when there is large amount of data communications [1]. However, with D2D communications in mobile cellular networks, mobile devices in proximity can directly communicate with each other using cellular frequency, bypassing the base station [2], [3], [4], [5]. D2D communications between mobile devices can be implemented with or without control of a base station [6], [7], [8]. The D2D communications under the control of base station allows mobile devices to communicate over direct link of longer range using cellular spectrum compared to traditional short range communication technology like Bluetooth [9].

Cooperative communications allows devices to relay information for each other taking advantage of spatial diversity. The cooperation between devices can provide significant performance gain in terms of link reliability, spectral efficiency, system capacity and transmission range [8]. In the case that bypassing the base station is beneficial, but two D2D users have a poor link, a relay can be utilized to extend communication range or improve Quality of Service (QoS) of the communication [4], [10]. Selecting a relay that offers maximum throughput is the focus of this thesis. Low power base stations facilitating communication between source and destination are already included in the 4G Long Term Evolution-Advanced (LTE-A) standard as fixed terminal relays. The full potential of cooperative communications can be experienced when user devices such as mobile phones, tablets or laptops cooperatively relay data for others [8].

Social information of users in the network can be used to have social-aware D2D communications [11], [12], [13]. Social-aware means discovering of interaction patterns among socially connected users to use that information in design of efficient solutions for D2D communication networks [14]. The information on social tie strength between users can be utilized to develop new mobile applications to promote collaboration, innovation, and effective knowledge transfer within organizations [15]. Granovetter [16] first introduced the idea of tie-strength and categorized into the strong ties strength and the weak ties strength [14]. The author suggests that the greater the overlap between friends circle of two individuals, the stronger the tie between them. The information on social tie is useful in communication networks [15]. Weak ties between individuals can be used to find local bridges that can potentially be sources of new information to each clique in the network. Strong ties between individuals can be used for information validation from untrusted weak ties or when trust is required [15].

D2D communications enabled 5G cellular networks are considered to have a macrocell tier and device tier [17]. Conventional cellular communications are supported by the macrocell tier and D2D communications are supported by the device tier. This benefits the devices at cell boundary and congested area within a cell. In the device tier, the network operator may have different control levels for communications [8]. A base station can have full, partial or no control over the resource allocation and link establishment leading to four types of device tier communications as follows:

1. *Device relaying with operator controlled link establishment*

A device located at the cell boundary or in a poor coverage area can communicate with the base station through relaying its information via other devices. This enhances the QoS of communication or increases the battery life of the device. Either partial or full control link establishment is performed by the operator. It is accomplished by communicating with the relaying devices.

2. *Direct D2D communication with operator controlled link establishment*
   The base station provides control links for the establishment of direct communication between two devices. Once the communication is established, the base station is not involved in data exchange between the devices. With the help of the base station, interference management is possible.

3. *Device relaying with device controlled link establishment*
   Two devices communicate with each other through third device as a relay in cellular networks. Resource allocation, setting up of a call, interference management and other issues all are performed by the devices themselves in a distributed approach. The base station does not establish or control the communication between devices.

4. *Direct D2D communication with device controlled link establishment*
   Two devices directly communicate with each other without any control from the network operator. The resources are allocated by the devices such that the communication has limited interference with other devices in the device tier and the macrocell tier.

The relay selection schemes proposed in this thesis are designed for networks where base stations have partial control over D2D communications. Next, we briefly present some of the major benefits of D2D communications.

1.2 Advantages of D2D communications

The increasing number of mobile users and data generated by those users will make it difficult for traditional cellular network to provide services to its users in future. This is because the physical limitation of spectrum resource and network infrastructure remains a problem. Therefore, social-aware D2D communication is a new paradigm introduced as an economical and efficient solution to improve performance of next generation wireless networks [5]. Implementation of D2D communications in existing cellular networks has the potential to provide various advantages. Some of the major advantages of D2D communications in cellular networks are:

- *Increase in network spectral efficiency*

  The use of D2D communications in cellular networks can enhance its efficiency [1]. D2D communication increases spectral efficiency because D2D communication can also be used without the use of cellular spectrum. In the cases when cellular spectrum is used for D2D communications, direct communication between mobile device bypassing the base station requires half of the resources compared to traditional cellular communication. This doubles the spectral efficiency per connection [18]. Additionally, transmission in D2D communication across short distances allows the same frequency to be utilized more often. As a result, spectrum utilization efficiency increases. The maximization of spectral utilization requires proper interference management, mode selection, resource allocation and network coding [7].

- *Increase in network energy efficiency*

  The number of information bits per unit of transmitted power (bit/ J) is defined as energy efficiency. It is one of the important factors in D2D communications because the mobile devices used in D2D communications are power constrained devices [19]. Energy efficiency can be achieved by transferring information directly between nodes that are in proximity without going through the base station. This reduces the power consumption of nodes for signal transmission [20]. When two mobile devices are in proximity of each other, transmission power levels used for direct communication between the devices could be lower compared to conventional cellular communication. This not only saves battery power on mobile devices, but also reduces interference levels in the system [18].

- *Reduction of transmission delay*

  D2D communications can decrease delay in transmission similar to short range wireless techniques such as WiFi, Bluetooth, Ultra Wide Bandwidth [20]. As the communication is directly between two devices in proximity, the data transfer is faster compared to traditional mobile cellular networks.

Other advantages of using D2D communications between mobile devices listed in [5], [19], [21], [22] are as follows:

- D2D communication allows significant data offloading from the cellular infrastructure. It reduces demand of traffic in the base station as data communication is possible directly between users without involvement of the base station. D2D communication is advantageous for socially influenced data offloading where a group of users are interested in the same data content.
- The transmission power requirement is low as the signal is to be transmitted over a short distance. When mobile devices are close to each other, direct communication saves transmission power of both mobile devices and base station [18].

D2D communications can be used in cellular networks for different applications such as multicasting, peer-to-peer communication, video dissemination and machine-to-machine communication [7]. D2D communication can be used in case of natural disasters to disseminate public safety messages [23]. In such situations, existing network infrastructure may get damaged. An urgent setup of a communication network can provide D2D communication functionality between devices as a quick solution [8].

1.3 Problem statement

In recent years, there has been research interest not only in D2D communication between devices, but also in maintaining Quality of Service (QoS) or extend the range of communications. This can be achieved by using another device as a relay for D2D communications [10]. A key research focus has been selecting a relay such that throughput of D2D communications is improved [11], [12], [13].

When a device is located at the coverage boundary of a base station, the signal received by the device is intermittent and/or of low strength due to large distance between the device and the base station. The communication between the cell-edge device and the base station can be improved with the assistance of a relay. Similarly, there could be situation when direct communication between two devices is poor. This usually happens when the devices are moving apart. This reduces throughput of the D2D communication. Using another device as a relay can improve the communication quality. Utilizing user devices as a relay is highly beneficial especially in underdeveloped countries (or remote areas) where communication infrastructure is limited.

Figure 1.1 depicts two scenarios of D2D communications using a relay in a mobile cellular network. The first scenario (on the left) considers that a relay (R_1) is used in a communication between a device (S_1) and a base station (BS). The second scenario (on the right) is where two devices (S_2 and D) communicate with each other using a relay (R_2). The use of a relay can improve communication quality, i.e. increase throughput of the communication.

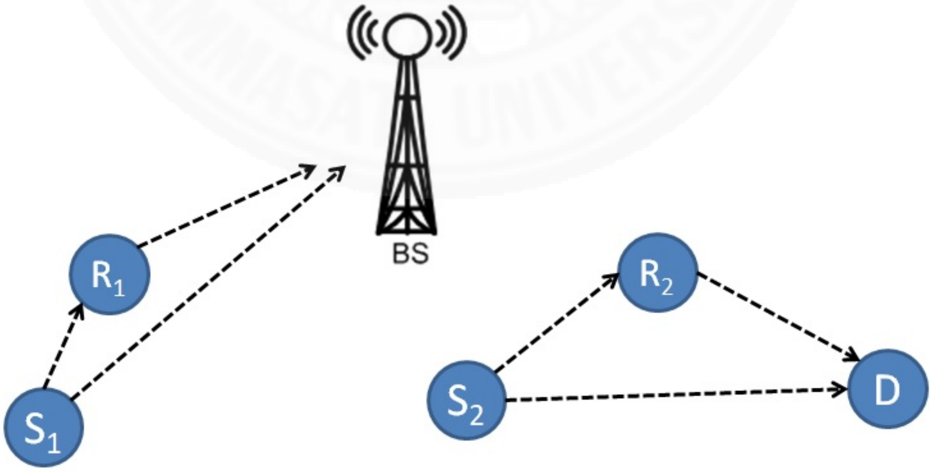


Figure 1.1 Relaying in D2D communications

D2D communication via a relay relies on cooperation of mobile devices and their users. Users of devices may have varying levels of willingness to cooperate as a relay. The rationale behind this assumption is that, mobile devices are power constrained devices and deplete battery power while relaying. They tend to preserve battery consumption by transmitting at low power while relaying data for others, whenever possible. In such scenario selecting an optimal relay becomes more challenging. This is particularly relevant when users in the network have social relationships. For example: a close friend's device selected as a relay may exhibit willingness to transmit at higher power compared to other devices. This may deliver higher performance to the source, but at the expense of more battery consumption on the friend's device. There are numerous scenarios where cellular networks may have users with social relationships in close proximity. For example, users in offices, educational institutes and factories will likely have strong social relationships. Also, events where a large number of people gather in a specific area, such as festivals, conferences and sports, some of those people will be socially related. Location information of devices to select short link lengths is not sufficient for relay selection. A source should select a relay based on both the link length and the transmission power that the relay will use, in order to achieve a high throughput. There are different approaches in which a relay can be selected for D2D communications. Naive approaches, such as brute force and random relay selection, are not suitable. Brute force relay selection probes all idle nodes present in the network to select a relay. For medium and high density networks, too much time is spent for probing, hence reducing average throughput. Random relay selection may result in lower throughput, when the relay selected has either long link lengths or low transmission power.

A promising state-of-the-art approach is Hybrid Relay Selection (HRS) proposed by Pan and Wang [12]. HRS probes devices that are located around a source that have social trust for the source above a certain threshold value and then selects a device as relay that offers maximum throughput. However, the scheme has some limitations. The two major limitations of HRS are:

- *Selection of a relay around source*

  The throughput of D2D communication also depends upon signal-to-noise ratio (SNR) of a link from relay to destination. Selecting a relay around the source may result in long link length from relay to destination. This reduces the throughput of D2D communication.

- *No limitation in number of probes*

  All the nodes within a circular region that have social trust values above a threshold value are probed sequentially in HRS. When node density is high, a large portion of each time slot is spent probing, reducing the overall throughput.

Our proposed relay selection schemes in Chapter 5, Chapter 6 and Chapter 7 have overcome these limitations. We compare the average throughput of each of our schemes with that of HRS along with other regular schemes.

In a real communication environment, the communication between two devices may sometimes be poor. The poor communication may be due to various reasons. There might be large obstacles (such as buildings) in the path between the communicating devices obstructing the signal; the distance between the devices could be large such that the signal strength becomes weak when it arrives at the destination end; some noise or interference sources may be present in the path between the source and the destination, etc. No matter what is the reason of poor communication, the quality of the communication can be enhanced by deploying a relay.

1.4 Aims and objective

The aim of this research is to design a relay selection scheme for D2D communication systems. The objective is to select the relay in D2D communications that maximizes the network throughput.

There are several ways to improve throughput of D2D communications, including: assigning higher bandwidth for the communication; minimizing the interference and noise present in the communication; increasing the transmission power of the communications. Under constrained environment (i.e. when all these alternatives are not feasible or cannot be implemented for various reasons), a nearby device can be used as a relay to improve the throughput of D2D communications. To design a relay selection scheme, importance must be given to the location of the relay relative to the source and destination. In addition, the relay selected should also transmit at a high power so that the throughput can be improved. The relay selection becomes more difficult when a relay device relays data with a transmission power proportional to the social trust it has for the source. The proper selection of a relay device is important to a range of wireless applications using power constrained devices such as mobile cellular networks, WiFi direct, etc.

The purpose of this research is to design a relay selection scheme for D2D communication system where a relay device can have a variable transmission power. The social information (social trust) among device users leveraged for the selection of a relay. The relay can be used whenever possible to maximize throughput of the communication.

1.5 Significance of the study

With the tremendous growth of mobile services and applications catering to increasing demand of mobile users, the network traffic has also increased enormously. This has made it difficult for the existing mobile network infrastructure to provide the services. As a solution to this problem, D2D communications can be used.

With the growth in mobile communications and increase in mobile devices, people are exchanging more information between them than in the past. The need for better communication quality has also increased significantly. This has significantly increased traffic to the cellular network base stations. The use of D2D communications utilizing cellular frequency can alleviate the traffic load on base stations. Our proposed relay selection schemes can further enhance the network throughput by selecting a relay whenever possible. Our relay selection technique can select a relay transmitting at a high power when devices in the network have variable transmission power.

The network coverage may not be available everywhere where people need it. Some places, the network coverage may be intermittent. The network coverage is significantly poor in underdeveloped countries like Nepal. In Nepal, the major cities have good network coverage. However, there are many villages where mobile network is not adequate or not available at all. For example, often only a single base station is providing service to people from multiple villages. So, the signal strength is poor at many places causing people to walk close to the direction of base station to experience better signal reception. D2D communications technology can be helpful in such situations. It reduces traffic in the network by allowing direct exchange of information between devices. Our relay selection techniques can be deployed to enhance the quality of service in those places. A device located at the cell boundary or those experiencing poor coverage will be capable to communicate with the base station through relaying information via other devices.

The use of a relay in D2D communication provides advantage to both network operators and subscribers. As network traffic load is reduced with the use of D2D communications, mobile network operators can provide services to more subscribers without upgrading or installing additional network infrastructures. The operator can also charge their subscribers for the services provided to generate more revenue. On the other hand, mobile subscribers also experience improved communication quality. The network operator can provide incentive to the relaying device. The relaying device may get additional data package or reduction in monthly bill proportional the amount of data it has relayed.

1.6 Scope of the study

The scope of this research is to model and design a D2D communication system and develop relay selection schemes for D2D communications underlaying cellular networks. The proposed relay selection schemes are especially designed to enhance network throughput by selecting socially trusted devices in its proximity as a relay. Our proposed relay selection techniques are applicable for only two hop D2D communications. A base station is assumed to keep track of all devices in the network. The devices are considered to be able to calculate social trust values using call history for the devices which are in the list of contacts. Social information collection techniques and actual calculation of social trust are out of our scope. Data privacy and communication security are not considered in this study.

1.7 Organization of this thesis

The rest of the thesis is organized as follows:

Chapter 2 aims to provide necessary background knowledge to readers to understand our research work. It initially presents classification of D2D communications based on resource allocation and highlights some of the challenges in D2D communications. Then it explains different physical factors affecting D2D communications, different mobility models available for simulating mobility of people and explains the ways social information users can be used in D2D communications.

Chapter 3 presents literature review of recent research works in the field of D2D communications. Initially it summarizes different survey papers related to D2D communications. Then it reviews different approaches taken to address challenges present in D2D communications including throughput optimization. The focus is on throughput optimization as throughput optimization using a relay exploiting social information of users is the scope of this thesis. Finally it discusses the papers specifically on relay selection in D2D communications utilizing social information of users.

Chapter 4 details the framework used for all the social-aware relay selection schemes proposed in Chapter 5, Chapter 6 and Chapter 7. It first presents the D2D communication system model and social trust model used in this thesis. It then describes how social trust among mobile users can be related to transmission power of a relay device. Finally it presents a system architecture of mobile devices under different assumptions about device capabilities (e.g. whether they support D2D and/or social information). The components of the architecture are referred to in the subsequent chapters.

Chapter 5 presents Midpoint Relay Selection with Social Awareness (MRS-SA) scheme. This is the initial version of our relay selection scheme presented in this thesis. We show that selection of a relay around the midpoint of the distance between the source and the destination can significantly improve throughput of the network compared to the Hybrid Relay Selection (HRS) scheme [12].

Chapter 6 presents Midpoint Relay Selection (MRS) scheme for D2D communications, an improved version of MRS-SA presented in Chapter 5. MRS selects a relay based on the combination of location and social trust among users in the network. MRS has two variations namely Midpoint Relay Selection with Social Trust (MRS-ST) and Midpoint Relay Selection with Social Distance (MRS-SD). MRS-ST and MRS-SD vary on the way nodes are prioritized when selecting a relay node. The average throughput of MRS-ST and MRS-SD are higher than that of Hybrid Relay Selection (HRS) scheme. The analysis is done for networks with different social trust scenarios.

Chapter 7 presents Adaptive Midpoint Relay Selection (Adaptive- MRS) scheme that can overcome the shortcoming MRS-ST by switching between MRS-ST scheme and nearest to the midpoint (M-Nearest) scheme depending upon social trust among the users in the network.

Chapter 8 briefly highlights our contribution in this thesis by summarizing our work. The chapter also presents areas for future research.

CHAPTER 2

BACKGROUND

This chapter provides the background on D2D communications necessary for subsequent chapters. Section 2.1 presents a classification of D2D communications based on resources allocated for D2D communications. The motive is to provide readers an idea of where our research fits within the field of D2D communications. Section 2.2 briefly describes the major challenges in D2D communications. Section 2.3 defines different links in D2D communications and shows throughput offered by those links in time division multiple access systems. Section 2.4 presents the implementation of mobility model used in analysis of relay selection schemes proposed in this thesis. Section 2.5 explains utilization of social information of users in D2D communications.

2.1 Classification of device-to-device communications

Our research is focused on developing relay selection schemes for D2D communications underlaying cellular networks. This section presents branching of our research in the field of D2D communications. Depending upon the types of resources that can be accessed by devices for communications, D2D communications can be classified as:

1. In-band D2D communications
2. Out-band D2D communications

Figure 2.1 illustrates the classification of D2D communications based on frequency resource usage as in [7].

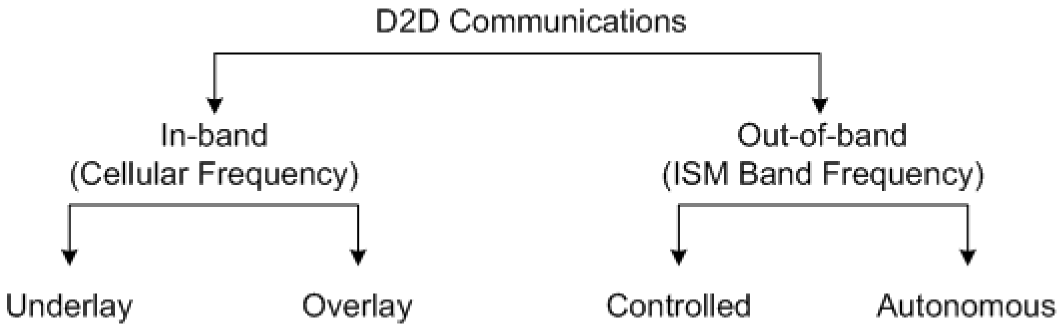


Figure 2.1 Schematic diagram of D2D communications based on frequency usage

2.1.1 In-band D2D communications

In in-band D2D communications, same frequency spectrum is used for D2D communications and cellular communications [21]. The in-band D2D communications can be further categorized as overlay and underlay D2D communications. In overlay mode of D2D communications, dedicated cellular frequency resources are used. The frequency resources dedicated for D2D communications are not used for cellular communications [7]. For D2D communications requiring high quality transmission, D2D communications in overlay mode is usually preferred [24]. However, in underlay mode of D2D communications, D2D communications share same frequency spectrum as cellular communications [7]. Spectrum is reused between direct D2D link and cellular link between BS and mobile device [24].

Overlay D2D communication is comparatively easier to implement than underlay D2D communications [21]. As separate frequency spectrum is used for D2D communications, there is no interference between D2D communications and cellular communications. In this mode of resource allocation, the major concern is to optimize resource allocation ratio [25]. A balance between resource allocated for D2D communication and cellular communication is necessary to optimize use of the resource. The research on overlay mode of D2D communications focuses on dynamic resource allocation [19]. When D2D overlay mode is used, resource allocation gain is given the utmost importance to prevent wastage of cellular resource [7]. Overlay D2D communications is out of scope of my research work.

The major advantange of adopting underlay mode of resource allocation is, it allows opportunistic and efficient ultilization of frequency spectrum. As there is no dedicated resource allocated for D2D communication, frequency spectrum is not wasted when there is no D2D communication between mobile nodes. However, the major disadvantage of inband D2D communication is the interference between D2D communications and cellular communications [7]. The D2D transmission links should be carefully monitored and managed by the BS to have interference between D2D communications and cellular communications within a tolerable level. The interference can be minimized by controlling transmission power and managing resource allocation [5], [19], [25]. Efficient scheduling and cross layer optimization can also be used. These techniques of interference management are further explained in Chapter 3. In addition to that, cellular mode of resource allocation can be used by considering BS as a relay for D2D communication [25]. Therefore, we can conclude that D2D communication underlaying cellular network enables devices to communicate directly and increases spectral efficiency [26]. The scope of our research is to develop a relay selection scheme for underlay mode of in-band D2D communications.

2.1.2 Out-band D2D communications

In out-band communications, nodes share the unlicensed spectrum that is publicly available other communication systems/wireless technologies including Bluetooth, WiFi Direct, ZigBee, etc. With the use of out-band D2D communication, the interference between D2D and cellular link can be eliminated. However, out-band D2D communication may experience interference because of unlicensed spectrum usage by other communication systems. As a result, out-band D2D communications will have some QoS constraints [7]. As D2D links in out-band D2D communication compete with various unknown devices, the performance of D2D communication is not guaranteed in comparison to in-band D2D communication [5]. When out-band D2D communication is used, cellular spectrum is not affected by D2D communications between devices. The coordination between radio interfaces is either autonomous or controlled by the BS. Mobile devices require two different wireless interfaces to have simultaneous cellular and D2D communications [7]. When controlled mode is used, communication radio interfaces between D2D links are controlled by the base station. In case of autonomous mode, communication devices manage the radio interfaces for the network setup [27].

2.2 Challenges in device-to-device communications

In [14], [21] and [22] technical challenges in D2D communications are presented. Major challenges in D2D communications are: synchronization, peer discovery, mode selection, resource allocation, interference management, D2D with mobility, pricing, security and energy efficiency. The issues are briefly explained in the following sections.

2.2.1 Synchronization

In D2D communications, synchronization helps mobile devices to use right time slot and frequency for discovering and communicating with peer devices [21]. Peer discovery process can be network assisted or autonomous. In autonomous approach, devices are synchronized by transmitting synchronization or reference signal sequence for device discovery [14]. Local synchronization among devices may be sufficient for D2D communications. In cellular networks, base station periodically broadcasts signal to synchronize mobile devices. Devices having D2D communications can use same synchronization signal if they are under the same BS. When mobile devices are under different BSs or some of the devices are out of coverage of BS or all devices are out of coverage, synchronization between devices become difficult. Complex algorithms can be used at mobile devices for synchronization in D2D communications compared to wireless sensor networks having resource limited sensors [21].

2.2.2 Peer discovery

In D2D communication underlaying cellular networks, a node finds other nodes in its proximity for D2D communication. This is known as a peer discovery method [14], [21]. Peer discovery initiation and peer discovery control are two phases of peer discovery process [14]. Peer discovery control can either be network assisted or autonomous. In network assisted peer discovery, paging or other signaling are used. In autonomous peer discovery, an user equipment (UE) discovers potential counterparts on its own by transmitting a known synchronization or reference signal sequence to mediate the discovery process. The advantage of using network assisted approach is that the network can have location information of UEs. The drawback of this approach is that it requires high signaling overhead compared to the autonomous peer discovery. On the contrary, the autonomous peer discovery drains more battery of UE because the discovery is done by the UE itself. This type of peer discovery becomes even more challenging when the UEs have limited battery power and processing capability [14].

The authors in [20], [21] have categorized peer discovery from user's perspective and network perspective. From user's perspective, restricted discovery and open discovery are two techniques to discover peer devices. In the restricted peer discovery, devices cannot be discovered by the other users without their permissions. This type of peer discovery is suitable for applications like multiplayer gaming and context sharing among friends. In case of open peer discovery, devices can be discovered whenever they are within the proximity of others. This type of peer discovery is less complex and is suitable for public safety services in case of natural disaster. From network perspective, tightly or lightly controlled by the BS are two techniques to discover peer devices. In tight BS controlled peer discovery, BS assists in the discovery by asking the devices interested in D2D services to transmit its beacon and specify the targeted device to receive the beacon. This type of peer discovery provides fast and accurate device discovery. However, the BS has high signal overhead. In light BS controlled peer discovery, BS broadcasts the set of transmitting and receiving discovery resources periodically. This type of peer discovery is less efficient as tight BS controlled peer discovery and requires less signal overhead.

The peer discovery becomes challenging in a network having multiple cells due to the requirement of cooperation between adjacent BSs. A way forward may be to develop incentive-based schemes. Therefore, it is necessary to have peer discovery procees simple and energy efficient [14], [21].

2.2.3 Mode selection

During the peer discovery process, devices that have discovered themselves are potential candidates for a D2D communication. The direct communication between the devices may not be possible if direct channel is noisy. In such case, cellular communication is preferred [21]. In D2D communications underlay cellular networks, the selection of cellular communication or direct D2D communication is known as mode selection [14]. An appropriate mode should be selected to achieve optimal system performance depending upon the available bandwidth [9]. Generally, the mode selection is done based on performance objective like high spectral efficiency, low latency, or low transmit power [21]. Achievable transmission rate in each mode can be estimated for each mode to select the mode resulting higher transmission rate [7].

2.2.4 Resource allocation

D2D communication and cellular communication links both can use cellular spectrum for communication. Cellular spectrum can be used for D2D communication either in underlay mode or overlay mode. In the underlay mode, D2D communication uses radio frequency (subcarrier) by reusing frequency of cellular user (conventional mobile cellular user) [14]. Here, the radio frequency allocation for D2D communication is one of the challenging task in cellular networks. This is because it is associated with creating and maintaining direct links between D2D pairs using cellular frequency [21]. In the overlay mode, dedicated cellular spectrum is used for D2D communications. The frequency resource used for D2D communication can be frequency resource used either for uplink or downlink, or even both of cellular communication. Generally, uplink cellular spectrum is targeted to be used for D2D communications. Most of the cellular users download data than uploading. Therefore, using cellular spectrum in underlay mode can significantly improve spectral efficiency [14]. A simple and general resource allocation framework for inband multicell architecture in overlay and underlay modes is proposed in [28].

2.2.5 Interference management

The throughput can be increased leveraging the potential of device-to-device communication, regardless of whether dedicated frequency spectrum is used or frequency is reused. However, the performance cannot be realized if interference in the system is not managed [20]. The interference management becomes more challenging when multiple D2D pairs and cellular user share the same spectrum portion [14].

Interference in D2D communication can be managed by having: proper power control mechanism, efficient scheduling and cross layer optimization.

1. *Proper power control mechanism*

   It is an approach to minimize interference by simply controlling transmission power. Interference in device-to-device communication system can be managed by restricting the transmission power. It is a direct way to limit the interference by restricting the transmitting power of D2D users. Power control mechanism can be coupled with mode switching to have maximum network throughput.

   Fixed power margin scheme is proposed to coordinate interference between multiple D2D pairs and multiple regular cellular users [20]. Power margin for cellular users is assumed and is known to D2D pairs. So, D2D pairs adjust their transmit power to achieve at least minimum Signal to Interference and Noise Ratio (SINR). This scheme is simple but may not be optimal because determining suitable power margin is difficult. Higher power margin reduces number of regular cellular users that can share resources with D2D users. Lower power margin decreases the probability of maintaining minimum SINR required for D2D users.

2. *Efficient scheduling*

   Different researches are done such as:

   - Time hopping based method to randomize interference generated by D2D pairs

- Successive interference canceling scheme for reliable demodulation at D2D receivers
- Heuristic scheduling algorithms to pair D2D users and regular cellular users to guarantee QoS for both types of users

3. *Cross layer optimization*

   Cross layer optimization can improve throughput of networks by reducing design margin. Joint admission control and resource allocation (power and channel) scheme can be used to maximize network throughput and guarantee QoS for both D2D users and regular cellular users [20]. Upto 60 percent of D2D users can be accessed while maintaining the performance of existing regular cellular users even in a fully loaded cellular network. Drawback of this scheme is that it requires perfect channel state information (CSI) for all links at BS.

   In D2D communications, it is difficult to obtain instantaneous CSI of interference links between regular cellular users and D2D pairs, and traditional training and channel estimation methods does not work. Thus, there is a tradeoff between performance and signalling overhead [20].

The D2D communication system underlying cellular network requires a mechanism to control the transmitting power and tackle the mutual interference among the CUs and D2D pairs [14].

2.2.6 D2D with mobility

Most of the research in the field of D2D communications are focused on static users. The analysis in realistic scenarios should be used to evaluate the performance gains. It is necessary to investigate dynamic scenarios like pedestrian mobility, vehicular mobility, interference between devices, handover mechanisms can capture realistic scenarios [21].

2.2.7 Pricing

Cellular operators need to control and charge for D2D services. The operators should analyze what they are charging for to avoid users turning to traditional D2D technologies like Bluetooth. The pricing models should motivate devices to have D2D communications [8]. Network operators can charge some money to provide secure environment during D2D communication [21]. The main challenge in device relaying with operator controlled link establishment is to develop incentive mechanisms to motivate devices for relaying. In order to motivate devices act as a relay, network operators can either provide discount on monthly bill or provide free services depending upon amount of data relayed. Complex techniques using game theory and auction theory can also be used to maximize revenue of network operator [8].

2.2.8 Security

Distributed storage of data in D2D communication makes D2D communication capable to provide stronger anonymity and data privacy compared to conventional cellular communication [21]. However, the exposed nature of wireless communication makes D2D communications vulnerable to threats [14]. D2D communication is prone to various common attacks like eavesdropping, denial of service, man-in-the-middle, node impersonification, IP spoofing, malware attack, D2D users' privacy, etc. With the increase in the number of D2D communication devices, the probability of having such attacks increases [21]. Gandotra and Jha [17] suggests data to be encrypted before transmission to prevent the attacks in D2D communications. The D2D users can use security schemes provided by the cellular operators if they are under their coverage. However, if D2D users are outside the coverage of the operators, security signals may be passed on through relays. As relays are most likely to be attacked, designing of security schemes for D2D communication is necessary.

2.2.9 Energy efficiency

As mobile devices are power-limited devices, energy efficiency is one of the major problems in socially-aware D2D networks [14]. The proper pairing of D2D devices in cooperative network helps in efficient resource utilization. To make the system power efficient, one should be careful from peer discovery process to design of resource allocation schemes. Mobile social network increased the power consumption at device as there is frequent exchange of data between devices. Additionally, it also increases the signalling overhead in cellular system. To resolve all these issues, it is necessary to come up with a solutions applicable for practical scenarios.

Next section explains different aspects related to performance evaluation in D2D communications.

2.3 Communication links performance in D2D communications

Section 2.3.1 differentiates between a direct link between devices and a D2D link which involves a relay. Section 2.3.2 explains the affect of signal strength of links in data rate of full duplex decode and forward relaying. Section 2.3.3 briefly describes the resource allocation in time division multiple access system. Section 2.3.4 differentiates between data rate and throughput. Additionally, this section graphically illustrates the region having high data rate for D2D communications using a relay. This will help readers to evaluate performance of different relay selection schemes by comparing data rate offered by different paths.

2.3.1 Direct link and D2D link

Consider two devices, a source and a destination, communicating directly with each other using a cellular frequency, by bypassing the BS. The communication link between the source and the destination is known as a *direct link*. In addition, when the link between a source and a destination is poor, a relay device can be used to improve the quality of communication. The link between the source and the destination via the relay is known as a *D2D link*. This means in D2D communications, a mobile device (source) communicates with another device (destination) either using a direct link or a D2D link as illustrated in Figure 2.2. The double-lined circle represents the source (s) and the destination (d). The solid line between s and d represents the direct link. The information exchange between the devices occurs directly with each other. The dashed-line from the source to another device (device 5) and from the device to the destination represents the D2D link. The source compares between the data rate offered by the direct link and the D2D link before the selection of a communication path. Here, device 5 is selected as a relay. The information from the source is initially sent to the relay (device 5) and the relay forwards the data to the destination.

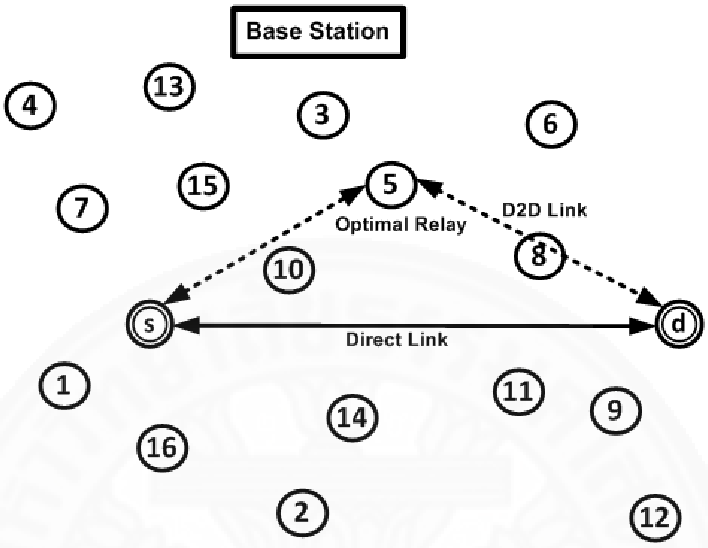


Figure 2.2 Links in D2D communications

2.3.2 Shannon’s channel capacity

The signal to noise ratio (SNR) of a direct link is given by

$$\gamma_{s,d} = \frac{P_{s,d} D_{s,d}^{-\theta}}{N} \tag{2.1}$$

where, $P_{s,d}$ is the transmission power of a signal from the source to the destination, $D_{s,d}$ is the distance between the source and the destination, N is the noise power and θ is the pathloss exponent.

According to Shannon’s capacity formula, the data rate of a direct link is given by

$$C_{s,d} = W \log_2(1 + \gamma_{s,d}) \tag{2.2}$$

where, W is the bandwidth of a channel.

The data rate of a D2D link having full duplex decode and forward relaying is given by

$$C_{s,r,d} = W \min\{\log_2(1+\gamma_{s,r}), \log_2(1+\gamma_{s,d}+\gamma_{r,d})\} \tag{2.3}$$

where, $\gamma_{s,r}$ is SNR of the signal from the source to the relay, $\gamma_{s,d}$ is SNR of the signal from the source to the destination and $\gamma_{r,d}$ is SNR of the signal from the relay to the destination [11], [12], [13].

In cellular systems, users transmit data within a time slot using a particular frequency band allocated to them. When a cellular frequency is used for D2D communications, the user data is transmitted within a time slot using that frequency. This is similar to time division multiple access explained later in this section. In case of a direct link, the throughput of D2D communication is equal to the data rate offered by the link. However, in case of a D2D link, a fraction of a time slot is spent for probing during the process of a relay selection. Therefore, when time spent for relay selection is taken into consideration, the throughput of a D2D communication is given by

$$T_{s,d} = C_{s,r,d}\{TSD - (PD \times NP)\} \tag{2.4}$$

where, TSD is the time slot duration, PD is the probe duration and NP is the number of probes. The relay selection schemes proposed in this thesis consider the time spent for probing. Section 4.1.3 presents the proposed probing protocol used for relay selection. Throughput and time slot duration are explained later in this section.

2.3.3 Time division multiple access

Time Division Multiple Access (TDMA) is a multiple access technique that allows multiple users to have access to a medium or resource at a different time allocated to them. Each user in the system is allocated a time slot and the user can use the resource at the time slot allocated for it. It provides a dedicated resource for a user at a particular time slot assigned to it. This allows proper utilization of resource. In cellular systems, users transmit data at a designated time slot.

2.3.4 Data rate and throughput of D2D communications

Data rate refers to the speed at which data can be transferred from a device to another device. It's units are bits per second (bps).

Throughput of a network is the average number of successful transfer of data from one device to the other. It does not include the overhead that is present during the transfer of data. In other words, throughput of a network is the average data rate of successful delivery of data over a specific communication channel. Its units are same as that of data rate i.e. bps.

The location of a relay plays an important role in data rate of two hop D2D communications. The data rate of D2D communication through a relay depends upon SNR of the signal from the source to the relay, that from the relay to the destination and that from the source to the destination, as per equation 4.3. To determine the location of a relay which yields higher data rate, we simulate in Octave different scenarios by considering different locations of the relay for a pair of source and destination located at (10,10) and (40,10) respectively. We calculated the data rate offered by the link from the source to a relay and that from the relay to the destination as per equation 4.3. The relay is set to transmit at maximum power same as that of the transmitter. The data rate is calculated for all the relay locations. Table 2.1 shows the detailed simulation setup used in the analysis.

Table 2.1 Simulation setup for analysis of relay location selection

Simulation Parameters	
Simulation software	Octave
Source location	(10,10)
Destination location	(40,10)
Channel bandwidth, B	1 MHz
Pathloss exponent, θ	4
Noise power, N	-114 dBm
Transmission power, $P_{s,d}$	20 dBm

Figure 2.3 illustrates contour graph of the data rate that can be achieved when a relay is located at various points around the source and the destination. It shows that the data rate is higher around the midpoint of the distance between the source and

the destination. Similarly, Figure 2.4 shows different viewpoints of surface graph of the data rate indicating that maximum data rate can be achieved around the midpoint. This motivated for the design of midpoint relay selection schemes.

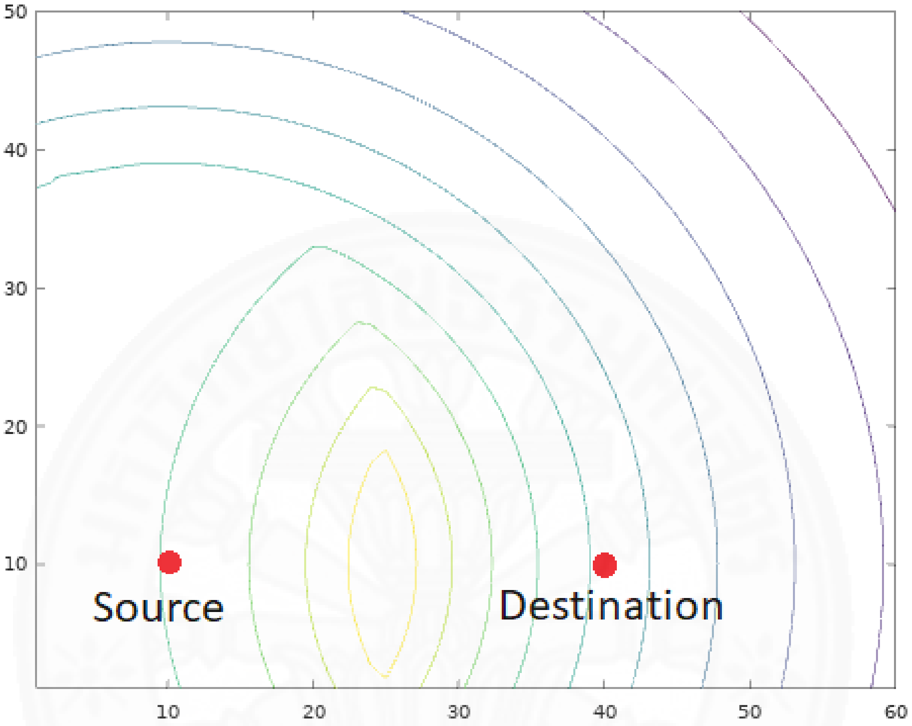
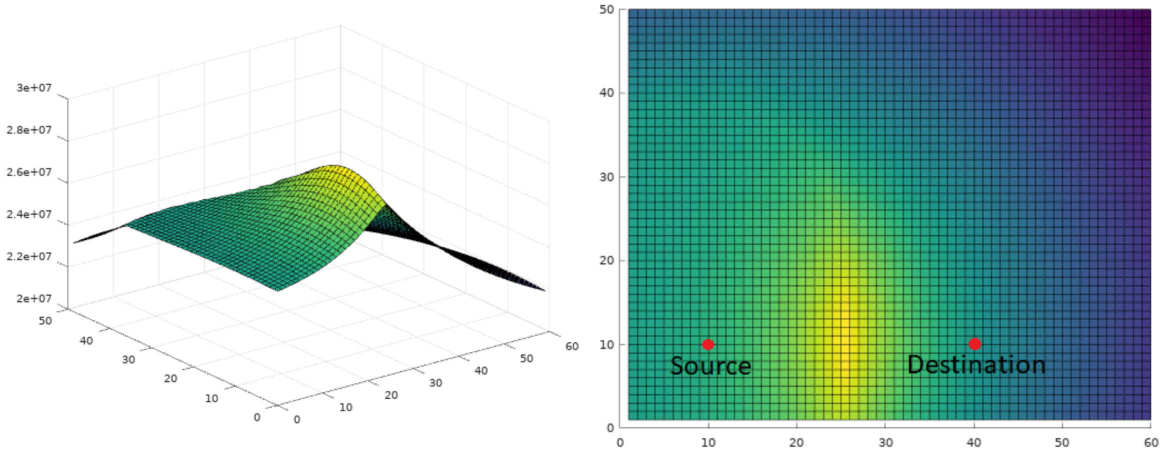


Figure 2.3 Contour diagram for relay selection region when source is at (10,10) and destination is at (40,10)

The data rate of D2D communication through a relay depends upon the SNR of the links from the source to the relay (SNR_{SR}), from the relay to the destination (SNR_{RD}) and from the source to the destination (SNR_{SD}) (see equation 4.3). From careful observation of the graphs in Figure 5.1 and Figure 5.2 we can see that the region with higher data rate is not symmetric and is located around the midpoint of the distance between the source and the destination. This suggests that data rate through a relay depends mainly upon SNR_{SR} and SNR_{RD}, not on SNR_{SD} considering there are no obstacles on the paths. This inspired us to develop a new relay selection scheme which chooses a relay around the midpoint of the distance between the source and the destination.



(a) Viewpoint 1

(b) Viewpoint 2

Figure 2.4 Surface diagram for relay selection region when source is at (10,10) and destination is at (40,10)

2.4 Mobility model for device-to-device communications

When experimentation with real users is not viable, mobility models are used to simulate how users move in a network. There are various mobility models that differ in terms of complexity and types of scenarios they attempt to simulate (e.g. people walking, cars driving on a highway or in a city). In this thesis, the Random Waypoint mobility model [29] is used. The parameters of this mobility model are presented in Chapter 4.

Bonn Motion [30], a software for creating mobility scenarios, is used for implementing Random waypoint model. The software allows to represent detailed mobility pattern of nodes such as number of nodes present in the network, the area of simulation ($length \times breadth$), how long the mobility scenario is to be simulated, maximum and minimum speed at which nodes move, how long does the nodes in the network stay idle.

2.5 Importance of social information in D2D communications

Two key characteristics of a social relationship between people is who they have a relationship with, referred to as a social link, and the strength of that relationship. In cellular networks, there are different ways to determine the social link and relationship strength. One approach is based on calls. Two people could be determined to have a social link if they have called each other. The strength of the relationship would depend on the frequency and duration of those calls during some period. Another approach is to also include other information about the mobile device users, especially that gathered from online networking services such as Facebook, Twitter, etc. The information from online networking services can potentially more accurately capture the social link and relationship strengths of users [13]. However, while call information is available to a network operator, access to online networking accounts (and the information within) may not be. Although that is changing, with some network operators offering free or discounted services if the users provide their social information (e.g. access to Facebook friends list).

With knowledge of social links and relationship strength, network operators can estimate the social trust one user has for another. This is important for relay selection schemes, when we assume that relays are more likely to transmit at higher power if doing so for trusted friends. More specifically, the social trust values can be used in design of relay selection schemes [11], [12], and data dissemination [5].

In summary, our interest is in in-band, not in out-of-band D2D communications. The scope of our research is to develop relay selection schemes for D2D communications underlaying cellular networks that enhances network throughput. The next chapter reviews the literature on D2D communications.

CHAPTER 3

LITERATURE REVIEW

This chapter presents literature review of research works in the field of D2D communications. Section 3.1 summarizes different survey papers related to D2D communications. Section 3.2 summarizes different approaches taken to address challenges present in D2D communications including throughput optimization. The focus is on throughput optimization as throughput optimization using a relay exploiting social information of users is the scope of this thesis. Section 3.3 reviews the papers specifically on relay selection in D2D communications utilizing social information of users.

3.1 D2D communications

D2D communication is expected to be a key feature supported by next generation cellular networks such as LTE-A and 5G [6], [14], [31]. D2D communications in cellular networks allows mobile devices to choose to communicate either through the BS or communicate directly using cellular resources [22]. The multitude of advantages of using D2D communications are explained earlier in section 1.2.

Comprehensive surveys on D2D communications are presented in [7], [17], [14], [27]. Gandotra et al. [17] presented an overview of different types of D2D communications. They briefly explained the additional features of D2D communications such as millimeter wave D2D, cooperative communications, ultra dense networks, cognitive D2D, handover procedure in D2D, network coding, hybrid automatic repeat request operation that can be used for enhancing cellular networks. They also identified the practical challenges in D2D communications which we summarized earlier in section 2.2. Ahmed et al. [14] presented systematic overview of the technical challenges in D2D communications without considering social aspect of the network. The social features used to tackle and improve the technical issues and the applications are briefly presented. Then, they did a survey on socially-aware D2D communications where different social features are used to overcome D2D technical issues and improve performance of prospective D2D applications. Security and privacy in D2D, impact of mobility of users, efficient distributed schemes, modelling practical and efficient approaches are some of the open research challenges in the field of D2D communications.

Asadi et al. [7] presented taxanomy on D2D communications based on frequency spectrum used. They found that majority of the literature is focused on inband D2D communications, particularly in D2D communications underlaying cellular networks. They broadly reviewed D2D communications that enhance the spectrum and power efficiency, and also improve performance while maintaining QoS/ power constraints. Spectrum efficiency can be increased by using advanced mathematical techniques that reduces or avoids interference by implementing self-organizing or network controlled methods. The self-organized methods are more efficient and requires less overhead. Power efficiency can be enhanced by using the proper switching between cellular and D2D modes. Heuristic algorithms or brute force technique can be used for mode selection. The performance of D2D communications in cellular network that has certain QoS or power requirements can be increased by using stochastic optimization, non-linear programming, and integer optimization techniques. They listed practical challenges as power allocation, resource allocation, modulation format, channel measurement, energy consumption and hybrid automatic repeat request.

Alotaibi and Mukherjee [32] did a survey of routing algorithms proposed for wireless adhoc and mesh networks. Wireless networks are more vulnerable to interference from other transmissions, varying channel characteristics, etc. Using general routing algorithms like Dynamic Source Routing (DSR) and Ad-hoc On-demand Distance Vector (AODV) routing are not applicable to wireless network because they were not designed to control network traffic. Using DSR and AODV creates problems like large area of flooding, greedy forwarding empty set of neighbours, flat addressing, widely-distributed information, large power consumption, interference, lack of load balancing, etc. The authors summarized different routing algorithms (listed later in section 3.2.4) that addresses the issues in DSR and AODV.

3.2 Addressing challenges in D2D communications

This section initially presents hierarchical diagram that illustrates technical challenges in D2D communications. Then it summarizes the different approaches taken to solve challenges in D2D communications including throughput optimization. The emphasis is on different relay selection techniques to optimize throughput in D2D communications, as it is the scope of this thesis.

Figure 3.1 illustrates the challenges in D2D communications which is explained in section 2.2. Throughput optimization in D2D communications is the scope of this thesis. Social information of users is used for relay selection to enhance throughput of the network.

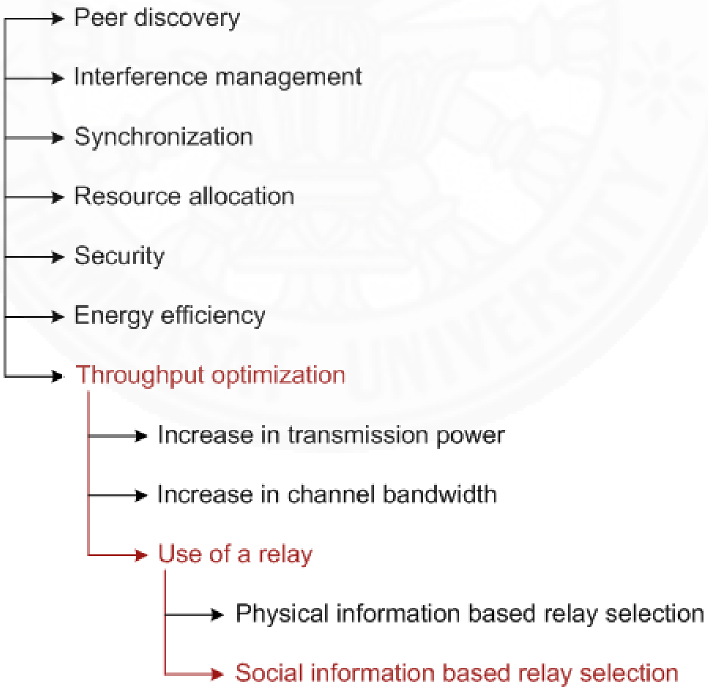


Figure 3.1 Hierarchical diagram addressing technical challenges in D2D communications

3.2.1 Incentive and reputation based D2D communications

We summarize some of the incentive and reputation mechanisms that motivate users in the network to have D2D communications between them. Incentive and reputation mechanisms can be used to enforce cooperation among devices, which intrinsically provides security features [33], [34], [35]. Relay devices in D2D communications are reluctant to relay data for others. The reason of unwillingness is due to consumption of power and bandwidth, and security threat while relaying data for others. In incentive based mechanisms, cooperation among users are stimulated by rewarding cooperative behaviours of users and punishing them for being selfish [6].

Anderegg and Eidenbenz [33] proposed a payment based incentive mechanism in mobile ad hoc networks having selfish agents. The contribution by a user is rewarded with virtual currency. This motivates user to cooperate with other users in the network.

Li and Guo [2] proposed the design of incentive mechanisms that encourage users to work under D2D mode. They designed incentive mechanisms for D2D communications where the network operator and mobile users are selfish and rational players that are only interested in maximizing their own profit. They designed two different mechanisms for two types of markets. For open markets, where players share their strategy knowledge with each other, they designed a Stackelberg game-based incentive mechanism. In this mechanism, the operator announces a fixed total budget for rewarding D2D users. For the sealed market, where the strategy is known to own and to the network operator, they designed an auction-based incentive mechanism. In this mechanism, each potential D2D pair asks for a payment from the network operator for switching to D2D mode. The network operator evaluates the prices asked by users, and determines to trade network resources with a set of winning users.

Li and Das [34] proposed a reputation-based framework to evaluate the potential to deliver data more accurately. This mechanism can be integrated with a large family of existing data forwarding protocols in opportunistic networks. They designed a reputation-assisted data forwarding protocol for opportunistic networks (RADON) to select a relay. RADON improves network performance by preventing malicious node from dropping and arbitrarily forwarding data.

Michiardi and Molva [35] proposed a CORE mechanism to maintain cooperation between devices in the network. The model is based on reputation where a central authority monitors cooperative behaviour of all the users. The reputation of a device is calculated based on data monitored by local entity and some information provided by other devices involved in each operation. The users having selfish behaviour are detected and punished. This enforces cooperation among devices in the network to prevent selfish behavior. The proposed mechanism prevents from denial of service attacks on legitimate devices caused by malicious broadcasting of negative ratings.

The review of [33], [34], [35] show that incentive and reputation mechanisms can enhance performance of D2D communications. These papers provided the insight to motivate users to cooperate with each other. Michiardi and Molva [35] presented the importance of reputation of a relay device as it is also associated with selfishness of the device. Higher value of reputation means higher cooperation between devices. The underlaying social relationship between users in the network can used for cooperation enhancement between source and relay [11]. This thesis proposes social aware relay selection schemes to improve performance of D2D communications.

3.2.2 Interference management based D2D communications

The throughput of a communication network can be enhanced by minimizing interference in the network as explained earlier in section 2.2. The interference between D2D communication and cellular communication can be mitigated by using dedicated cellular frequency for D2D communications. When underlay in-band D2D communication is used, complex resource allocation methods can be implemented to mitigate the interference caused [7]. The use of a relay can enhance quality of the communication and/ or increase range of the communication, without introducing significant co-channel interference to devices in nearby cells [36]. Interference coordination and power control can be used to control the interference between links of cellular network and D2D communications. With the adaptation of these techniques, the range of D2D communication is limited [6]. Although co-channel interference may be reduced with the use of power control techniques, interference still exists and is necessary to be dealt with seriousness. MIMO transmission schemes can be used to avoid interference. The use of MIMO schemes results in D2D signal-to-noise and interference ratio (SINR) enhancement [17].

Zhou et al. [37] optimized transmission power, transmission rates and interference cancellation configuration at receiver to optimize utility of D2D communication underlaying cellular network. The result of proposed algorithm significantly increases spectral efficiency when the number of D2D pairs are large. Wang et al. [38] proposed a novel interference coordination scheme for enhancing system throughput and increase resource utilization in a multicast D2D communication underlaying cellular network. Yu et al. [39] proposed a power control model for D2D communications underlaying cellular network. When the BS can control transmit power and radio resource for D2D links, their power control mechanism helps to coordinate the interference between cellular and D2D communications.

Kim and Stark [1] proposed a full duplex D2D communication protocol for cellular networks that uses Orthogonal Frequency Division Multiple Access (OFDMA). Their system model shares same frequency band for D2D communication and cellular communication. The mobile devices are considered to be equipped with two antennas. In a D2D mode, full duplex communication is achieved by transmitting in one antenna and receiving in the other. Self interference caused by the use of two antennas is reduced by analog and digital interference cancellation. They show that the cell bandwidth efficiency can be enhanced using single frequency for D2D communications.

The interference in a network can be managed by allocating separate frequency resources for D2D communications or using resource allocation methods [7]. MIMO and transmission power control techniques also help to mitigate interference in the network. These techniques can be used while designing two-hop D2D communication networks.

3.2.3 Security based D2D communications

Security is one of the major issues considered in a relay D2D communications. Wang et al. [40] presented a general architecture for securing D2D communication. Optimal power can be allocated to the communicating devices to prevent eavesdropping. Design of security algorithms need to consider the communication overhead and the time taken for key generation time.

Wang et al. [24] investigated the selection of jamming partner for D2D node to hamper reception by social outcasts for high quality transmission in D2D overlay mode. They developed joint optimized power allocation and jammer selection scheme to improve communication privacy of D2D overlay mode of communications in cellular networks. They used social trust to determine willingness to act as a friendly jammer. Higher value of social trust represented more dependable jammer, which means higher D2D secrecy rate. Lower value of social trust represented less dependable jammer, which means high probability of wasting allocated jamming power.

Security in a network can be improved by utilizing social information of its users. Researchers have found that binary relational ties among users can enhance behavior prediction [41]. This is advantageous in fraud detection and viral marketing.

3.2.4 Throughput optimization based D2D communications

To improve throughput of D2D communications means to increase capacity of the communications. As per the Shannon's capacity formula, increasing channel bandwidth and/or transmission power can increase throughput of D2D communications (as explained in Chapter 2). When increment in transmission power or channel bandwidth is not possible, performance enhancement of D2D communication can be done using a relay. Reduction in delay in message delivery and message overhead also improves throughput. This thesis is focused on improving the throughput of D2D communications by selecting a relay whenever possible.

Now we briefly discuss different relay selection schemes used in D2D communications.

Different relay selection techniques in D2D communications

A relay in D2D communications can be useful when channel condition between two mobile devices is poor. The relay not only enhances user experience, but also significantly reduces the traffic in BS [31].

A simple way to select a relay is to probe all the nodes in the network and choose a node that has maximum data rate. The disadvantages of this approach are that it requires huge amount of energy and is time-consuming. This reduces throughput of D2D communication. An alternative can be random relay selection which does not require probing. But the selected relay may have low transmission power and longer links. This results in reduced data rate. Therefore, discovering other ways of selecting a relay has become an area of interest.

Alotaibi and Mukherjee [32] conducted a survey on routing algorithms for wireless adhoc and mesh networks. The paper did broad survey of routing algorithms that overcome the limitations of dynamic source routing (DSR) and ad-hoc on-demand distance vector routing (AODV) (routing algorithms developed in early stage of wireless networks). Some of the routing algorithms addressing to issues in DSR and AODV are distance routing effect algorithm for mobility, location-aided routing, geographic distance routing, temporally-ordered routing, zone routing protocol, mobile just-in-time multicast, greedy perimeter stateless routing, greedy distributed spanning tree routing, geographic routing without location information, grid location service, augmented tree-based routing, infra-structure AODV for infrastructured adhoc networks, link quality source routing, load-balancing curvebell routing.

Ryu et al. [42] proposed a sub-optimal relay selection schemes for an orthogonal amplify-and-forward relaying system with half-duplexing in a multi-cell environment. The selection schemes are to maximize the instantaneous received SINR even when the channel gains for the other cells are not fully known.

All the relay selection schemes presented in [32], [42] do not consider social aspect in selection of a relay. There are several relay selection schemes which utilize social information of users for relay selection. As relay selection using social information of users is the scope of this thesis, section 3.3 presents relay selection schemes utilizing social information of users.

3.2.5 Other issues addressed in D2D communications

Motivating devices for cooperation between them is another challenge in cooperative D2D communications. Generally, mobile devices are power limited. The power consumption in a relay device while relaying data for others is the reason behind nodes behaving selfishly in a cooperative D2D communications [43].

Wang et al. [43] analyzed the impact of social selfishness on cooperative D2D communications. In their study, they show that communities having large number of members are less affected by social selfishness. Devices in the same community show more willingness to help each other, whereas devices in other communities show less interest. Moreover, the impact of social selfishness on the number of selected relay devices is maximized when the total number of relay devices and non relay devices are equal. Although this study considers the selfish behaviour of nodes to have a realistic nature of nodes, it does not analyze the impact of social trust on throughput of D2D communications.

For D2D communication between devices, the device need to discover other devices in its proximity. Now, we will summarize some of different device discovery techniques proposed in recent literature. Zou et al. [23] reviewed different proximity discovery techniques that are used for D2D techniques such as Bluetooth, WiFi direct, WiFi adhoc. They also proposed a proximity discovery for D2D communication in a cellular network. Signature-based discovery is proposed for cellular applications. Choi and Han [44] proposed a D2D discovery scheme for proximity-based services in Long-Term Evolution Advanced (LTE-A) system utilizing location information of devices. The discovery scheme is based on random access procedure in LTE-A system. Lee and Quek [45] proposed a framework for the design of reliable D2D communications in wireless mobile social network. They used transmission mode selection algorithm to select between a D2D mode and a cellular mode. A D2D mode is selected only when a communication link distance is less than a threshold value. Throughput is used as a performance metric to measure spectral efficiency.

Proper resource utilization is another important aspect in D2D communications. Hasan and Hossain [10] addressed resource allocation problem in a two-hop D2D communication network where the relay nodes serve both for cellular and D2D users. Zhao et al. [46] utilized social community information to establish efficient long range links that reduces transmission delay in a multi hop D2D communication networks. Wei et al. [4] proposed a two-time-slot physical-layer network coding scheme for multihop D2D communications. They analytically derive the average energy efficiency and spectrum efficiency of the multihop D2D communications underlaying cellular networks under orthogonal sharing mode. The analysis is done by comparing with traditional cellular communication and direct D2D communications. The analysis results show that performance of multihop D2D is significantly better than the other two.

Xiao et al. [5] used social information of users in the network for decision making process of corresponding physical D2D communication system. They have proposed a belief-based stable marriage game framework to analyze socially aware D2D communication. The proposed framework optimizes in-band spectrum sharing problem in socially aware D2D communication network. It establishes a socially aware preference over all the possible decisions by combining social connections among users with physical preference specified by physical condition of environment and properties of the available resources.

Niyato et al. [47] proposed a friend matching algorithm that allows energy sharing between nodes by identifying best friendship pair to minimize energy outage probability in mobile social energy networks. The results from relay matching solution obtained from a graph based approach show that social selfishness affects more when there are less mobile nodes in communities. The impact is largest when the total number of non-relaying devices are equal to relaying devices.

Fan et al. [48] presented an architecture to analyze the network capacity when channel resources are shared between D2D communications and cellular links. They proposed a cooperative caching strategy to improve the network capacity. The strategy caches the files having greatest popularity in the D2D group. Jung and Kim [49] presented relay assisted D2D communications to extend network coverage in Third Generation Partnership Project (3GPP). Wu et al. [50] proposed a synchronous peer-to-peer wireless physical/ medium access control network architecture called FlashLinQ. This architecture for D2D communications underlaying cellular networks enables signal-to-interference ratio based distributed scheduling.

Transmission power of a device plays an important role in performance enhancement of D2D communications. Behzad and Rubin [51] showed that throughput of ad-hoc wireless networks can be maximized by increasing transmission power of a device, independent of distribution of devices and traffic pattern. Higher degree of freedom in joint scheduling and routing scheme due to increase in transmission power helps to increase the throughput. Jambli et al. [52] investigated the impact of Transmission Power Control (TPC) technique on Ad-hoc On-demand Distance Vector (AODV) routing protocol in mobile ad-hoc networks having low mobility. They showed that implementation of TPC can reduce transmission energy consumption and improve received signal strength indicator in a multi-hop networks. Camps-Mur et al. [53] presented overview of novel functionalities in Wi-Fi Direct and expected experimental evaluation in realistic scenario. They quantified the delay when Wi-Fi Direct devices discover each other and connection is established. They also implemented a novel power saving protocol and evaluated performance variation in different realistic scenarios.

Now we will discuss relaying schemes used in D2D communications. Sharma and Garg [54] analyzed the outage probability of decode and forward relaying in two hop cooperative systems over Nakagami-m fading channels. The comparative analysis show that outage performance full-duplex relaying is better than that of half-duplex relaying for lower values of signal-to-noise ratio. Wei et al. [4] used amplify-and-forward (AF) scheme for relaying information in a multi-hop D2D communication underlaying cellular networks. The scheme utilizes two-time slot physical-layer network coding scheme. Zhang et al. [11], Pan and Wang [12], Chen et al. [13] used decode and forward relaying technique is used to forward data. In this thesis, we will also use decode and forward full duplex relaying scheme for D2D communications between devices.

Due to availability of limited frequency band, traditional cellular networks are not able to meet the ongoing demand of mobile data communications. New schemes like Femtocells caching, cognitive radio, whitespace, etc. are considered to solve the issue [48]. Similarly, D2D communications is also considered as one of the promising approach to increase network capacity that promotes direct communication between devices [13]. Resource allocation, mode selection, interference management, transmission power control, security are some of the important aspects to be considered in the design of D2D communications.

Next we explain the ways to collect social information of users in communications and present social trust models proposed for D2D communications. Then we summarize different relay selection schemes utilizing social information of users in D2D communications.

3.3 Social information based D2D communications

Social-interactions are now considered as a novel and imperative dimension in design of communication systems [14]. Analysis of social network structures in the field of biology, physiology, mental care has revealed interesting features of social networks [22]. Similarly, the characteristics of social networks formed by humans can assist in the analysis and prediction of behaviour of mobile devices in wireless communications [43]. The offline human-interactions which are assisted by human encounter patterns, together with continuous growth of both online social networks and mobile social networks generates traces of human social-connections [14]. This information can be used in D2D communications. Additionally, the characteristics of social networks formed by humans can assist in the analysis and prediction of behaviour of mobile devices in wireless communications [43]. Many papers [5], [6], [11], [12], [13], [55] have incorporated social information of users in

D2D communications.

3.3.1 Social information collection

Socially aware D2D communication is a new paradigm to enhance performance of D2D communication where each user equipment or network operator utilizes social network information of its users [5].

Xiao et al. [5] have presented different ways that nodes can collect social information of users using offline and online social networks to determine social relationship among users. Social information can be gathered from centralized and distributed network. The social relationship information obtained from online social networks are more detailed and are complex in structure as compared to offline social networks. The specific information to be utilized as a social information from online social networks is decided by nodes to enhance their performance.

Xiang et al. [41] used Facebook profile similarity among users to evaluate the quality of the estimated link strengths. The logarithms of the normalized counts of common networks, common groups, and common friends are three features that are used to capture the similarity among their profiles and their connections. They also considered two types of user interactions in the model: posting on Facebook wall and tagging on pictures.

Pan and Wang [12] used contact history to measure social tie strength in a social-aware cooperative D2D communication network. Similarly, Li et al. [31] used time factor and interactivity factor to measure social relationship strength. They represented time factor by average contact duration and interactivity factor by common friend index.

3.3.2 Social trust models used for D2D communications

A strong social tie between a pair of people represents close social bonds that they have. Difference in tie strengths are used to describe social relationships between people in social science. Those people having brief connections (connected only via acquaintance) represent weak ties among them [15].

When the network size is large, aggregated call duration of users in the network can be used as a proxy to estimate social tie strength between them. Bandford et al. [15] presented a method to estimate social tie strength in networks having small number of users. They found that aggregated call duration can also be used for tie strength estimation when users in the network are less than one hundred. They also found that tie strength estimated using aggregated call duration produces similar results as when the total call count is used. In addition to that, proximity duration and total proximity count can also be used as proxies for tie strength estimation. The accuracy of tie strength estimation can be improved by combining many proxies such as email, instant messaging, SMS.

Just having binary relational ties (whether there is a relational tie or not) increases noise level in social trust model leading to performance degradation. Xiang et al. [41] used the interaction information of users in the network to model continuous-valued social strength. For example, a Facebook user may have hundreds of friends in his/her account. Any of his/her friends can post messages on Wall page or write a message to interact. Users communicate more frequently with friends with strong ties compared to those having acquaintances. Users on online social networks have both strong and weak ties. The users having strong ties (e.g., close friends) generally exhibit greater similarity compared to those with weak ties (e.g., acquaintances). The relationship strength is estimated formulating a link-based latent variable model, along with a coordinate ascent optimization procedure for inference. The estimation is based on interaction activity (e.g., communication, tagging) and similarity in account profile of users. The estimation model is not limited to distinguish between strong and weak relationships for links. Rather it provides continuous-valued relationship strength. The authors used real-world data from public Prudue Facebook network to show that the estimated link weights result in higher autocorrelation and lead to improved classification accuracy.

In this thesis, we use call history to estimate the social trust among users in the network. The detailed explanation of how we are using social trust in relay selection is presented in section 4.2.

3.3.3 Different social-aware relaying schemes for D2D communications

Generally, mobile devices have limited battery power and storage capacity. In networks allowing relay assited D2D communications, unselfish relays might always be honestly forwarding data for others, causing it to run out of battery power. On the contrary, selfish nodes might be using relay to enhance their D2D communications. However, those selfish nodes may not be forwarding data for others. Therefore it is necessary to design a D2D relay selection mechanism that is energy efficient and have low complexity [31].

Recent research in developing efficient D2D communication systems is exploring more into social aspect of mobile users. The information related to social relationship between users can be utilized for selection of relay in D2D communications. Now we summarize some of the recent works related to social-aware relay selection.

Chen et al. [13] created physical-social graphs for cooperative D2D communications. Li et al. [22] investigated social features of social network influencing D2D communications. The social features are required for design of social-aware D2D communication systems. They suggest that the rate at which a node sends a signal to discover other nodes in its surrounds can be adjusted by users depending upon the strength of social relations among users. Ying et al. [55] introduced geo-social metrics that comprises location and social relationship among users to route data in mobile opportunistic networks. Similarly, Tao et al. [56] designed a characteristic based opportunistic forwarding scheme using contact frequency and characteristics of users.

Xiao et al. [5] used online social information to establish a belief function and used the belief function to optimize socially aware D2D communication system. Public belief function can be used in network assisted D2D communication network where BS helps to establish the belief function for each nodes in the network. On the other hand, in a distributed network, private belief function can be used. Each node have private belief function whose value is determined using private information obtained from its online social networks known only to the individual node. Furthermore, the belief function can be fixed or dynamic depending upon the adaptation and learning ability of nodes. None of these work relate social information of users to transmission power of a relay.

Pan and Wang [12] proposed a Hybrid Relay Selection (HRS) scheme which utilizes social information of users to select a relay. We compare HRS scheme with relay selection schemes proposed in this thesis. Their premise, and one that we also use in this thesis, is that (users of) mobile devices that have a strong relationship with each other usually have a high value of social trust between them, and thus potential to contribute more in terms of transmission power. They consider both link characteristics and social trust between users for relay selection.

In HRS, a relay is selected around the source. A source probes devices that are not engaged in communication and located within a circular region with the source at the center as illustrated in Figure 3.2. The devices must also have a social trust greater than a threshold value. HRS assumes the transmission power of a relay is linearly proportional to the social trust between the source and the relay. Pareto distribution is used to model the social trust between the users. The source calculates the data rate offered by each of the probed nodes and chooses the node that offers maximum data rate as a relay. Pan and Wang show average throughput of HRS is higher than two other schemes: Distance-based Relay Selection (DRS) and Social-based Relay Selection (SRS). For relay selection, DRS considers distance between the source and the relay, while SRS considers social trust between the source and the relay. Moreover, they suggested relay selection region should neither be too small nor too large. The major drawback of the HRS scheme is that it achieves low throughput when the search radius is small due to frequent selection of long distance links. Also, when the search radius is large, throughput is again low due to significant time spent for probing. Additionally, the performance of HRS is not compared against relay selection schemes proposed by other researchers.

Chen et al. [13] advocates an interdisciplinary approach to integrate social network structure into the design of cooperative D2D relaying by utilizing social trust

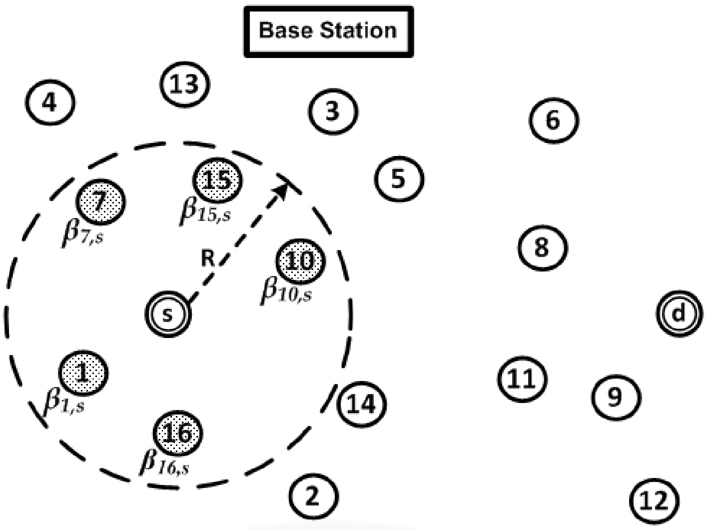


Figure 3.2 System model for HRS in [12]

among mobile users while selecting a relay. Social distance that is created from the social relationship between nodes and physical distance created from the physical relationship are used for analysis of cooperative D2D communications. Figure 3.3 illustrates the graphs for physical distance between nodes in the network and Figure 3.4 illustrates the graphs for social distance between nodes in the network. They assumed that a mobile node relays data for other nodes at high transmission power when it has a social relationship with them. When there is no social relationship between mobile users, social reciprocity is used for relaying data in D2D communications. In their study, they show that a relay selection based on social trust and/or social reciprocity can make significant improvement in average throughput. Moreover, this improvement also increases with the increase in number of users in the system. Experiment results showed that the proposed mechanism can achieve upto 122% performance gain over the case without D2D cooperation.

Similarly, Zhu et al. [6] proposed two social-aware relay selection schemes using social information of users. They are rate-based selection scheme (RBS) and hybrid relay selection based on rate and cooperation probability (CRBS). The encounter history is used to measure the tie strength of users with the source. Social tie is used to determine the transmission power of a relay. Reputation is used to ensure reliable data communication and reflect willingness to forward data. They combined

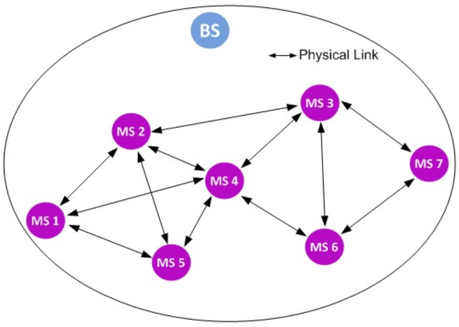


Figure 3.3 Physical links among nodes

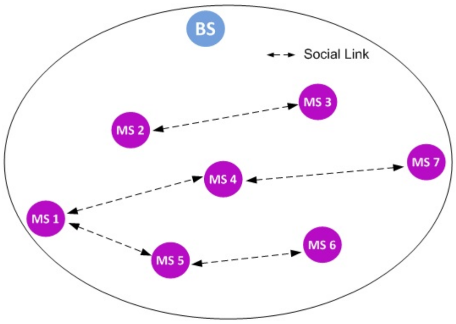


Figure 3.4 Social links among nodes

social tie and reputation to determine cooperation probability of a relay. The relay is selected among the nodes located within a circular region with center at the source. They assumed that there is no interference between D2D pairs because different cellular resources are used for different D2D pairs. Pareto distribution is used to model the social tie strength between the users in simulation. The results show that there is a trade-off between cooperation probability and transmission rate of potential relay. The hybrid relay selection based on rate and cooperation probability (CRBS) has best performance when transmission time is short. However, rate-based scheme (RBS) has best performance when transmission time is long.

Li et al. [31] proposed an optimal stopping relay selection scheme that uses social threshold to enhance throughput of D2D communications in a distributed network. They used average contact duration and common friends to represent social relationship weight coefficient. The use of social threshold helps to filter candidate relay nodes. Then a relay is selected using an optimal stopping approach. The proposed scheme significantly reduces the time taken for probing of nodes before selection of a relay. This helped to balance between probing time and throughput gain.

Zhang et al. [11] developed a social trust based cooperative D2D relaying which considers physical and social distances among users. In their research, the transmission power of relay node is determined by social trust. The relay is assumed to be willing to contribute more in terms of power resource, when there is strong relationship between source and relay. Decode and forward relaying technique is used to forward data. Optimal stopping approach is used to select the relay by probing socially trusted nodes sequentially in each time slot. It is used to maintain balance between relay probing cost and performance gain. Their simulation results show that, source node probes 10-15 nodes sequentially before transmitting data. The nodes are probed to measure SNR of the links and identify the node offering maximum data rate. The limitation of their research is that they just compared the proposed scheme with generic schemes (direct communication and random relay selection). They assumed that the social trust among the users follow uniform distribution, which is not realistic. Additionally, they analyzed the scheme only for a specific distance (100 m) between source and destination. In reality, source - destination distance is not a constant, but varies at different time.

In this thesis, different versions of midpoint relay selection schemes that utilizes social trust of users are proposed in Chapter 5, 6 and 7 to enhance performance of D2D communication. All the schemes proposed are applicable for centralized systems. When D2D communications are implemented in cellular mobile networks, network operator can keep track of the D2D communications. This helps network operator for billing its subscribers for using cellular frequency for D2D communications.

CHAPTER 4

A FRAMEWORK FOR SOCIAL-AWARE RELAY SELECTION SCHEMES

This chapter presents a framework for the design of relay selection schemes for D2D communications leveraging social information of users. This framework is used in the design of detailed schemes in Chapter 5, 6 and 7.

This chapter first presents the assumed environment for social-aware D2D communications. Section 4.1 presents assumptions about devices, the network topology used in D2D communication system, communications link model and the mobility model. Section 4.2 explains characteristics of people having social trust and modelling of social trust among people using Pareto distribution. Section 4.3 describes how social trust among mobile users can be related to transmission power of a relay device. Section 4.4 presents the system architecture of different types mobile devices, those supporting and not supporting D2D communications. The aim of this section is to give the reader an idea about the differences in capabilities of mobile devices that do or do not support D2D with social information.

4.1 D2D communication system model

This section presents the set of assumptions made about the devices, network model considered and communication channel used for the communication between the devices. Section 4.1.1 explains the assumptions related to devices and network topology used in this system model. Section 4.1.2 defines the channel used for communication, transmission power of devices, capacity and throughput calculation of a channel. These are used for comparative performance analysis of the relay selection schemes presented in subsequent chapters. Section 4.1.3 illustrates the information exchange between devices for selection of a relay in D2D communication and communication protocols used.

4.1.1 Network model

We assume the system contains a single BS and n_{total} mobile devices held by people. The devices are located across a rectangular area of x and y meters. Section 4.1.4 further details about device locations and mobility. Figure 4.1 illustrates the search location of a socially trusted relay device that improves the D2D communication between mobile devices. The double-lined circles are source device s and destination device d. The dashed circle with radius R represents a relay selection region which is centered at the midpoint M of the distance between s and d. A socially trusted relay device is selected among the nodes which are located within this circle. $\beta_{r,s}$ represents the social trust value that a device has for the source.

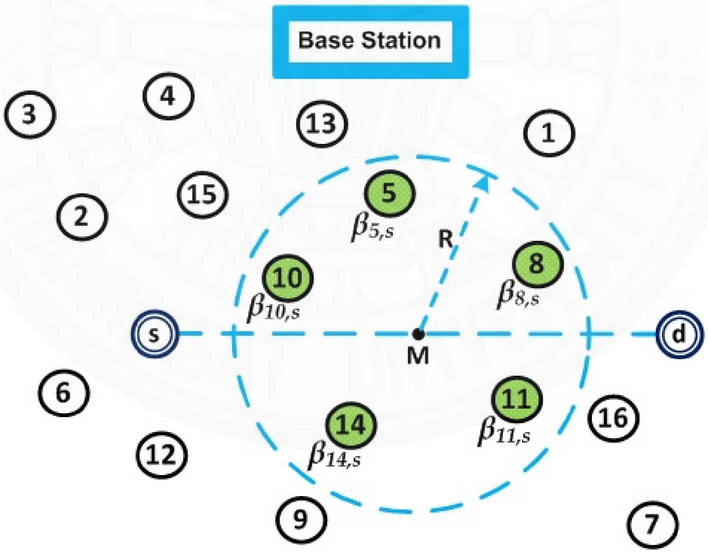


Figure 4.1 A system model for D2D communications

We assume this is a cooperative network. This means all mobile devices which are not engaged in communication are willing to act as a relay by forwarding the information sent by the source to the destination. However, we also assume that the devices do not transmit with the same power while relaying information for other devices [6], [11], [12]. Section 4.3 further explains details about transmission power of a relay device.

We assume each MS periodically informs the BS of its geographical coordinates. Each MS has a Global Positioning System (GPS) or a location tracker which is used to update the BS about its location. This helps the BS to locate devices within its coverage area and recommend a list of devices that are located within the circular region for relay selection.

4.1.2 Communication link model

When a mobile device (source) wants to have a D2D communication with another mobile device (destination) using cellular frequency, there are two ways for the information exchange between the source (s) and the destination (d) bypassing the BS. One way is to send data packets directly to the destination from the source. An alternative way is to initially send a data packet to another mobile device in proximity which acts as a relay device (r). Then the relay forwards the data packet to the destination. In this thesis, decode-and-forward (DF) relaying scheme is used for D2D communications to forward data as in [11], [12], [13], [43].

Channel of D2D communications. Operator controlled link establishment is used for both direct D2D communication or D2D communication via a relay as envisioned in [57]. Cellular channel is considered to be used for D2D communication where the channel is synchronously used for communication between the source to the relay and from the relay to the destination. We assume that a BS assigns frequencies for D2D communication between each active pair of mobile devices. The frequency assigned for the communication is such that each device pair get different frequency (channel) for a certain time (time slot) that do not interfere with regular mobile communications and D2D communications between other pair of devices in proximity. When a relay is selected for D2D communications, the same frequency is used for communication between the source to the relay and that from the relay to the destination.

Transmission power of D2D communications. In a cellular network, the transmission power of mobile devices are low, limited to a certain value, so that the transmission from a device do not interfere with the transmissions from other devices in the cell as well as neighbouring cells. Similarly, in D2D communications underlying cellular networks, the communication between a source and a destination should not interfere other D2D communication pairs and traditional cellular communications. Therefore, we assume that the BS determines the transmission power of D2D communication between mobile devices based on the network parameters and protection required for neighbouring cellular devices [11], [13]. This transmission power is known as maximum allowable transmission power and is denoted by P_{max}. All the mobile devices in the network having D2D communications transmit at a power $P_{i,j} \leq P_{max}$. A source, s, always transmits at the maximum allowable transmission power i.e. $P_{s,j} = P_{max}$. We assume that a relay may not transmit at P_{max}. Later in section 4.3, we explain the rationale behind this assumption. We assume the background noise is constant and there is interference in the system due to high frequency reuse factor [45].

Signal-to-noise-ratio of a link. A source communicates with a destination either using a direct link or a D2D link. The source compares between the data rate offered by direct link and D2D link before the selection of communication path. The signal-to-noise-ratio (SNR) of a link is used to calculate the data rate offered by the link. The SNR of a direct link can be expressed as

$$\gamma_{s,d} = \frac{P_{s,d} D_{s,d}^{-\theta}}{N} \tag{4.1}$$

where, $P_{s,d}$ is the transmission power of a signal from the source to the destination, $D_{s,d}$ is the distance between the source and the destination, N is the noise power and θ is the pathloss exponent.

Data rate of a link. According to Shannon's capacity formula, the maximum reliable data rate of a direct link is given by

$$C_{s,d} = B\log_2(1+\gamma_{s,d}) \tag{4.2}$$

where, B is the bandwidth of the channel.

The data rate of a D2D link having full duplex decode-and-forward (DF) relaying is given by

$$C_{s,r,d} = B\min\{\log_2(1+\gamma_{s,r}), \log_2(1+\gamma_{s,d}+\gamma_{r,d})\} \tag{4.3}$$

where, $\gamma_{s,r}$ is SNR of the signal from the source to the relay, $\gamma_{s,d}$ is SNR of the signal from the source to the destination and $\gamma_{r,d}$ is SNR of the signal from the relay to the destination [6], [11], [58].

Throughput of D2D communications using TDMA mechanism. We assume that TDMA mechanism is used for data transmission. TDMA allows only one user to transmit in each time slot using different frequency (channel) assigned by the BS. Within a time slot, a source initially tries to find a relay device by probing neighbouring devices that are located within a circular region that can potentially transmit at a high power, after which the actual user data transmission occurs. A fraction of a time slot is used for probing and the rest is used for actual data transmission. Time slot duration is represented by t and probe duration is represented by τ such that $t >> \tau$. The time taken for sequential probing of candidate relay nodes and time left for actual data transmission is illustrated in Figure 4.2.

Taking into account the time wasted while probing different devices, the throughput of a D2D communication is calculated as

$$T_{s,d} = \frac{C_{s,r,d}\{t-(\tau\times p)\}}{t} \tag{4.4}$$

where, t is the time slot duration, τ is the probe duration and p is the number of probes.

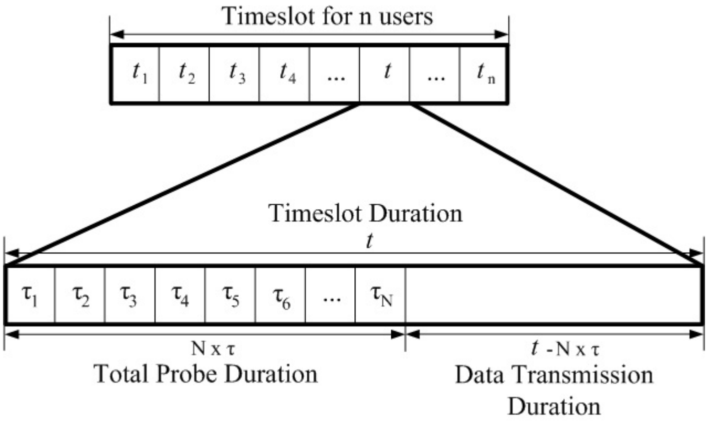


Figure 4.2 Representation of time slot

By comparing the throughput offered by the direct link and that offered by the D2D link, the performance of D2D communication can be improved by selecting a relay device whenever possible.

Since the background noise is considered to be constant and is interference free, the transmission power of a relay and its location are two primary factors that determines the data rate of a signal through a D2D link. The above expression is accurate only when the communication occurs in a free space where SNR value depends only on the transmission power of a relay and its location. In reality, there might be some cases where obstacles are located around the midpoint area causing the SNR value to be low, while nodes located far apart from the midpoint, through reflection may provide higher values of SNR. Our simulation model does not take this factor into account.We consider there are no major obstacles present in the path when the signal propagates from the source to the destination. However, our proposed schemes also take into account such factor. By utilizing the probing, one can obtain the actual values of the SNR.

4.1.3 Probing of devices and related protocol

Probes are short messages used to exchange information between a source, other devices in proximity, and a destination necessary to select a relay. A source probes the nearby devices to learn about link conditions for relaying data from the source to the destination. We design a communication protocol for relay selection that constitutes an exchange of information during sequential probing of devices as shown in Figure 4.3. It consists of three phases: Initiation phase, Probing phase and Data transmission phase.

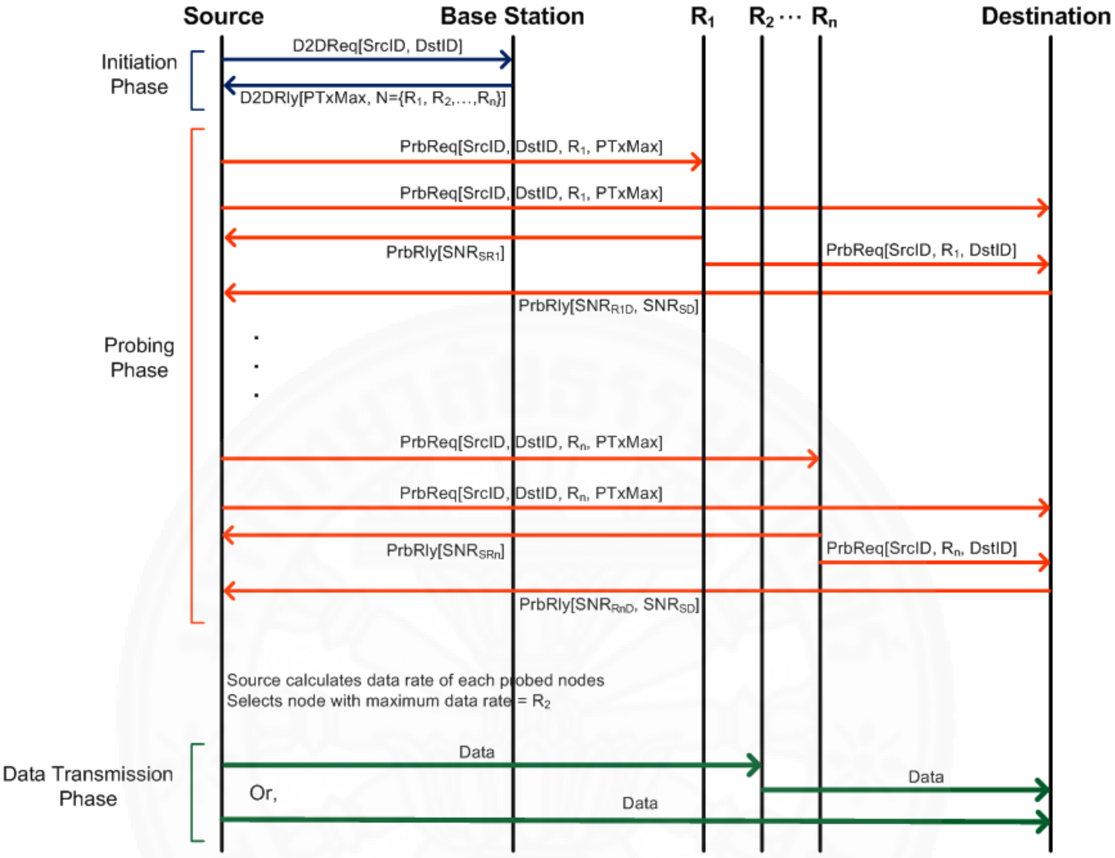


Figure 4.3 Probing for relay selection

In the initiation phase, a source which wants to have a relay to assist in communication with a destination sends a D2D communication request message to the BS. The message contains source and destination identity. Upon receiving the request message, BS identifies location of the source and the destination, and calculates the corresponding midpoint *m* using the location information. The BS then identifies the idle nodes that are located within a circular region of radius *R* with the center at the midpoint. The BS also determines the maximum transmission power *Pmax* that is allowable for D2D communication of based on the system parameters (geo-location) and protection requirement of neighbouring cellular devices [11], [13]. After that, the BS sends a message back to the source containing the list of idle devices that can be probed and maximum allowable transmission power for D2D communication.

Upon receiving the message from the BS, the source determines the socially trusted devices in the list using its contact list and initiates probing of those devices sequentially as in [11]. The trusted devices are identified as explained later in section 4.2.1. A source probes devices by sending a message containing source identity, destination identity, probed device identity and maximum allowable transmission power. The message is also received by the destination. As a reply to a probe, each of the devices which are available for relaying data, individually responds to the source with SNR of the probe signal they have received and forwards the probe message to the destination. Each of the relaying devices transmits at a power proportional to the social trust it has for the source [11], [12]. The destination calculates SNR for each of the received probing packets and sends the SNR values to the source. The source calculates estimated data rate offered by each of those devices based upon link conditions and transmission power, and selects a device which offers maximum rate.

The source takes into account time wasted while probing devices. The more candidate devices to be probed, the more time is wasted for real communications. The source estimates the throughput offered by that selected device and compares it with the direct communication. Data transmission phase starts after the source decides whether to use the selected device as a relay or not. If a relay is to be used, the source sends the data to the relay which is forwarded to the destination.

4.1.4 Mobility model

A mobility model is used to describe the pattern in which mobile users moves in a network. It explains how the location of mobile users changes over time and the associated velocity and acceleration change. The mobility pattern of devices considered may affect performance of a communication protocol. Therefore, the mobility model chosen should properly emulate movement pattern of scenarios as close as possible where we are using that communication protocol.

In this thesis, a random waypoint mobility model [29], [59] is used to model mobility of users in the network. In random waypoint mobility model, a node moves from a waypoint towards the next waypoint along a straight line segment at a certain velocity from an interval $[v_{min},v_{min}]$ after waiting for a constant pause time. Once the node arrives at the waypoint, it waits for a constant pause time and selects the next waypoint. Uniform distribution is used to choose the next waypoint for a node. This is similar to the movement of people carrying mobile devices [59], [60].

This model is suitable when nodes are moving, but with limited mobility [61]. For example: a scenario where large number of people gather in a small area for certain duration of time such as educational institutions, organizations, industries, or events like concerts, conferences or exhibitions. When the nodes are not moving fast and pauses for certain time in between, the source can get fairly accurate SNR of the communication links by probing a node within a probe duration (τ) before relay selection (as explained in section 4.1.3). This mobility model may not be suitable when the mobile devices have high mobility i.e. when we are considering vehicular networks. The limitations of this mobility model are:

1. Temporal dependency of velocity
2. Spatial dependency of velocity
3. Geographic restrictions of movement

In random waypoint model, velocity of mobile node is a memoryless random process. It means that the velocity at current epoch does not depend upon the previous epoch. This may lead to frequent occurance of sudden stop, sudden acceleration and sharp turn. However, in reality, the speed of vehicles and pedestrians accelerate gradually, with a smooth change in direction [62]. In random waypoint model, nodes move independently of each other [29]. This kind of mobility model is classified as entity mobility model. However, movement of mobile nodes can sometimes be influenced by other node. For example, in a battlefield communication and museum touring, the movement pattern of a mobile node depends upon its leader node. Hence, the mobility of various nodes is indeed correlated [62]. Although there are some drawbacks, this mobility model is widely used in the performance evaluation of adhoc networks [60]. Next section presents the social trust model used for the nodes. Social trust model is used to estimate the social relationship strength between users of the devices.

4.2 Social trust model

Section 4.2.1 explains the importance of social information in D2D communications using a relay and how this information can be collected under different scenarios. Section 4.2.2 explains why and how Pareto distribution is used to model social trust.

4.2.1 Social information collection system

Social trust is developed among two individual by mutual relationship. The information on social trust among users in the network can be utilized to improve D2D communication performance. When we analyze the behaviour of people in a community, people having strong social trust with each other show more willingness to help compared to other members in the community [6], [11]. This behaviour of people can be utilized in designing a relay selection scheme of D2D communications.

Social information of users can be collected either at a BS or at a node. Calls and messages suggest social links among users; and frequency and duration of calls reflect social relationship strength between them as in [12]. In this thesis, one can then estimate the social trust values from; e.g. call history. A social trust node n_2 has on node n_1, denoted by $\beta_{2,1}$, can be calculated depending upon the call duration between the two nodes and total duration of call n_2 has with other nodes in the network. In such a case, the social trust $\beta_{2,1}$ is only known to n_2. When the value of social trust that a relay has for a source is high, the relay transmits at a high power and when the social trust value is low, the relay transmits at a low power.

Software can be implemented on a mobile node that calculates value of social trust based upon call history. Social trust values are calculated for nodes on contact list of a user using frequency and duration of calls. However, social trust calculated by a BS and sent to source can be more accurate. Such information is readily recorded by the service provider anyway for billing purpose. Social information of users that are available to the public in online networking sites on the Internet, such as Facebook or Twitter or any other networking platforms, can be incorporated to increase accuracy of the trust values predicted. Many mobile operators are gathering social information of mobile users by encouraging them to provide their social information in an exchange of free internet services to limited online social networking sites. In case of multiple BSs, movement of users into coverage area of another BS requires a centralized system to keep track of call history. The exchange of call history among BSs is required and additional processing to calculate social trust. On the other hand, software on a user device can easily calculate social trust even when the user moves to coverage of different BSs. Our proposed scheme can be applied regardless of where the social trust values are calculated. More specifically, MRS-SA, MRS-ST and MRS-SD can be used when social trust is calculated at the nodes. Adaptive-MRS can be used when BS calculates the social trust values. The following paragraphs explain the statistical social trust model used in this work.

4.2.2 Social trust model using Pareto distribution

In order to simulate social relationships between users, a statistical model of social trust is needed. One challenge while analyzing schemes that use social trust is developing an accurate model of social trust. Generally, social trust among majority of people in a community are weak. Only few people have high social trust between them. The users having strong social relationship with each other usually have high social trust between them. A mathematical model of a social trust would therefore have a heavy tailed distribution. The authors in [6], [12] have modeled social trust using Pareto distribution to represent a heavy-tailed distribution. Here, the social trust among people is characterized by a Pareto probability density function which is defined as

$$f_X(x) = \frac{\alpha L^{\alpha} x^{-\alpha-1}}{1-\left(\frac{L}{H}\right)^{\alpha}}, L \leq x \leq H, \text{and } \alpha > 0 \tag{4.5}$$

where α, L and H denote the shape, scale and upper limit parameters, respectively

[63]. The value of α determines how fast the distribution tail decays and L also represent the lower limit of the support. Different values of social trust among nodes are achieved by varying α and L, keeping H constant at a value of 1.

The social trust model is used to get a social trust value for a link between devices. Each node knows social trust value it has for other nodes. The social trust value that a source has for a relay may not be exactly equal to the actual social trust value the relay has for the source. However, the social trust values that the source has for other devices provide an idea of which devices have the potential to transmit at a high power. Surveyed data in [57] suggests that strength of social trust among people is bidirectional, at least 75% of the time. Therefore, in this work, social trust among users in the network is considered to be bidirectional, which means the source knows how much it is trusted by other nodes in the network. The social trust value can be used to select nodes that can potentially transmit at a higher power.

In the next section, we explain the rationale behind assuming transmission power of a relay proportional to the social trust in a social-aware D2D communication system.

4.3 Relay transmission power

The network is considered to have mobile devices, which are power constrained devices. These devices try to save its battery power whenever possible. Therefore, even in a cooperative D2D communication network, a relay device may not always transmit at a maximum power possible because high transmission power drains more battery power of the device. This means, a cooperative relay device prefers to transmit at a low power that is still equal to or greater than a minimum threshold value of transmission power.

We assume that the transmission power of a relay is linearly proportional to the strength of social trust between the relay and the source [12]. It is denoted by $\beta_{r,s}$. The rationale behind this assumption is that when people carrying mobile devices have strong social trust with each other, they show more willingness to help each other by transmitting at a higher power compared to those with weak social trust. The social trust value for the link between two devices (a source and a relay) is modelled using Pareto distribution as explained in section 4.2.

Transmission power of a relay is one of the major factors affecting the throughput of D2D communications as explained in section 4.1.2. Higher transmission power results in throughput enhancement considering other factors to be constant. Therefore, a desirable relay should have strong social trust with the source so that the relay transmits at a high power. As a result, higher throughput can be achieved.

At present, mobile devices that are available in market are not capable of sending information directly with each other using cellular spectrum. The system architecture a mobile device supporting D2D communications using cellular spectrum is different than that of mobile devices that are available these days. In section 4.4, differences in system architecture of general mobile devices and mobile devices having D2D communication features are presented.

4.4 System architecture of mobile devices

This section presents the different sets of assumptions about mobile devices. The aim of this section is to give the reader general idea of the differences in system architecture and capabilities of mobile devices that are present in the market today and those supporting D2D communications using cellular spectrum. The main focus is to show how the system architecture of a mobile device that utilizes social information of users for relay selection in D2D communication differs from the others. In the subsequent chapters, mobile devices are considered to be social-aware D2D enabled mobile devices.

4.4.1 General mobile device components

General mobile devices that are available in the market today support D2D communications for the information exchanges between the devices using Bluetooth, Infrared or WiFi technologies. However, D2D communication functionality that uses mobile cellular frequency is not available yet.

Figure 4.4 shows simplified system architecture of two mobile devices in proximity communicating via a BS. The mobile device are assumed to have three layers namely Application, Transport/ Network and Physical layers. In the Application layer, there are Phone calling application, Web browsers, Online social applications such as Facebook, Twitter, Instagram, etc. All these applications communicate via Transport and Network protocols and the wireless hardware (transmit and receive antennas). A transceiver in wireless hardware of the mobile device transmits user information to the nearby BS and also receives the information from the BS. Similarly at the destination end, information exchange occurs in the same fashion. This is how all the data traffic goes via a BS when mobile devices communicate using cellular spectrum.

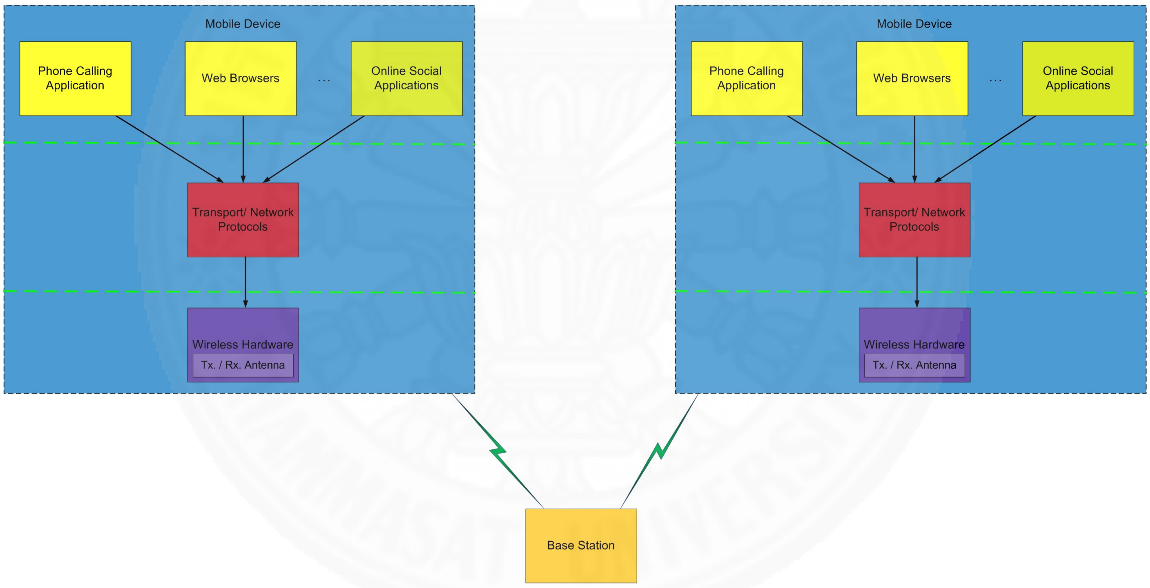


Figure 4.4 System architecture of general mobile devices

4.4.2 General D2D enabled mobile device components

Figure 4.5 shows the D2D communications between two mobile devices.

In a general mobile phone that is capable of D2D communications, the transmission power of a wireless antenna is assumed have a fixed value which is set according to the maximum allowable transmission power determined by the BS. It helps to avoid the interference caused by the D2D communications. It is assumed that

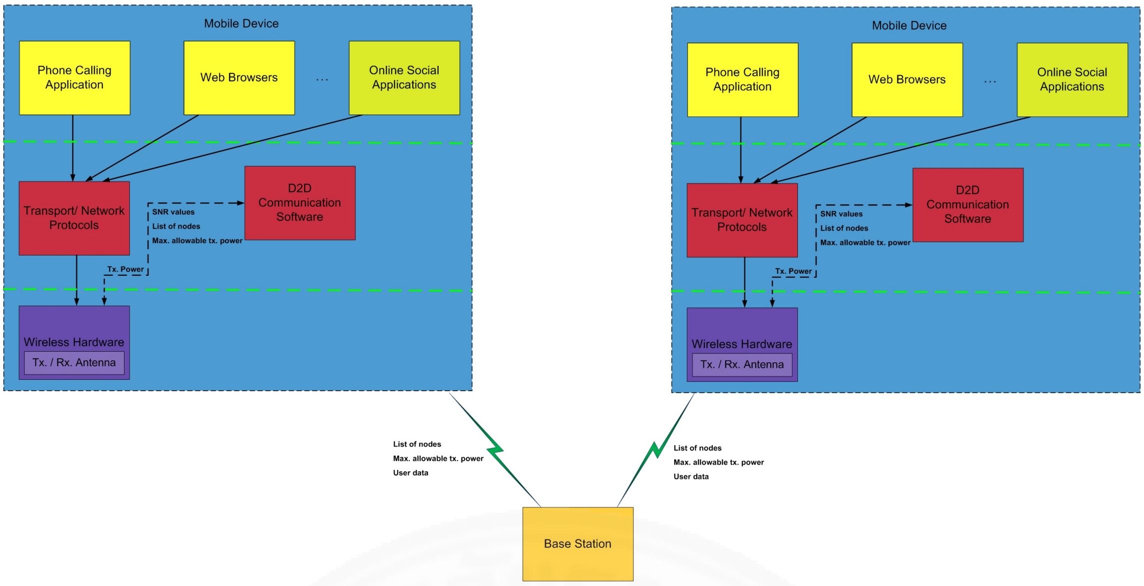


Figure 4.5 System architecture of D2D enabled mobile devices

there is an information exchange between the BS and D2D communication software through wireless hardware on a mobile device.

4.4.3 Social-aware D2D enabled mobile device components

In Section 4.4.2, we explained the components of mobile devices when they have D2D communication capability. However, if the mobile devices are also socially aware, then the components and capabilities of mobile devices are assumed to be different. Now, in this section we present the components and capabilities of mobile devices supporting social-aware D2D communications. Figure 4.6 shows the communication between social-aware D2D enabled mobile devices and a BS. One of the mobile devices is enlarged to emphasize the layering model of system architecture of a mobile device, information that are required from other components in the mobile device and source (component of mobile) of those information.

D2D enabled mobile phone is assumed to have an operating system with additional functionality. We assume that it receives information from online social platforms/ applications and call history to select a relay and set transmission power of the relay.

Inside simplified architecture of a mobile device, there are three layers. Appli-

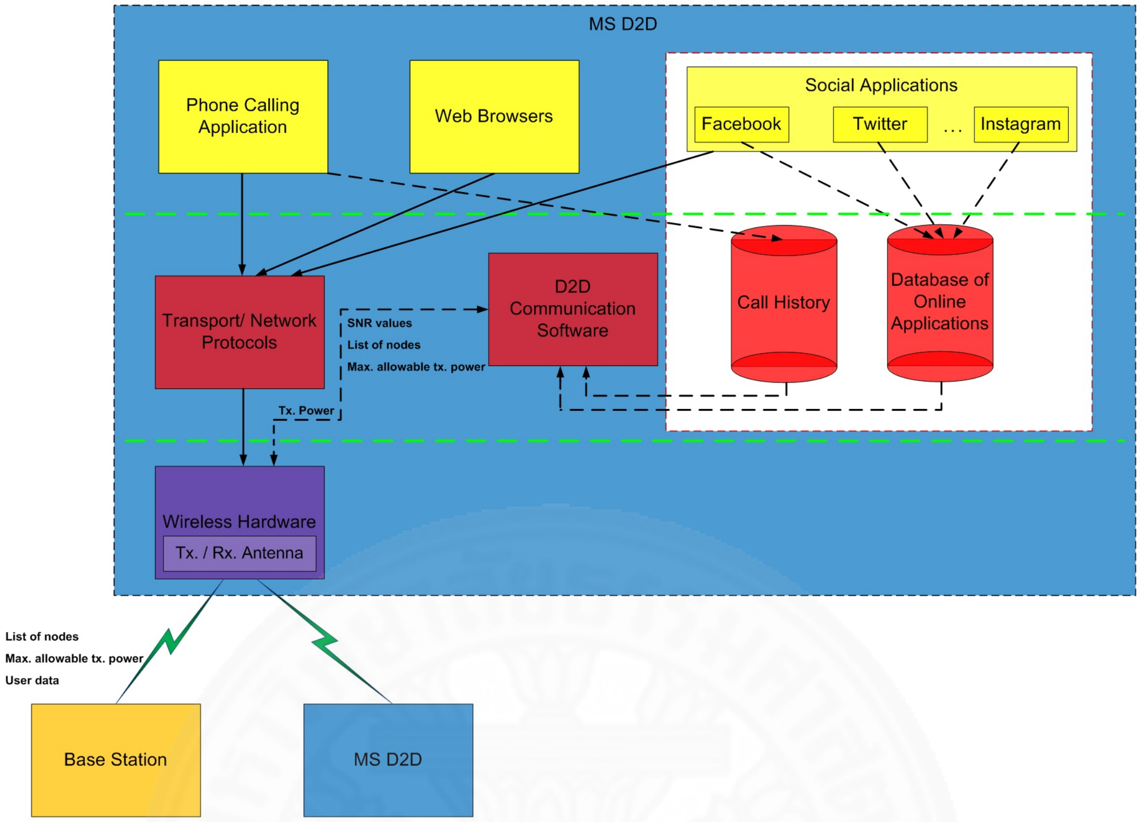


Figure 4.6 System architecture of social-aware D2D enabled mobile device

cation, Transport/ Network and Physical. In Application layer, there are Phone calling application, Web browsers, Social applications such as Facebook, Twitter, Instagram, etc. They all communicate via Transport and Network protocols, the wireless hardware (transmit and receive antennas). In addition, we assume that some of them populate the call history and database of online applications. D2D communication software reads that information and sends the information to wireless hardware.

The flow of user data is represented by solid lines and the flow of control information is represented by dashed lines. Applications send user data to transport/ network protocols and then to the wireless hardware. The Phone Calling Application sends information to Call History and Social Applications sends information to database of Online Applications. The information from these databases are sent to D2D Communication Software which is used to set the transmission power of antenna for D2D communications. D2D Communication Software also receives some information from Wireless Hardware that is used to determine the transmission power of D2D communications.

Database of online applications fetches the social information of users in the network. The social information of different applications together with call history of users are sent to D2D communication software. This software also receives the information such as list of nodes, maximum allowable transmission power from the Base Station. All these information together with information from Call History and Online Application databases are used to produce a social trust value. Depending upon the social trust value, the transmission power of the device is set.

Based upon the framework design presented in this chapter, different relay selection schemes are presented in subsequent chapters.

Location and social trust value are required for selection of a relay device. The design of a two hop relay communication system can vary depending upon which entity in the network has these information. In this thesis, we consider two different scenarios. We consider a scenario where the BS know only the location of the mobile devices. Only the mobile device knows the social trust the device user has for other device users in the network. In another scenario, we consider that the BS not only knows the location information, but also the social trust value that a user has for other users in the network. These scenarios are used in the subsequent chapters.

CHAPTER 5

MIDPOINT RELAY SELECTION WITH SOCIAL AWARENESS

This chapter presents the Midpoint Relay Selection with Social Awareness (MRS-SA) scheme. This is the initial version of our relay selection scheme presented in this thesis. The authors in [12] presented a method of selecting a relay around a source in the Hybrid Relay Selection (HRS) scheme. In this chapter we show that selection of a relay around the midpoint of the distance between the source and the destination can significantly improve throughput of the network compared to the scheme presented in [12]. Over time we have investigated multiple different schemes. MRS-SA was our first proposed scheme. However, from further analysis it is found that it can be improved upon. We still present MRS-SA here to demonstrate the progression of our research. It is also beneficial to present because of the simplicity of the scheme. The improved version of this scheme is presented in Chapter 6.

The MRS-SA scheme presented in this chapter is published in the paper entitled ”Social-aware Relay Selection for Device-to-Device Communications in Cooperative Cellular Networks” in proceedings of the 2017 International Electrical Engineering Congress (iEECON 2017), Pattaya Thailand, 8-10 March 2017. The paper presents Midpoint Relay Selection Scheme (MRSS). MRSS is renamed to be MRS-SA in this chapter to have similarity with the naming of other relay selection schemes presented in subsequent chapters. The results produced in this chapter are different and have more realistic comparison than the results published in paper [64] because we have improved following aspects:

- modelling of social trust is improved

- modelling of power of a relay is improved according to our assumption
- time taken for probing is taken into consideration while plotting the average throughput graphs.

Additionally, we are presenting more results as listed below:

- Comparison of average number of direct communications in MRS-SA with that in HRS
- Comparison of average distance between chosen nodes for DTS, HRS and MRS-SA with the increase in search radius.

Section 5.1 presents the idea of balancing the distance from a source to a relay and that from the relay to a destination to improve throughput of D2D communications. Section 5.2 presents different issues to be considered in the design of a relay selection scheme followed by the actual design of the proposed scheme. Section 5.3 initially presents the simulation setup used for the performance analysis of MRS-SA. We then present the analysis of the comparison of average throughput of MRS-SA with other schemes, the comparison of average frequency of direct communications of MRS-SA with HRS and the comparison of distance between nodes of MRS-SA with other schemes. Finally, section 5.4 concludes that MRS-SA can be used to achieve higher throughput than HRS.

5.1 Motivation

The authors in [12] have presented HRS scheme, where a source node selects a relay by probing idle nodes that are located within a circular region around the source and are also friends of the source. This approach may not be optimal.

We simulated different scenarios placing a relay at different locations between the source and the destination, and plotted the data rate offered by each of those relay locations. This data was presented in Chapter 2. However, for the convenience of readers we are presenting the results again in Figure 5.1 and Figure 5.2. From careful observation of the graphs, we can see that the region with higher data rate is not symmetric and is located around the midpoint of the distance between the source and the destination. This suggests that data rate through a relay depends mainly upon SNR_{SR} and SNR_{RD}, not on SNR_{SD}. Our idea is to select a relay around the midpoint of the distance between the source and the destination. Therefore, we proposed a Midpoint Relay Selection with Social-Awareness (MRS-SA) scheme.

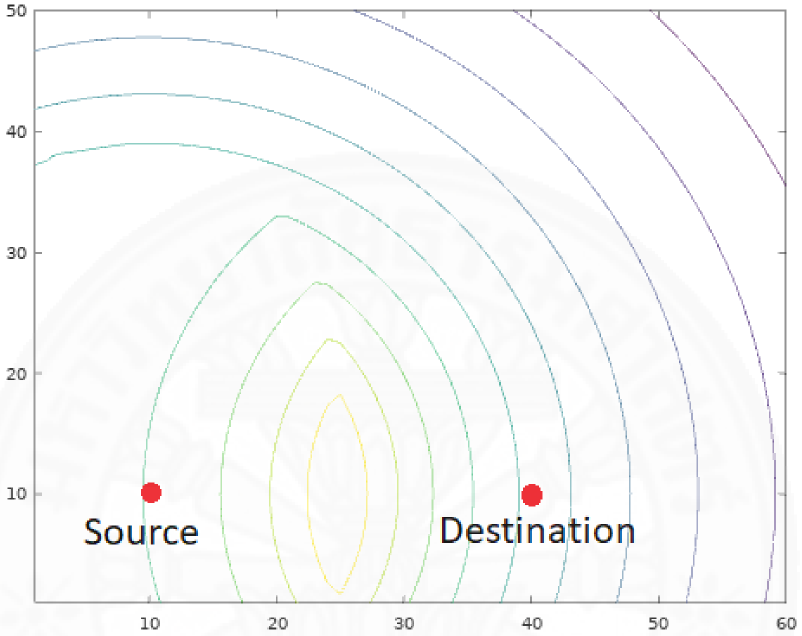
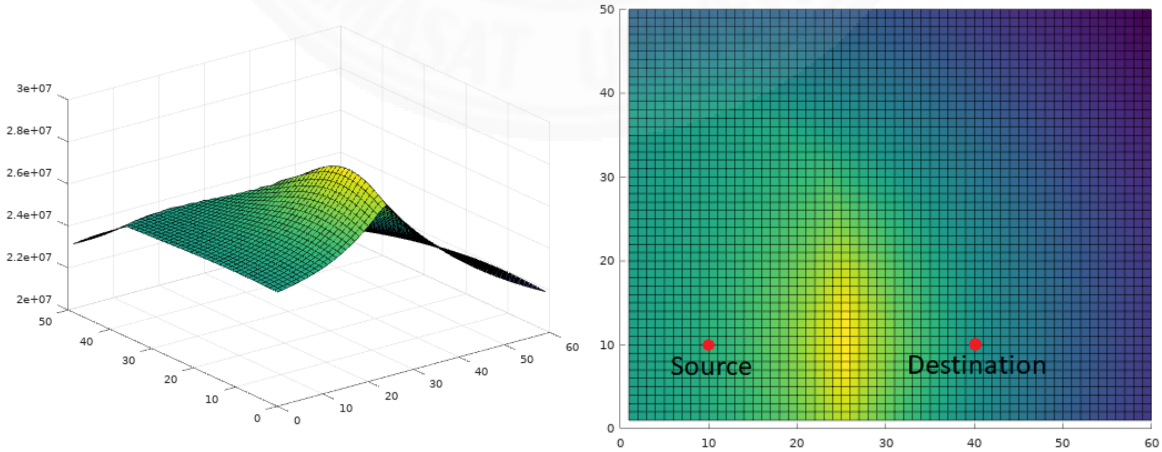


Figure 5.1 Contour diagram for relay selection region when source is at (10,10) and destination is at (40,10)



(a) Viewpoint 1

(b) Viewpoint 2

Figure 5.2 Surface diagram for relay selection region when source is at (10,10) and destination is at (40,10)

5.2 System design of MRS-SA

5.2.1 Key design factors

We consider a scenario where the BS knows location of all the nodes in the network. A mobile device only knows whom it has relationship with and its corresponding social trust value as explained in Chapter 4. The key issues in the design of a relay selection scheme are to find the location of relay selection region and identify a device that transmits at a high power.

The authors in [12] proposed a scheme of selecting a relay (transmitting at a high power) within a circular region around the source. This approach may not be optimal as explained earlier in section 5.1. Finding a relay node nearest to the midpoint of the distance between a source and a destination, and also transmitting at a high power is potentially better. Thus, instead of finding a relay node in proximity of the source, we aim to find a relay within a circular region with a center at the midpoint of distance between the source and the destination. This helps to maintain the balance between SNR of the two signal paths.

Filtering out devices that do not have potential to transmit at a high a power is another important factor while selecting candidate relay nodes. To do that filtering we define social trust threshold. Social threshold (S_{thres}) is used to filter devices that have the potential to transmit at a high power. As relay devices are assumed to transmit at a power proportional to the social trust, devices having high social trust values should only be considered as a relay. When a social trust threshold is applied, the devices that are within the circular region but with low social trust value are not probed. This helps to minimize the waste of duration of a time slot caused by unnecessary probing of devices. Social threshold has a huge significance to reduce unnecessary probing of devices when social trust among the majority of devices in the network are low and only few devices have high social trust value. This helps to increase the throughput of D2D communications.

In paper [12], the source probes socially trusted devices (within a circular region around the source) to select a relay transmitting at a high power. The scheme uses social threshold to filter the nodes that can potentially transmit at a high power. To find a relay for D2D communications offering maximum data rate, search radius needs to be large so that the distance of the two signal paths is balanced. However, with large search radius, many nodes are probed when the node density is high. This causes the throughput to decrease. On the contrary, our searching for a relay near the midpoint can potentially increase throughput of D2D communications. Even with small search radius, there is possibility of finding a relay transmitting at a high power. This reduces number of devices to be probed while maintaining the balance between SNR of the two signal paths. A source can compare the throughput offered by the direct link and D2D link. After that, the source can decide whether to communicate via a direct link or D2D link to maximize the throughput.

5.2.2 Proposed design

This section presents the design of a relay selection scheme for D2D communications utilizing social trust among users in the network. The proposed design is based upon the communication protocol presented in Chapter 4. The key contribution of this proposed design is the location where a relay is selected. In this system design, a relay is selected using social information of users among the devices that are located around the midpoint of the distance between the source and the destination. All the entities in the network perform certain tasks to have either direct D2D communications or D2D communications through a relay as in the algorithms presented in later in this section. The regular tasks done by entities in the network to have conventional cellular communication is not illustrated in the algorithms presented. The main focus of this section is on the information exchange between different entities of the network for selection of a relay in D2D communications. Table 5.1 lists variables that are used in the Algorithm 1, Algorithm 2, Algorithm 3, Algorithm 4 and Algorithm 5.

When a source wants to have a relay for D2D communication, it sends D2D communication request to the BS. In response, the BS sends list of idle devices and maximum allowable transmission power that can be used for D2D communications

Table 5.1 Table of definitions used in design of MRS-SA

Parameters	Definitions
s	Source node
d	Destination node
n	List of nodes
n_{total}	Total number of nodes
n_{circle}	List of nodes within a circular area
$n_{density}$	Node density
$n_{S_{thres}}$	List of nodes above social threshold
P_{max}	Maximum allowable transmission power
S_{thres}	Social trust threshold
R	Radius of circular region
T	Time slot duration
τ	Probe duration
C	Data rate
$C_{s,d}$	Data rate of Direct Communication
$C_{s,r,d}$	Data rate of D2D Communication
$t_{s,r,d}$	Throughput of D2D Communication

to the source as implemented in Algorithm 1.

```
Algorithm 1 Tasks performed at Base Station
// This algorithm consists of sequence of tasks performed by BS for relay selection.
Input: $s$, $d$ and $R$
Output: $n_{circle}$ and $P_{max}$
Receive D2D request from $s$
Calculate Midpoint, $m$ = Midpoint($s$, $d$)
for $radius = 1 : R$ do
    Identify $n_{circle}$ = NodesWithinCircle($m$, $radius$)
end for
Determine $P_{max}$ depending upon system parameters
Send $n_{circle}$ and $P_{max}$ to $s$
```

Source uses information received from the BS to determine whether to have direct D2D communication or use a relay for D2D communication as implemented in Algorithm 2. Initially, the source further filters the list of devices received from the BS down to those that have social trust with the source above certain social threshold (S_{thres}). These devices are known as candidate relay nodes. Source probes these candidate relay nodes and the destination sequentially. The importance of using social threshold in this design is that it reduces the number of probes sent for relay selection while preserving the possibility of finding devices transmitting at a high power. The source takes into consideration the time spent for probing of nodes while calculating throughput of D2D communication.

Algorithm 2 Tasks performed at Source

```
// This algorithm consists of sequence of tasks performed by a node for relay selection.
Input: $s$, $d$ ,$n_{circle}$, $S_{thres}$, $P_{max}$ and $\tau$
Output: $t_{s,r,d}$
if len($n_{circle}$) = 0 then
    Calculate $C_{s,d}$ as in equation 4.2
    $t_{s,r,d} = C_{s,d}$
else
    Identify $n_{S_{thres}}$
    if len($n_{S_{thres}}$) = 0 then
        $t_{s,r,d} = C_{s,d}$
    else
        Sequentially probe nodes in $n_{S_{thres}}$ and $d$
        Calculate $C_{s,r,d}$ through each of nodes in $n_{S_{thres}}$ as in equation 4.3
        Select maximum $C_{s,r,d} = max(C_{s,r,d})$
        if $max(C_{s,r,d}) > C_{s,d}$ then
            Relay is selected
            $t_{s,r,d} = max(C_{s,r,d}) \times (T - (\tau \times n_{S_{thres}}))$
        else
            $t_{s,r,d} = C_{s,d} \times (T - (\tau \times n_{S_{thres}}))$
        end if
    end if
end if
```

Upon receiving probe request from the source, each candidate relay node who is available for D2D communication sends SNR of the received probing packet to the source and forwards the packet to destination with a transmission power proportional to social trust it has for the source as implemented in Algorithm 3. If the device is selected as a relay, it also forwards the packets containing user data to the destination as implemented in Algorithm 4.

Algorithm 3 Tasks performed at Candidate Relay Nodes

```
//This algorithm consists of sequence of tasks performed by candidate relay node for relay selection.
Input: $s$, $d$, $P_{max}$ and probe
Output: SNR values
Receive probe message from $s$
Send SNR value of probe received to $s$
Send probe to $d$ with transmission power linearly proportional to social trust
```

Algorithm 4 Tasks performed at a Relay Node

```
//This algorithm consists of sequence of tasks performed by a relay node in D2D communications.
Input: $s$, $d$, $P_{max}$ and user data
Output: relay data
Receive user data from $s$
Send user data to $d$ with transmission power linearly proportional to social trust
```

At the destination end, destination device calculates SNR for each of the received probing packets and sends that information to the source as implemented in Algorithm 5. The source calculates achievable data rate of each of the candidate relay nodes and selects the device offering maximum data rate. The selected device has the potential of providing maximum data rate for D2D communication and is known as the potential relay device. The source calculates throughput of direct link (not using a relay) and D2D link through the potential relay device. When the throughput of a D2D link is greater than the throughput of a direct link, the source selects the D2D link for data transmission and vice-versa.

Algorithm 5 Tasks performed at Destination

```
//This algorithm consists of sequence of tasks performed by destination node for relay selection.
Input: probe and data
Output: SNR values, data
Receive probe messages from $s$ and $r$
Send SNR values of probe received from $s$ and $r$ to $s$
Send probe reply to $s$
Receive data from $r$ sent by $s$
Send user data to $s$ via $r$
```

5.3 Performance analysis of MRS-SA

We analyze the performance of different relay selection schemes. The comparative analysis of MRS- SA is done against following schemes:

- DTS, direct communication between the source and destination
- HRS, proposed in [12].

Section 5.2 presents different simulation parameters used in the performance analysis different schemes. Section 5.3.2 initially analyzes the comparison of average throughput across all nodes of MRS- SA with DTS and HRS in different network area. Next, we analyze the impact of search radius on frequency of relay selection in D2D communications by counting direct communications in HRS and MRS-SA. We also analyze the impact of search radius on distance from source to relay and that from relay to destination in D2D communications. In addition to that, we analyze how the average throughput of MRS-SA varies with an increase in R at different node densities.

5.3.1 Simulation setup

Table 5.2 shows the details simulation setup used in the analysis. A custom simulation model of DTS, HRS, MRS-SA was developed in Octave [59]. One thousand devices are distributed uniformly at random across a square network area, with widths of 100, 200, 300, 400, 500 and 1000 meters. Devices follow a random waypoint mobility model implemented using BonnMotion [30]. We are considering a scenario where people carrying mobile devices are walking within a certain area. Therefore, the speed of devices is varied between 0–2 m/s and have maximum pause time of 5 s. The social trust value between two devices follows Pareto distribution. A social trust scenarios are achieved by setting the Shape and Scale parameters as illustrated in Table 5.2. Source and destination are selected randomly from the 1000 devices. We set the transmission power of a source device $P_{s,d}$ = 20 dBm, noise power N = -114 dBm, pathloss exponent $\theta = 4$, bandwidth of channel B = 1 MHz as in [1], [12]. We assume the duration of a time slot for D2D communications $T = 1$ sec and that for a probe τ = 0.01 sec [31]. Each simulation runs for 1000 seconds. In this analysis, the maximum allowable transmission power for a relay is considered to be equal to transmission power of source. The results reported are averaged across time.

Table 5.2 Simulation setup for analysis of MRS-SA

Simulation Parameters	
Simulation software	Octave
Mobility model	Random waypoint
Number of nodes, n_{total}	1000
Network width	100, 200, 300, 400, 500 and 1000 m
Speed of nodes, S	0 - 2 m/sec
Maximum pause time	5 sec
Simulation period	1000 sec
Channel bandwidth, B	1 MHz
Pathloss exponent, θ	4
Noise power, N	-114 dBm
Social trust, β	$0 - 1$
Social threshold, S_{thres}	0.3
Shape, α	1.01
Scale, L	0.01
Upper limit, H	1
Transmission power, $P_{s,d}$	20 dBm
Max. allowable tx power, $P_{s,j}$	20 dBm
Time slot duration, t	1 sec
Probe duration, τ	0.01 sec
Search radius, R	Upto 1000 m

5.3.2 Results

Comparison of throughput of MRS-SA with other schemes

Figure 5.3, Figure 5.4 and Figure 5.5 depict average throughput across all nodes in the network having network width of 100 m, 500 m and 1000 m respectively. The simulation data are recorded at an interval of 2 m for network width of 100 m upto search radius, $R = 60$ m and those for network width of 500 m and 1000 m are recorded at an interval of 5 m upto $R = 300$ m and 1000 m respectively. These graphs show the average throughput comparison of MRS-SA with DTS and HRS in different network area. The network area is varied to investigate the impact of node density on throughput.

When the search radius R is large, the average throughput of HRS and MRS-SA in Figure 5.3, Figure 5.4 and Figure 5.5 goes below the average throughput of direct communication. This is because with the increase in search radius, more nodes are probed, which from equation 4.4, ultimately reduces the throughput of D2D com-

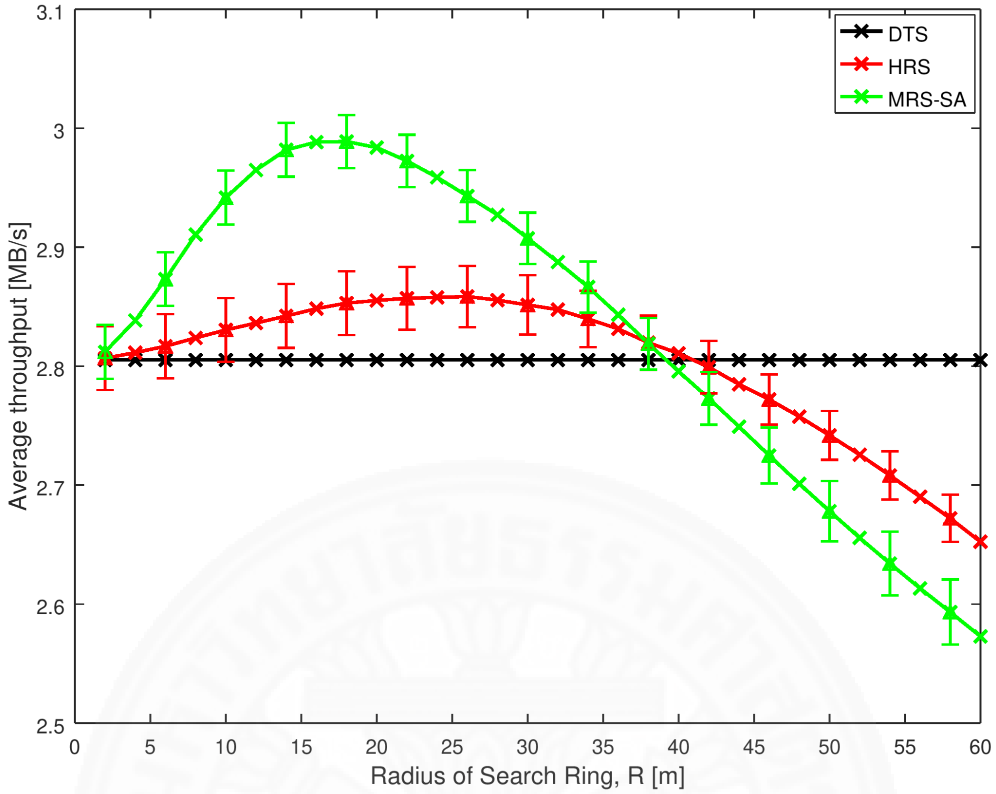


Figure 5.3 Average throughput of different schemes when network width =100 m

munication.

For network area of width 100 m, the average distance between source and destination is 53 m. Analytically, this should be

$$D_{s,d} = \frac{2+\sqrt{2}+5\ln(\sqrt{2}+1)}{15} \times width \tag{5.1}$$

We run the simulation for different values of *R* to investigate how exactly does the radius of search ring impact on performance of MRS-SA, HRS and DTS. Results are shown in Fig. 5.3. The bars on the plot illustrates the confidence interval of 95%.

When *R* is varied from 2 m to 60 m, the average throughput of DTS is constant throughout the range. This is as expected because this scheme does not utilize or depend on the search radius *R*. The average throughput of MRS-SA is gradually increased with the increase in *R*, until it reaches 18 m. This is because, as *R* is increased, the number of nodes within area covered by *R* also increases. This increases

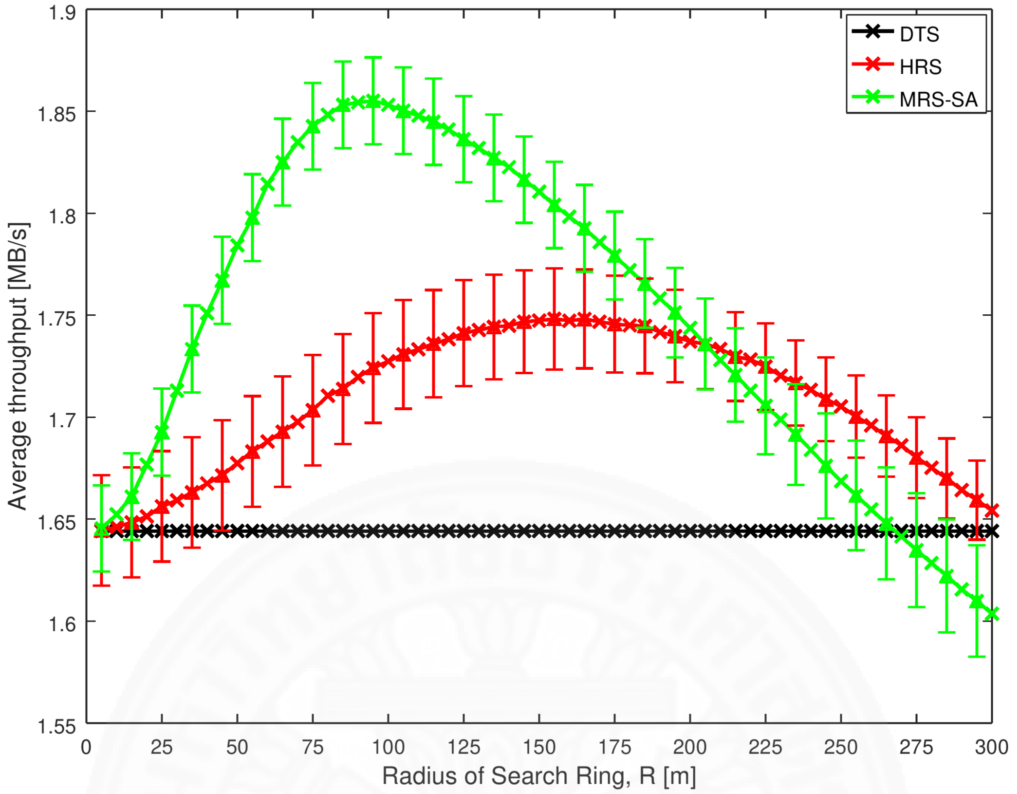


Figure 5.4 Average throughput of different schemes when network width =500 m

the probability of finding nodes transmitting at high power and reduces the number of occurrence of direct communication between source and destination. At R = 18 m, MRS-SA attains its maximum throughput value equal to 2.98 MB/s. For the R beyond 18 m, the throughput is not improved. In contrast, it is decreased gradually because of the increase in number of candidate relay nodes; the time required for probing increases with the increase in R. For larger values of R, the throughput is even lower than that for DTS. The rationale behind this low value of throughput is that the large duration of a time slot is spent for probing of nodes before actual data transmission. As a result, the throughput of MRS-SA becomes lower than that of DTS.

In the case of HRS, throughput is increased until R reaches 26 m. Since the search ring is around the source, and candidate relay nodes are not near to the midpoint of distance between a source and a destination for lower values of R. The maximum throughput of 2.85 MB/s is attained at R = 26 m because there is a balance between the link length from the source to the relay and that from the relay to the des-

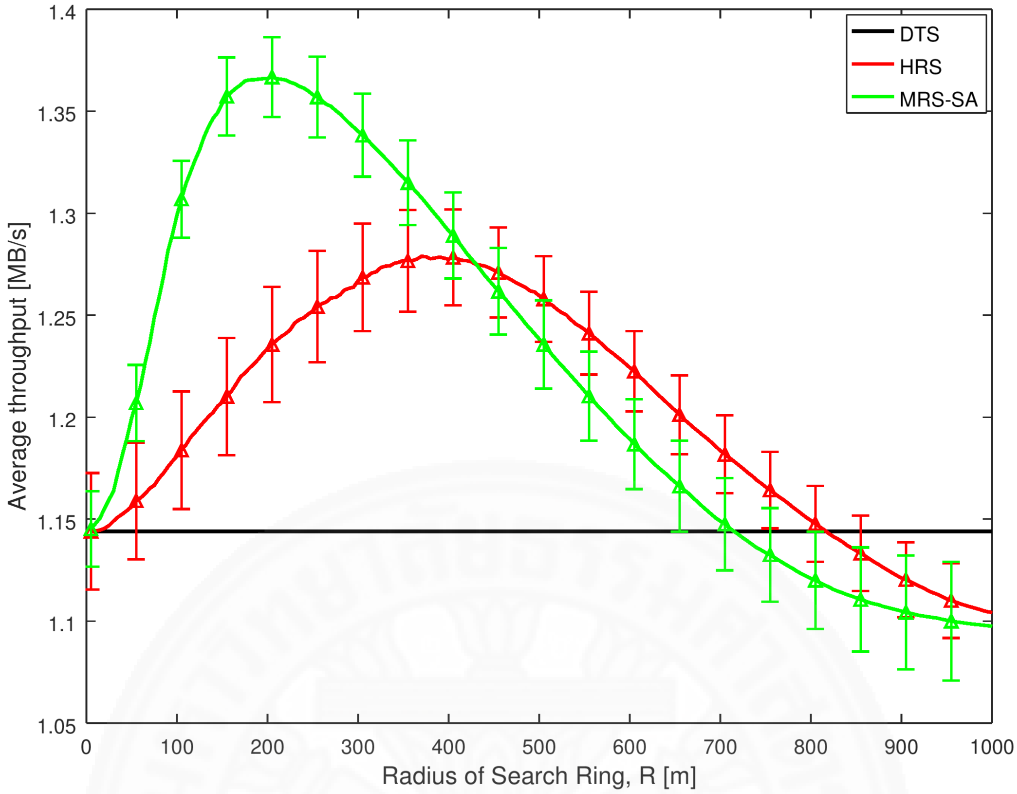


Figure 5.5 Average throughput of different schemes when network width =1000 m

tination. From the graph it can be seen that the maximum throughput of HRS is still lower than that of MRS-SA. From the results, it can be observed that MRS-SA can achieve upto 4.9% performance gain over HRS and 6.5% performance gain over DTS when R = 16 m. The throughput of MRS-SA is lower than HRS for higher values of R because number of probes in MRS-SA is higher than that in HRS. This is because MRS-SA probes nodes around the midpoint, while HRS probes nodes around the source. When the source is near the boundary of the simulation area, the number of nodes within circular area for HRS is lower as nodes are located only within the simulation relay. Higher number of probes in MRS-SA consume larger duration of time slot and as a result throughput is decreased.

The variation in average throughput for all the schemes in Figure 5.4 and Figure 5.5 follow same pattern as in Figure 5.3. In Figure 5.4, average throughput of MRS-SA is gradually increased with the increase in R and attained its maximum value 1.85 MB/s at R = 95 m. Likewise, with the increase in R, the average throughput of HRS is gradually increased, attending its maximum value 1.75 MB/s at *R* = 155 m, after which it is decreased. While in Figure 5.5, the average throughput of MRS-SA attained its maximum value 1.37 MB/s at *R* = 205 m. HRS required even higher search radius, *R* = 370 m, to attain its maximum average throughput of 1.28 MB/s. The graphs illustrates that larger *R* is required to achieve maximum throughput value when node density is decreased. Furthermore, the average throughput of MRS-SA is 12% higher than that of HRS at *R* = 155 m.

In the next section, we analyze how the increase in search radius impacts frequency of relay selection in D2D communications. This is done by counting the number of direct communication between source and destination for different relay selection schemes.

Comparison of frequency of direct communications of MRS-SA with HRS

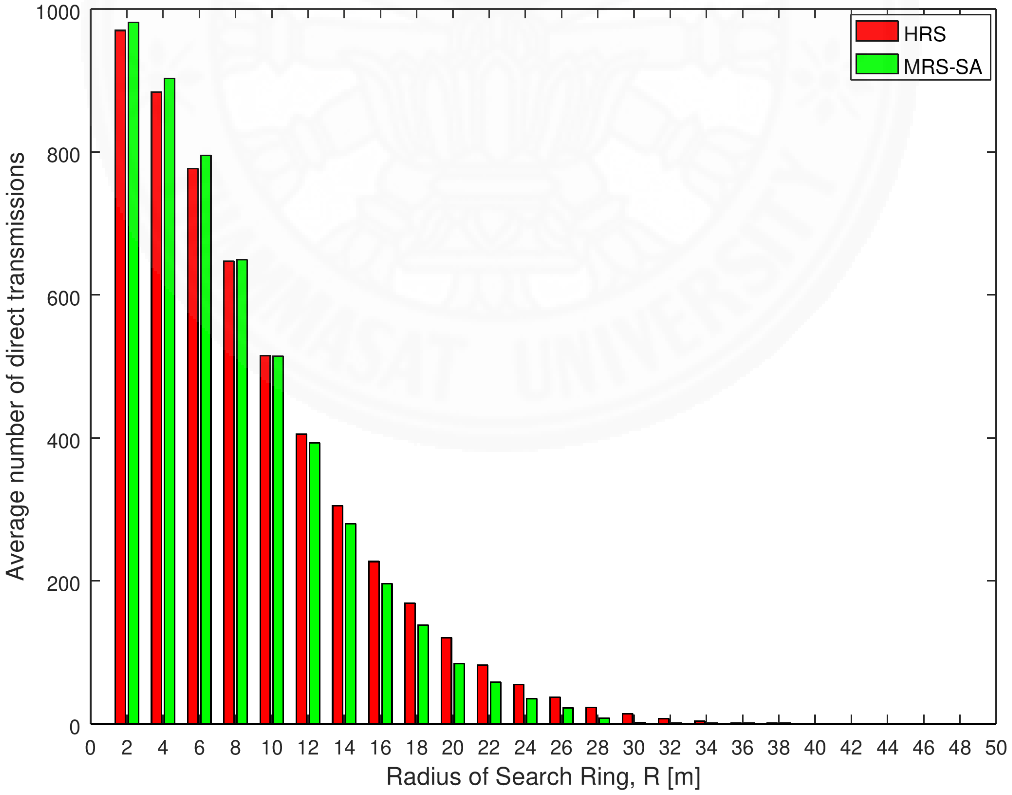


Figure 5.6 Comparison of count of direct communications of MRS-ST with HRS when network width = 100 m

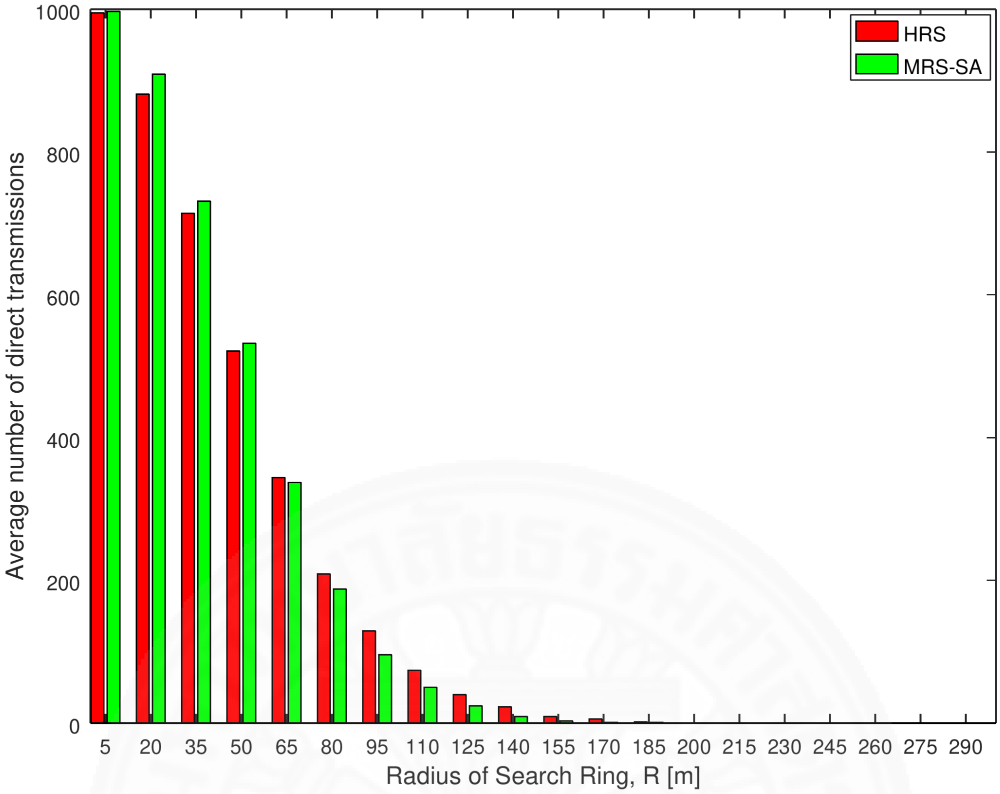


Figure 5.7 Comparison of count of direct communications of MRS-ST with HRS when network width = 500 m

Figure 5.6, Figure 5.7 and Figure 5.8 show the comparison of average number of direct D2D communication between source and destination at different search radius when the network widths are 100 m, 500 m and 1000 m respectively. The data collected from simulation is at an interval of 2 m for network width of 100 m upto R = 60 m and that for network width of 500 m and 1000 m is at an interval of 5 m upto R = 300 m and 1000 m respectively. However, for clarity in presentation on the graph, we sample the data at an interval of 15 m and 25 m for network width of 500 m and 1000 m respectively. Furthermore, the graph for network width of 100 m and 1000 m are shown upto R = 50 m and 480 m only because the number of direct communication beyond that is zero.

Figure 5.6 illustrates that initially there is direct communication between source and destination most of the time when the search radius has a low value. However, with the increase in R, the number of direct communication decreases because more

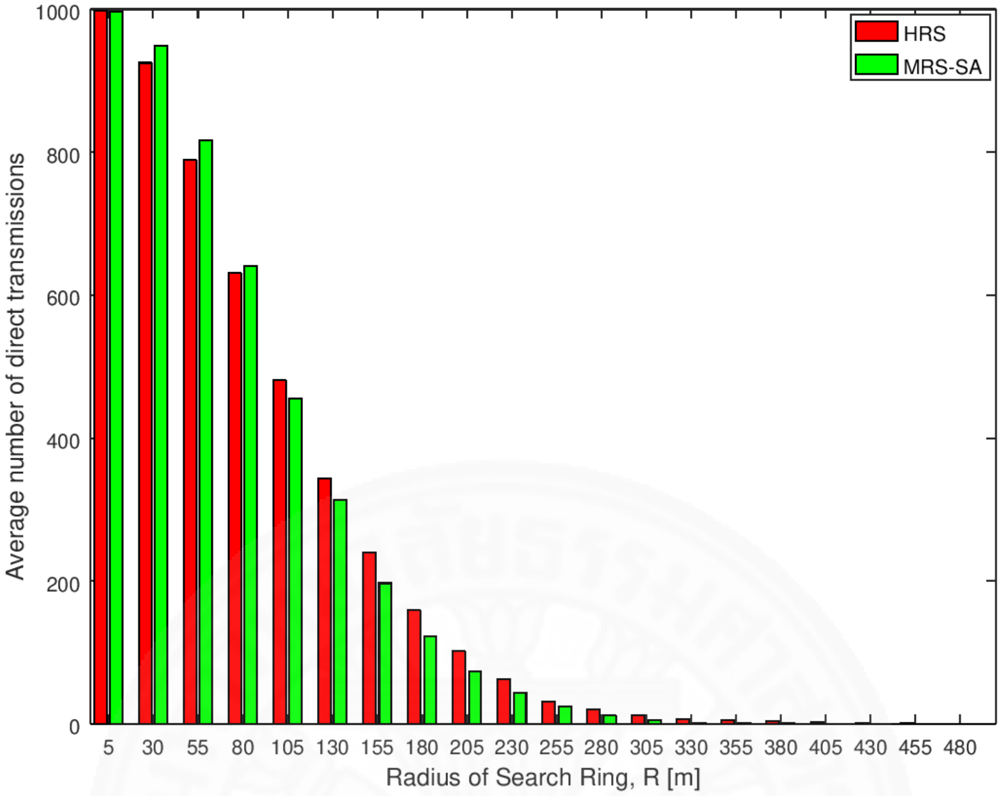


Figure 5.8 Comparison of count of direct communications of MRS-ST with HRS when network width = 1000 m

candidate relay nodes are probed which enhanced the possibility of selection of a relay transmitting at a high power.

Similar trend is observed in Figure 5.7 and Figure 5.8. When we compare Figure 5.6, Figure 5.7 and Figure 5.8, the decrease in number of direct communications in Figure 5.6 is faster compared to Figure 5.7 and Figure 5.8. Similarly, the decrease in number of direct communications in Figure 5.7 is faster than in Figure 5.8. This is because node density in Figure 5.6 is highest among all and that in Figure 5.8 is lowest among all. As larger number of nodes are probed, the possibility of a node being selected as a relay for D2D communications is also increased. Therefore, number of direct communications decreases quickly in Figure 5.6 with the increase in *R* compared to Figure 5.7 and Figure 5.8.

In the next section, we present how the distance of a relay from a source and that from a destination varies with the increase in search radius for different relay selection schemes. This analysis explains the reason why MRS-SA can attain higher throughput than HRS even with smaller values of *R*.

Comparison of distance between nodes of MRS-SA with other schemes

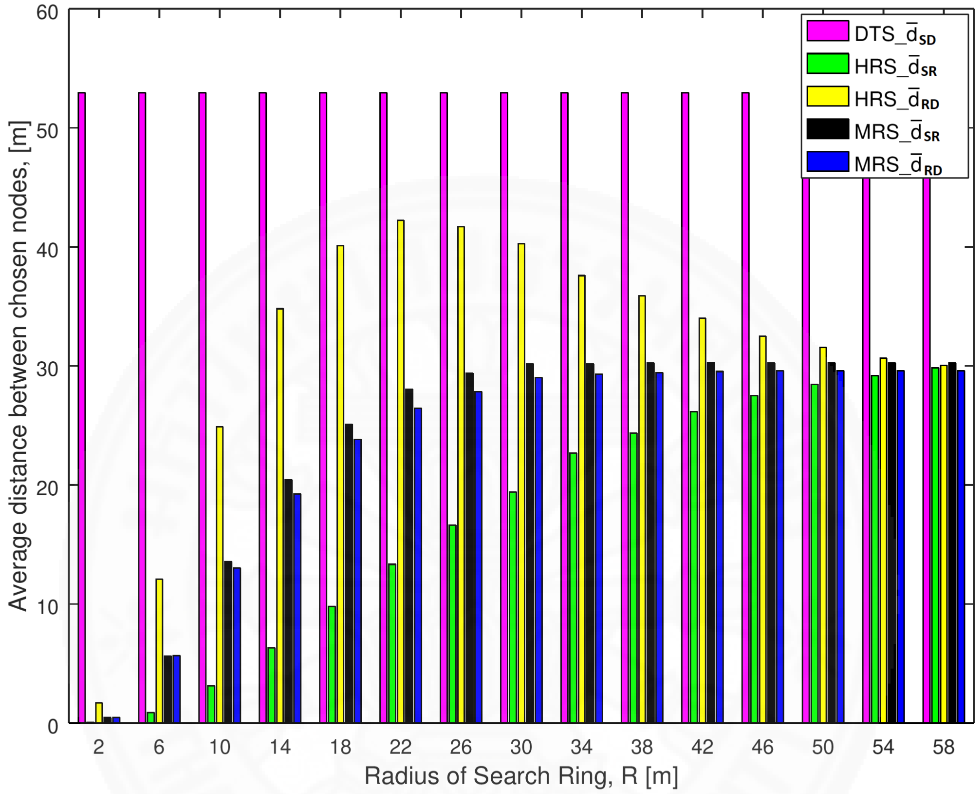


Figure 5.9 Comparison of distance between nodes in different schemes when network width = 100 m

Figure 5.9, Figure 5.10 and Figure 5.11 shows the comparison of distance between nodes for DTS, HRS and MRS-SA schemes when network widths are 100 m, 500 m and 1000 m respectively. The data collected from simulation is at an interval of 2 m for network width of 100 m and that for network width of 500 m and 1000 m is at an interval of 5 m. However, for clarity in presentation on the graph, we sample the data at an interval of 4 m, 20 m and 50 m for network width of 100 m, 500 m and 1000 m respectively.

Figure 5.9 shows average distance between a source and a destination for DTS remains constant throughout the range of *R*. The difference between average distance

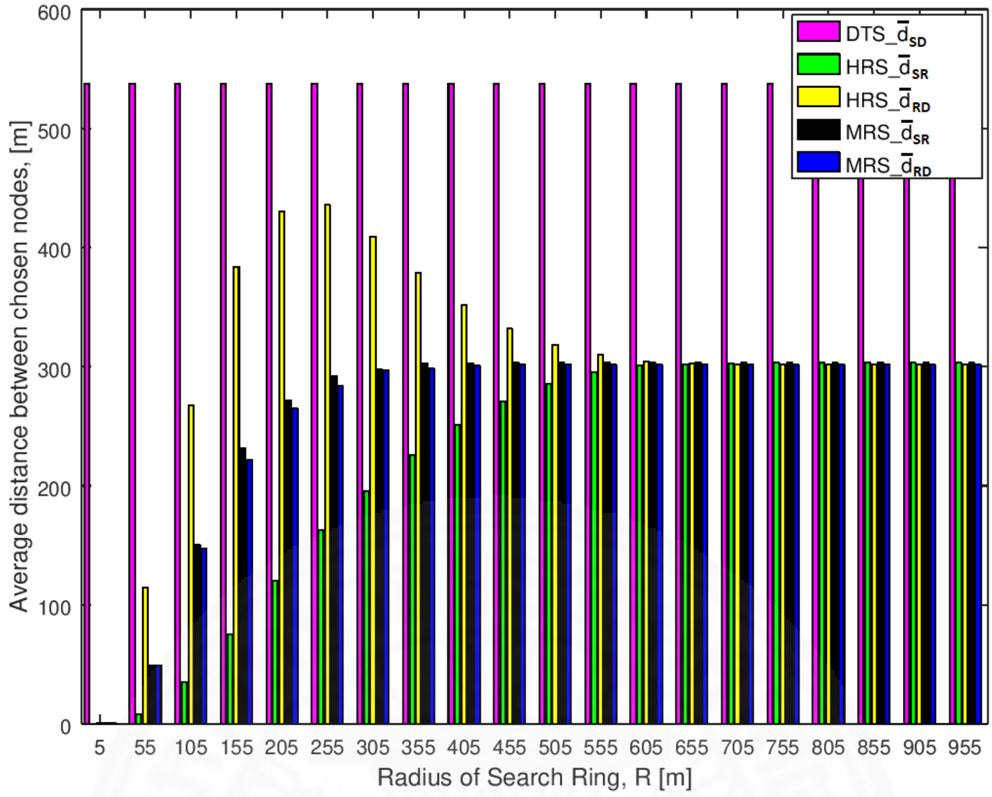


Figure 5.10 Comparison of distance between nodes in different schemes when network width = 500 m

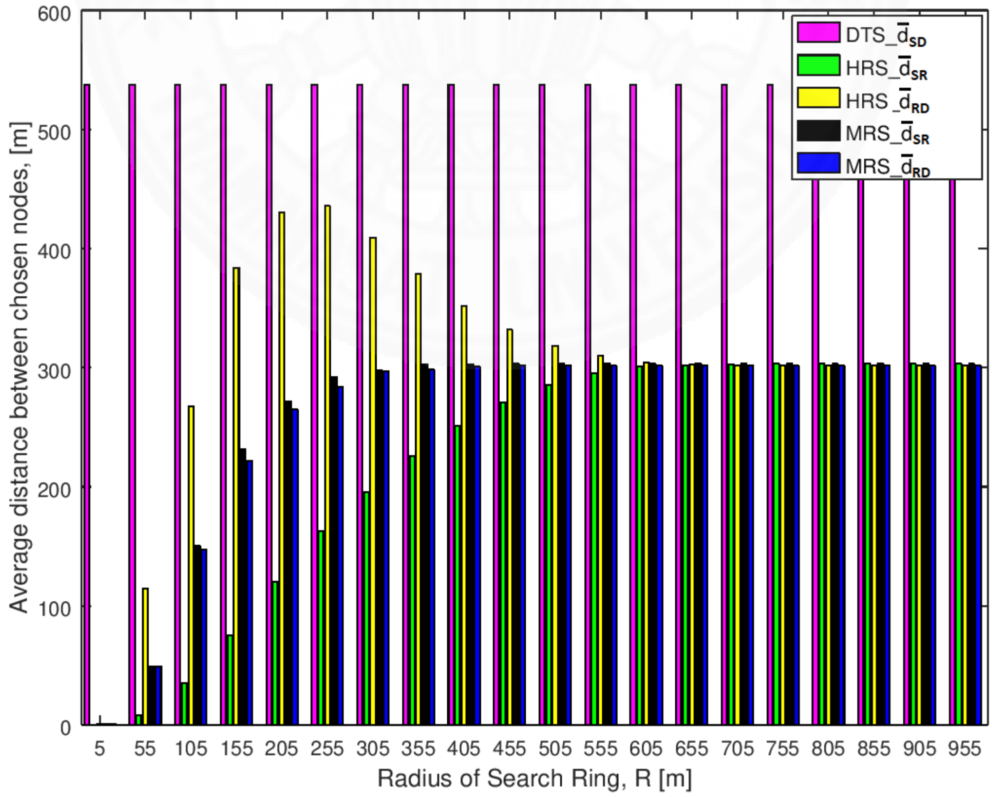


Figure 5.11 Comparison of distance between nodes in different schemes when network width = 1000 m

from a source to a relay and that from the relay to a destination is large for HRS when the search radius has a small value. The difference between the distances reduces gradually with the increase in search radius. The distance between a source and a relay increases with the increase in search radius because a relay is selected further away from the source. However, in case of MRS-SA, the difference between the distances is comparatively quite low. The difference between the distances in HRS minimizes for larger values of R. However, with the increase in R more nodes are being probed which results in lower throughput.

Similar pattern of throughput is observed in Figure 5.10 and Figure 5.11. In summary, MRS-SA has the ability to find candidate relay nodes that have balanced distances at small R values. This makes MRS-SA perform better than HRS.

Next section presents how the change in node density impact the performance of MRS-SA.

Comparison of throughput of MRS-SA with node density

Table 5.3 Distance between source and destination at different node densities

Network Width	Average distance between source and destination	Maximum average throughput
100	77	2.6880
200	76.65	2.6238
300	77.44	2.5643
400	76.65	2.5366
500	77.29	2.5074

Figure 5.12 shows how average throughput of MRS-SA at different node densities varies with an increase in R. The throughput is recorded at an interval of 5 m upto $R = 50$ m at each node density. The node density is varied by changing width of square network to be 100, 200, 300, 400 and 500 meters keeping number of nodes in the network constant. We try to randomly select source and destination pairs that have equal distance between them for all node densities to have fair comparison of throughput that can be achieved using MRS-SA at different node densities. The first column on Table 5.3 represents different node densities. The second column on the

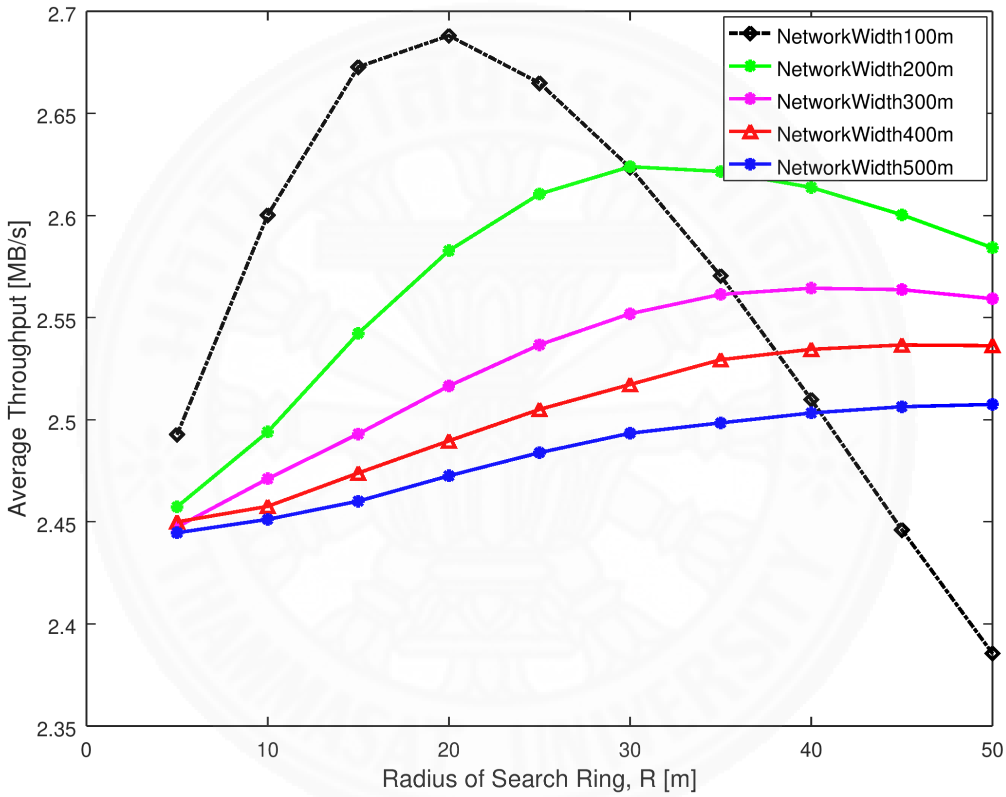


Figure 5.12 Comparison of average throughput of MRS-SA at different network widths

table lists the average distance between source and destination and the third column lists the corresponding maximum average throughput offered by MRS-SA at different node densities.

The average distance between source and destination is limited between 76 - 78 m. Figure 5.12 demonstrates that the maximum average throughput of D2D communication for network width of 100 m has the maximum value, while network width of 1000 m has the minimum value. Moreover, when node density is high, the average throughput attained its maximum value quickly and also dropped down to minimum value rapidly with an increase in R. This is because, the number of nodes within an area covered by R increased faster, compared to that when node density is low. While node density is low, throughput changes slowly and gradually with an increment in R. This suggests that when the node density increases, the average throughput also increases and vice-versa.

5.4 Summary

MRS-SA scheme for selecting a relay in two-hop D2D mobile networks is beneficial in future networks where users of nearby nodes are friends, and friends are willing to consume more power to forward each others data. It can improve average throughput across all nodes upto 6.87% compared to that offered by HRS. Furthermore, the average throughput of D2D communications increases with the increase in node density. This motivated for the design of new relay selection schemes that can minimize the time spent for probing and at the same time preserve the probability of selecting a node that has the potential to transmit at a high power. Therefore, we present an improved version of MRS-SA in Chapter 6.

CHAPTER 6

MIDPOINT RELAY SELECTION

This chapter presents the Midpoint Relay Selection (MRS) scheme for D2D communications. MRS selects a relay based on the combination of location and social trust among users in the network. MRS is an improved version of MRS-SA presented in Chapter 5. MRS has two variations namely Midpoint Relay Selection with Social Trust (MRS-ST) and Midpoint Relay Selection with Social Distance (MRS-SD). MRS-ST and MRS-SD vary in the way nodes are prioritized when selecting a relay node. In Chapter 5, there is no limit in the number of probes used for relay selection. Only social threshold is used for filtering of nodes for relay selection. However, in this chapter a probe limit is used both in MRS-ST and MRS-SD in addition to social threshold. The probe limit is used together with social threshold to improve the average throughput of D2D communication by reducing the time spent for probing. The average throughput of MRS-ST and MRS-SD are higher than that of Hybrid Relay Selection (HRS) scheme presented in [12]. The analysis is performed for networks with different social trust scenarios.

The MRS-ST and MRS-SD schemes presented in this chapter are published in the journal paper entitled ”Base Station Assisted Relay Selection in Device-to-Device Communications”, in International Journal of Ad Hoc and Ubiquitous Computing (IJAHUC), Vol. 33, Issue 1, Jan 2020. The paper presents Midpoint Relay Selection Scheme with Social Trust (MRSS-ST) and Midpoint Relay Selection Scheme with Social Distance (MRSS-SD). MRSS-ST and MRSS-SD are renamed to be MRS-ST and MRS-SD respectively in this chapter to have similarity with the naming of other relay selection schemes presented in this thesis.

In addition to the results published in the paper [65], we present the following results:

- Average throughput comparison of different schemes for a network width of 500 m at different social trust scenarios and social threshold
- Average number of probes comparison of different schemes for a network width of 500 m at different social trust scenarios and social threshold.

Now, we present the organization of this chapter. Section 6.1 presents the need of a probe limit in MRS-SA scheme presented in Chapter 5 to improve throughput of D2D communications. This inspired the design of MRS-ST and MRS-SD. Section 6.2 presents the system design of MRS scheme. Section 6.3 presents the theoretical analysis of the communication protocol used in MRS and is compared with that of HRS. Section 6.4 presents the performance analysis of the average throughput of MRS-ST and MRS-SD and compares them with other schemes. Finally section 6.5 concludes that MRS-ST and MRS-SD can be used to achieve higher throughput than HRS.

6.1 Motivation

For small value of search radius, the average throughput of MRS-SA gradually increases with the increase in search radius. This is illustrated in Figure 5.3, Figure 5.4 and Figure 5.5. However, for beyond a certain value of search radius, the throughput of MRS-ST starts to decrease and eventually becomes lower than that of DTS. Additionally, the throughput decreases faster when the node density increases. This is because more nodes are probed with the increase in search radius. When node density in the network is high or when the search radius is large, the nodes having social trust above social threshold also increases. As a result, a significant duration of a time slot is spent for probing of nodes in search of a node that has the potential to transmit at a high power. This made us interested to the design of new relay selection schemes that can minimize the time spent for probing, but at the same time preserving the probability of selecting a node that has the potential to transmit at a maximum power. Therefore, we propose MRS scheme that limits the number of probes while selecting a relay. The two variations of MRS are designed depending upon the way candidate relay nodes are prioritized while choosing a relay.

6.2 System design of MRS-ST and MRS-SD

6.2.1 Key design factors

We consider a scenario where the BS knows the location of all the nodes in the network. Each node knows whom it has relationship with and its corresponding social trust value as explained in Chapter 4.

The devices among which a relay is selected for D2D communications are known as candidate relay nodes. The selection of candidate relay nodes are important in selection of a relay for D2D communications. The four different factors considered in our design presented in this chapter while selecting candidate relay nodes are:

1. Location of candidate relay nodes
2. Probe limit
3. Social trust threshold
4. Way of filtering / prioritizing devices as candidate relay nodes.

The combination of all these factors are used in our system design to boost the throughput of network.

Location of candidate relay nodes. The data rate of a D2D link is the smaller of the data rate offered by the source to the relay link and that offered by the relay to the destination link. This suggests that the location where candidate relay nodes are selected plays an important role to maximize throughput. Therefore, we choose devices within a circular region with a center at the midpoint of the distance between the source and the destination as the candidate relay nodes. The aim is to find a relay within the circular region that is close to the the midpoint and also transmitting at a high power. This helps to maintain the balance between SNR of the signal from the source to the relay and that from the relay to the destination. When this condition is satisfied, it maximizes the throughput.

Probe limit. Probing of devices are done while selecting a relay device. A probe limit (l) defines the maximum number of devices that can be probed during the selection of a relay. Another factor that influences throughput of D2D communication is number of devices that are probed during the relay selection process as shown in equation 4.4. Probe limit improves the throughput of the network particularly when the search radius is large or the node density is high. From Figure 5.3, Figure 5.4 and Figure 5.5, it can be seen that the throughput of MRS-SA decreases with the increase in search radius. When more devices are probed, significant duration of a time slot is spent in selection of a relay and short duration of a time slot is only left for actual user data transmission. Therefore, a proper balance between number of probes and time for real data transmission maximizes network throughput.

Social threshold. Selection of nodes having potential to transmit at a high power is necessary in selection of candidate relay nodes. This can be achieved by using a social trust threshold. Social threshold (S_{thres}) filters devices that have the potential to transmit at a high power. The purpose of using social threshold in this chapter is same as in Chapter 5. The detailed explanation on social threshold is provided in section 5.2.1.

Prioritization of candidate relay devices. The prioritizing devices within the circular region as a candidate relay nodes also plays an important role in maximizing throughput of the network. The received signal strength depends upon the distance between a source and a destination as well as the transmission power of the signal (see equation 4.1). The candidate relay nodes can be selected by prioritizing social trust value that a device has for the source or by prioritizing the devices that are located nearest to the midpoint between the source and the destination.

6.2.2 Proposed design

This section presents the design of a relay selection scheme for D2D communications utilizing social trust values of mobile users in the network. The proposed design is based upon the communication protocol presented in Chapter 4. A relay is selected among the nodes that are located around the midpoint of the distance between the source and the destination using social information of users. The main focus of proposed design is on the set of tasks performed by different entities of the network for relay selection in D2D communications, not on conventional cellular communications. We present information exchange between different entities of the network for relay selection in D2D communications. These information exchange are illustrated in the algorithms presented later in this section.

The two variations of MRS are designed depending upon the way candidate relay nodes are prioritized while choosing a relay.

1. Midpoint Relay Selection with Social-Trust (MRS-ST): Filters the nodes having social trust above social threshold. The candidate relay nodes are selected by further filtering at most l nodes having highest value of social trust.

2. Midpoint Relay Selection with Social-Distance (MRS-SD): Filters candidate relay nodes by selecting at most l nodes nearest to the midpoint. Then the nodes above social threshold are probed.

This is the key contribution in design of relay selection. Table 6.1 lists variables that are used in the Algorithm 6, Algorithm 7, Algorithm 8 and Algorithm 10.

The design of a two-hop relay communication can be varied depending upon information available to the entities in the network. When a source wants to have a relay for D2D communication, it sends D2D communication request to the BS which contains the source and the destination identity. In response, the BS sends a message to the source containing list of idle devices that are located within certain search radius (R) and maximum allowable transmission power (P_{max}) that can be used for D2D communications as implemented in Algorithm 6. The tasks performed by BS

Table 6.1 Table of definitions for design of MRS-ST and MRS-SD

Parameters	Definitions
s	Source node
d	Destination node
n	List of nodes
n_{total}	Total number of nodes
n_{circle}	List of nodes within a circular area
$n_{density}$	Node density
$n_{S_{thres}}$	List of nodes above social threshold
P_{max}	Maximum allowable transmission power
$scheme$	Selection of a scheme, e.g. $scheme$ = [MRS-ST or MRS-SD]
S_{thres}	Social threshold
R	Radius of circular region
T	Time slot duration
τ	Probe duration
l	Probe limit
p	Number of probes
C	Data rate
$C_{s,d}$	Data rate of Direct Communication
$C_{s,r,d}$	Data rate of D2D Communication
$t_{s,r,d}$	Throughput of D2D Communication

in MRS-ST is same as that of MRS-SA. However, in MRS-SD, the BS also sends location of nodes in proximity to the source.

Algorithm 6 Tasks performed at Base Station

// This algorithm consists of sequence of tasks performed by BS for relay selection.
Input: s, d and R
Output: n_{circle} along with location and P_{max}

```
Receive D2D request from $s$
Calculate Midpoint, $m$ = Midpoint($s$, $d$)
for $radius = 1 : R$ do
    Identify $n_{circle}$ = NodesWithinCircle($m$, $radius$)
end for
Determine $P_{max}$
Send $n_{circle}$ along with location and $P_{max}$ to $s$
```

The social trust values that the source has for other devices provide an idea of which devices have the potential to transmit at a high power as explained in Chapter 4. Therefore, among the list of idle devices received from the BS, the devices having social trust with the source are identified by the source. These devices are known as potential relay nodes. The devices having social trust values above certain social threshold are selected among the potential relay nodes as implemented in Algorithm 7.

Algorithm 7 Tasks performed at Source

```
// This algorithm consists of sequence of tasks performed by a node for relay selection.
Input: $s$, $d$, $n_{circle}$, location of nodes listed in $n_{circle}$, $S_{thres}$, $P_{max}$, $l$, $\tau$ and $scheme$

Output: $t_{s,r,d}$
if len($n_{circle}$) = 0 then
    Calculate $C_{s,d}$ as in equation 4.2
    $t_{s,r,d} = C_{s,d}$
else
    if $scheme$ == $MRS$-$ST$ then
        Identify $n_{S_{thres}}$
        if len($n_{S_{thres}}$) = 0 then
            $t_{s,r,d} = C_{s,d}$
        else
            if len($n_{S_{thres}}$) > $l$ then
                $n_{S_{thres}}$ = $l$ nodes with maximum social trust values
            end if
        end if
    else
        if len($n_{circle}$) > $l$ then
            $n_{circle}$ = $l$ nodes nearest to midpoint
        end if
        Identify $n_{S_{thres}}$
        if len($n_{S_{thres}}$) = 0 then
            $t_{s,r,d} = C_{s,d}$
        end if
    end if
    Sequentially probe nodes in $n_{S_{thres}}$ and $d$
    Calculate $C_{s,r,d}$ through each of nodes in $n_{S_{thres}}$ as in equation 4.3
    Select maximum $C_{s,r,d} = max(C_{s,r,d})$
    if $max(C_{s,r,d}) > C_{s,d}$ then
        Relay is selected
        $t_{s,r,d} = max(C_{s,r,d}) \times (T - (\tau \times n_{S_{thres}}))$
    else
        $t_{s,r,d} = C_{s,d} \times (T - (\tau \times n_{S_{thres}}))$
    end if
end if
```

In TDMA systems, each device is given a time slot for data transmission. In such system devices are sequentially probed within a time slot allocated for each user as depicted in Figure 4.2. When many devices are probed for selection of a relay, large duration of a time slot is spent for probing resulting in decrease in throughput.

Therefore devices having shorter link lengths and also having strong social trust with the source are filtered in this scheme. For that further filtering of potential relay nodes is done. The devices are filtered in two different ways to achieve variation in design of MRS as detailed in Algorithm 7 (line 5 to 22). In MRS-ST, at most l nodes having higher value of social trust are selected. In MRS-SD, at most l nodes nearest to midpoint are selected. This filtering reduces number of probes required for relay selection.

The resulting potential relay nodes, known as candidate relay nodes, and destination are probed by the source. When the probing packet is received by a candidate relay node, it sends SNR of received probing packet to the source and also forwards the packet to destination with a transmit power proportional to social trust as in Algorithm 8.

Algorithm 8 Tasks performed at Candidate Relay Nodes

```
//This algorithm consists of sequence of tasks performed by candidate relay node for relay selection.
Input: $s$, $d$, $P_{max}$ and probe
Output: SNR values
Receive probe message from $s$
Send SNR value of probe received to $s$
Send probe to $d$ with transmission power linearly proportional to social trust
```

Upon receiving user data from the source, the relay forwards the user data to the destination as illustrated in Algorithm 14.

Algorithm 9 Tasks performed at a Relay Node

```
//This algorithm consists of sequence of tasks performed by a relay node in D2D communications.
Input: $s$, $d$, $P_{max}$ and user data
Output: relay data
Receive user data from $s$
Send user data to $d$ with transmission power linearly proportional to social trust
```

The destination calculates SNR for each of the received probe packet and sends to the source as in Algorithm 10 (according to equation 4.1). The destination also sends user data to the source via the selected relay.

The system is designed such that a source decides whether to communicate

Algorithm 10 Tasks performed at Destination

```
//This algorithm consists of sequence of tasks performed by destination node for relay selection.
Input: probe and data
Output: SNR values, data
Receive probe messages from $s$ and $r$
Send SNR values of probe received from $s$ and $r$ to $s$
Send probe reply to $s$
Receive data from $r$ sent by $s$
Send user data to $s$ via $r$
```

via a direct link or D2D link after comparing data rate offered by both the links. Upon receiving probe reply from the candidate relay nodes and destination, the source calculates achievable data rate of each of the candidate relay nodes and direct link. The source selects the path which offers higher data rate. When data rate through a relay is greater than the data rate of the direct link, the source selects the relay for data transmission and vice-versa. The source takes into consideration the time spent for probing of nodes while calculating throughput of D2D communication. The source chooses the link offering maximum data rate to maximize throughput as shown in Algorithm 7 (line 26 to 30).

In the next section, we present the calculation of average number of probes required for HRS, MRS-ST and MRS-SD to analyze performance of both the schemes.

6.3 Theoretical analysis of MRS communication protocol

We present the comparison of the probing overheads of HRS, MRS-ST and MRS-SD. For that, we calculate the average number of messages exchanged for each of the schemes before actual data transmission. The comparison of average number of probes, denoted by p, is useful to understand how much time is consumed by each scheme for probing. The less the time is used for probing, more the time is utilized for real data transmission and vice-versa.

As shown in Figure 4.3, messages are exchanges between source, candidate relay nodes and the destination in MRS. During the D2D initiation phase in both the schemes, the source sends a D2D request message to a BS and the BS sends a

D2D reply message back to the source. During the probing phase, each candidate relay nodes are probed to learn about link conditions. Probing of each candidate relay node consists of 4 short messages: From source to relay, relay to source (SNR value from s to r), relay to destination, destination to source (SNR value from s to d, SNR value from r to d). A similar message exchange also occurs in HRS. Therefore, the average number of messages exchanged in MRS-ST, MRS-SD and HRS before establishing a D2D communication are

$$M = 2 + 4 \times p \tag{6.1}$$

which shows that the number of messages exchanged is proportional to the number of nodes being probed. Section 6.4.2 presents the results illustrating graphical representation of average number of probes for each of the schemes.

Now we calculate the number of nodes probed, by first defining the node density and number of nodes in a circular region. Node density $n_{density}$ is achieved using a network of width W and n_{total} number of nodes in the network such that

$$n_{density} = n_{total}/W^2 \tag{6.2}$$

Given the radius of a circular region within which a relay node is selected, denoted as R, the average number of nodes that can be a relay is

$$n_{circle} = R \times n_{total}/W^2 \tag{6.3}$$

Let x be the fraction of nodes whose social trust values are above the social threshold. Its value can be calculated from the social distribution discussed in Chapter 4.

In HRS, the number of nodes above the social threshold are

$$n_{\mathrm{HRS}} = x \times \frac{R \times n_{total}}{W^2} \tag{6.4}$$

The average number of nodes to be probed, denoted as p_{HRS}, is equal to the number of nodes above the social threshold.

$$p_{\text{HRS}} = n_{\text{HRS}} \tag{6.5}$$

In MRS-ST and MRS-SD, the number of nodes to be probed depends upon the nodes are filtered. In MRS-ST, the number of nodes above the social threshold are

$$n_{\text{MRS-ST}} = x \times n_{circle} \tag{6.6}$$

At most l nodes are probed in MRS-ST. $n_{\text{MRS-ST}}$ nodes are arranged with their social trust in descending order. Then, the average number of nodes to be probed are

$$p_{\text{MRS-ST}} = \begin{cases} l & \text{if } l < n_{\text{MRS-ST}}; \\ n_{\text{MRS-ST}} & \text{otherwise.} \end{cases} \tag{6.7}$$

At most l nodes are probed in MRS-SD. Nodes are arranged according to distance from the midpoint in ascending order. Then, the average number of nodes above social threshold are

$$n_{\text{MRS-SD}} = \begin{cases} x \times l & \text{if } l < n_{circle}; \\ x \times n_{circle} & \text{otherwise.} \end{cases} \tag{6.8}$$

The average number of nodes to be probed is

$$p_{\text{MRS-SD}} = n_{\text{MRS-SD}} \tag{6.9}$$

From equation 6.5, equation 6.7 and equation 6.9, we see that the average number of probes used for HRS is higher than that used for MRS-ST and MRS-SD. The average number of probes used for MRS-SD is less than that required for MRS-ST when social trust values for the links that source has for the nodes are low. This is because, when the social trust values for at most l nodes are low, number of nodes having the trust values above social threshold becomes less in MRS-SD.

6.4 Performance analysis of MRS

We analyze the performance of different relay selection schemes. The comparative analysis of MRS-ST and MRS-SD are done against following schemes:

- DTS, direct communication between the source and destination
- HRS scheme, proposed in [12].
- Modified-HRS scheme, similar to HRS but with probe limit.
- M-Nearest scheme, where a relay is selected nearest to midpoint of the distance between the source and the destination.
- M-Nearest_MaxTx scheme, where a relay is selected nearest to midpoint of the distance between source and destination assuming relay always has maximum allowable transmission power. In reality, nearest to midpoint node does not always transmit at maximum power but the scheme is used as a benchmark scheme.

Section 6.4.1 details the network configuration used in simulation for the performance analysis. Section 6.4.2 presents analysis of impact of social trust on the performance of different relay selection schemes while varying the parameters shape, scale, social threshold and search radius. The key observation from our analysis is that our proposed scheme MRS has significantly higher throughput than HRS in all of the analyzed scenarios, although in some cases MRS has less throughput than M-Nearest scheme.

6.4.1 Simulation setup

Table 6.2 shows the detail of simulation setup used in this analysis. A custom simulation model of DTS, HRS, Modified-HRS, M-Nearest, M-Nearest_MaxTx, SMRS-ST and SMRS-SD was developed in Octave [59]. One thousand devices are distributed uniformly at random across a square network area, with widths of 100, 500 and 1000 meters. Devices follow a random waypoint mobility model implemented using BonnMotion [30]. We are considering a scenario where people carrying mobile devices are walking within a certain area. Therefore, the speed of devices is varied between 0–2 m/s and have maximum pause time of 5 s. The social trust value between two devices follows Pareto distribution. Different social trust scenarios among devices in the network are achieved by varying the Shape and Scale parameters. Source and destination are selected randomly from the 1000 devices. We set the transmission power of a source device $P_{s,d}$ = 20 dBm, noise power N = -114 dBm, pathloss exponent $\theta = 4$, bandwidth of channel B = 1 MHz as in [1], [12]. We assume the duration of a time slot for D2D communications T = 1 sec and that for a probe $\tau = 0.01$ sec [31]. Each simulation runs for 1000 seconds. In this analysis, the maximum allowable transmission power for a relay is considered to be equal to transmission power of source. The results reported are averaged across time.

Table 6.2 Simulation setup for analysis of MRS-ST and MRS-SD

Simulation Parameters	
Simulation software	Octave
Mobility model	Random waypoint
Number of nodes, n_{total}	1000
Network width, W	100, 500 and 1000 m
Speed of nodes, S	0 - 2 m/sec
Maximum pause time	5 sec
Simulation period	1000 sec
Channel bandwidth, B	1 MHz
Pathloss exponent, θ	4
Noise power, N	-114 dBm
Social trust, β	$0 - 1$
Social threshold, S_{thres}	0.2, 0.3, 0.5
Shape, α	1.001, 1.01, 1.1, 1.2, 1.3
Scale, L	0.001, 0.01, 0.1, 0.15, 0.2
Upper limit, H	1
Transmission power, $P_{s,d}$	20 dBm
Max. allowable tx power, $P_{s,j}$	20 dBm
Time slot duration, t	1 sec
Probe duration, τ	0.01 sec
Probe limit, l	10
Search radius, R	Upto 500 m

To analyze the impact of social threshold on D2D throughput, we vary the social threshold from 0.2 to 0.5 in a network having friendship probability of 1. Table

6.3 lists different (shape, scale) pairs, while upper threshold $H = 1$, that are used for the analysis to represent network having different number of candidate relay nodes. The table also shows the number of social links that are present in the network for which the social trust is above the threshold. With the increase in (shape, scale) pair, the number of useful social links above social threshold values increases. Additionally, with the increase in social threshold value, the number of useful social links decreases for a pair of shape and scale.

Table 6.3 Useful links for different shape and scale pairs

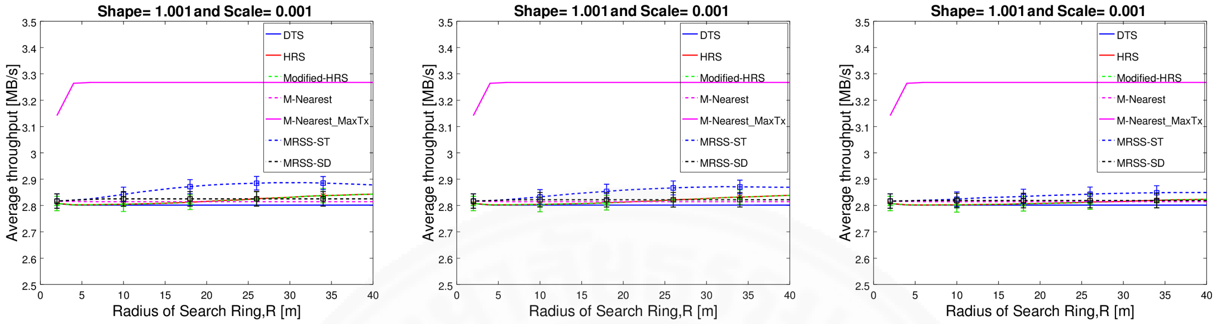
Shape	Scale	Number of useful links when social threshold are		
		0.2	0.3	0.5
1.001	0.001	2012	1153	506
1.01	0.01	19483	11329	4814
1.1	0.1	210289	119376	49740
1.2	0.15	336999	185416	74482
1.3	0.2	499500	265964	103233

6.4.2 Results

Throughput comparison of MRS with other schemes

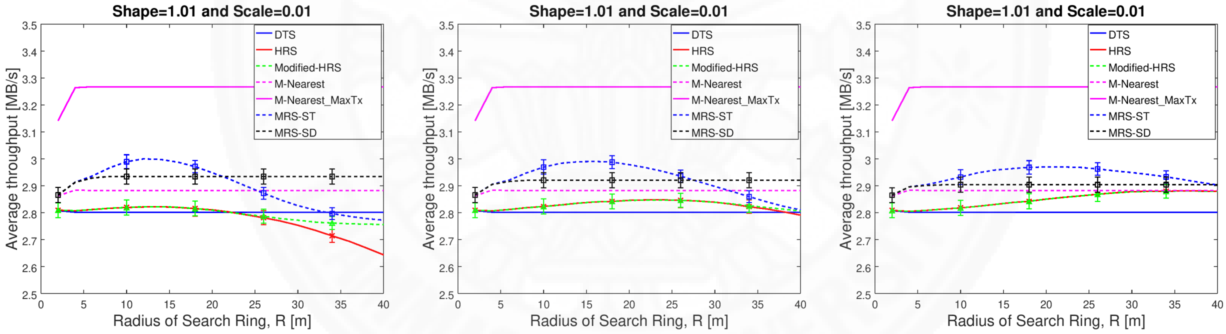
Figure 6.1 to Figure 6.5 shows the comparison of average throughput of different relay selection schemes at different social trust scenarios for network having width of 100 meter. Figure 6.6 to Figure 6.10 shows the comparison of average throughput of different relay selection schemes at different social trust scenarios for network having width of 500 meter. Similarly, Figure 6.11 to Figure 6.15 shows the comparison of average throughput of different relay selection schemes at different social trust scenarios for network having width of 1000 meter. The graphs in each of these figure shows the average throughput of different schemes when the social threshold is varied. In all the graphs, average throughput is on the y-axis and radius of search ring is on the x-axis. Each plot shows a line for each scheme analyzed (DTS, HRS, Modified-HRS, M-Nearest, M-Nearest_MaxTx, MRS-ST and MRS-SD) and the values of shape and scale for social trust are given on the top of the plot.

For network width of 100 m, the simulation data are recorded at an interval of 2 m upto R = 40 m. For network width of 500 m and 1000 m simulation data are recorded at an interval of 5 m. The search radius for network width = 500 m, ranges from 5 m upto 200 and that for network width = 1000 m ranges from 5 m upto 500 m.



(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

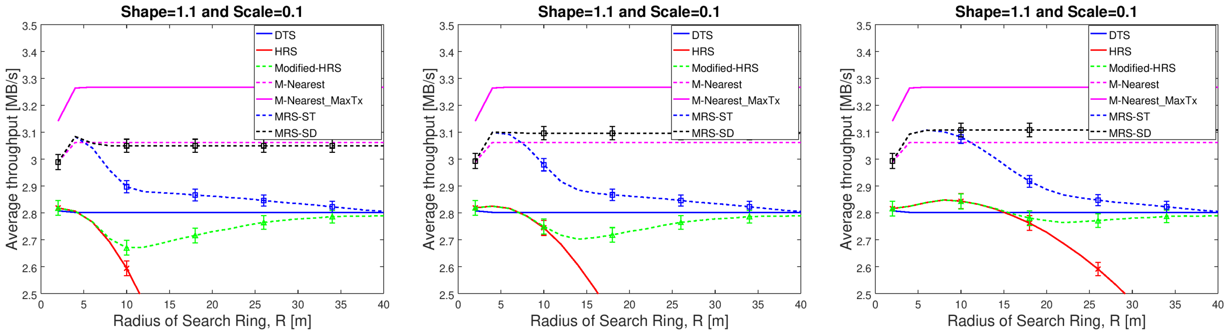
Figure 6.1 Average throughput of different schemes when Shape=1.001 and Scale=0.001 in a network having width of 100 m



(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

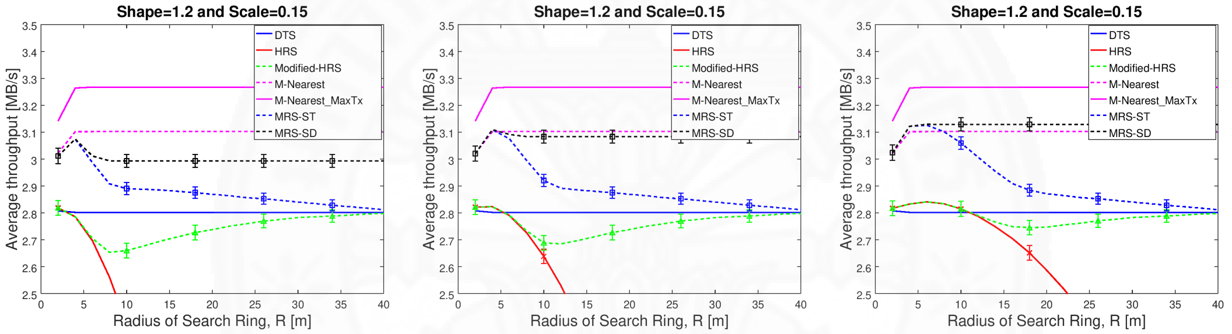
Figure 6.2 Average throughput of different schemes when Shape=1.01 and Scale=0.01 in a network having width of 100 m

The graphs in Figure 6.1 and Figure 6.2 show that average throughput of MRS is highest among all other schemes. The average throughput of MRS gradually increases with the increase in search radius. This is due to the increasing number of nodes within the MRS search region, and in turn, increased probability of finding nodes with higher value of social trust. However as the search radius increases further, the number of nodes probed increases. This gives less time for data transmission. Eventually, this leads to a decrease in throughput. In addition, with the increase



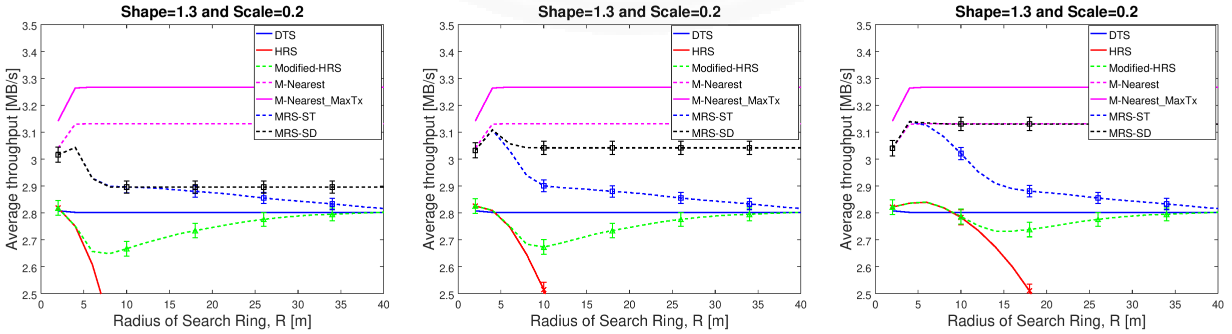
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.3 Average throughput of different schemes when Shape=1.1 and Scale=0.1 in a network having width of 100 m



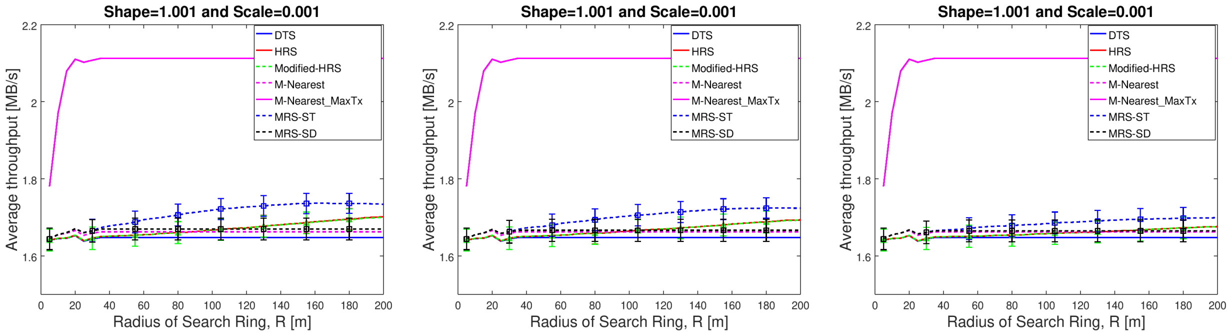
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.4 Average throughput of different schemes when Shape=1.2 and Scale=0.15 in a network having width of 100 m



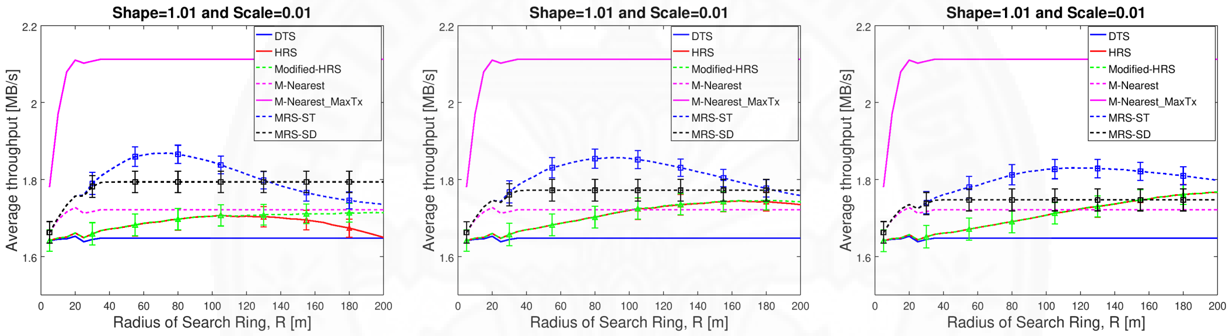
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.5 Average throughput of different schemes when Shape=1.3 and Scale=0.2 in a network having width of 100 m



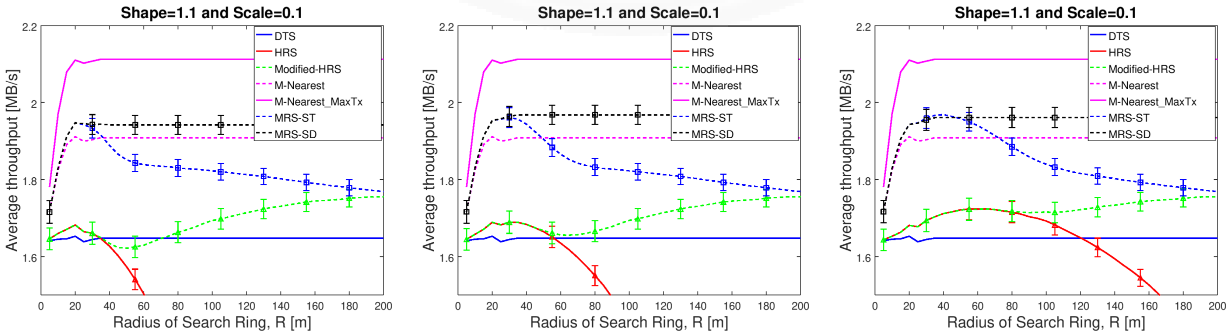
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.6 Average throughput of different schemes when Shape=1.001 and Scale=0.001 in a network having width of 500 m



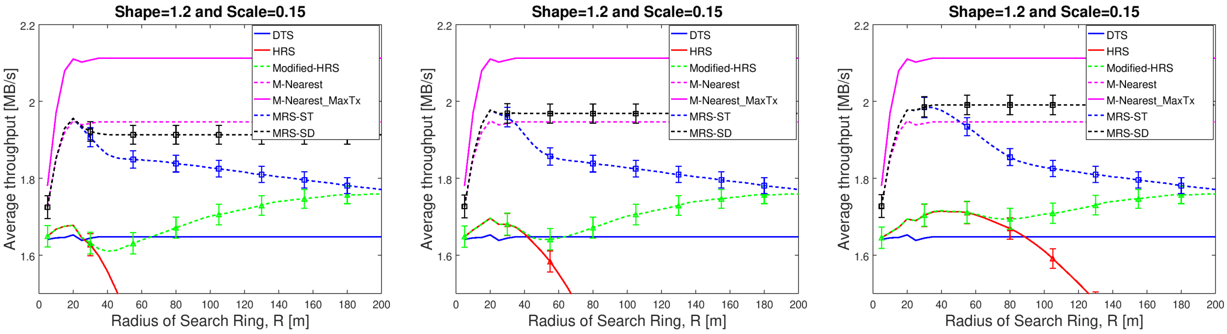
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.7 Average throughput of different schemes when Shape=1.01 and Scale=0.01 in a network having width of 500 m



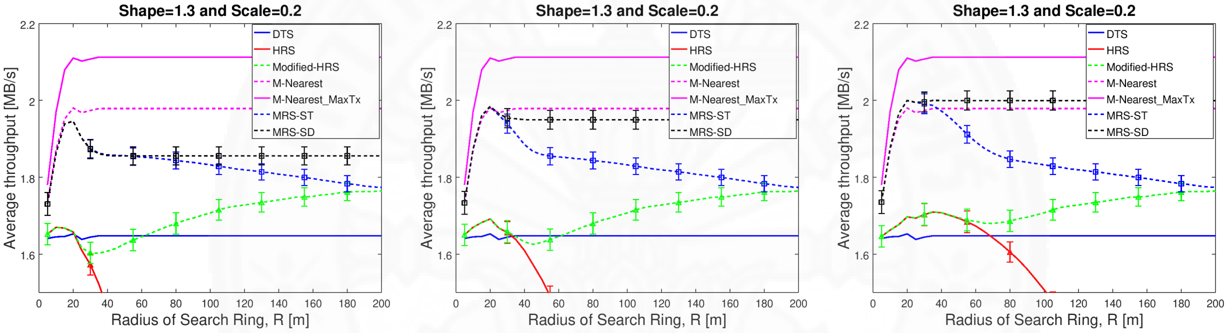
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.8 Average throughput of different schemes when Shape=1.1 and Scale=0.1 in a network having width of 500 m



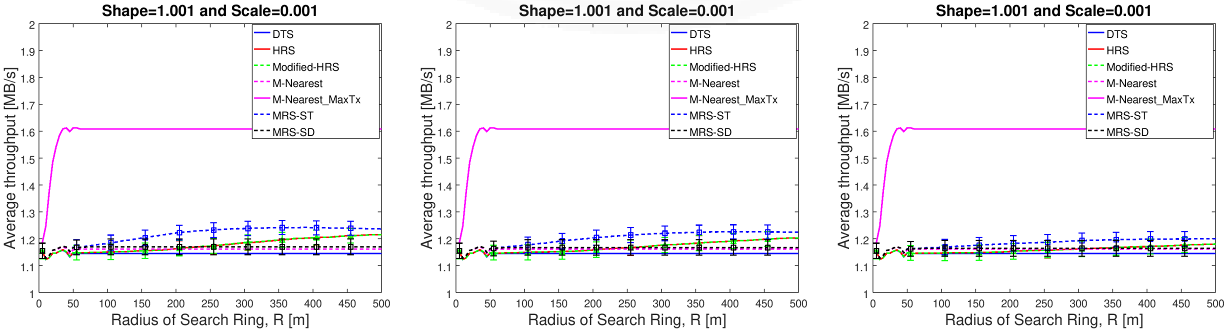
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.9 Average throughput of different schemes when Shape=1.2 and Scale=0.15 in a network having width of 500 m



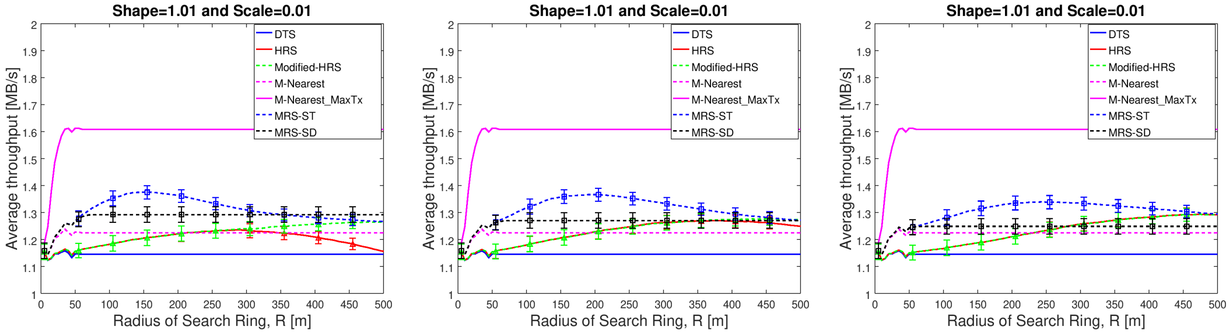
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.10 Average throughput of different schemes when Shape=1.3 and Scale=0.2 in a network having width of 500 m



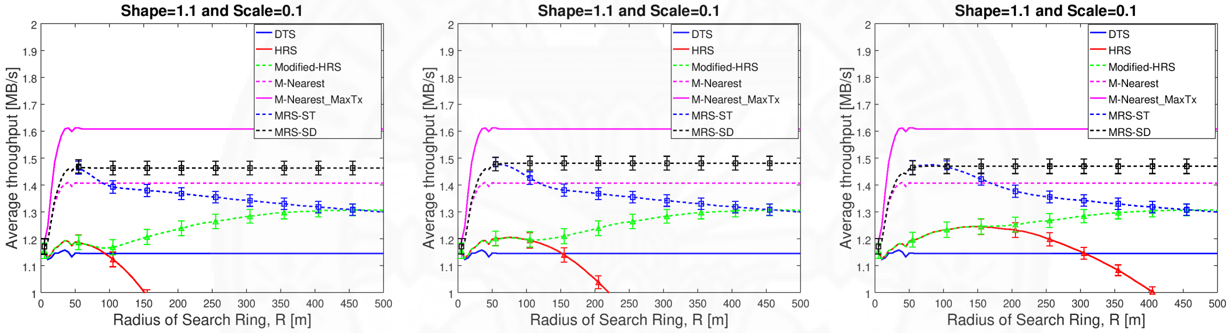
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.11 Average throughput of different schemes when Shape=1.001 and Scale=0.001 in a network having width of 1000 m



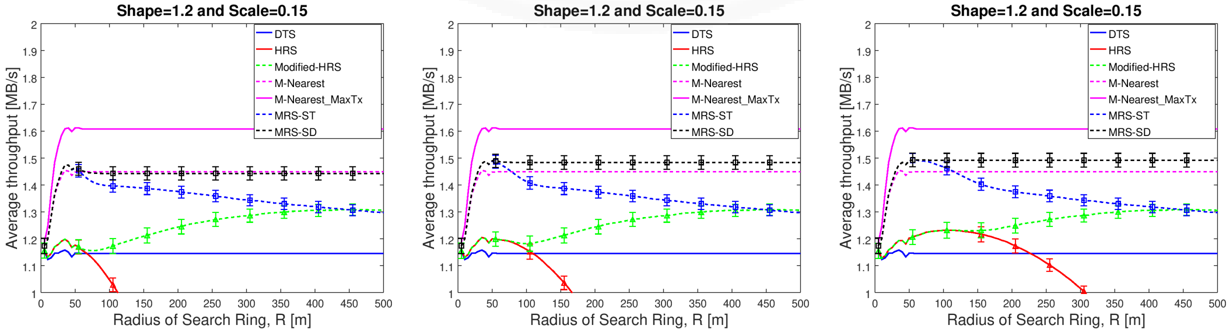
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.12 Average throughput of different schemes when Shape=1.01 and Scale=0.01 in a network having width of 1000 m



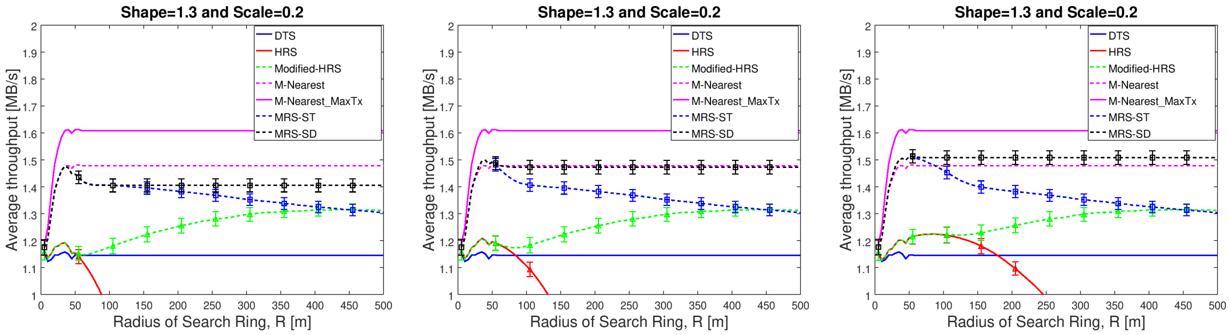
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.13 Average throughput of different schemes when Shape=1.1 and Scale=0.1 in a network having width of 1000 m



(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.14 Average throughput of different schemes when Shape=1.2 and Scale=0.15 in a network having width of 1000 m



(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.15 Average throughput of different schemes when Shape=1.3 and Scale=0.2 in a network having width of 1000 m

in search radius, nodes with higher value of social trust located further away from the midpoint may get selected as candidate relay nodes. As a result, throughput is reduced.

Similarly, for network width of 500 m and 1000 m we analyze the average throughput of different relay selection schemes. The graphs in the Figure 6.6, Figure 6.7, Figure 6.11 and Figure 6.12 shows average throughput of MRS is highest among all other schemes.

The graphs in the Figure 6.4 and Figure 6.5 shows that average throughput of MRS is lower than that of M-Nearest scheme. This suggests that when the social trust among nodes is high, maximum throughput can be attained by selecting relay node nearest to the midpoint, rather than wasting time for probing in an attempt to select the best node. A similar throughput trend is observed for network width of 500 m and 1000 m in Figure 6.9, Figure 6.10, Figure 6.14 and Figure 6.15.

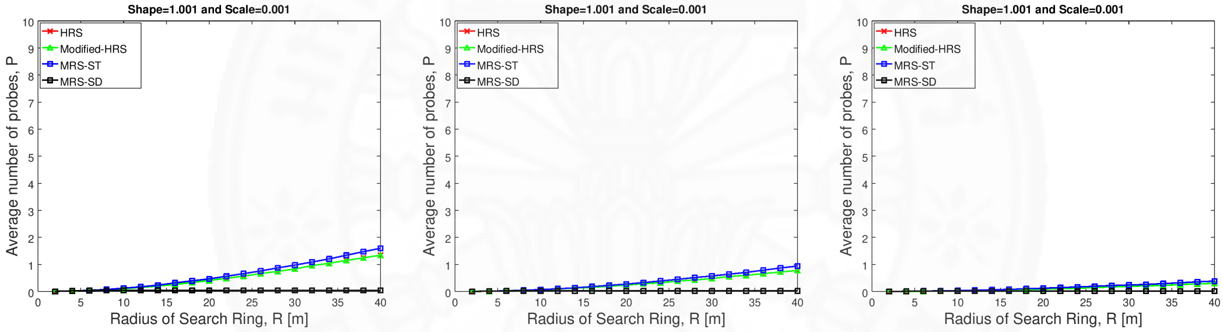
Impact of node density variation on throughput

When we compare the graphs in Figure 6.1 to Figure 6.15, we can see that the average throughput increases with the increase in node density. From these figures, it is also evident that average throughput of MRS increases with the increase in social trust among nodes even when the node density is not altered. The main observation is that the more links having social trust above social threshold, the greater the probability of selecting a relay with higher transmission power.

Number of probes vs search radius

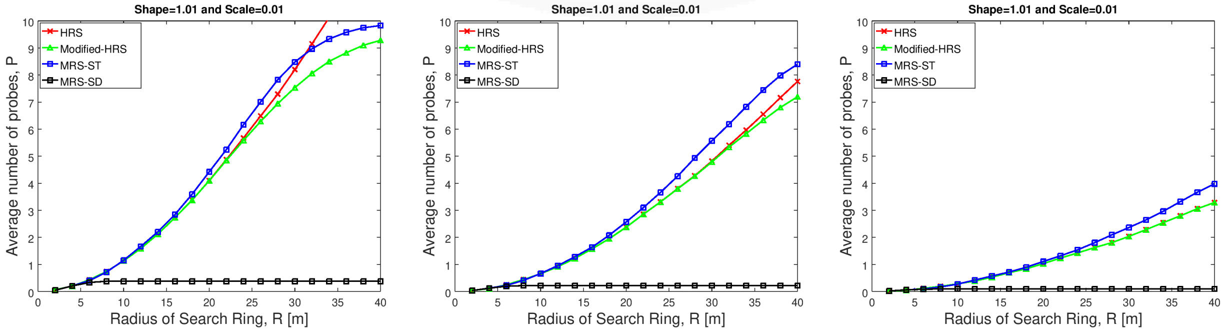
Now we investigate how the average number of probes for different schemes respond with an increase in search radius. The graphs for HRS and MRS in Figure 6.16 to Figure 6.30 are backed up by predictive analysis performed in Section 6.3. The results show that the average number of probes increases with an increase in search radius.

For network width of 100 m, the simulation data are recorded at an interval of 2 m upto R = 40 m. For network width of 500 m and 1000 m simulation data are recorded at an interval of 5 m. The search radius for network width = 500 m, ranges from 5 m upto 200 and that for network width = 1000 m ranges from 5 m upto 500 m.



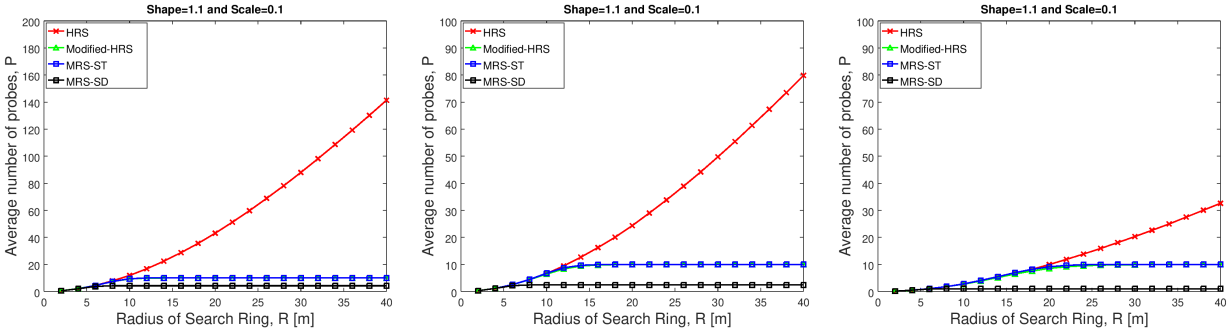
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.16 Average number of probes used by different schemes when Shape = 1.001 and Scale = 0.001 at network width of 100 m



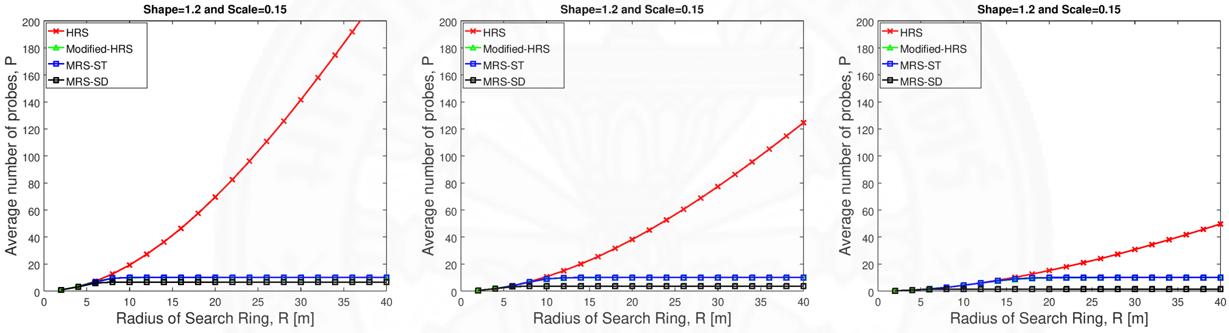
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.17 Average number of probes used by different schemes when Shape = 1.01 and Scale = 0.01 in a network having width of 100 m



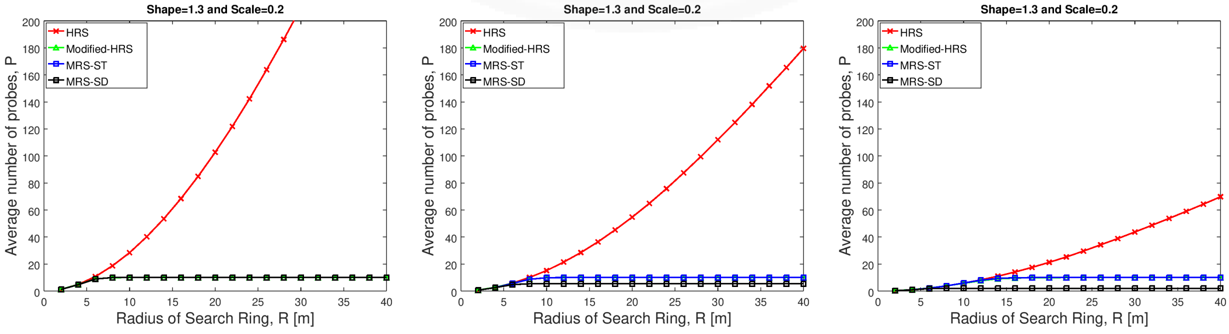
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.18 Average number of probes used by different schemes when Shape = 1.1 and Scale = 0.1 in a network having width of 100 m



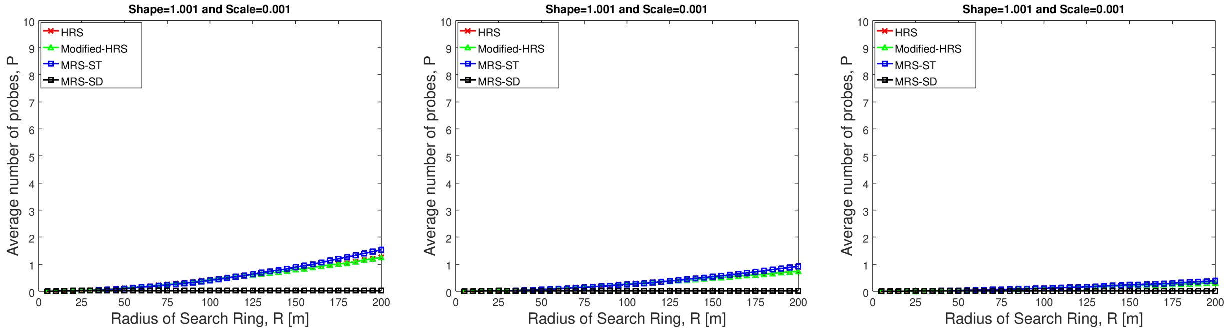
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.19 Average number of probes used by different schemes when Shape = 1.2 and Scale = 0.15 in a network having width of 100 m



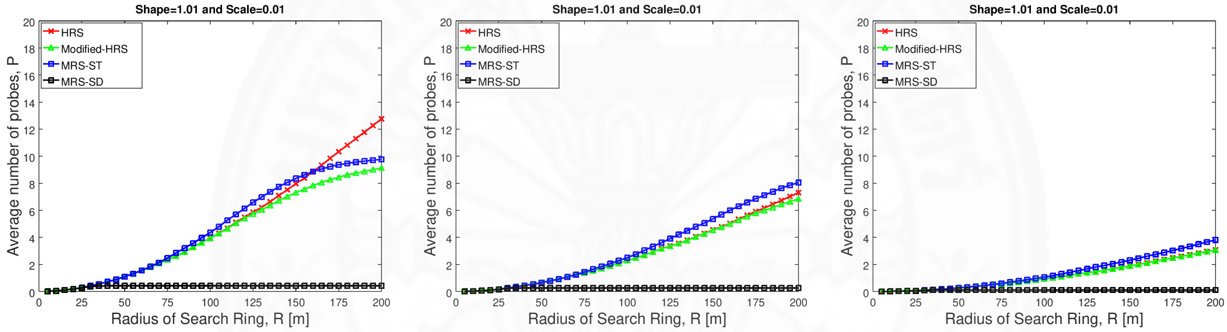
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.20 Average number of probes used by different schemes when Shape = 1.3 and Scale = 0.2 in a network having width of 100 m



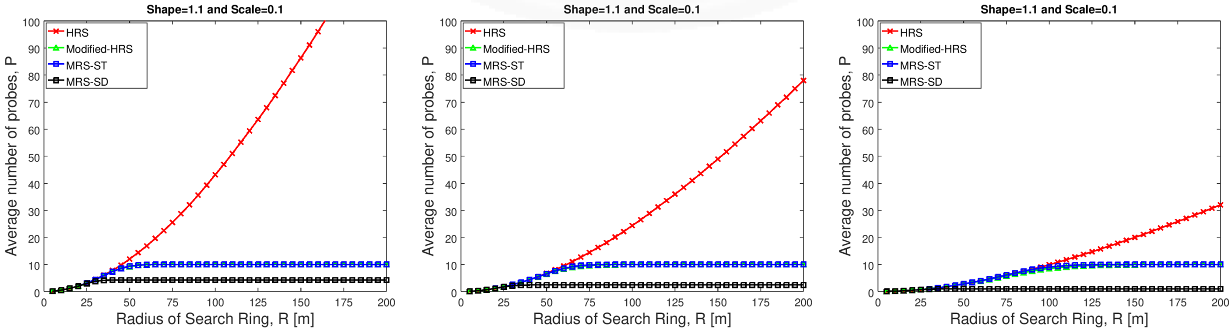
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.21 Average number of probes used by different schemes when Shape = 1.001 and Scale = 0.001 in a network having width of 500 m



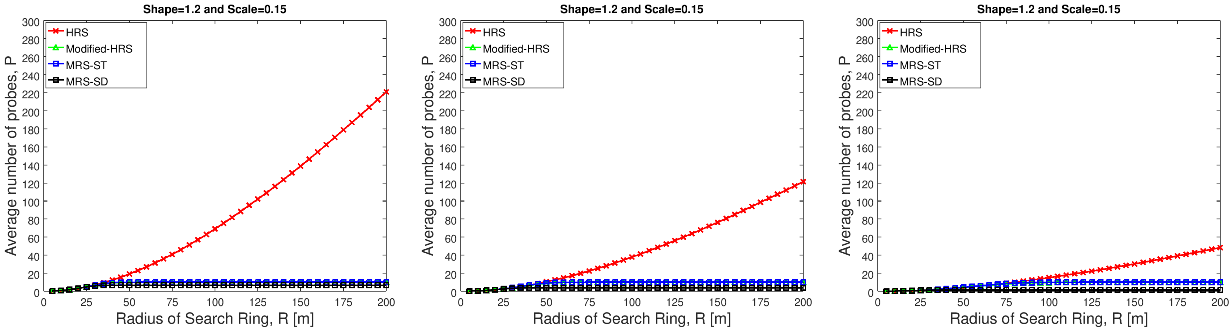
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.22 Average number of probes used by different schemes when Shape = 1.01 and Scale = 0.01 in a network having width of 500 m



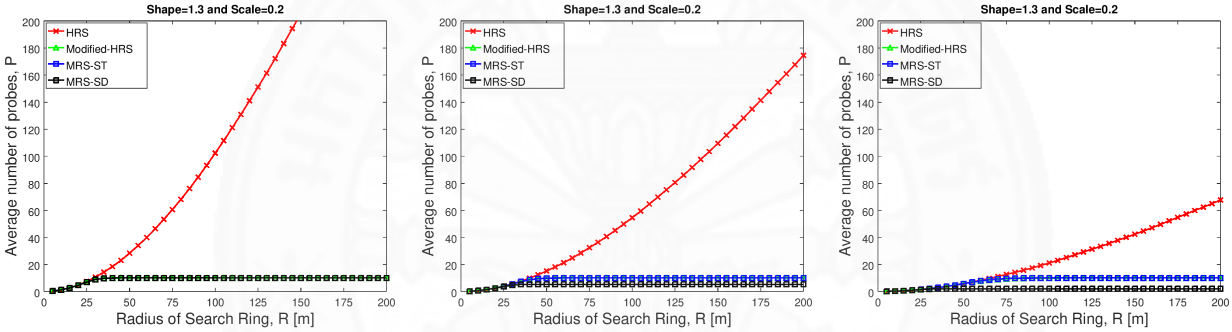
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.23 Average number of probes used by different schemes when Shape = 1.1 and Scale = 0.1 in a network having width of 500 m



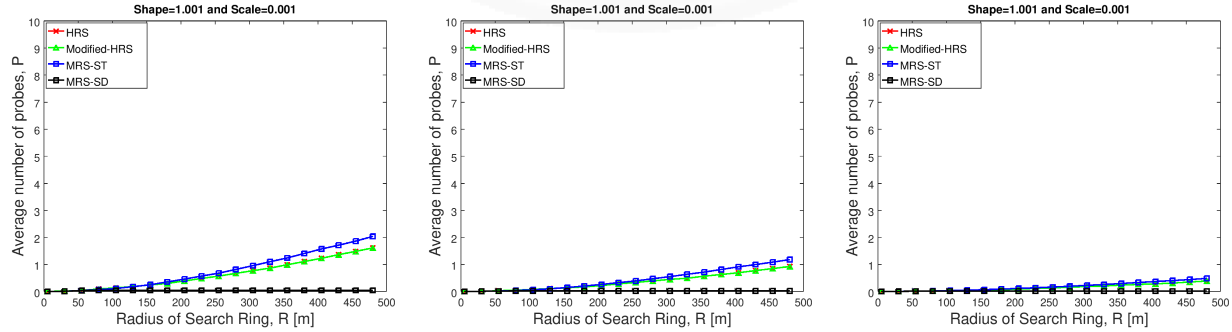
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.24 Average number of probes used by different schemes when Shape = 1.2 and Scale = 0.15 in a network having width of 500 m



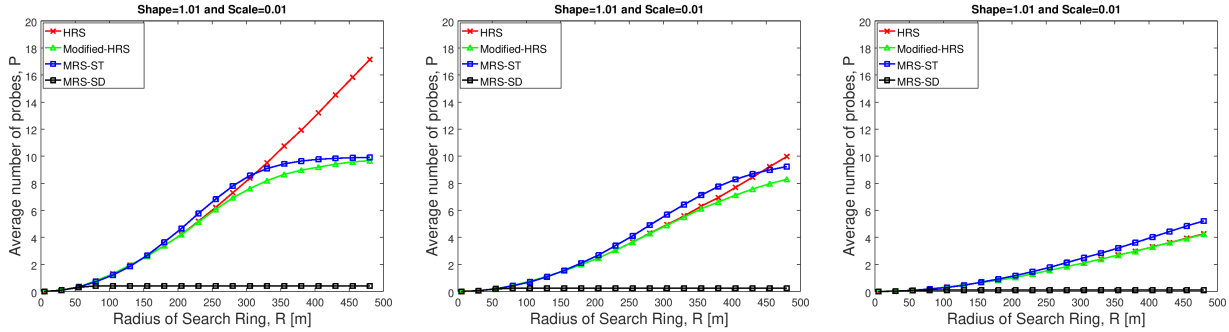
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.25 Average number of probes used by different schemes when Shape = 1.3 and Scale = 0.2 in a network having width of 500 m



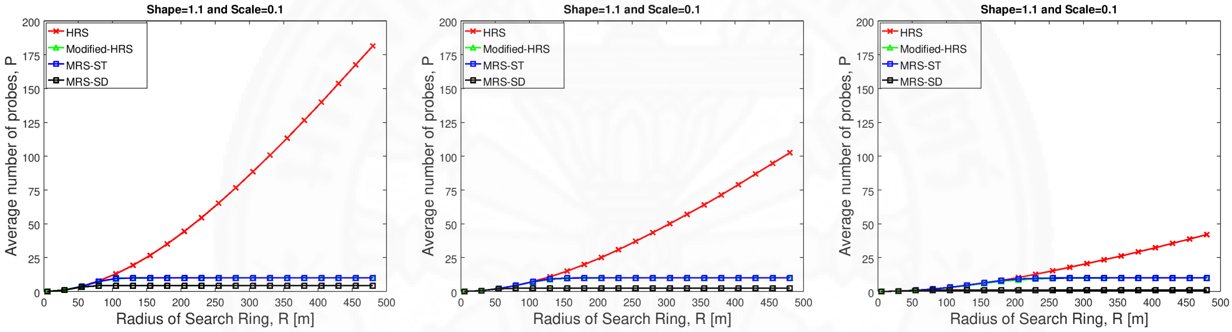
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.26 Average number of probes used by different schemes when Shape = 1.001 and Scale = 0.001 in a network having width of 1000 m



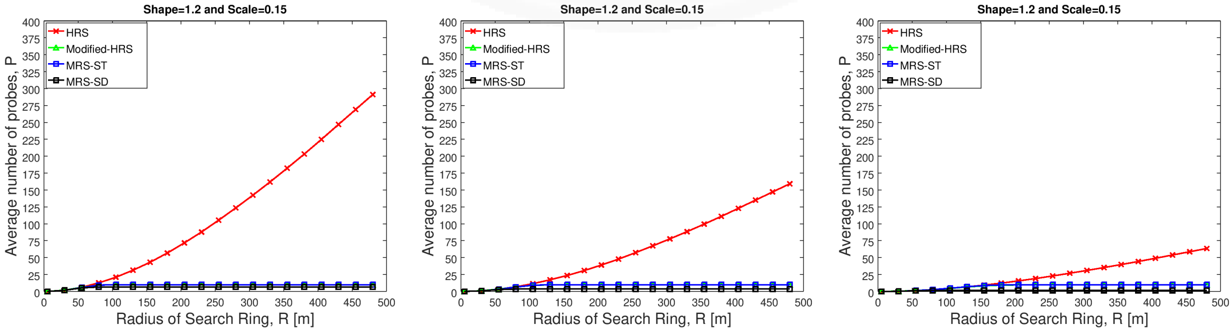
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.27 Average number of probes used by different schemes when Shape = 1.01 and Scale = 0.01 in a network having width of 1000 m



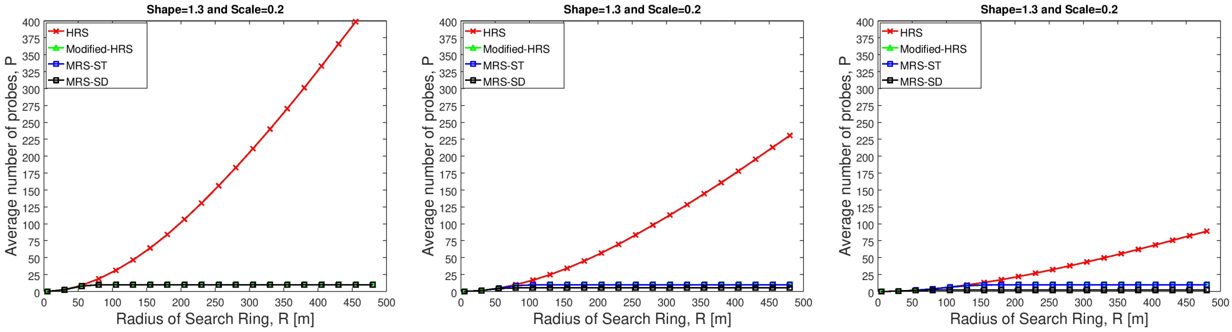
(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.28 Average number of probes used by different schemes when Shape = 1.1 and Scale = 0.1 in a network having width of 1000 m



(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.29 Average number of probes used by different schemes when Shape = 1.2 and Scale = 0.15 in a network having width of 1000 m



(a) Social Threshold 0.2 (b) Social Threshold 0.3 (c) Social Threshold 0.5

Figure 6.30 Average number of probes used by different schemes when Shape = 1.3 and Scale = 0.2 in a network having width of 1000 m

The graphs in Figure 6.16 to Figure 6.20, Figure 6.21 to Figure 6.25 and Figure 6.26 to Figure 6.30 show the comparison of average number of probes for different relay selection schemes in networks having width of 100, 500 and 1000 meters respectively. In these figures, average number of probes is on the y-axis and search radius of search ring is on the x-axis. The graphs in Figure 6.16 to Figure 6.20 show that the average number of probes in HRS increases with the gradual increase in search radius, as more nodes are located within the circular region. This increase in the number of probes decreases the time duration left for real data transmission in each time slot, resulting in reduction of average throughput of D2D communications. However average number of probes for Modified-HRS is lower than that of HRS in most of the cases. This is because Modified-HRS has a probe limit which allows at l nodes being probed. The source probes only l nodes having maximum social trust values once the number of nodes within the search circle exceeds the probe limit. MRS-ST also has the similar trend with an increase in search radius because MRS-ST also uses probe limit.

In contrast to other schemes, the average number of probes for MRS-SD has the minimum value among all other schemes and remains almost constant even with the increase in search radius. This scheme initially prioritizes distance of nodes from the midpoint and then selects a limited number of nodes. Among those selected nodes, only those with trust above social threshold are probed. In case of MRS-ST, the source probes at most l times. However, in case of MRS-SD, the source probes l

times only when the chosen *l* nodes nearest to midpoint have social trust values above the social threshold. Otherwise, the number of probes is less than *l*. A similar trend is observed in graphs for network widths of 500 and 1000 meters.

Impact of social threshold on throughput

This section shows that with an increase in social trust among nodes, increasing the social threshold delivers an increased average throughput of MRS. Figure 6.1 and Figure 6.2 represents weak social trust scenario among nodes in the network for a network width of 100 m. Similarly Figure 6.6 and Figure 6.7 represents weak social trust scenario among nodes in the network for a network width of 500 m, and Figure 6.11 and Figure 6.12 for a network width of 1000 meter.

The graphs in Figure 6.1 and Figure 6.2 shows that when social trust among nodes is low, increasing social threshold reduces average throughput of MRS. This is because fewer nodes get selected as candidate relay nodes with the increase in social threshold. Similar trend of change in throughput is observed in Figure 6.6, Figure 6.7, Figure 6.11 and Figure 6.12.

The graphs on Figure 6.3 show that the average throughput of MRS-ST can be improved by increasing social threshold, while improvement in average throughput of MRS-ST is not significant in the graph of Figure 6.13. This suggests that increasing social threshold is not beneficial when node density is low.

For the network scenarios with stronger social trust among users represented in Figure 6.4, Figure 6.5, Figure 6.9, Figure 6.10, Figure 6.14 and Figure 6.15, increasing the social threshold increases average throughput of our proposed scheme even if the node density is low. This is because with an increase in social threshold, nodes with high social trust values only get selected as candidate relay nodes. Therefore, comparatively less number of nodes are being probed to be selected as a relay. This contributes for the increment in throughput.

Comparison between M-Nearest and MRS schemes

Our proposed scheme performs better than all other schemes, except M-Nearest in selected cases. Table 6.4 summarizes the throughput results of MRS compared to M-Nearest, for various distributions of social trust among users when network widths are 100, 500 and 1000 meters. When average throughput of MRS is greater than that of M-Nearest, it is denoted as Yes; otherwise, —.

Table 6.4 Summary comparison of M-Nearest Scheme with MRSS

Social trust (shape, scale)		**(1.001, 0.001)**			**(1.01, 0.01)**			**(1.1, 0.1)**			**(1.2, 0.15)**			**(1.3, 0.2)**		
Social threshold, S_{thres}		0.2	0.3	0.5	0.2	0.3	0.5	0.2	0.3	0.5	0.2	0.3	0.5	0.2	0.3	0.5
Network width	**100**	Yes	Yes	Yes	Yes	Yes	Yes	—	Yes	Yes	—	—	Yes	—	—	—
	500	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	—	—	Yes	—	—	—
	1000	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	—	Yes	Yes	—	—	Yes

The results show that when social trust values among nodes are low and node density is also low, social threshold should be set to a low value, as high value of social threshold lowers average throughput of our proposed scheme compared to M-Nearest scheme. However, setting social threshold to a high value can enhance throughput of our proposed scheme, when social trust among nodes are high and node density is low.

On the contrary, when social trust among nodes as well as node density are high, M-Nearest scheme out-performs MRS even after setting social threshold to a higher value. When large number of links have high trust values, a relay selected nearest to the midpoint transmits at high power most of the time. Probing of nodes to select a relay with maximum transmission power unnecessarily consumes time before data transmission, resulting in lower average throughput. Moreover, when social trust among nodes are low and node density is high, having social threshold set to a high value can improve throughput of our proposed scheme.

These results suggest that average throughput of D2D communication between nodes depends upon social trust distribution of nodes in the network. Increasing the social threshold can reduce the number of probes significantly, contributing to increased average throughput. However, the social threshold should not be set to a very high value such that no nodes in the network becomes eligible to be probed. Therefore, the BS should dynamically select the social threshold and recommend relay nodes, taking into account the social trust distribution of nodes.

6.5 Summary

MRS-ST and MRS-SD schemes select a relay such that there is a balance in the length of physical links, and with stronger social links. This significantly improves throughput compared to the current state-of-the-art relay selection schemes. The performance of MRS-ST and MRS-SD schemes depends upon distribution of social trust among nodes in the network. Our simulation analysis shows that proposed schemes MRS-ST and MRS-SD have significantly higher throughput than HRS in all of the analyzed scenarios, although in some cases M-Nearest scheme has higher throughput than MRS-ST and MRS-SD.

Additionally, the results show that MRS-ST performs significantly better than MRS-SD. This suggests that filtering nodes according to social trust is better than filtering of nodes according to social distance while selecting a relay. Our analysis also suggests that proper selection of social threshold value reduces time spent for probing, increasing throughput. An algorithm that automatically determines the social threshold based on network characteristics can be developed. This motivated for the design of new relay selection scheme presented in next chapter.

CHAPTER 7

ADAPTIVE-MIDPOINT RELAY SELECTION

The Midpoint Relay Selection with Social Trust (MRS-ST) scheme presented in Chapter 6 has superior performance compared to other schemes. However, the scheme has unsatisfactory performance when social trust among the users is high. Therefore, this chapter presents the Adaptive Midpoint Relay Selection (Adaptive-MRS) scheme that can overcome this shortcoming by switching between MRS-ST scheme and nearest to the midpoint (M-Nearest) scheme depending upon social trust among the users in the network.

Adaptive-MRS presented in this chapter is published as a book chapter entitled Adaptive Midpoint Relay Selection: Enhancing Throughput in D2D Communications, in Studies in Computational Intelligence Series (SCIS), Vol. 850, pages 191-207, 2019 [66].

Section 7.1 presents additional performance analysis of MRS-ST with other schemes at different social trust scenarios. This motivated the design of Adaptive-MRS scheme. Section 7.2 presents the system design of Adaptive-MRS scheme. Section 7.3 presents the comparative performance analysis of Adaptive-MRS with other relay selection schemes for networks with different node densities. The analysis is done for networks having different social trust scenarios. Finally, section 7.4 concludes that Adaptive-MRS has improved performance upon MRS-ST even when social trust among the devices in the network are high.

7.1 Motivation

In Chapter 5 and Chapter 6, we assume that the social trust among the users in the network is stable all the time. The analysis is done for certain set of social trust scenarios. However, with the movement of people, particularly the social trust among users in the network may vary over time. A relay selection scheme working well for a scenario of social trust among users may not perform well in other scenarios.

When a set of users in the network have different social trust relationships, then one relay selection scheme is better than the other. For example, when the social trust among all the nodes in the network are very high, using a M-Nearest scheme results higher throughput. However, choosing a node nearest to the midpoint not always maximize throughput for all social trust scenarios. Using another scheme, MRS-ST scheme, in all social trust scenarios do not result improved throughput as well. The results are illustrated in section 7.1.2. Therefore, a relay selection scheme should be designed depending upon the users in the network and how they trust each other. A scheme which can adaptively switch between different schemes depending upon social trust scenarios in the network is necessary to enhance throughput of the network. On its own the MRS-ST is not good when the BS knows social information of users in the network. This has motivated for the design of Adaptive-MRS.

The purpose of this section is to illustrate the requirement of Adaptive-MRS by analyzing performance of MRS-ST in various social trust scenarios. The comparative analysis of MRS-ST is done against following schemes:

- HRS scheme, proposed in [12]

- M-Nearest scheme, where a relay is selected nearest to midpoint of the distance between the source and the destination

- M-Nearest_MaxTx scheme, where a relay is selected nearest to midpoint of the distance between source and destination assuming relay always has maximum allowable transmission power. In reality, nearest to midpoint node does not always transmit at maximum power but the scheme is used as a benchmark scheme.

7.1.1 Simulation setup

Table 7.1 shows the details of the simulation setup used in our research. A custom simulation model of HRS, M-Nearest, M-Nearest_MaxTx, MRS-ST and PA-MRS was developed in Octave [59]. In square network area having widths of 100 and 1000 meters, one thousand devices are uniformly distributed at random. BonnMotion [30] is used to implement mobility of devices using random waypoint mobility model. We are considering a scenario where people carrying mobile devices are walking within a certain area. Therefore, the speed of devices is varied between 0–2 m/s and have maximum pause time of 5 s. The social trust value between two devices follow Pareto distribution. Different social trust scenarios among devices in the network are achieved by varying the Shape and Scale parameters. Source and destination are selected randomly from the 1000 devices. We set the transmission power of a source device $P_{s,d}$ = 20 dBm, noise power N = -114 dBm, pathloss exponent $\theta = 4$, bandwidth of channel B = 1 MHz as in [1], [12]. We assume the duration of a time slot for D2D communications T = 1 sec and that for a probe τ = 0.01 sec [31]. Each simulation runs for 1000 seconds. In this analysis, the maximum allowable transmission power for a relay is considered to be equal to transmission power of source. The average throughput values reported for each of the schemes in this analysis are the time average of the maximum throughput attained by the schemes, regardless of the search radius used for relay selection. The results based on the simulation setup is presented next.

7.1.2 Results

The comparative analysis of average throughput of different schemes presented in Chapter 5 and 6 were performed at the same search radius. However, different schemes attain maximum throughput at different search radius. Therefore in this chapter, the radius that maximizes the average throughput is used for each scheme. This radius is referred as an optimal search radius. Such comparison makes more sense because each scheme can adaptively adjust the search radius to achieve its best

Table 7.1 Simulation setup for analysis of MRS-ST and Adaptive-MRS

Simulation Parameters	
Simulation software	Octave
Mobility model	Random waypoint
Number of nodes, n_{total}	1000
Network width, W	100 and 1000 m
Speed of nodes, S	0 - 2 m/sec
Maximum pause time	5 sec
Simulation period	1000 sec
Channel bandwidth, B	1 MHz
Pathloss exponent, θ	4
Noise power, N	-114 dBm
Social trust, β	$0 - 1$
Social threshold, S_{thres}	0.3
Probe limit, l	10
Shape, α	1.001, 1.01, 1.1, 1.2, 1.3, 2, 5
Scale, L	0.001, 0.01, 0.1, 0.2, 0.5, 0.8, 0.99
Upper limit, H	1
Transmission power, $P_{s,d}$	20 dBm
Max. allowable tx power, $P_{s,j}$	20 dBm
Time slot duration, t	1 sec
Probe duration, τ	0.01 sec
Search radius, R	Upto 500 m

performance. We analyze the performance of different relay selection schemes in various social trust scenarios under different node densities.

Figure 7.1 shows the three dimensional comparison of maximum of average throughput offered by the different relay selection schemes in a square network having network width of 100 m. The graph in the vertical axis represents the maximum average throughput that a scheme can attain for a social trust scenario (Shape, Scale pair). As expected, the throughput of M-Nearest_MaxTx has the highest value among all the other schemes and remains constant for all values of shape and scale. For all the other schemes, the throughput increases with the increase in Scale value. Comparatively the throughput is less affected by the shape value. The throughput of MRS-ST is significantly higher than that of HRS for all range of shape and scale. This is mainly because of the balance of link lengths between the source to the relay and from the relay to the destination in MRS-ST.

In addition, a probe limit also contributes to the performance enhancement of MRS-ST in dense networks with high probability of social trust. This is because in such networks, number of nodes having social trust above social threshold can be large. Probing of all those nodes can consume large duration of a time slot. As a result, the throughput decreases. However, with the use of probe limit, at most l nodes having maximum social trust values are only probed, thereby contributing to enhance the throughput.

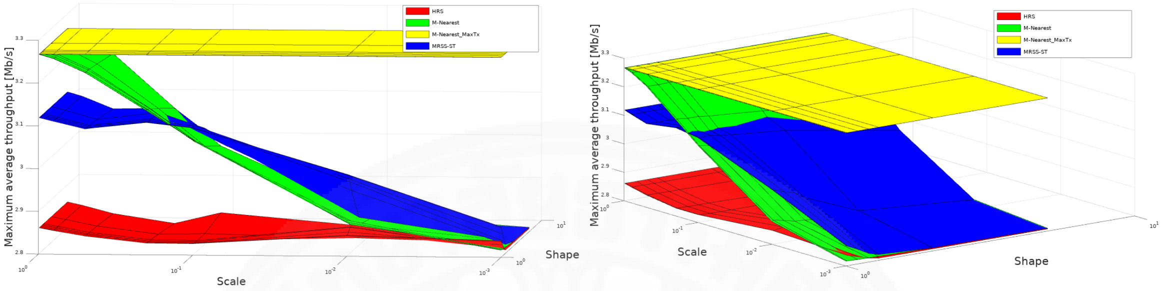


Figure 7.1 Maximum of average throughput attained by different relay selection schemes for network width of 100 m (two different viewpoints of the same 3D plots)

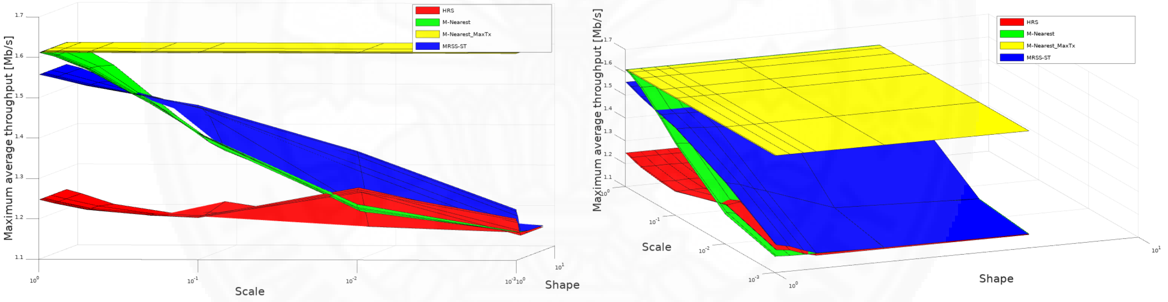


Figure 7.2 Maximum of average throughput attained by different relay selection schemes for network width of 1000 m (two different viewpoints of the same 3D plots)

For the higher values of scale (approximately above 0.15), the throughput of M-Nearest is greater than that of MRS-ST. When social trust among the nodes are very strong, all the nodes can potentially transmit at a high power. The probing of nodes before selection of a relay in MRS-ST reduces time for actual data transmission. However, user data is directly transmitted in M-Nearest. This results in superior performance of M-Nearest compared to MRS-ST for high value of scale.

Figure 7.2 shows the comparison of maximum of average throughput offered by the different relay selection schemes in a square network having network width of 1000 m. The trend of throughput variation for all the schemes are similar to that in network having width of 100 m. The comparison shows that Figure 7.1 has higher value of the throughput than that of Figure 7.2.

More importantly we also show that the maximum of average throughput of MRS-ST increases significantly with the increase in scale value and is less dependent with variation of shape value in both the network scenarios. The insights obtained from the results motivated to develop Adaptive-MRS scheme presented in the next section.

7.2 System design of Adaptive-MRS

7.2.1 Key design factor

In this chapter, we consider that the BS not only knows the location information, but also the social trust value that a user has for other users in the network. The BS utilizes social trust information to maximize throughput of D2D communication. The BS sends the information to the source whether to probe or not for selection of a relay. As we use social trust model following Pareto distribution, we assume that the BS is capable of determining current Shape and Scale values using social trust values. Additionally, we assume that the BS can adaptively adjust a search radius such that maximum throughput can be achieved.

When social trust among devices in a network are low, probing of devices are necessary before selection of a relay. The relay can be selected as in MRS-ST scheme presented in Chapter 6. However, when social trust among the devices are high, the performance of MRS-ST is lower than that of M-Nearest scheme as illustrated in Figure 7.1 and Figure 7.2. Therefore, when social trust among the devices are high, the source should not be probing devices within the circular region for relay selection. On the contrary, a relay needs to be selected that is located nearest to the midpoint of the distance between the source and the destination, without any probing of devices. This suggests that there should be a switching mechanism that controls the switching between probing of devices for relay selection or direct selection of a relay depending upon the social trust scenario in the network.

7.2.2 Proposed design

This section presents the design of a relay selection scheme for D2D communications utilizing social trust values of mobile users in the network. The proposed design is based upon the communication protocol presented in Chapter 4. A relay is selected among the nodes that are located around the midpoint of the distance between the source and the destination using social information of users. The main focus of proposed design is on the set of tasks performed by different entities of the network for relay selection in D2D communications, not on conventional cellular communications. We highlight the differences in tasks performed at each entities of the network compared to those in Chapter 5 and Chapter 6. These information exchange are illustrated in the algorithms presented later in this section.

Table 7.2 lists variables that are used in the Algorithm 11, Algorithm 12, Algorithm 13 and Algorithm 15.

The main difference in the design of Adaptive-MRS compared to the design of MRS-SA, MRS-ST and MRS-SD is due to the assumption that the BS can adaptively adjust a search radius to maximize throughput. Another reason for the difference in design is because the BS is also assumed to know the social trust nodes have for others as well as location of nodes. With these assumptions, BS is assumed to do some additional tasks compared to the task of BS in MRS-SA, MRS-ST and MRS-SD. Now we will explain the tasks of a BS implementing Adaptive-MRS in next paragraph.

In practise, as implemented in [6], [11], [12], BS obtains this information using call history of users and information collected from online social networks like Facebook and Twitter. The same technique is implemented for obtaining social trust values in Algorithm 11. With the known values of social trust, the BS fits the social trust values to a Pareto distribution with a particular scale and shape. Then the BS knows the current scale and shape, and uses those values to compare to the scale and shape threshold values denoted as $Scale_{thres}$ and $Shape_{thres}$ respectively. A good estimation techniques such as Minimum Mean Square Error (MMSE) estimator or

Table 7.2 Table of definitions for design of Adaptive-MRS

Parameters	Definitions
s	Source node
d	Destination node
n	List of nodes
n_{total}	Total number of nodes
n_{circle}	List of nodes within a circular area
$n_{density}$	Node density
$n_{S_{thres}}$	List of nodes above social threshold
$Shape$	Shape of network
$Scale$	Scale of network
$Shape_{thres}$	Shape threshold
$Scale_{thres}$	Scale threshold
P_{max}	Maximum allowable transmission power
S_{thres}	Social threshold
R	Radius of circular region
T	Time slot duration
τ	Probe duration
l	Probe limit
p	Number of probes
C	Data rate
$Probing$	Probing decision
$C_{s,d}$	Data rate of Direct Communication
$C_{s,r,d}$	Data rate of D2D Communication
$t_{s,r,d}$	Throughput of D2D Communication

Least Mean Square Error (LSME) estimator can be deployed to determine the threshold values after which the throughput of M-Nearest scheme exceeds MRS-ST. When the actual scale and shape values exceed the threshold values, the BS tells the source to select a node that is located nearest to the midpoint and also has a social trust above social threshold (S_{thres}) as a relay. Otherwise, the BS tells the source to do sequential probing of nodes for relay selection as shown in Algorithm 11.

The data rate of D2D communication can be optimized by minimizing the difference between the data rate offered by a link from the source to the relay and that from the relay to the destination (see equation 4.3). Therefore, a node is selected as a relay which is located within a circular region with a center at the midpoint of the distance between the source and the destination. A BS identifies the idle nodes that are located within the circular region and sends the list of nodes (n_{circle}) and maximum allowable transmission power (P_{max}) to the source. The key difference in

Algorithm 11 Tasks performed at Base Station

```
// Given a source and a destination pair, BS determines candidate relay nodes, maximum allowable transmission power. For a relay selection, a BS also determines whether to probe or not.
Input: $s$ and $d$
Output: $n_{circle}$, $P_{max}$ and $Probing$
Estimate social trust between nodes using call history or available user information
Determine the empirical values for $Scale$ and $Shape$
Estimate $Scale_{thres}$ and $Shape_{thres}$
Receive D2D request from $s$
Calculate Midpoint, $m$ = Midpoint($s$, $d$)
Identify $n_{circle}$ = NodesWithinCircle($m$, $radius$)
if $Scale < Scale_{thres}$ and $Shape < Shape_{thres}$ then
    Probe nodes for relay selection i.e. $Probing = 1$
else
    Select a node nearest to the midpoint as a relay i.e. $Probing = 0$
end if
Determine $P_{max}$
Send $n_{circle}$, $P_{max}$ and $Probing$ to $s$
```

the communication protocol of Adaptive-MRS compared to MRS-SA, MRS-ST and MRS-SD is the additional information sent by the BS to the source during the D2D initiation phase. The BS sends list of devices within the circular region (n_{circle}) and maximum allowable transmission power (P_{max}) value to the source as in previous schemes. Additionally, the BS also tells the source whether to probe devices for relay selection or select a device nearest to midpoint as a relay. This additional information sent to the source, when to switch between probing and non-probing of devices for relay selection, plays a vital role in throughput enhancement when social trust among the devices in the network are high.

The major difference in tasks performed by a source in Adaptive-MRS compared to those in MRS-SA and MRS-ST is the decision that the source makes while selecting a relay. The source selects a relay depending upon the message received from the BS as shown in Algorithm 12. When $Probing = 0$, the source selects a relay that is located nearest to the midpoint. When $Probing = 1$, the source probes devices for relay selection. With the probing of a device, the source knows the signal to noise ratio (SNR) value that incorporates actual transmission power of the device and channel conditions. Source does not probe all the devices in the list sent by the BS. The source arranges the devices in the list received from the BS, according to the distance of the device from the midpoint. Among the devices in the list, at most l devices on the top of the list are selected to be probed. These devices are known as candidate relay nodes and have social trust above S_{thres}. The source sequentially probes candidate relay nodes for the relay selection. The source also probes the destination. As a reply to a probe, a candidate relay node sends a SNR value of the received probing packet to the source and also forwards the packet to the destination as in Algorithm 13. The actual data rate that can be achieved is calculated by the source. The throughput of D2D communication is calculated by taking time taken for probing of nodes under consideration as shown in Algorithm 12.

Upon receiving the packets from the candidate relay node and the source, the destination replies back to the source by sending the SNR values as in Algorithm 15. The source decides whether to communicate via a direct link or D2D link after comparing the data rate offered by both the links. The source selects the link offering maximum data rate to maximize throughput as shown in Algorithm 12.

In a summary, Adaptive-MRS is designed to achieve the performance of MRSS-ST when the social trust among the nodes are low and achieve the performance of M-Nearest when the social trust are high.

7.3 Performance analysis of Adaptive-MRS

We analyze the performance of different relay selection schemes. The comparative analysis of Adaptive-MRS is done against following schemes:

- HRS scheme, proposed in [12]
- M-Nearest scheme, where a relay is selected nearest to midpoint of the distance between the source and the destination
- M-Nearest_MaxTx scheme, where a relay is selected nearest to midpoint having maximum allowable transmission power
- MRS-ST, proposed in Chapter 6.

Algorithm 12 Tasks performed at Source

```
// A source determines whether to use a relay or not. If a relay is to be used, it selects a relay that maximizes the throughput of D2D communication.
Input: $s$, $d$, $n_{circle}$, $S_{thres}$, $P_{max}$, $l$, $\tau$ and $Probing$
Output: $t_{s,r,d}$
if len($n_{circle}$) = 0 then
    Calculate $C_{s,d}$ as in equation 4.2
    $t_{s,r,d} = C_{s,d}$
else
    Identify $n_{S_{thres}}$
    if $Probing = 0$ then
        Select a node from $n_{S_{thres}}$ located nearest to the midpoint as a relay
        Calculate $C_{s,r,d}$ as in equation 4.3
        $t_{s,r,d} = C_{s,r,d}$
    else
        if len($n_{S_{thres}}$) = 0 then
            $t_{s,r,d} = C_{s,d}$
        else
            if len($n_{S_{thres}}$) > $l$ then
                $n_{S_{thres}} = l$ nodes with max social trust values
                Sequentially probe nodes in $n_{S_{thres}}$ and $d$
                Calculate $C_{s,r,d}$ through each of nodes in $n_{S_{thres}}$ as in equation 4.3
                Select maximum $C_{s,r,d} = max(C_{s,r,d})$
                if $max(C_{s,r,d}) > C_{s,d}$ then
                    Relay is selected
                    $t_{s,r,d} = max(C_{s,r,d}) \times (T - (\tau \times n_{S_{thres}}))$
                else
                    $t_{s,r,d} = C_{s,d} \times (T - (\tau \times n_{S_{thres}}))$
                end if
            end if
        end if
    end if
end if
```

The simulation setup used for the analysis of Adaptive-MRS is same as the simulation setup presented earlier in section 7.1.

The three dimensional graphs in Figure 7.3 show the comparison of maximum of the average throughput of different schemes at different node densities. Different node density is achieved by varying width of a square network. The graph in the vertical axis represents the maximum average throughput that a scheme can attain for a social trust scenario (shape, scale pair). The average throughput values reported for each of schemes in this analysis are the maximum throughput attained by the scheme

Algorithm 13 Tasks performed at Candidate Relay Nodes

```
// Given a source ($s$) and a destination ($d$) pair, candidate relay nodes forward probes to the $d$. User data is also forwarded from the $s$ to the destination ($d$) and vice-versa.
Input: $s$, $d$, $P_{max}$ and probe
Output: SNR values
Receive probe message from $s$
Send SNR value of probe received to $s$
Send probe to $d$
```

Algorithm 14 Tasks performed at a Relay Node

```
//This algorithm consists of sequence of tasks performed by a relay node in D2D communications.
Input: $s$, $d$, $P_{max}$ and user data
Output: relay data
Receive user data from $s$
Send user data to $d$ with transmission power linearly proportional to social trust
```

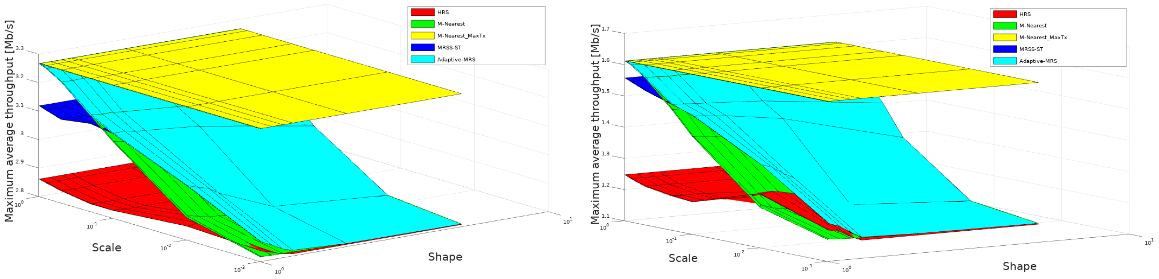
regardless of the search radius used for relay selection.

The graphs in Figure 7.3 show that the throughput of M-Nearest_MaxTx has the highest value among all the other schemes and remains constant for all values of shape and scale. It is used as a benchmark scheme. For all the other schemes, the throughput increases with the increase in Shape and Scale values. From the graphs it is evident that the throughput is less affected by the Shape value compared to Scale value. The throughput of Adaptive-MRS is significantly higher than that of HRS for all range of shape and scale. This is because of the balance of link lengths and probe limit in Adaptive-MRS as explained earlier in section 7.1.2.

Additionally, the performance of Adaptive-MRS has the maximum throughput of M-nearest and MRS-ST. The proposed Adaptive-MRS scheme can have higher throughput compared to HRS scheme by up to 29% when social trust among the

Algorithm 15 Tasks performed at Destination

```
// Receives probes and data sent to destination. It sends SNR values of the probes to the source as well as data.
Input: probe and data
Output: SNR values, data
Receive probe messages from $s$ and $r$
Send SNR values of probe received from $s$ and $r$ to $s$
Receive data from $r$ sent by $s$
Send user data to $s$ via $r$
```



(a) Network width 100 m

(b) Network width 1000 m

Figure 7.3 Maximum of average throughput attained by different relay selection schemes for different node densities

nodes are high in a network having low node density. When the node density is high, Adaptive-MRS scheme can provide upto 14% performance gain. This simulation is considering the ideal situation, where we can estimate the scale and shape with 100% accuracy. However, the result may deviate from this performance because in reality there might be some estimation error. If the estimated scale parameter is not very close to cross-over of MRS-ST and M-Nearest, we can still expect to get good performance of Adaptive-MRS even with minor estimation error. From the graphs it is also evident that the average throughput of relay selection schemes is more dependent on the lower limit of the support (scale) as compared to how fast the distribution tail decays (shape).

7.4 Summary

With proper estimation of scale value, proposed Adaptive-MRS scheme can overcome shortcomings of MRS-ST scheme present when scale value is high. Additionally, from the study we can conclude that the average throughput of relay selection schemes is more dependent on the lower limit of the support (scale) as compared to how fast the distribution tail decays (shape). In the future we will analyze the impact of the estimation error on the performance of Adaptive-MRS. This will allow us to compare Adaptive-MRS to MRS-ST and other schemes in more realistic scenarios.

CHAPTER 8

CONCLUSIONS

This chapter presents the conclusions of my research. Section 8.1 summarizes the key contribution of this thesis, in particular the different relay selection schemes and how they improve upon the state-of-the-art. Section 8.2 identifies areas where improvements can be made and new research opportunities exist in the field of social-aware relay selection for D2D communications. Section 8.3 concludes the thesis.

8.1 Contributions of the thesis

D2D communications is expected to be a key component of future cellular networks, supporting improved end-user service, while efficiently using the limited spectrum. The use of relays in D2D further expands the service offerings. With the increased availability of social information to network operators, new schemes can identify optimal relays that take into account end-users' willingness to forward their friends data. This is especially relevant in scenarios with a high density of users that have social relationships, e.g. universities, festivals and conferences. This thesis contributes four novel schemes for social-aware relay selection in D2D communications. Each scheme has clear throughput advantages compared to existing state-of-the-art (e.g. HRS by Pan and Wang [12]), and in some cases increase the throughput by 29%.

The proposed MRS-SA, MRS-ST and MRS-SD schemes assume that users only know the social trust for other nodes (not known by the base station). The Adaptive-MRS scheme proposed in this thesis assumes users as well as the base station know the social trust values that a user have for others. The search radius in

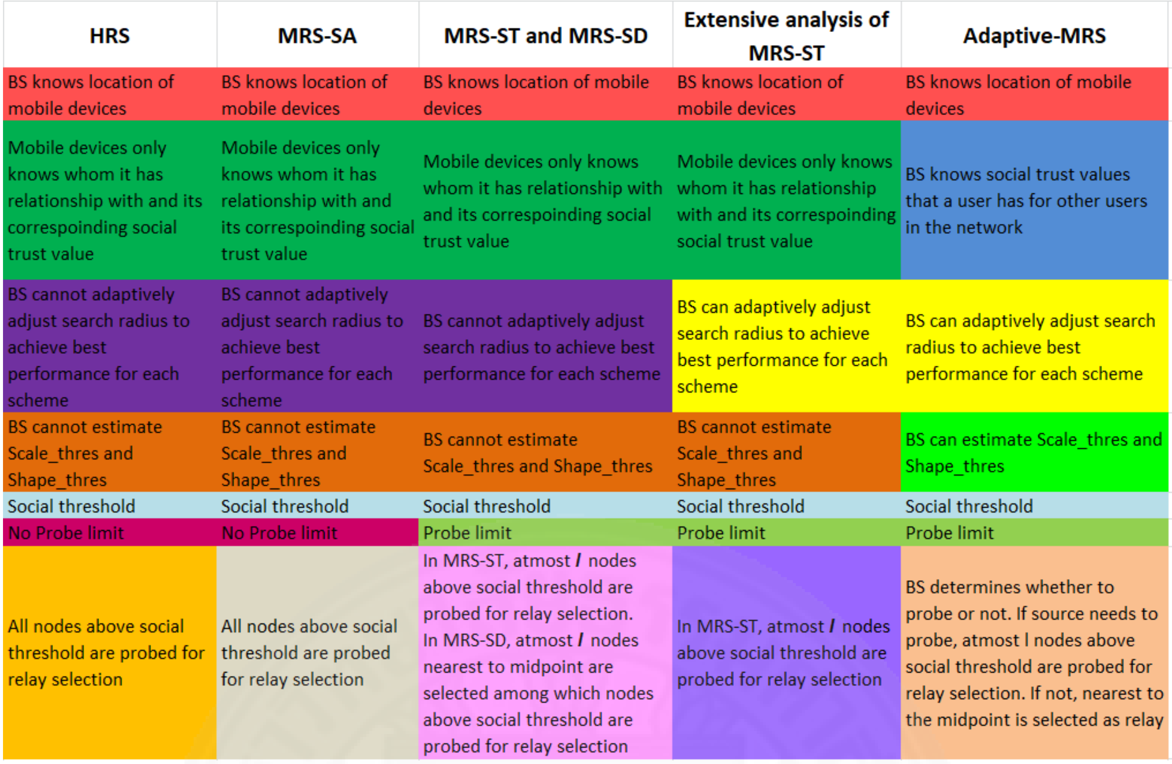
Adaptive-MRS is assumed to be capable of adjusting adaptively. All the schemes proposed in this thesis increase average throughput of the network by taking assistance of a relay whenever possible (by comparing average throughput of direct communication and that of D2D communication through a relay). A relay is selected among the devices that are located within a circular region with the center at the midpoint between the source and the destination. The way nodes are filtered within the circular region for relay selection differs for each schemes.

In MRS-SA, all devices that have social trust above a social threshold are sequentially probed for selection of a relay. MRS-SA can achieve upto 4.9% performance gain over HRS. The performance of MRS-SA reduces when node density is high because many nodes may have social trust above the social threshold. We proposed MRS-ST and MRS-SD to overcome this shortcoming by introducing a probe limit. MRS-ST and MRS-SD differ in the way they prioritize nodes for relay selection. Adaptive-MRS further increases the network throughput by adaptively switching between different schemes depending upon social trust scenarios in the network. The switching is done either to probe for selection of a relay or direct selection of a relay. The newly developed Adaptive-MRS scheme has significantly higher throughput than that of HRS scheme in all the network scenarios considered. The key result is that the proposed Adaptive-MRS can improve network throughput by upto 29% when social trust among the devices are high in a network having low node density. Figure 8.1 summarizes the key characteristics and tradeoffs of the four proposed schemes along with HRS.

8.2 Recommendations for future research

8.2.1 Use of real dataset to model user's mobility

One of the limitations of this research is that the performance analysis of relay selection schemes is done using Random Waypoint mobility model. The model is used to simulate mobility of nodes in the network. We assumed that the speed of nodes is varied between 0–2 m/s and have maximum pause time of 5 s. There



HRS	MRS-SA	MRS-ST and MRS-SD	Extensive analysis of MRS-ST	Adaptive-MRS
BS knows location of mobile devices	BS knows location of mobile devices	BS knows location of mobile devices	BS knows location of mobile devices	BS knows location of mobile devices
Mobile devices only knows whom it has relationship with and its correspoinding social trust value	Mobile devices only knows whom it has relationship with and its correspoinding social trust value	Mobile devices only knows whom it has relationship with and its correspoinding social trust value	Mobile devices only knows whom it has relationship with and its correspoinding social trust value	BS knows social trust values that a user has for other users in the network
BS cannot adaptively adjust search radius to achieve best performance for each scheme	BS cannot adaptively adjust search radius to achieve best performance for each scheme	BS cannot adaptively adjust search radius to achieve best performance for each scheme	BS can adaptively adjust search radius to achieve best performance for each scheme	BS can adaptively adjust search radius to achieve best performance for each scheme
BS cannot estimate Scale_thres and Shape_thres	BS cannot estimate Scale_thres and Shape_thres	BS cannot estimate Scale_thres and Shape_thres	BS cannot estimate Scale_thres and Shape_thres	BS can estimate Scale_thres and Shape_thres
Social threshold	Social threshold	Social threshold	Social threshold	Social threshold
No Probe limit	No Probe limit	Probe limit	Probe limit	Probe limit
All nodes above social threshold are probed for relay selection	All nodes above social threshold are probed for relay selection	In MRS-ST, atmost ***l*** nodes above social threshold are probed for relay selection. In MRS-SD, atmost ***l*** nodes nearest to midpoint are selected among which nodes above social threshold are probed for relay selection	In MRS-ST, atmost ***l*** nodes above social threshold are probed for relay selection	BS determines whether to probe or not. If source needs to probe, atmost l nodes above social threshold are probed for relay selection. If not, nearest to the midpoint is selected as relay

Figure 8.1 Comparison of our four proposed schemes with HRS

might be situations when nodes in the network remain stationary for some duration. Furthermore, in Random Waypoint model, there is frequent occurrence of sudden stop, sudden acceleration and sharp turn. However, in reality, the speed of pedestrians accelerate gradually, with a smooth change in direction. The analysis is done for a scenario where nodes are moving, but with limited mobility. It is considering a scenario where large number of people gather in a small area for certain duration of time such as educational institutions, organizations, industries, or events like concerts, conferences or exhibitions. This research does not take into consideration when the mobile devices have high mobility i.e. the outcome of this research is not applicable for vehicular networks. The use of random waypoint model cannot capture the realistic scenarios of mobility of users. This limitation can be overcomed by using real datasets for the analysis of relay selection schemes. The trace of node contacts from MIT Reality Mining Project [67] can be used for more realistic performance analysis of the proposed schemes in this thesis.

8.2.2 Use of real dataset to model social trust among users

The social trust among users in the network can be modelled using call history information or information from online social networks. Using Pareto distribution to model social trust among users in the network is another limitation of this research. We did not use the real dataset to model social trust among users.

The analysis of the proposed relay selection schemes assumes that a device has friendship with all other devices in the network i.e. friendship probability is 100%. In reality, a node may not be familiar to all the other nodes in the network. A node may have friendship with only a fraction of nodes present in the network. Therefore, with the change in the friendship probability in the network, the chance of finding a relay may also vary. This variation may produce different impacts on networks with different social trust scenarios and node density. In future, it is beneficial to explore the impact of change in friendship probability on throughput of our newly developed relay selection schemes.

Aharony et al. [57] conducted a survey on Friends and Family community composed of over 400 people to determine the social closeness between people in the community. It would be interesting to analyze the performance of our proposed schemes using real the dataset to model social trust among users in the network.

8.2.3 Analysis of variation in communication link

Our research assumes the noise in the system is constant and is interference free. In reality, there could be interference in D2D communications. Additionally, noise in the system may vary over time. The reduction in signal strength may vary for different locations. The performance of the proposed relay selection schemes are not analyzed for such scenarios. A new system can be designed which captures all such scenarios. Future work could involve the investigation of performance of our proposed schemes in such system.

8.2.4 Analysis of variation in social links

The analysis of different relay selection schemes presented in this thesis assumes that social trust value between a pair of devices is constant and bidirectional. In reality, the friendship among nodes in the network may change over time. Also the social trust value is not necessarily bidirectional all the time. The analysis presented in this thesis does not include all real scenarios.

In future, a system can be designed where social trust value among the pair of nodes are not necessarily bidirectional and vary with time. Such system incorporating the dynamics of social link may have different impact in the performance of relay selection schemes presented in this thesis. This can be investigated further.

8.2.5 Analysis of variation in probing frequency

The analysis of different relay selection schemes presented in this thesis is based on the assumption that a pair of devices having D2D communication does device discovery every second. We assumed random waypoint mobility model where the speed of nodes is varied between 0–2 m/s and have maximum pause time of 5 s. There might be a situation when nodes in the network remain stationary for some duration. In that situation, probing of nodes every second may be waste of a resource (duration within a time slot). Using the same relay may increase the network throughput. The source may probe for a relay only after some interval of time. Reducing the frequency of probing reduces the power consumption at nodes. Analyzing the impact of probing frequency variation on average network throughput could be done in future. Additionally, a system may be designed which initiates probing only when the location of the source and destination change. This may produce different impact on the throughput of a network. Another parameter worth analyzing is variation in power consumption at nodes with the change in probe frequency. The analysis can be done for networks with different social trust scenarios and different node densities.

8.2.6 Analysis of transmission behaviour of a relay having high social trust for many nodes

In all the work presented in this thesis, we assume that nodes in the network are cooperative. A node relays data for other nodes with a transmission power proportional to the social trust. If a node has strong social relationship with many other nodes, will it transmit at a power proportional to the social trust while relaying? This may be a disadvantage for the node as relaying can quickly drain battery power of the node. The node may try to reduce its battery consumption. The way such a relay node behaves in this situation may significantly impact performance of others. One can analyze the impact on network throughput when a node's behaviour deviates from the transmission power assumption used in this thesis.

8.2.7 Analysis of battery power variation on transmission power

When a relay node has a high battery power, we assume that the node always transmits at a power proportional to the social trust value it has for the source. Does a relay transmit at a power proportional to social trust even when battery power is low? If the node has a low battery power, it may not be realistic to assume that the node still transmits accordingly. Rather it may transmit at a low (minimum) power to all the nodes regardless of the social trust value. It would be intriguing to investigate the transmission behaviour of a relay when it's battery power is low.

8.3 Closing remarks

We have highlighted some of the potential areas of future work in the field of social-aware relay selection. There are others areas which could be explored in future such as security, synchronization mechanism, pricing mechanism etc. In closing, this thesis has contributed four novel schemes for social-aware relay selection for D2D communications. These schemes, and in particular Adaptive-MRS, are an important step to improve cellular network services in the increasingly social world.

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APPENDIX

APPENDIX A

PERFORMANCE ANALYSIS FULL SIZED GRAPHS

Some graphs in the previous chapters presented in a manner so that the reader could easily see and compare multiple graphs on one page. This allowed general trends across graphs to be observed, but made it hard to read the details due to the reduced size of the graphs. For completeness, graphs in the previous chapters which were significantly reduced in size have been reproduced in full size here. Note there are no new results presented here; just duplications of previous graphs (results) but in a larger size.

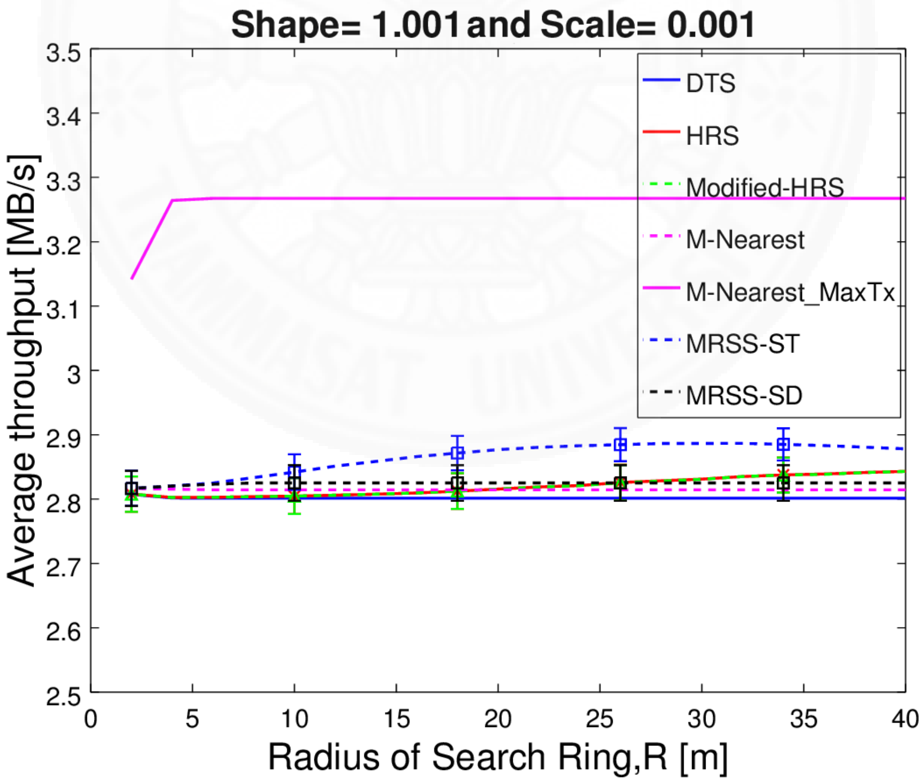

Figure A.1 Average throughput of different schemes when Shape = 1.001, Scale = 0.001, social threshold = 0.2 and network width = 100 m

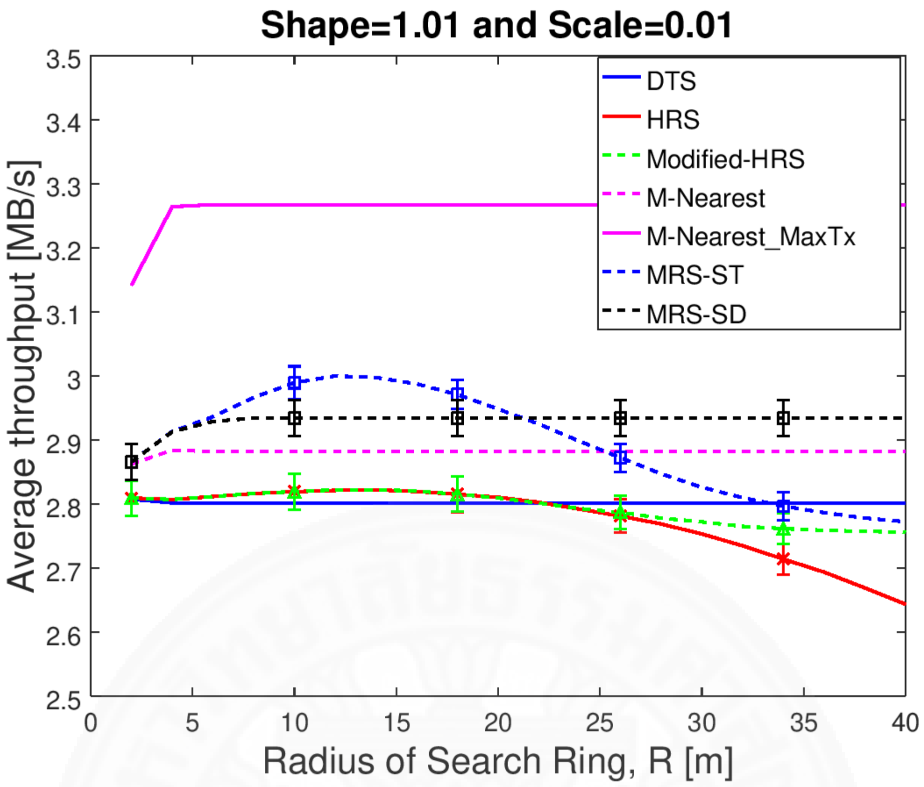

Figure A.2 Average throughput of different schemes when when Shape = 1.01, Scale = 0.01, social threshold = 0.2 and network width = 100 m

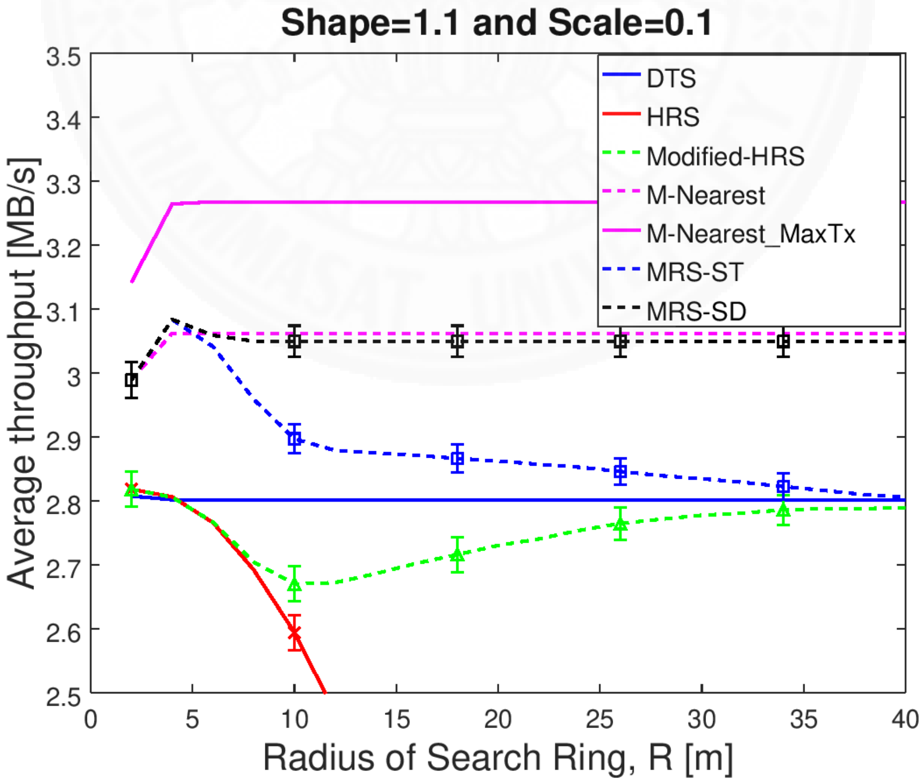

Figure A.3 Average throughput of different schemes when Shape = 1.1, Scale = 0.1, social threshold = 0.2 and network width = 100 m

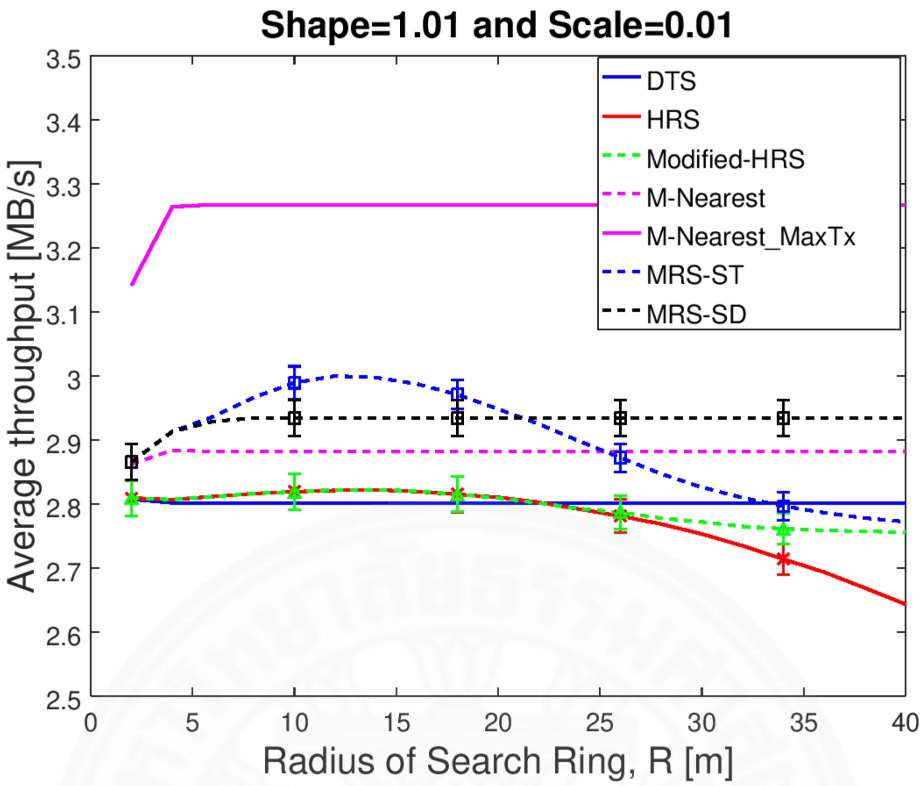

Figure A.4 Average throughput of different schemes when Shape = 1.01, Scale = 0.01, social threshold = 0.2 and network width = 100 m

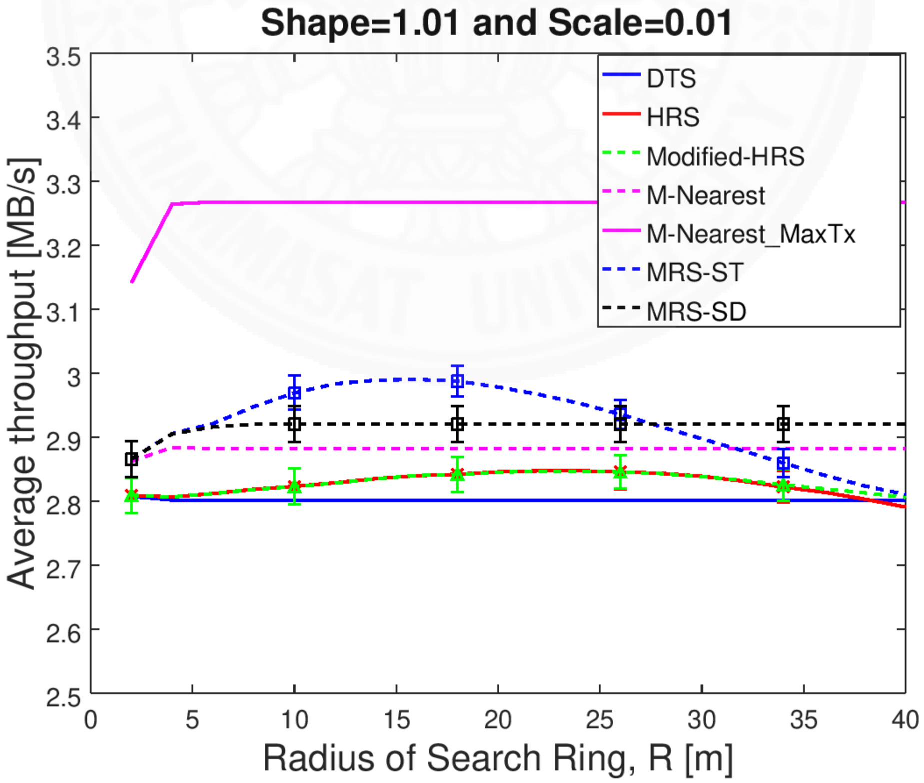

Figure A.5 Average throughput of different schemes when Shape = 1.01, Scale = 0.01, social threshold = 0.3 and network width = 100 m

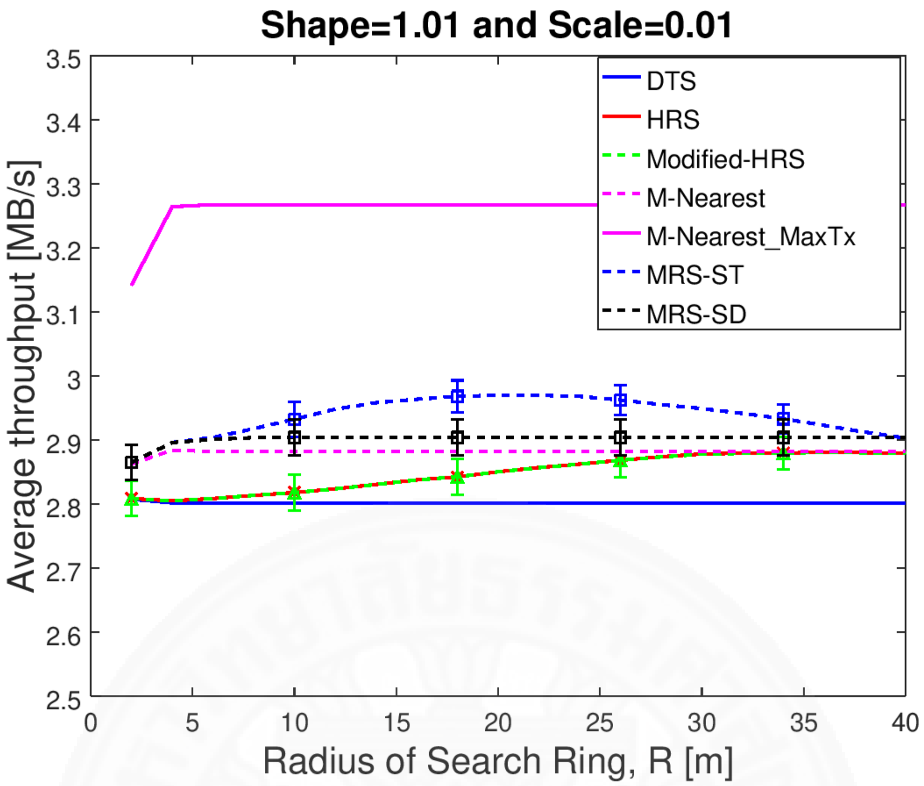

Figure A.6 Average throughput of different schemes when Shape = 1.01, Scale = 0.01, social threshold = 0.5 and network width = 100 m

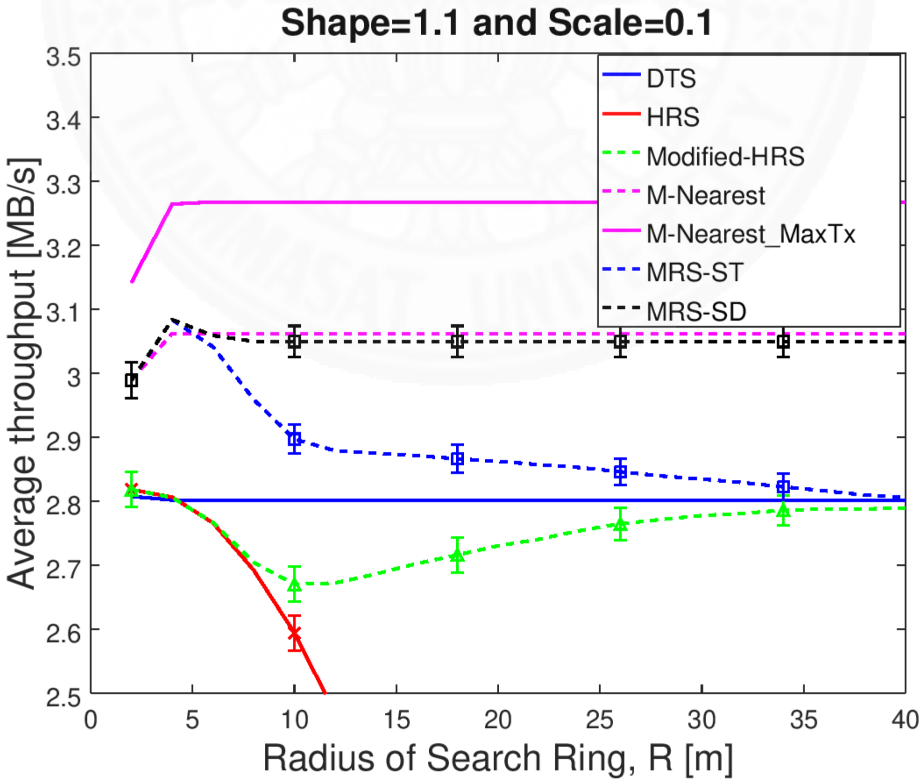

Figure A.7 Average throughput of different schemes when Shape = 1.1, Scale = 0.1, social threshold = 0.2 and network width = 100 m

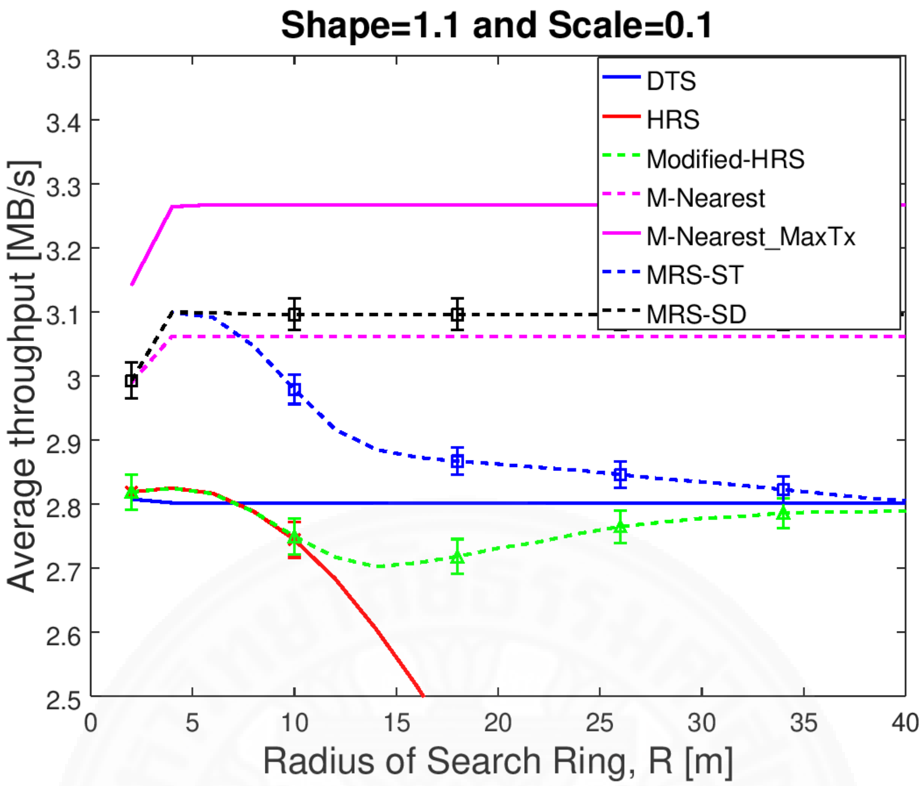

Figure A.8 Average throughput of different schemes when Shape = 1.1, Scale = 0.1, social threshold = 0.3 and network width = 100 m

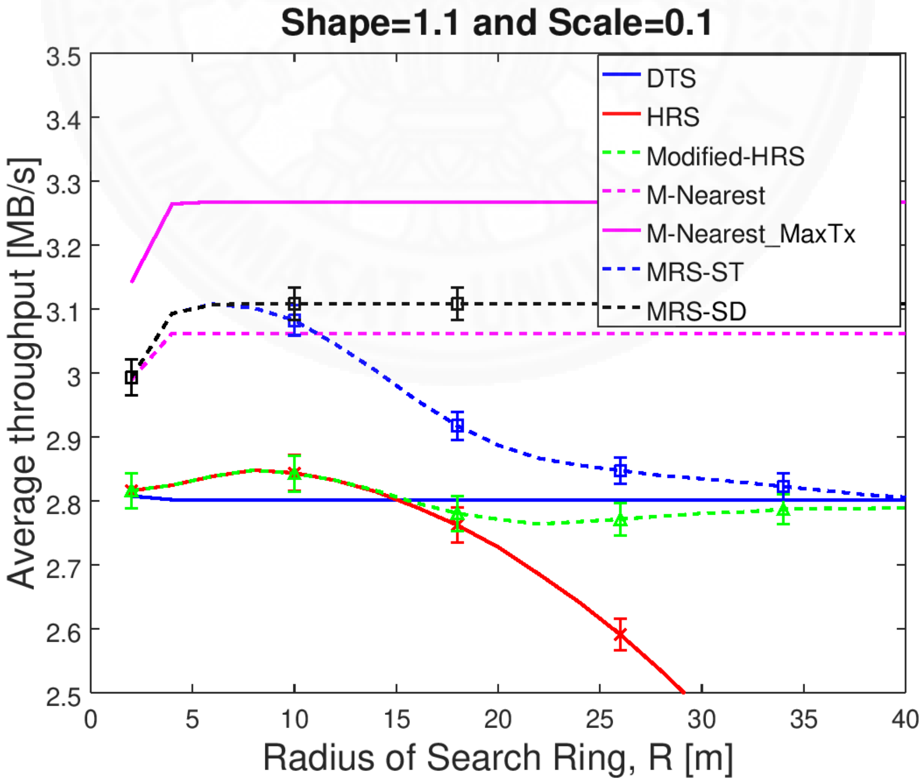

Figure A.9 Average throughput of different schemes when Shape = 1.1, Scale = 0.1, social threshold = 0.5 and network width = 100 m

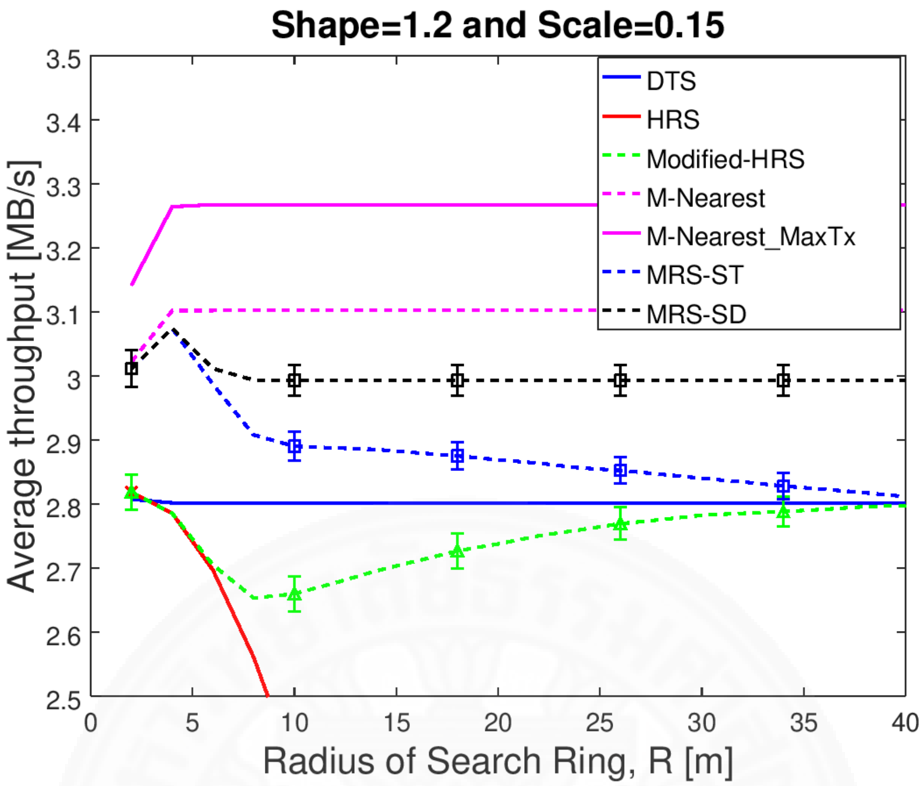

Figure A.10 Average throughput of different schemes when Shape = 1.2, Scale = 0.15, social threshold = 0.2 and network width = 100 m

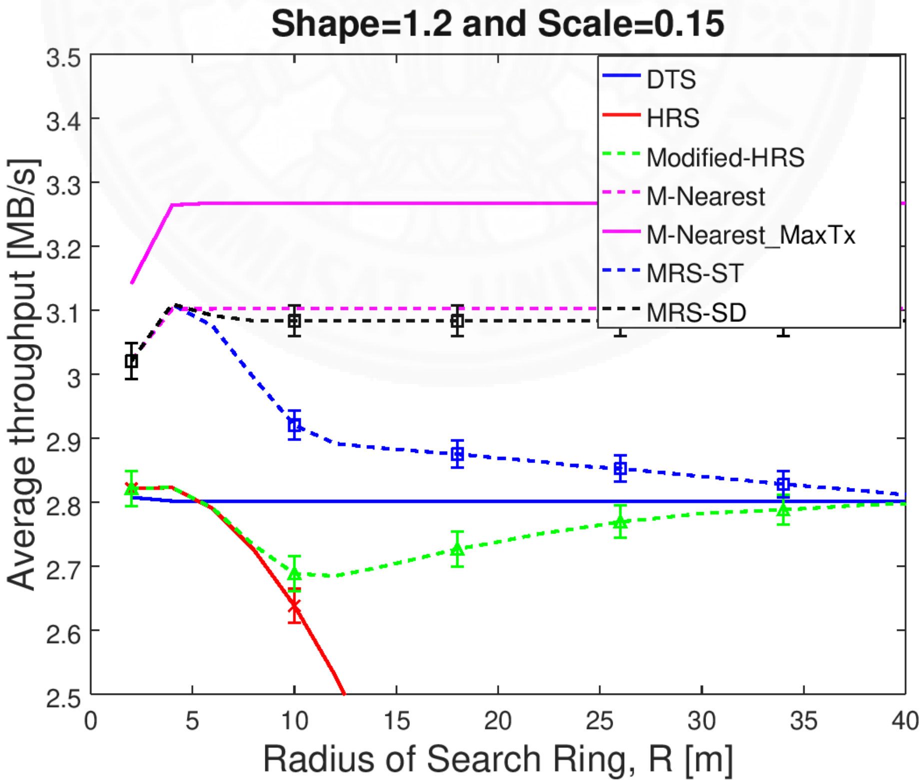

Figure A.11 Average throughput of different schemes when Shape = 1.2, Scale = 0.15, social threshold = 0.3 and network width = 100 m

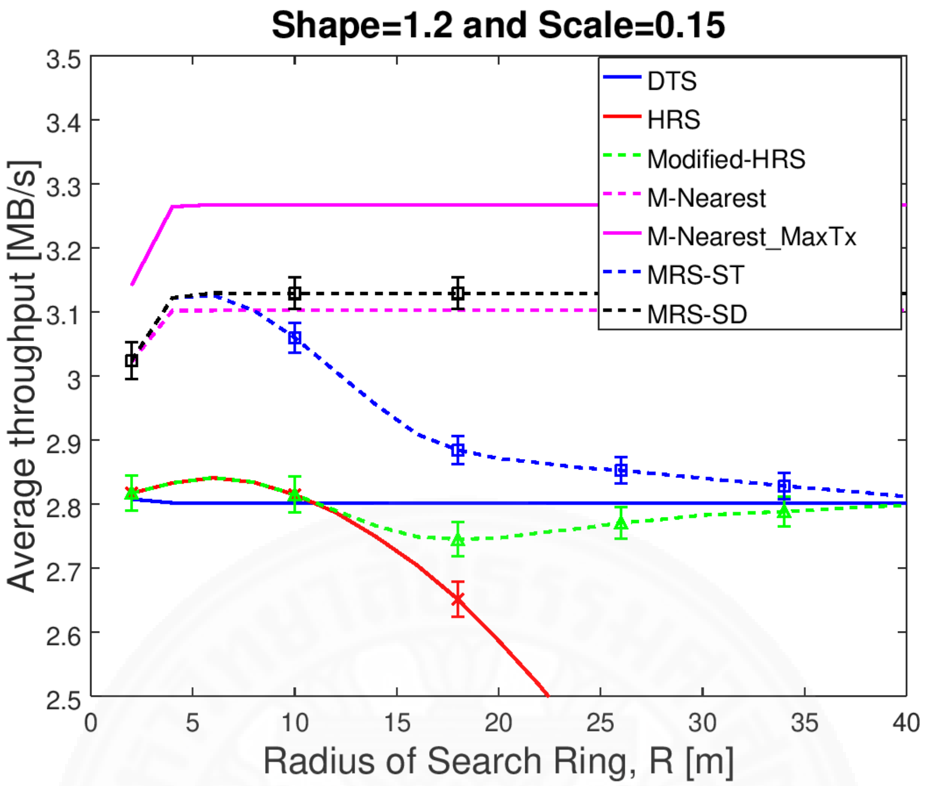

Figure A.12 Average throughput of different schemes when Shape = 1.2, Scale = 0.15, social threshold = 0.5 and network width = 100 m

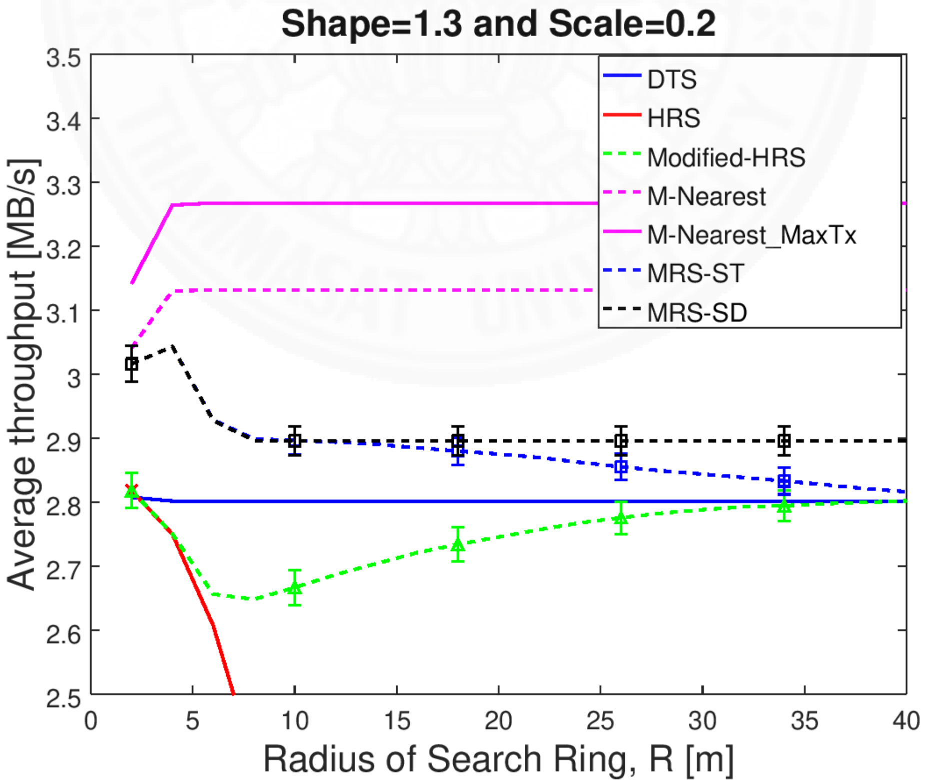

Figure A.13 Average throughput of different schemes when Shape = 1.3, Scale = 0.2, social threshold = 0.2 and network width = 100 m

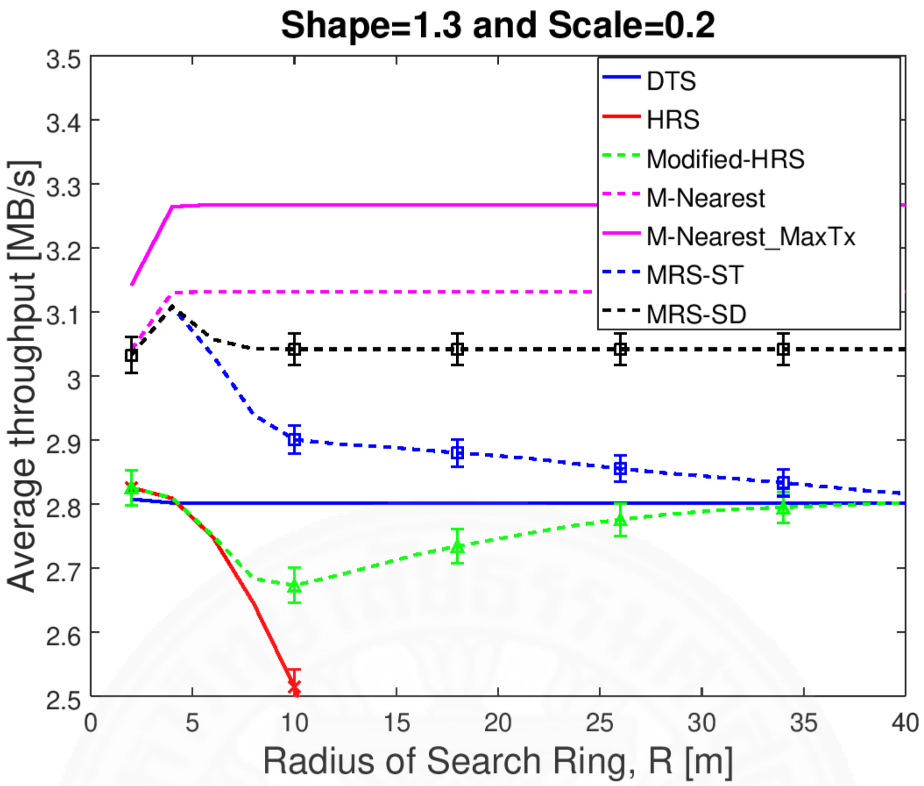

Figure A.14 Average throughput of different schemes when Shape = 1.3, Scale = 0.2, social threshold = 0.3 and network width = 100 m

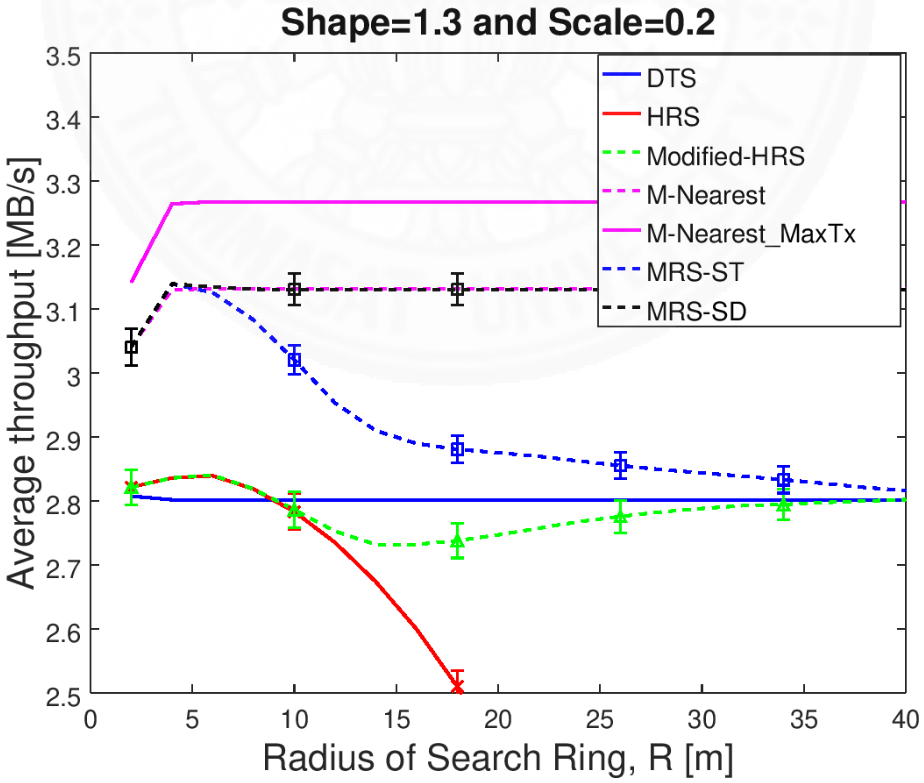

Figure A.15 Average throughput of different schemes when Shape = 1.3, Scale = 0.2, social threshold = 0.5 and network width = 100 m

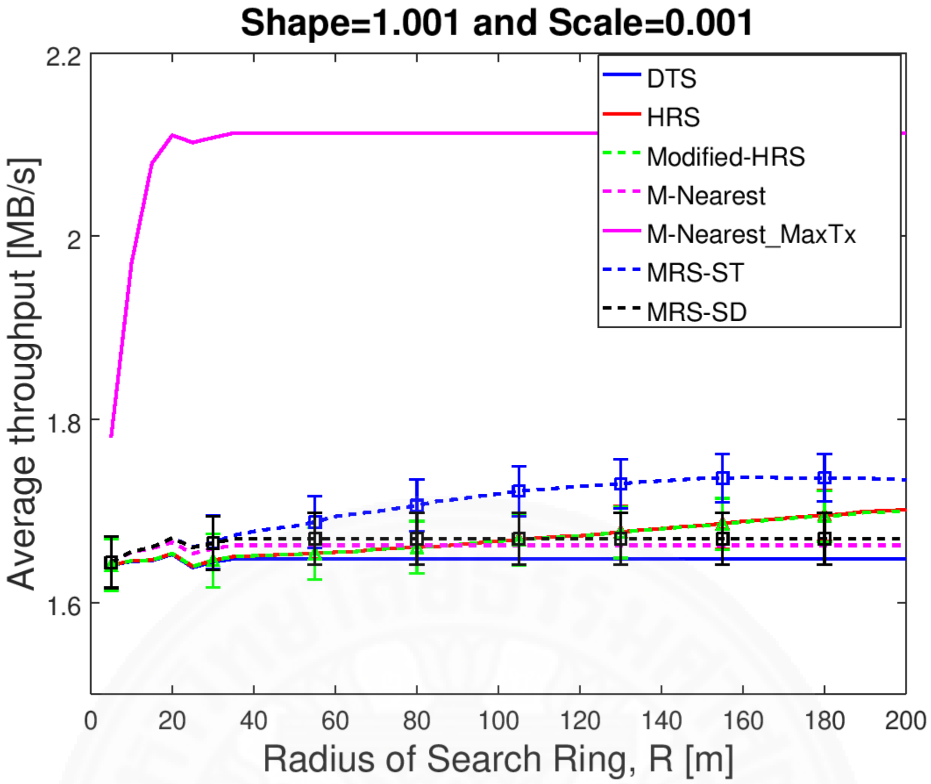

Figure A.16 Average throughput of different schemes when Shape = 1.001, Scale = 0.001, social threshold = 0.2 and network width = 500 m

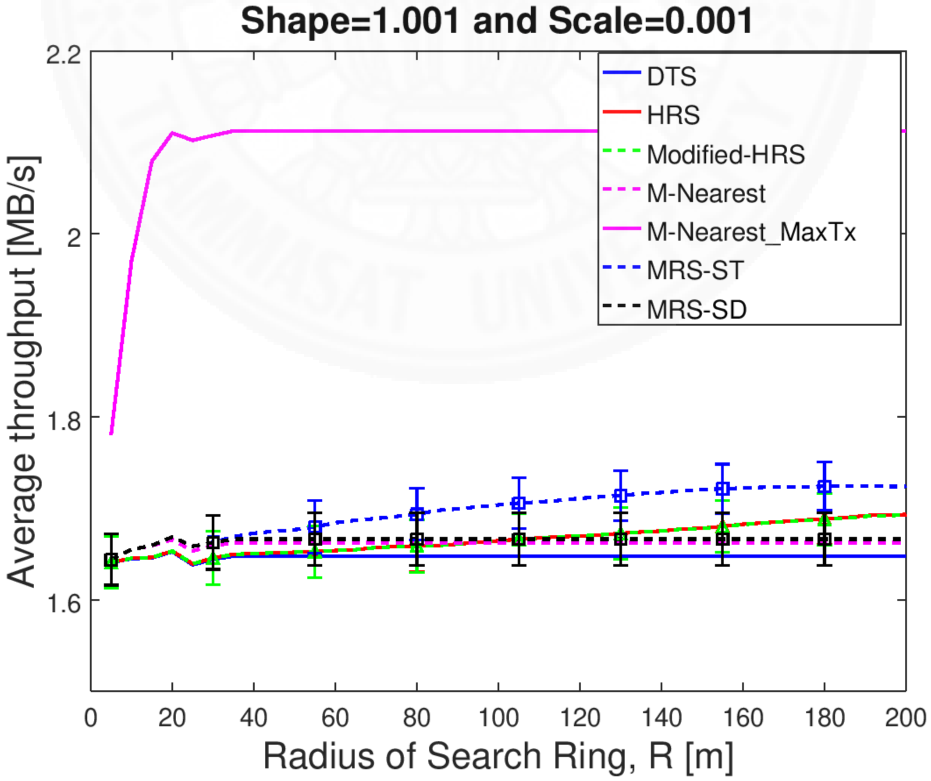

Figure A.17 Average throughput of different schemes when Shape = 1.001, Scale = 0.001, social threshold = 0.3 and network width = 500 m

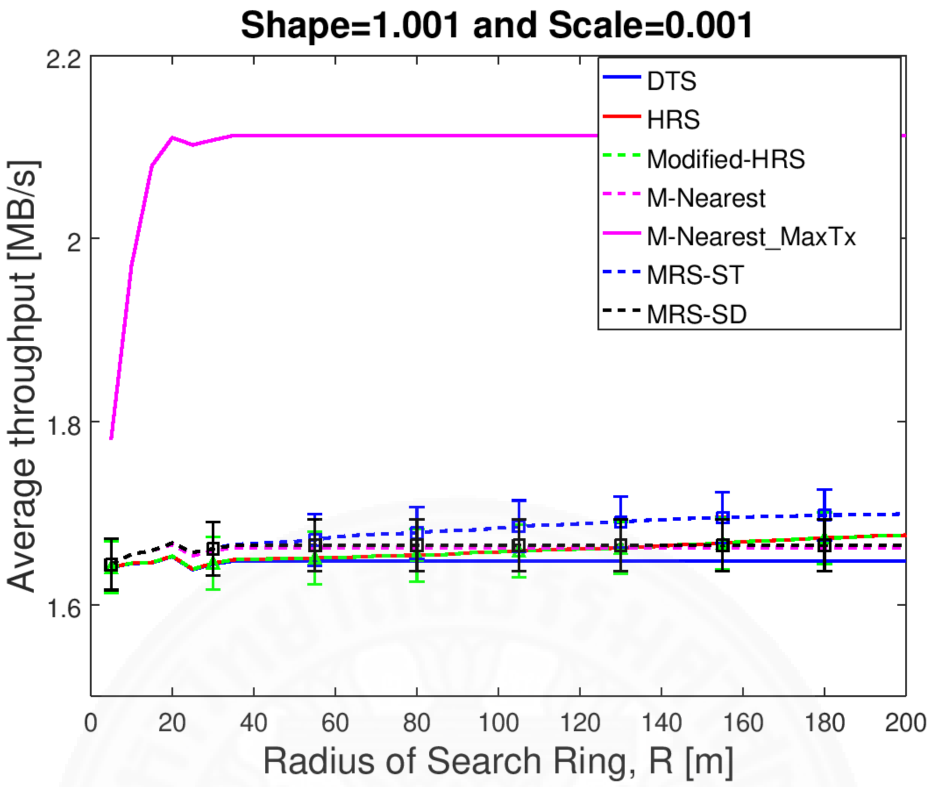

Figure A.18 Average throughput of different schemes when Shape = 1.001, Scale = 0.001, social threshold = 0.5 and network width = 500 m

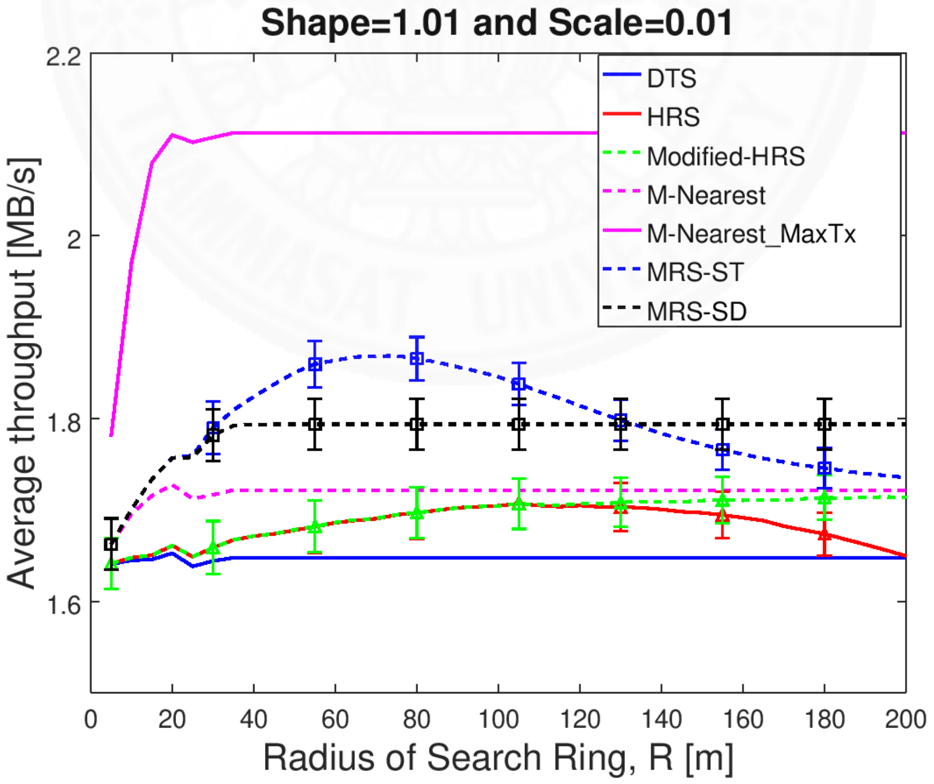

Figure A.19 Average throughput of different schemes when Shape = 1.01, Scale = 0.01, social threshold = 0.2 and network width = 500 m

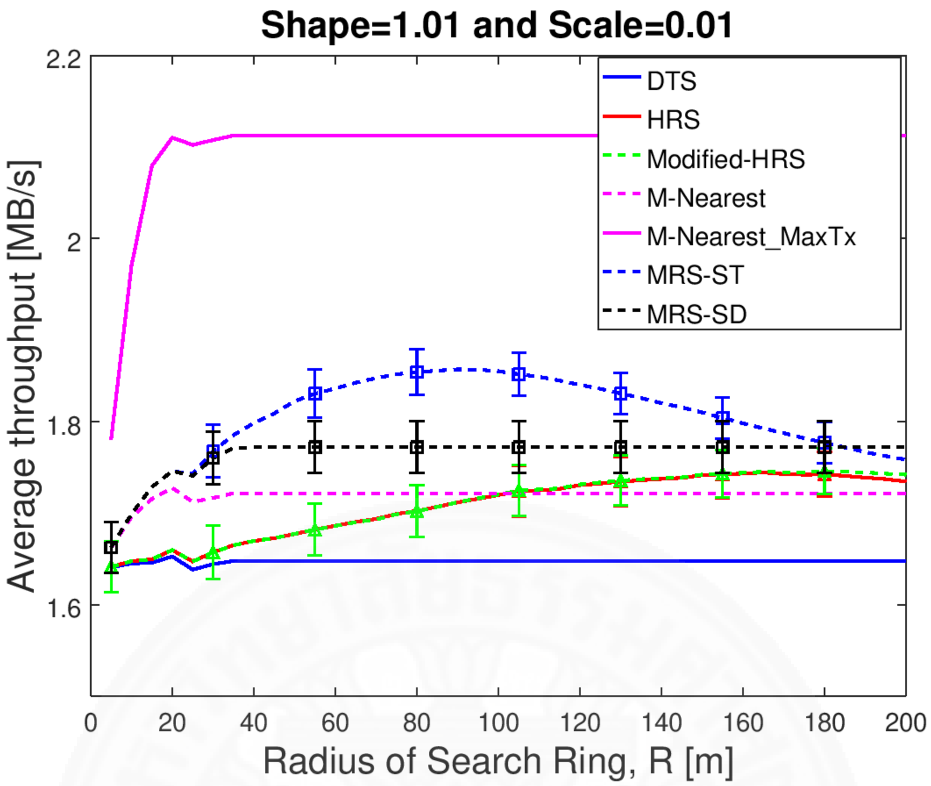

Figure A.20 Average throughput of different schemes when Shape = 1.01, Scale = 0.01, social threshold = 0.3 and network width = 500 m

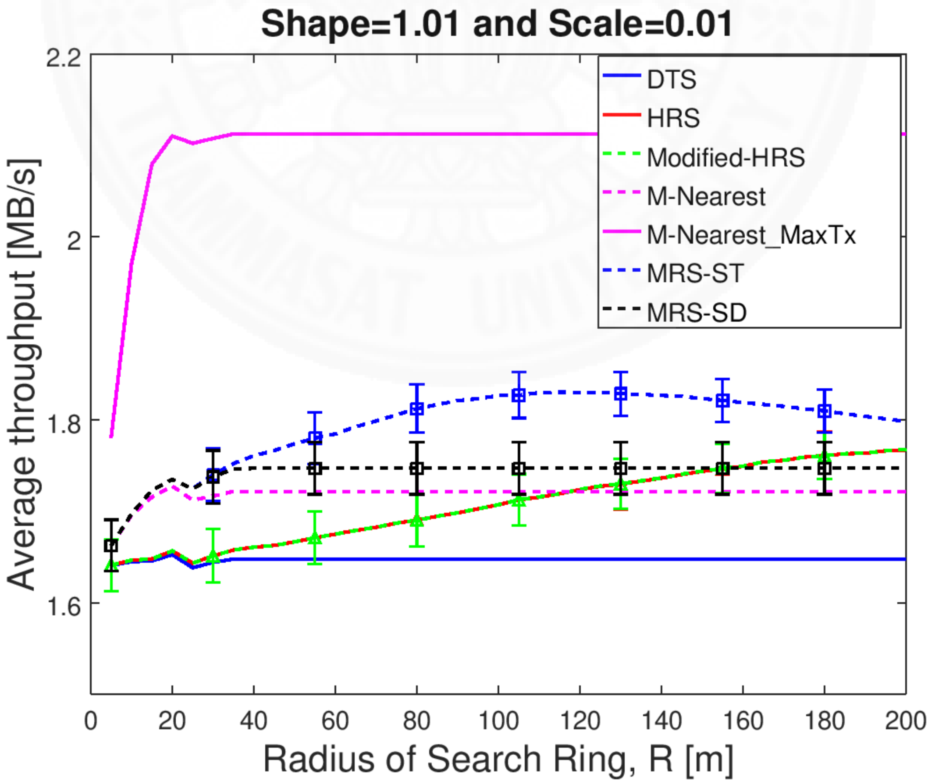

Figure A.21 Average throughput of different schemes when Shape = 1.01, Scale = 0.01, social threshold = 0.5 and network width = 500 m

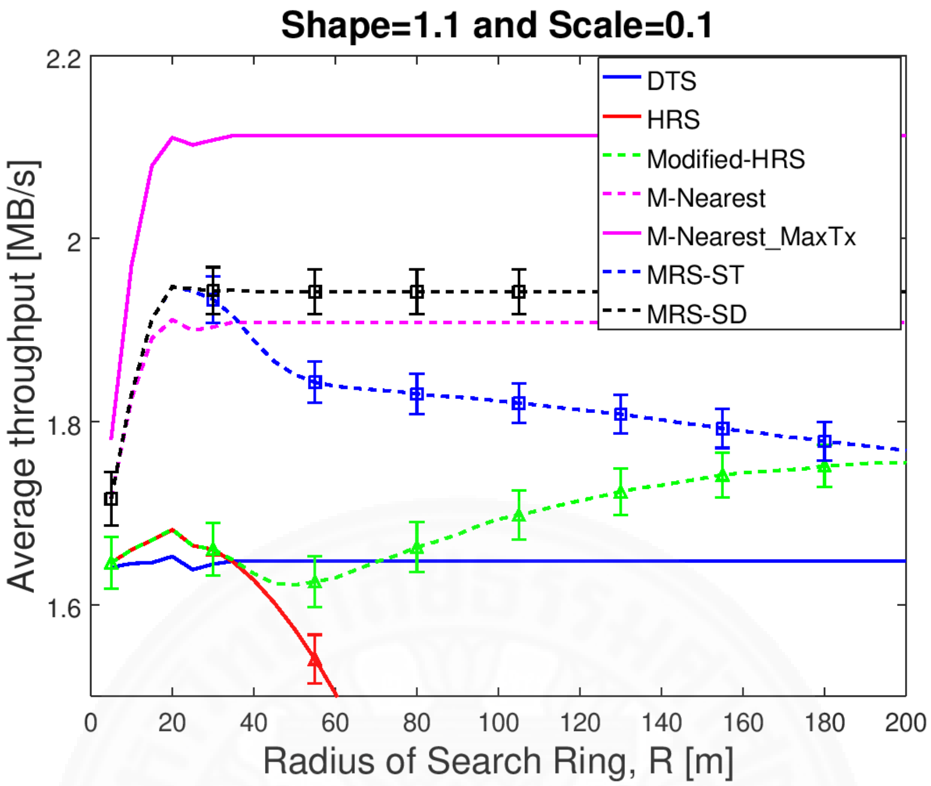

Figure A.22 Average throughput of different schemes when Shape = 1.1, Scale = 0.1, social threshold = 0.2 and network width = 500 m

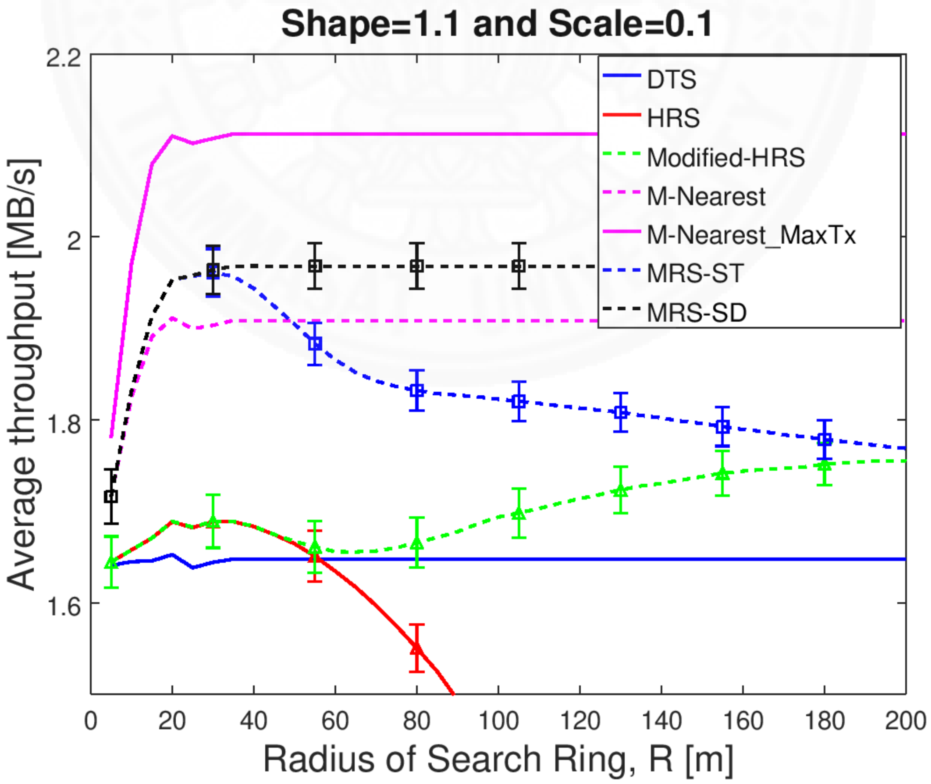

Figure A.23 Average throughput of different schemes when Shape = 1.1, Scale = 0.1, social threshold = 0.3 and network width = 500 m

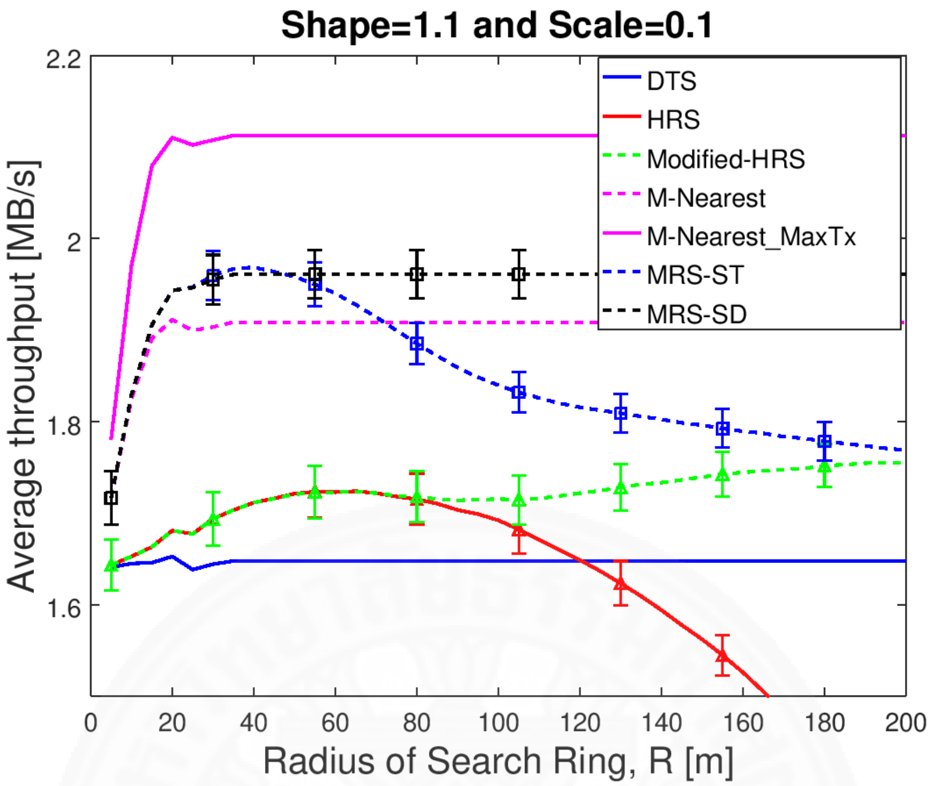

Figure A.24 Average throughput of different schemes when Shape = 1.1, Scale = 0.1, social threshold = 0.5 and network width = 500 m

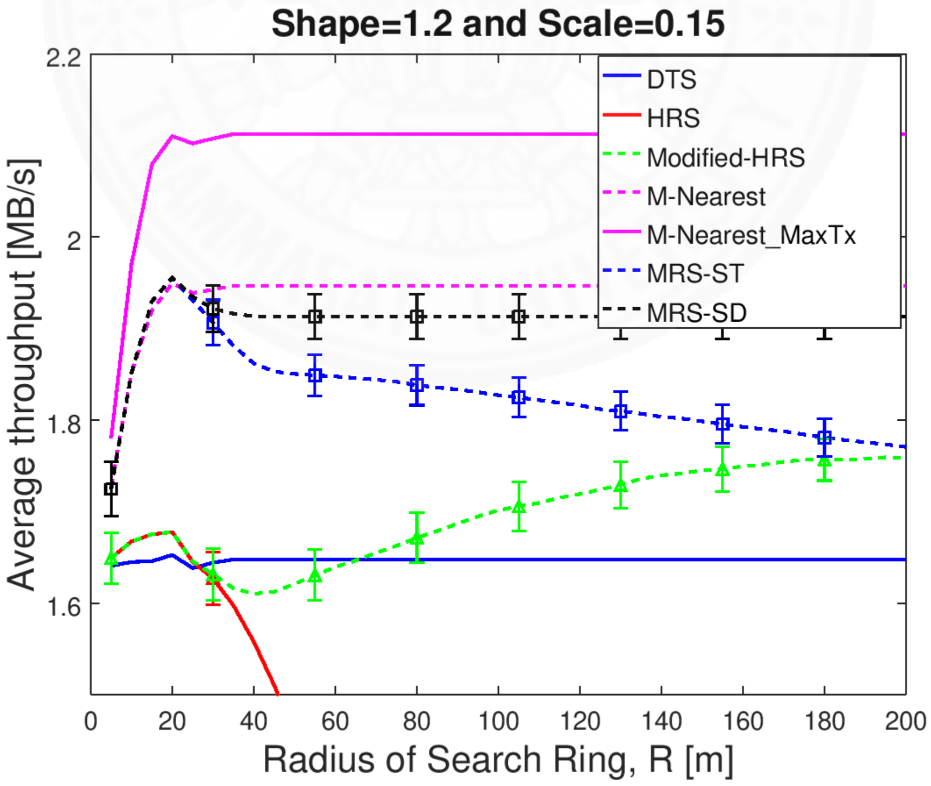

Figure A.25 Average throughput of different schemes when Shape = 1.2, Scale = 0.15, social threshold = 0.2 and network width = 500 m

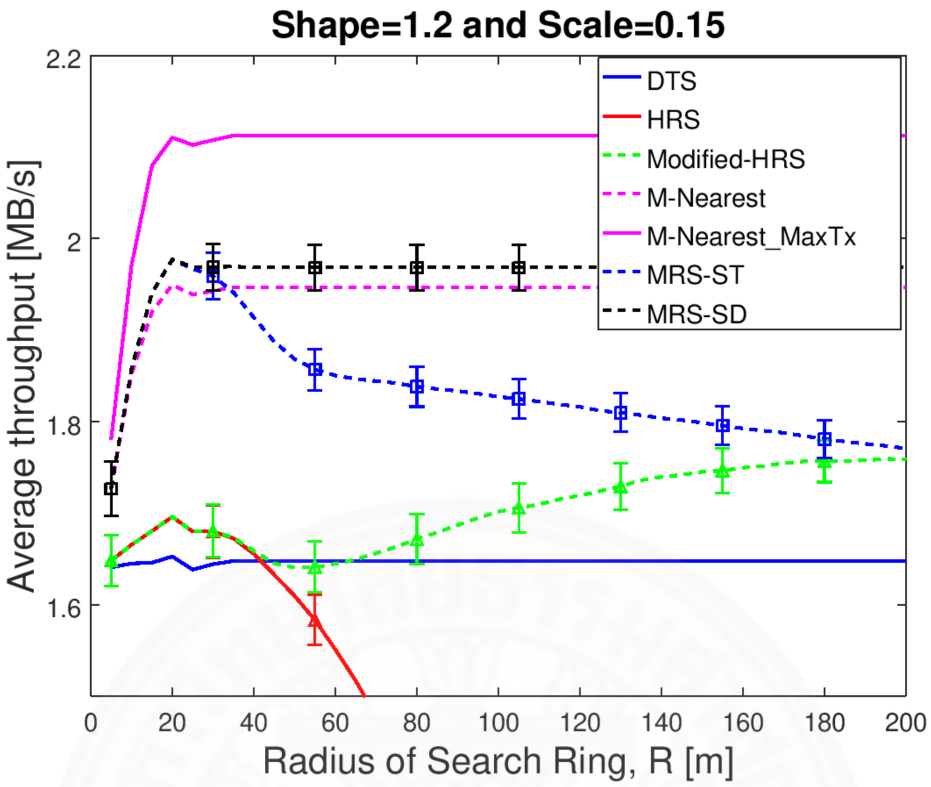

Figure A.26 Average throughput of different schemes when Shape = 1.2, Scale = 0.15, social threshold = 0.3 and network width = 500 m

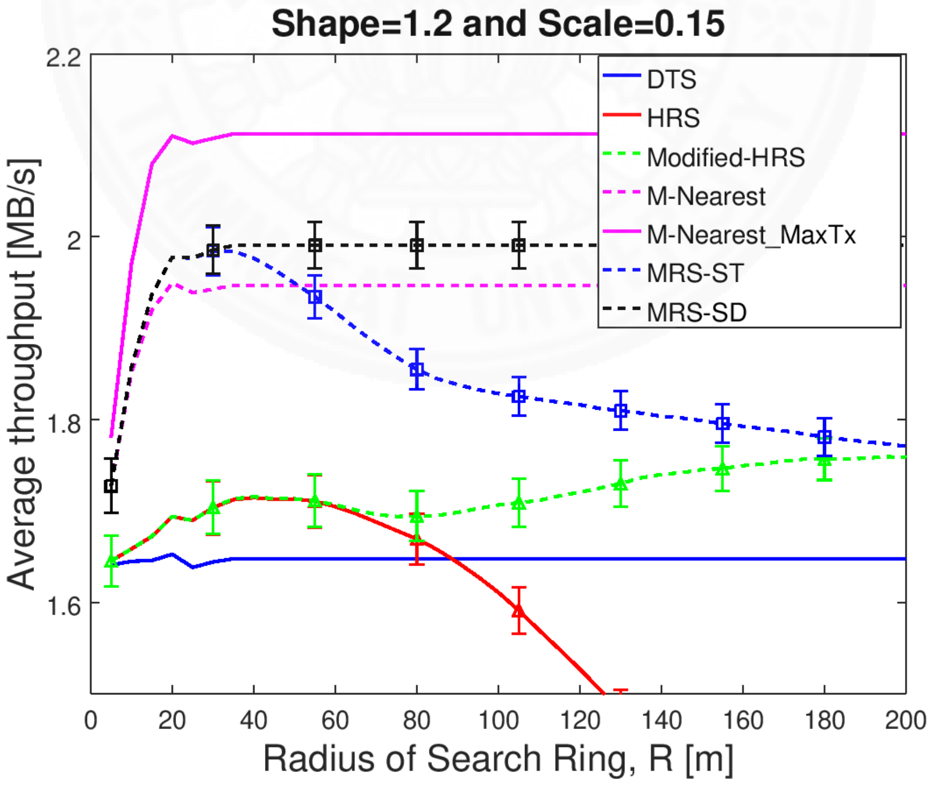

Figure A.27 Average throughput of different schemes when Shape = 1.2, Scale = 0.15, social threshold = 0.5 and network width = 500 m

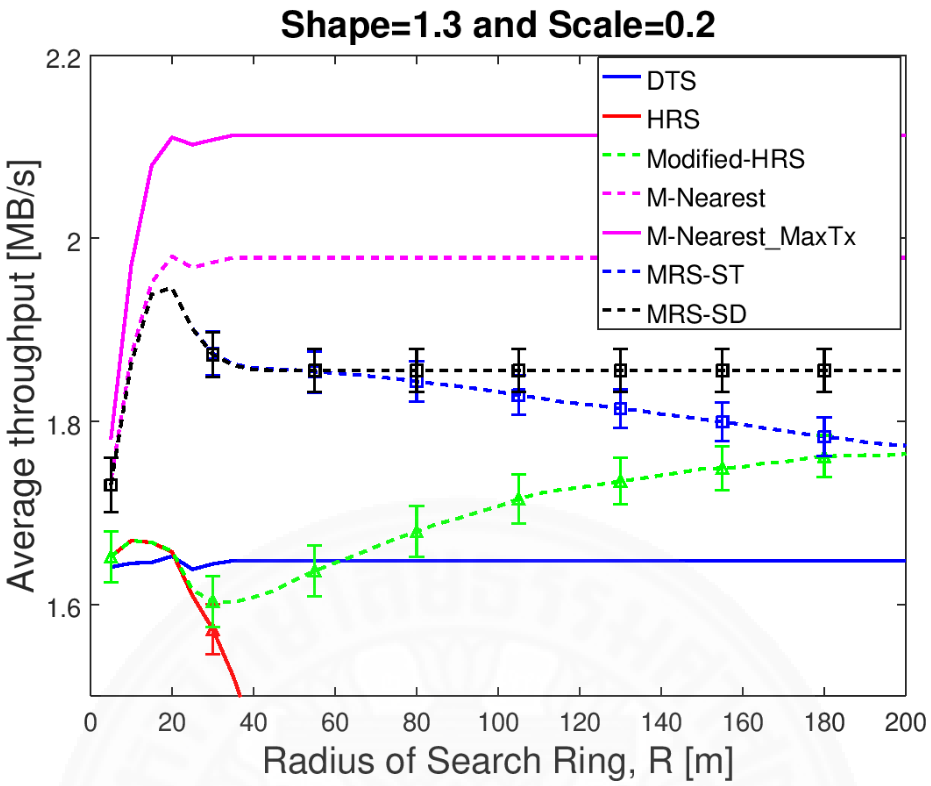

Figure A.28 Average throughput of different schemes when Shape = 1.3, Scale = 0.2, social threshold = 0.2 and network width = 500 m

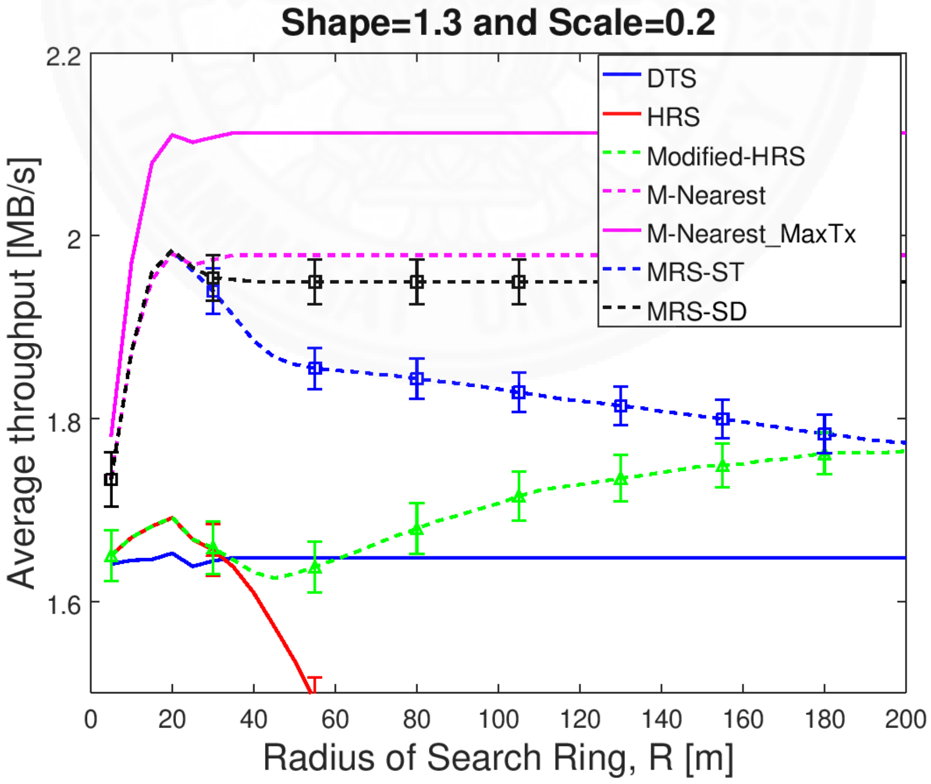

Figure A.29 Average throughput of different schemes when Shape = 1.3, Scale = 0.2, social threshold = 0.3 and network width = 500 m

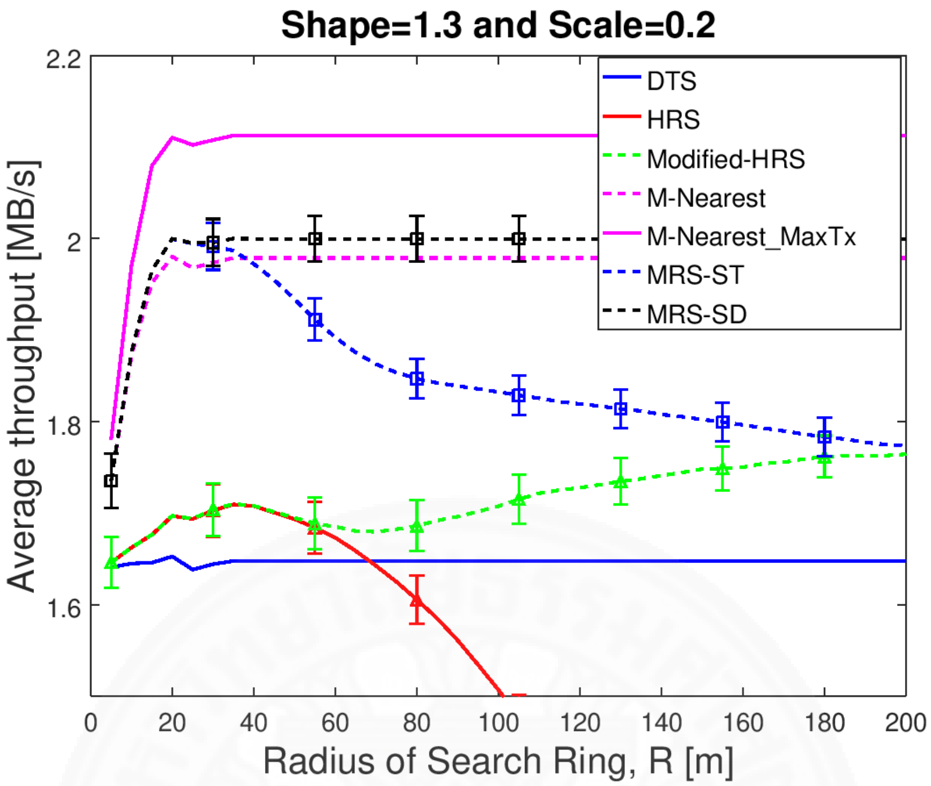

Figure A.30 Average throughput of different schemes when Shape = 1.3, Scale = 0.2, social threshold = 0.5 and network width = 500 m

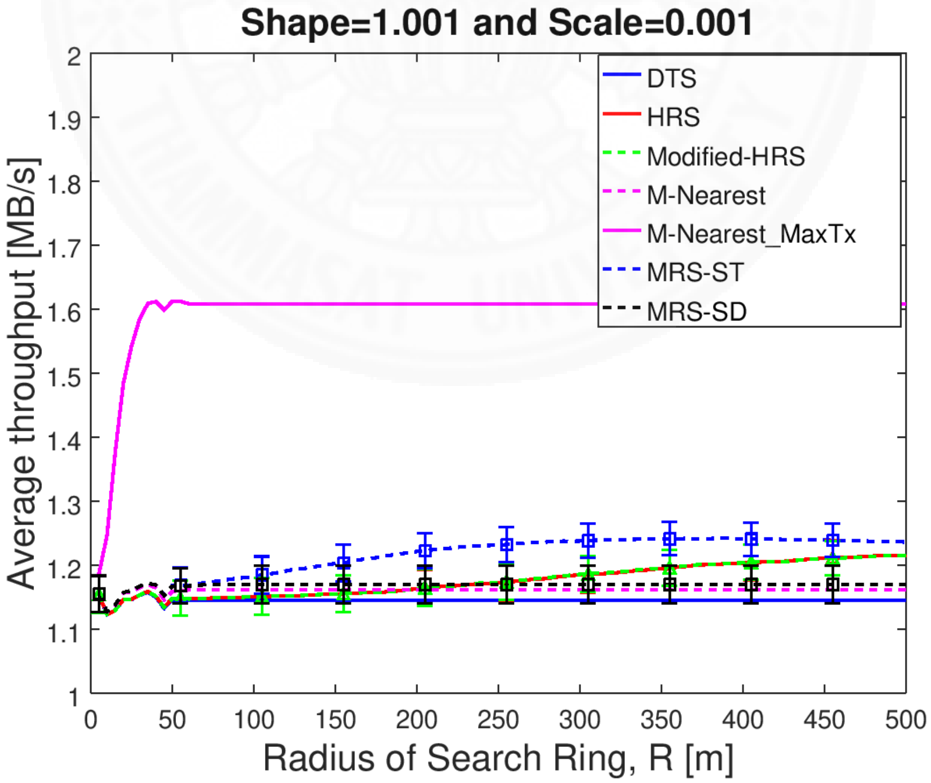

Figure A.31 Average throughput of different schemes when Shape = 1.001, Scale = 0.001, social threshold = 0.2 and network width = 1000 m

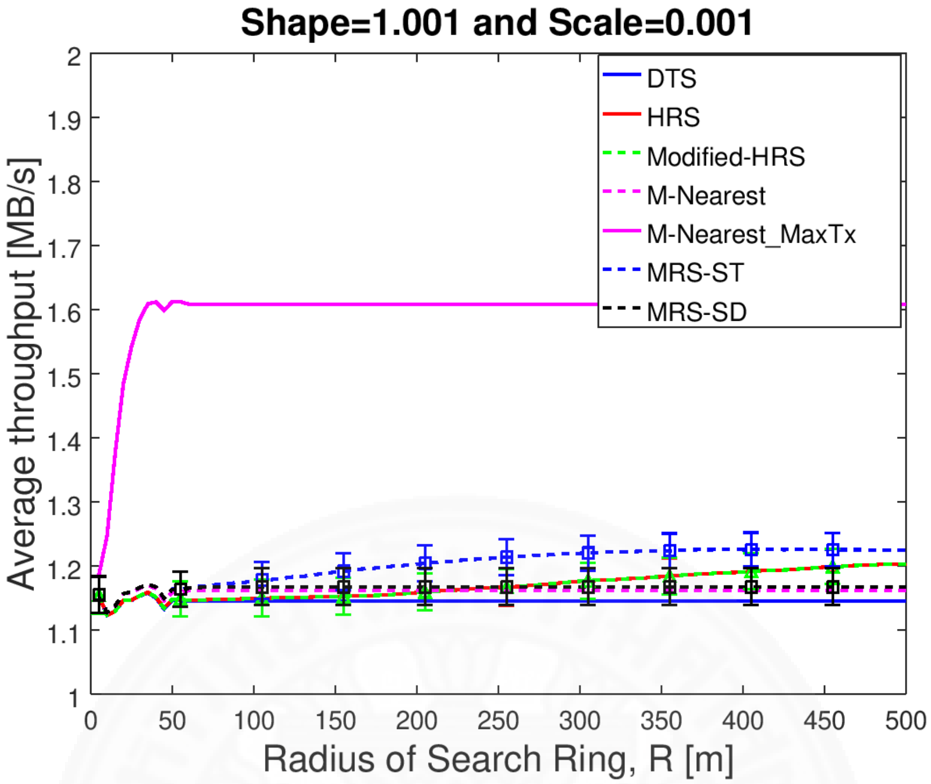

Figure A.32 Average throughput of different schemes when Shape = 1.001, Scale = 0.001, social threshold = 0.3 and network width = 1000 m

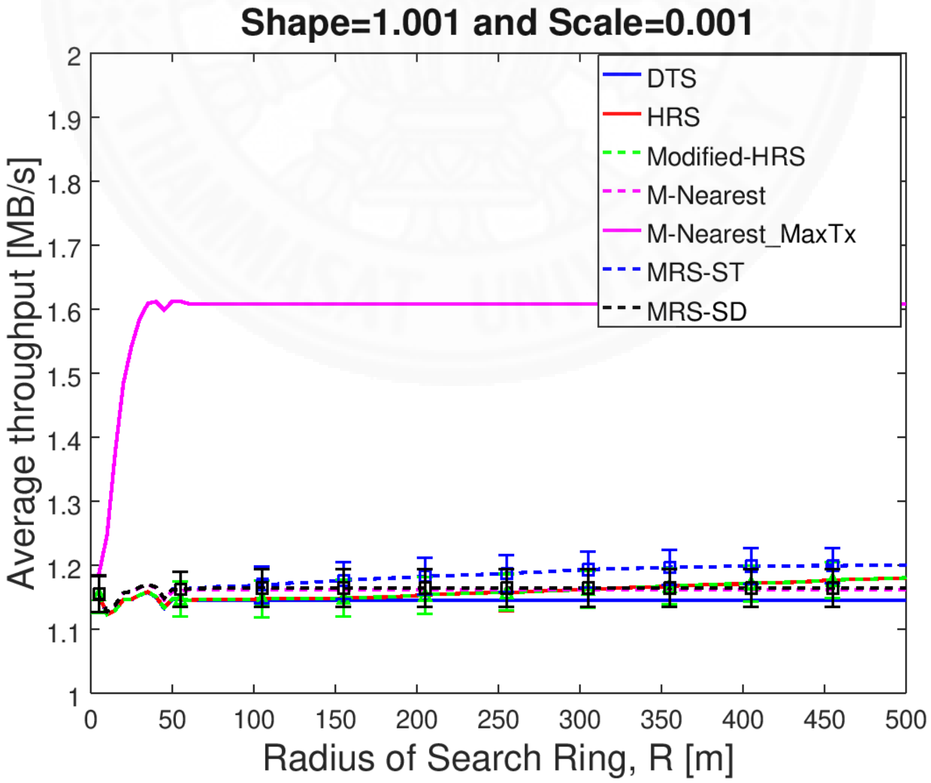

Figure A.33 Average throughput of different schemes when Shape = 1.001, Scale = 0.001, social threshold = 0.5 and network width = 1000 m

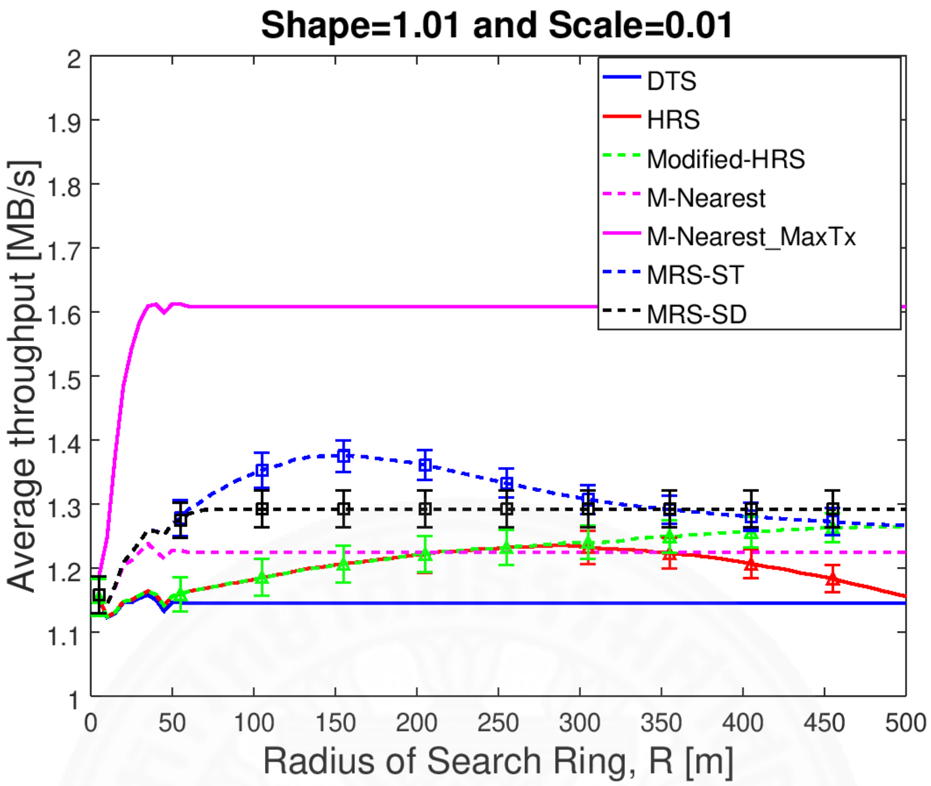

Figure A.34 Average throughput of different schemes when Shape = 1.01, Scale = 0.01, social threshold = 0.2 and network width = 1000 m

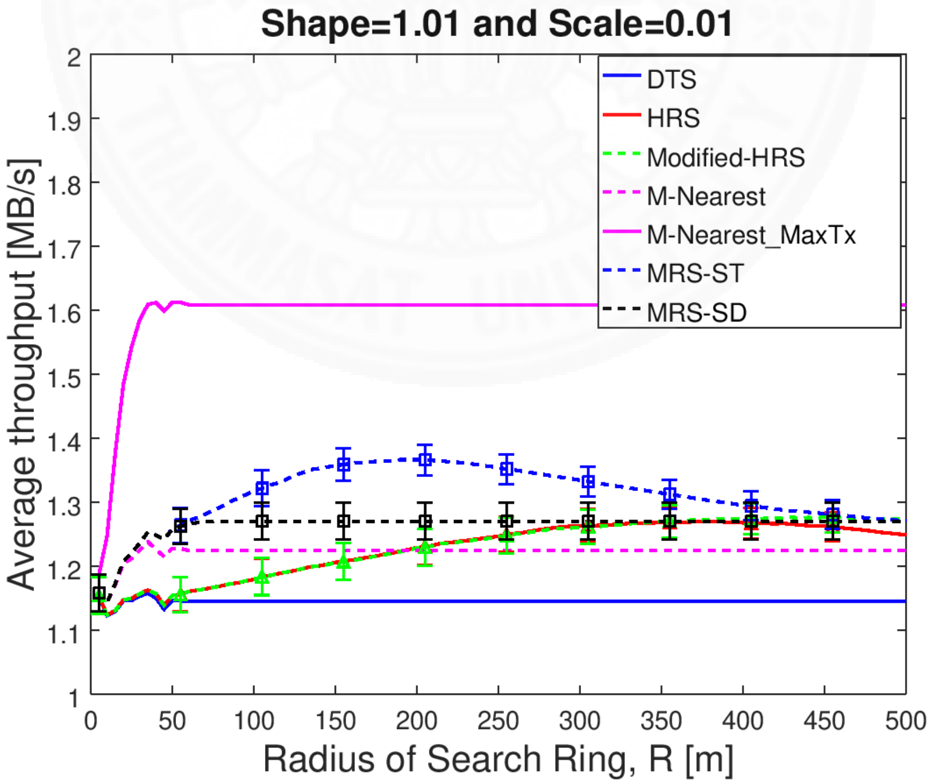

Figure A.35 Average throughput of different schemes when Shape = 1.01, Scale = 0.01, social threshold = 0.3 and network width = 1000 m

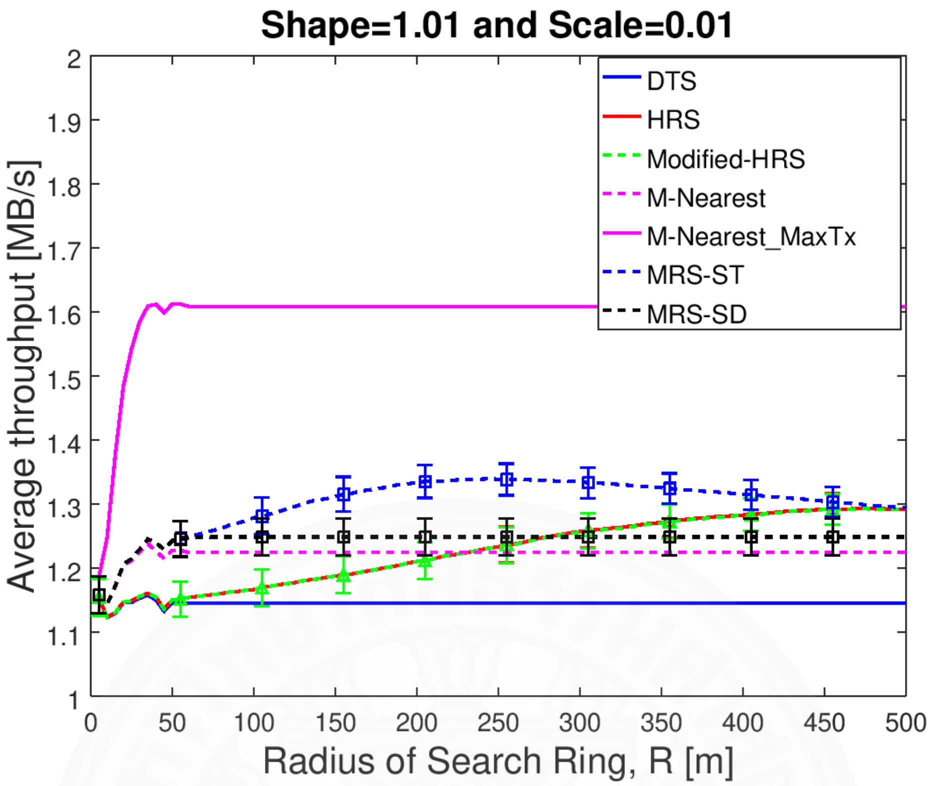

Figure A.36 Average throughput of different schemes when Shape = 1.01, Scale = 0.01, social threshold = 0.5 and network width = 1000 m

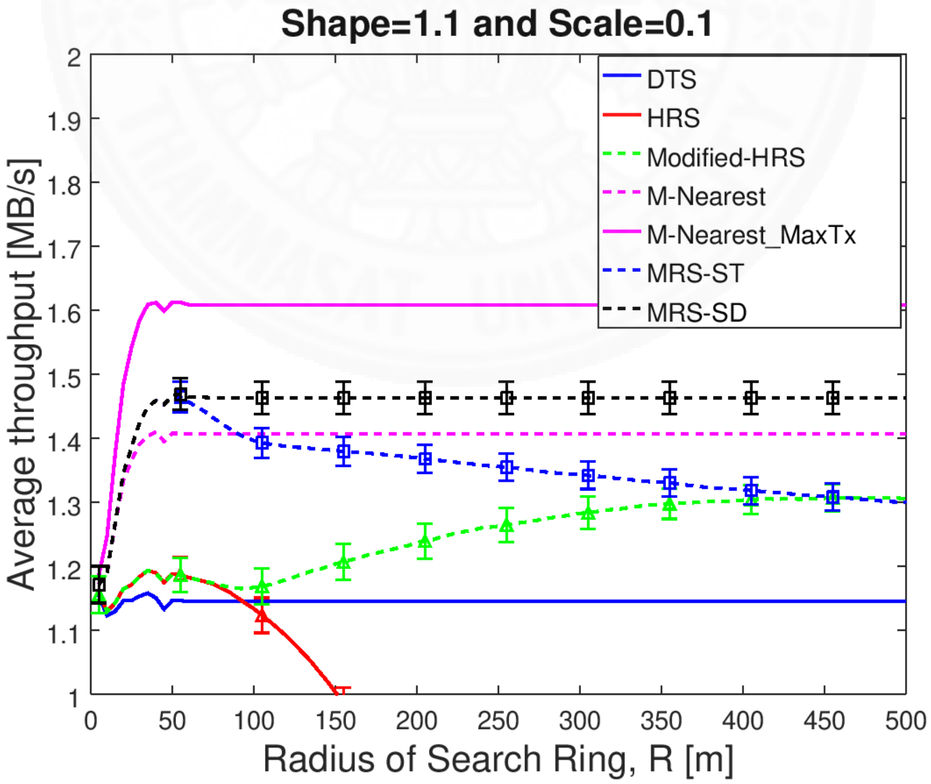

Figure A.37 Average throughput of different schemes when Shape = 1.1, Scale = 0.1, social threshold = 0.2 and network width = 1000 m

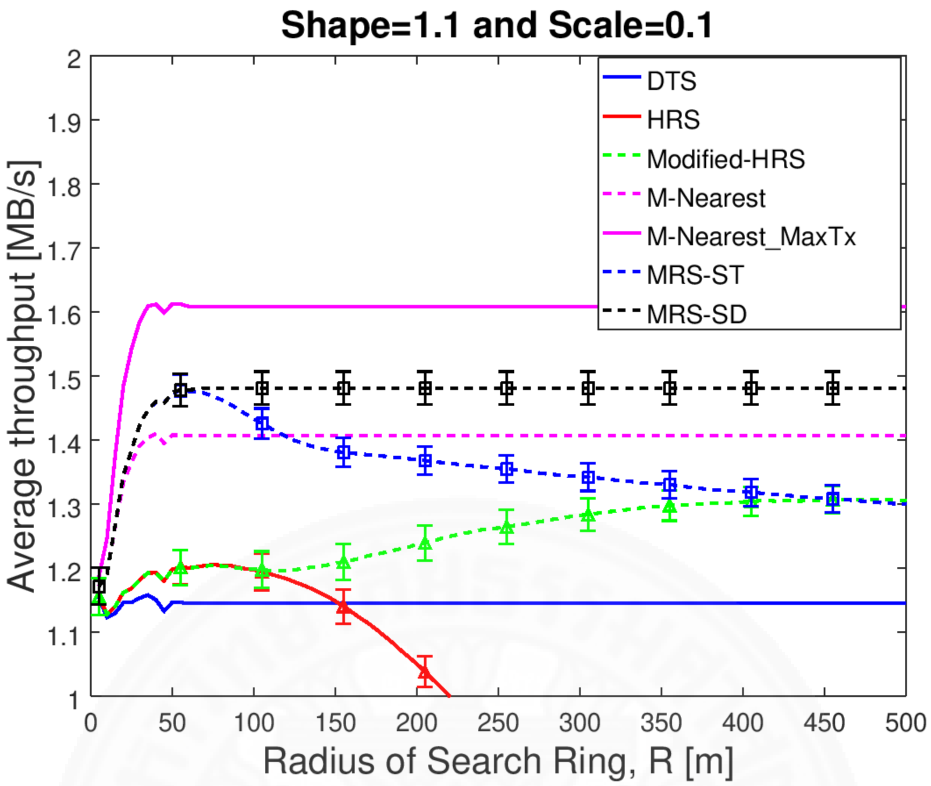

Figure A.38 Average throughput of different schemes when Shape = 1.1, Scale = 0.1, social threshold = 0.3 and network width = 1000 m

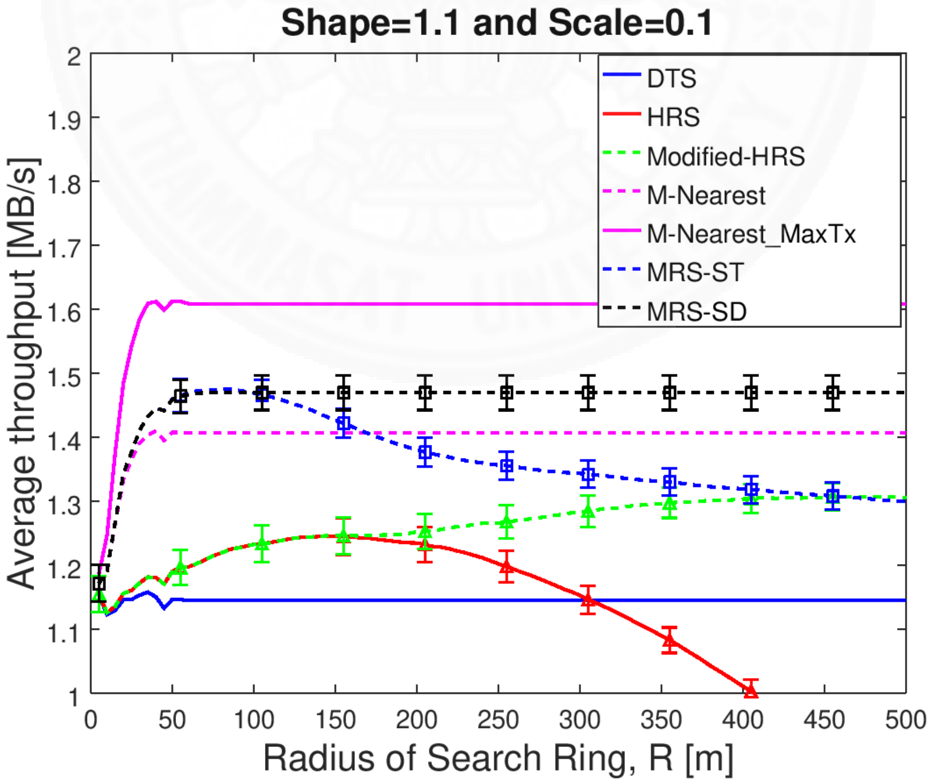

Figure A.39 Average throughput of different schemes when Shape = 1.1, Scale = 0.1, social threshold = 0.5 and network width = 1000 m

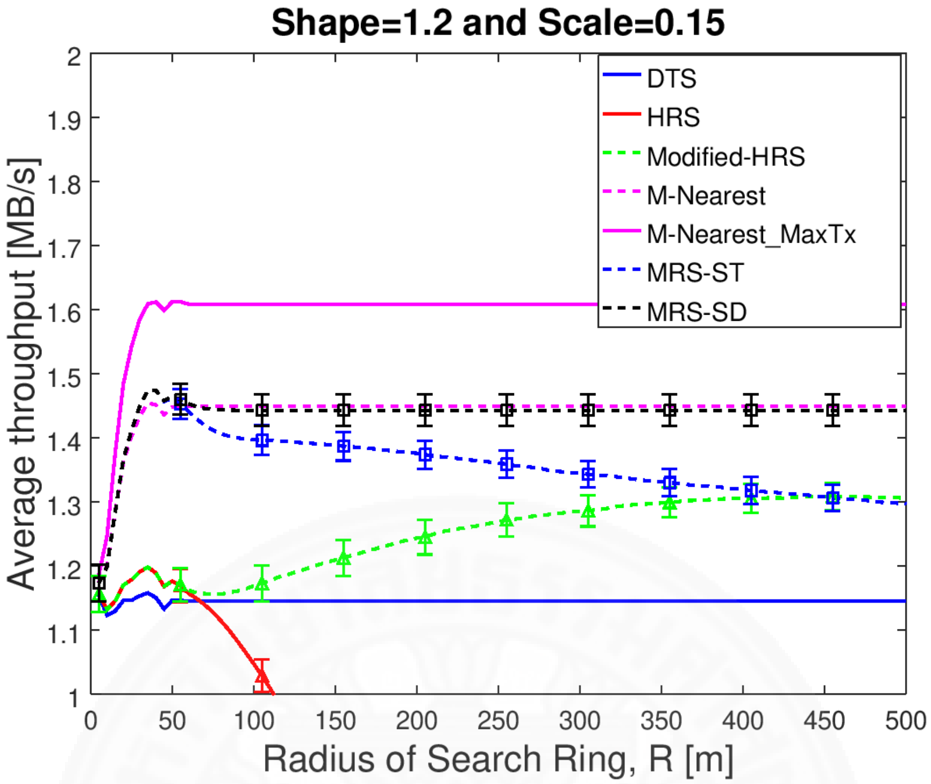

Figure A.40 Average throughput of different schemes when Shape = 1.2, Scale = 0.15, social threshold = 0.2 and network width = 1000 m

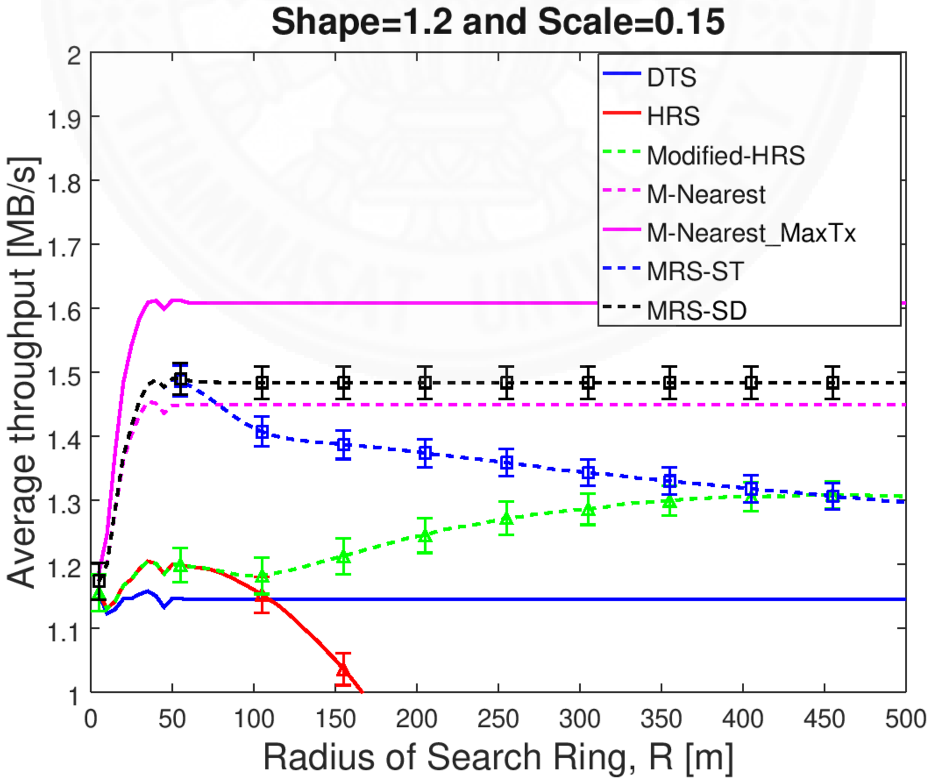

Figure A.41 Average throughput of different schemes when Shape = 1.2, Scale = 0.15, social threshold = 0.3 and network width = 1000 m

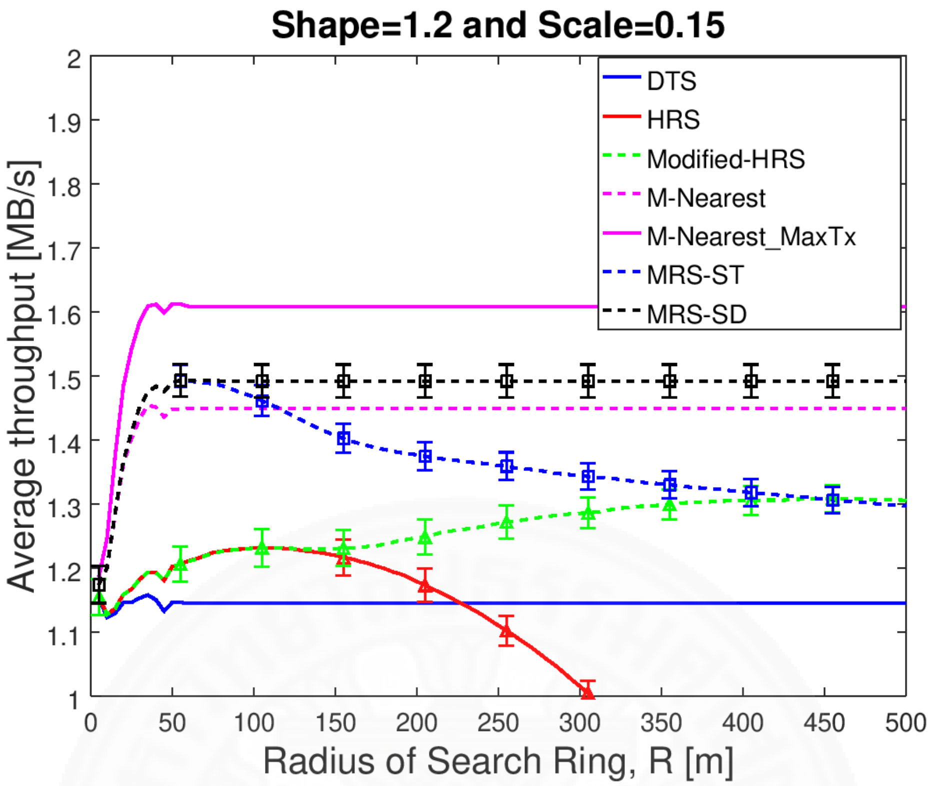

Figure A.42 Average throughput of different schemes when Shape = 1.2, Scale = 0.15, social threshold = 0.5 and network width = 1000 m

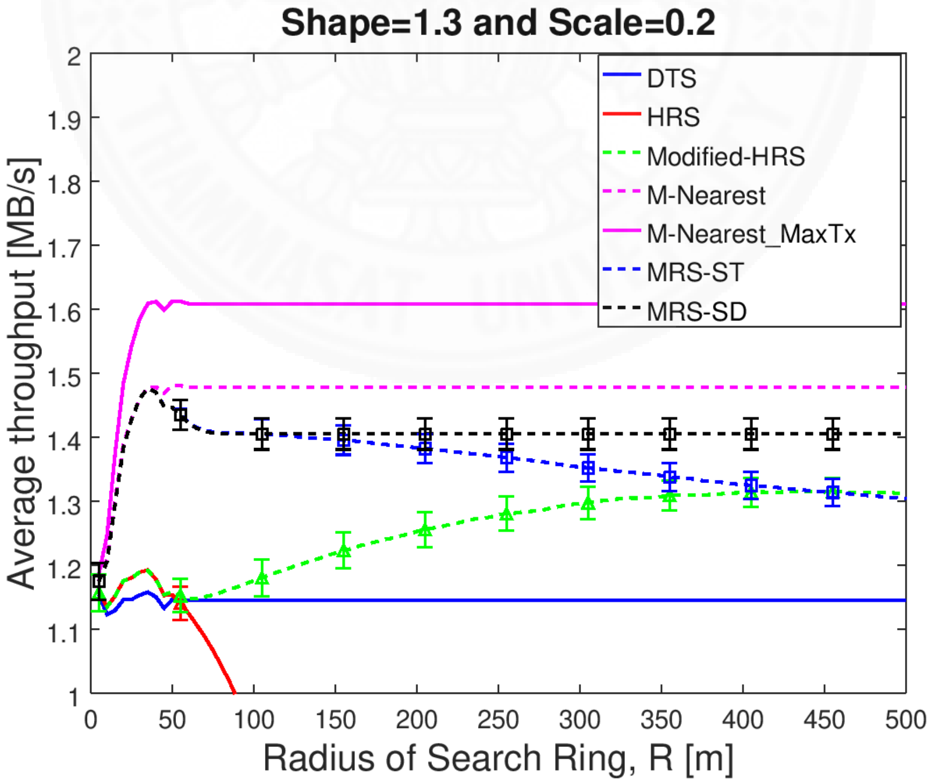

Figure A.43 Average throughput of different schemes when Shape = 1.3, Scale = 0.2, social threshold = 0.2 and network width = 1000 m

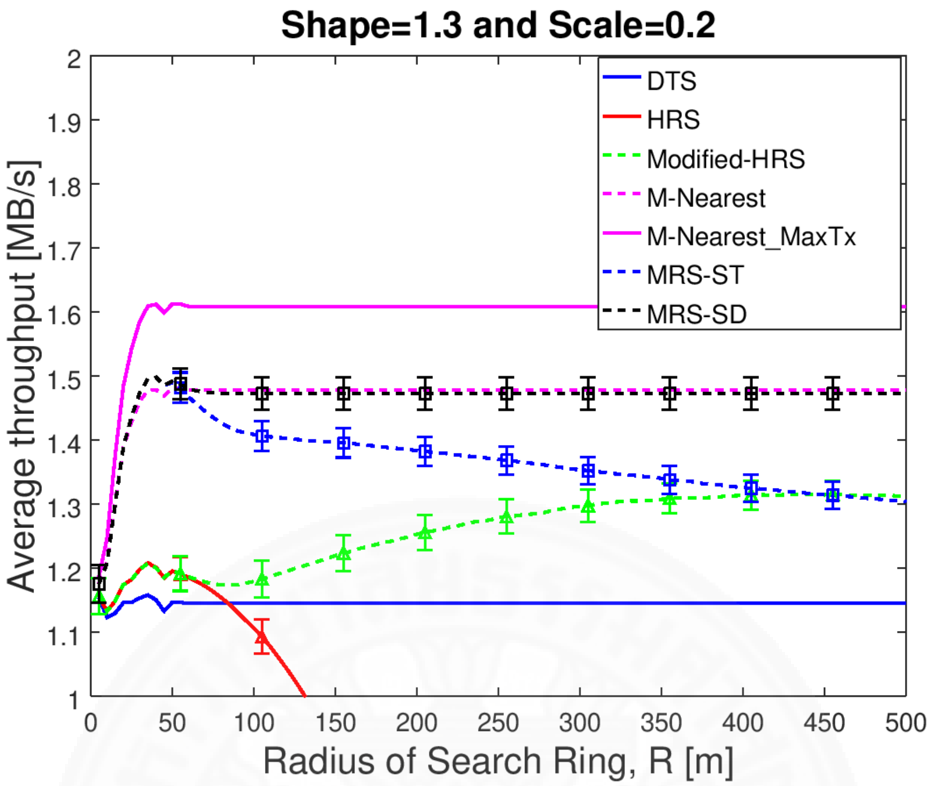

Figure A.44 Average throughput of different schemes when Shape = 1.3, Scale = 0.2, social threshold = 0.3 and network width = 1000 m

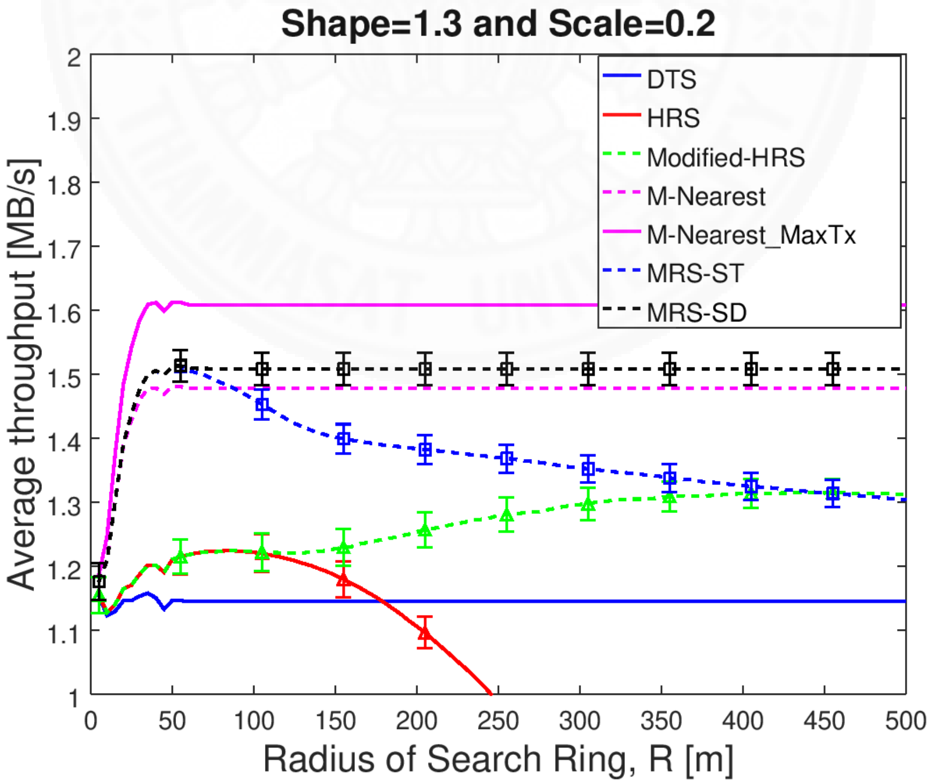

Figure A.45 Average throughput of different schemes when Shape = 1.3, Scale = 0.2, social threshold = 0.5 and network width = 1000 m

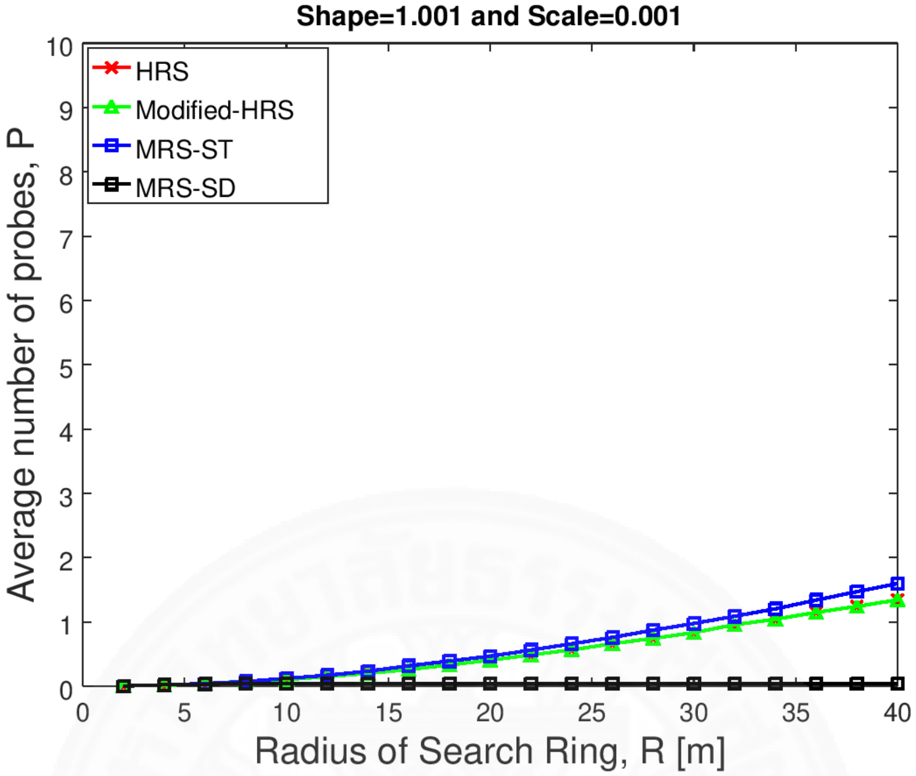

Figure A.46 Average number of probes of different schemes when Shape = 1.001, Scale = 0.001, social threshold = 0.2 and network width = 100 m

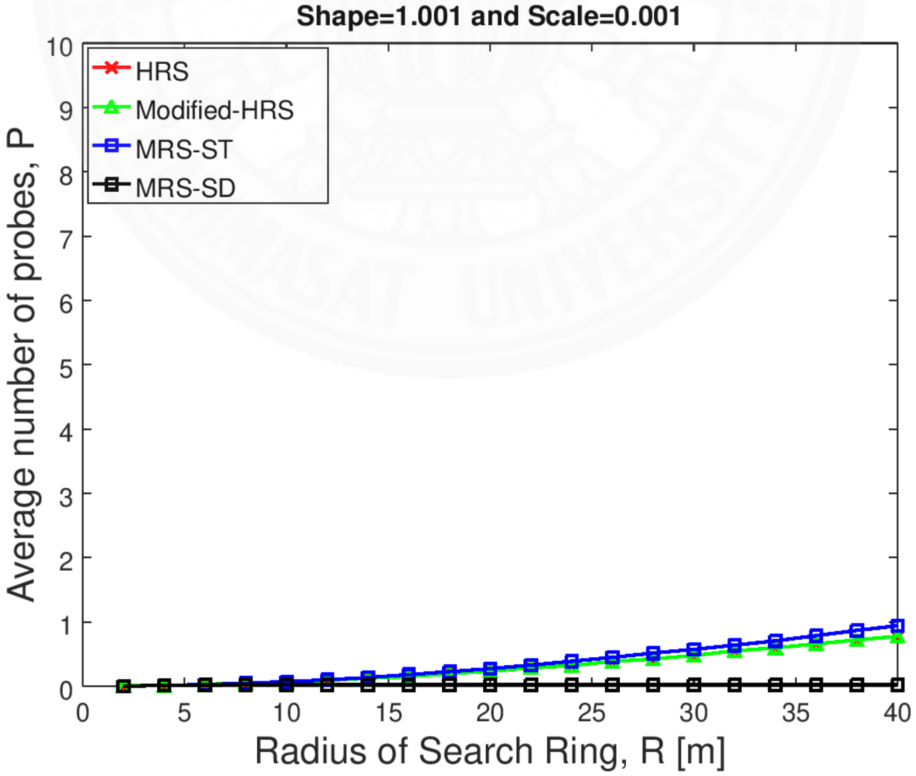

Figure A.47 Average number of probes of different schemes when Shape = 1.001, Scale = 0.001, social threshold = 0.3 and network width = 100 m

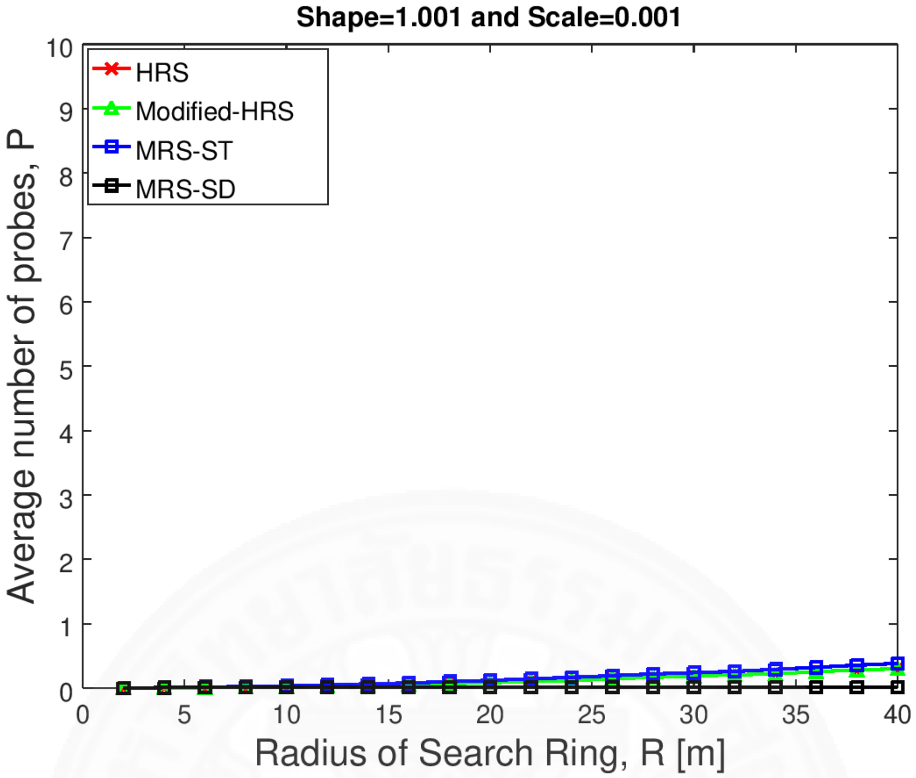

Figure A.48 Average number of probes of different schemes when Shape = 1.001, Scale = 0.001, social threshold = 0.5 and network width = 100 m

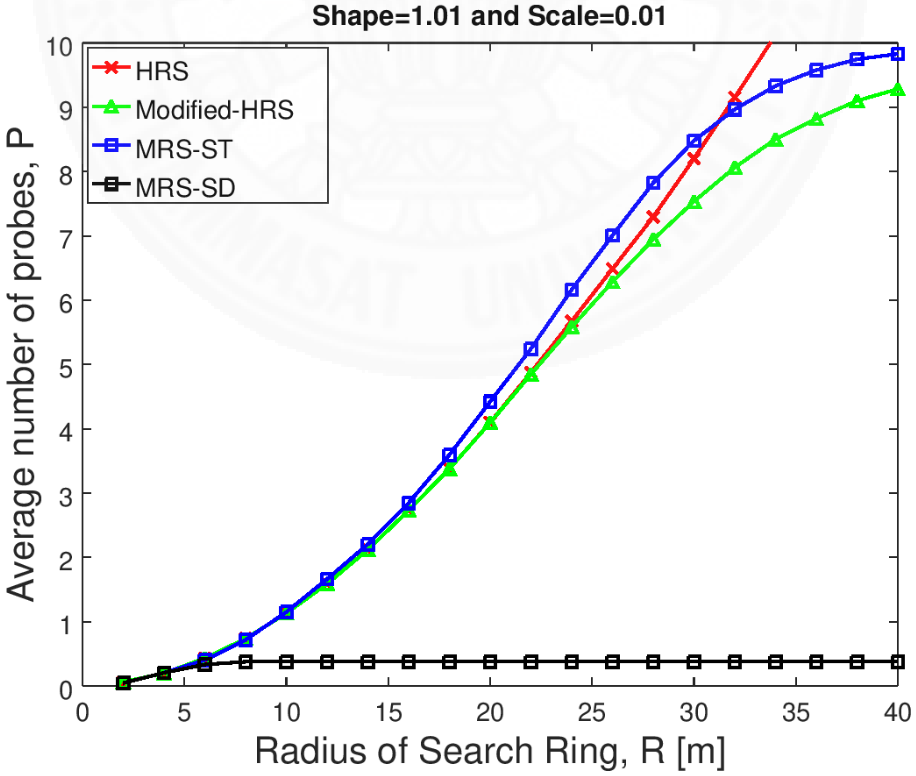

Figure A.49 Average number of probes of different schemes when Shape = 1.01, Scale = 0.01, social threshold = 0.2 and network width = 100 m

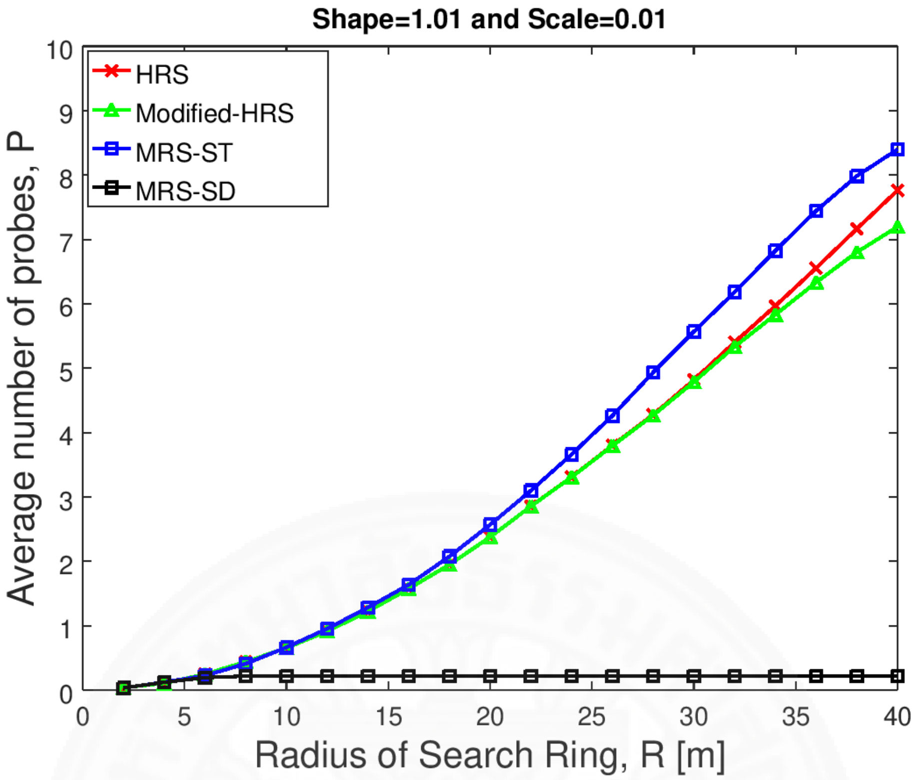

Figure A.50 Average number of probes of different schemes when Shape = 1.01, Scale = 0.01, social threshold = 0.3 and network width = 100 m

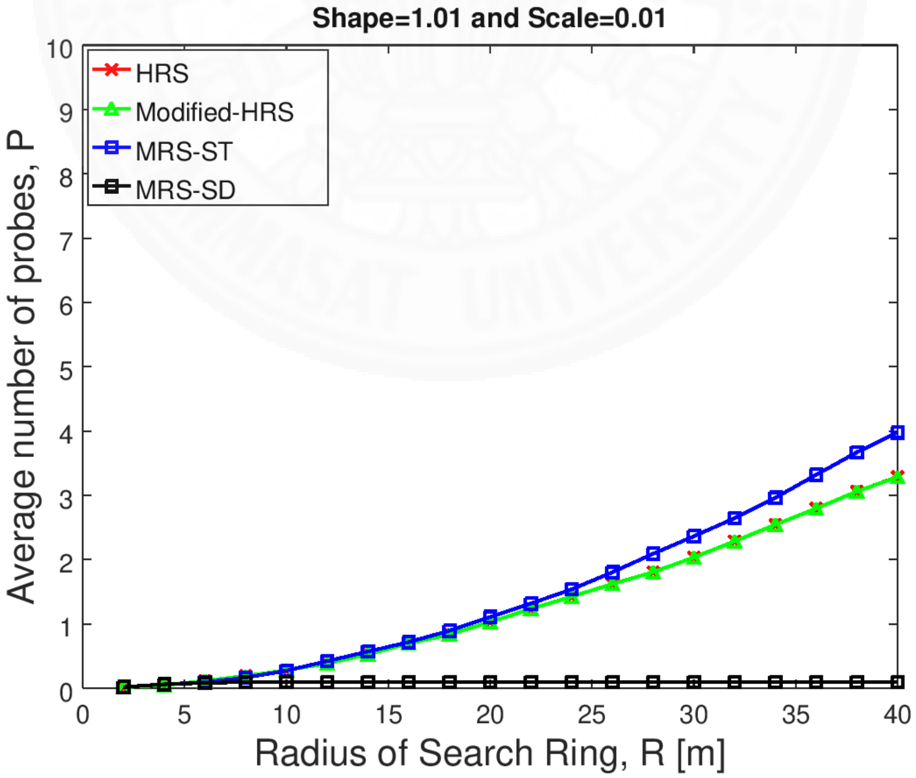

Figure A.51 Average number of probes of different schemes when Shape = 1.01, Scale = 0.01, social threshold = 0.5 and network width = 100 m

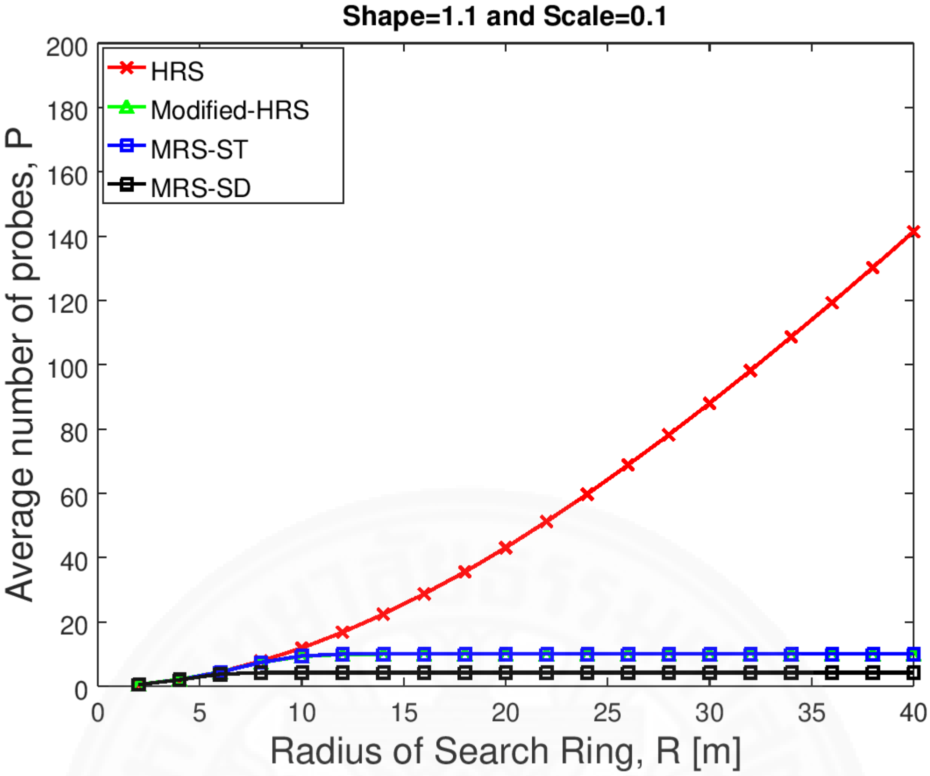

Figure A.52 Average number of probes of different schemes when Shape = 1.1, Scale = 0.1, social threshold = 0.2 and network width = 100 m

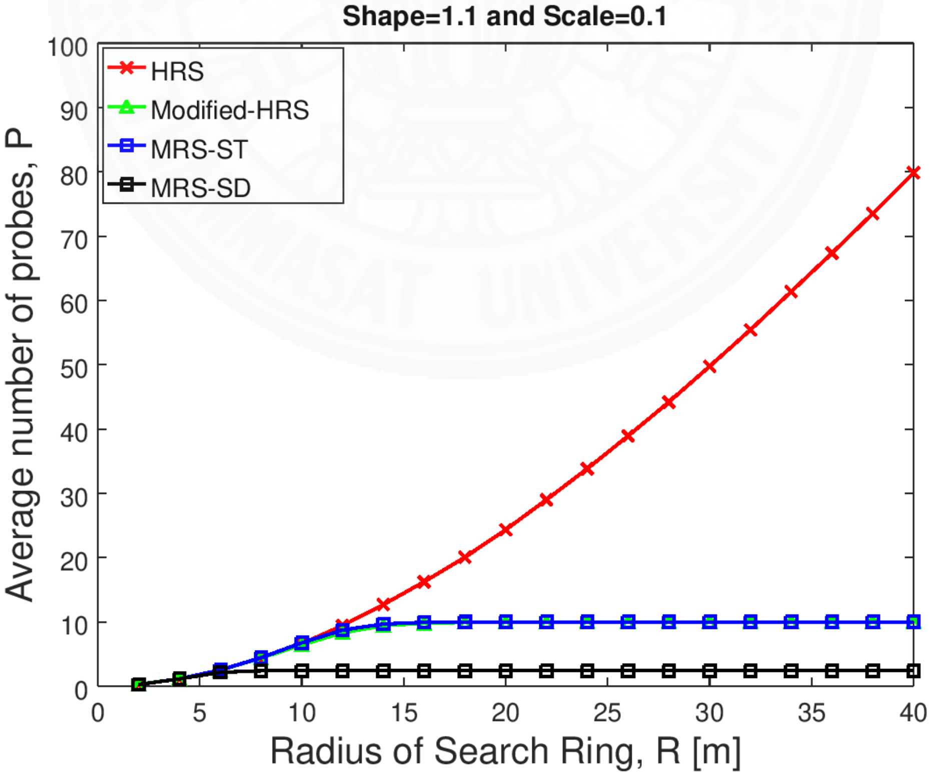

Figure A.53 Average number of probes of different schemes when Shape = 1.1, Scale = 0.1, social threshold = 0.3 and network width = 100 m

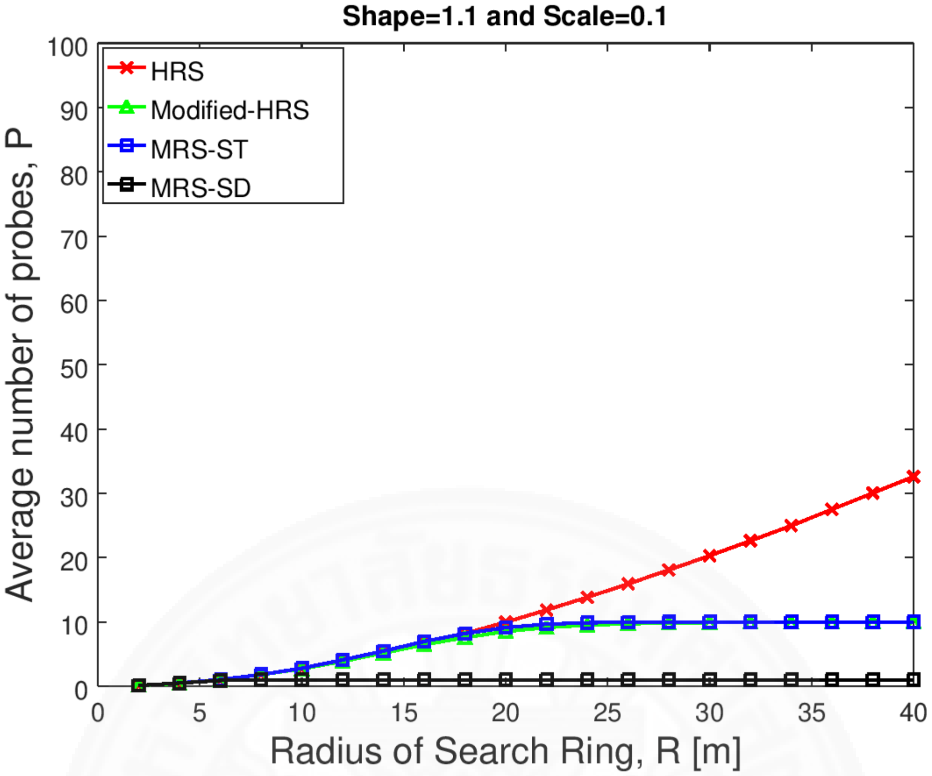

Figure A.54 Average number of probes of different schemes when Shape = 1.1, Scale = 0.1, social threshold = 0.5 and network width = 100 m

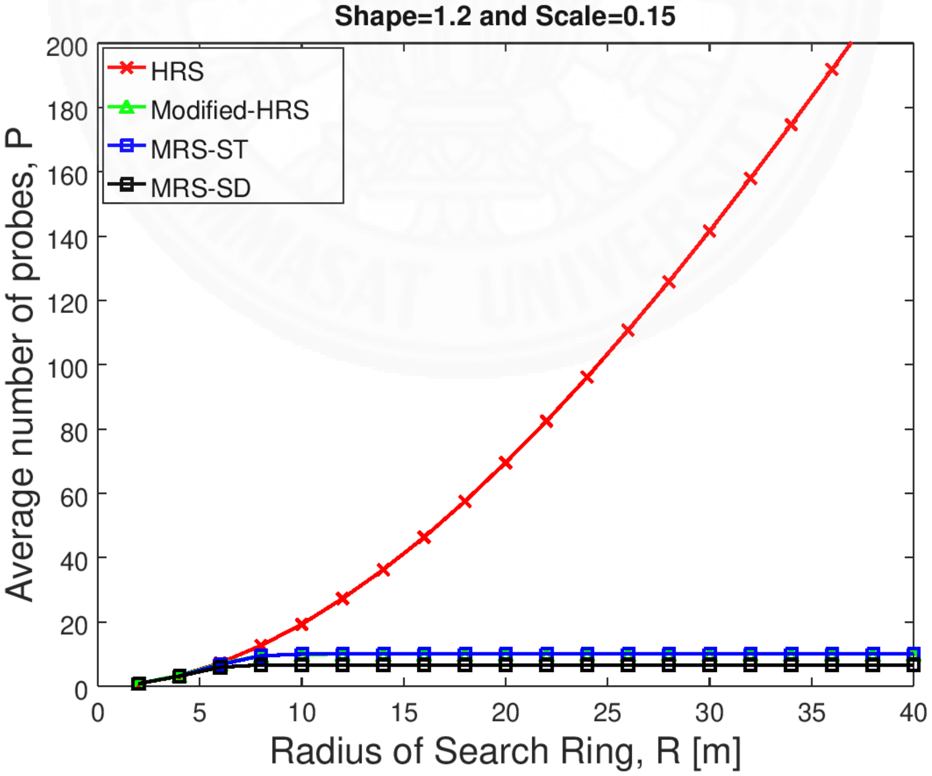

Figure A.55 Average number of probes of different schemes when Shape = 1.2, Scale = 0.15, social threshold = 0.2 and network width = 100 m

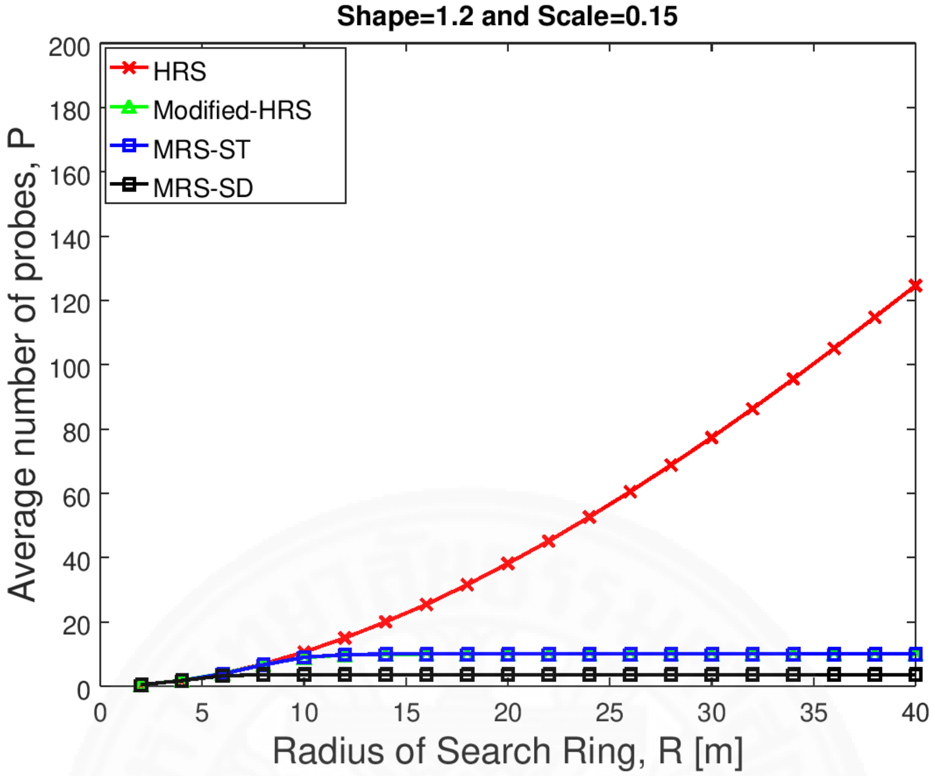

Figure A.56 Average number of probes of different schemes when Shape = 1.2, Scale = 0.15, social threshold = 0.3 and network width = 100 m

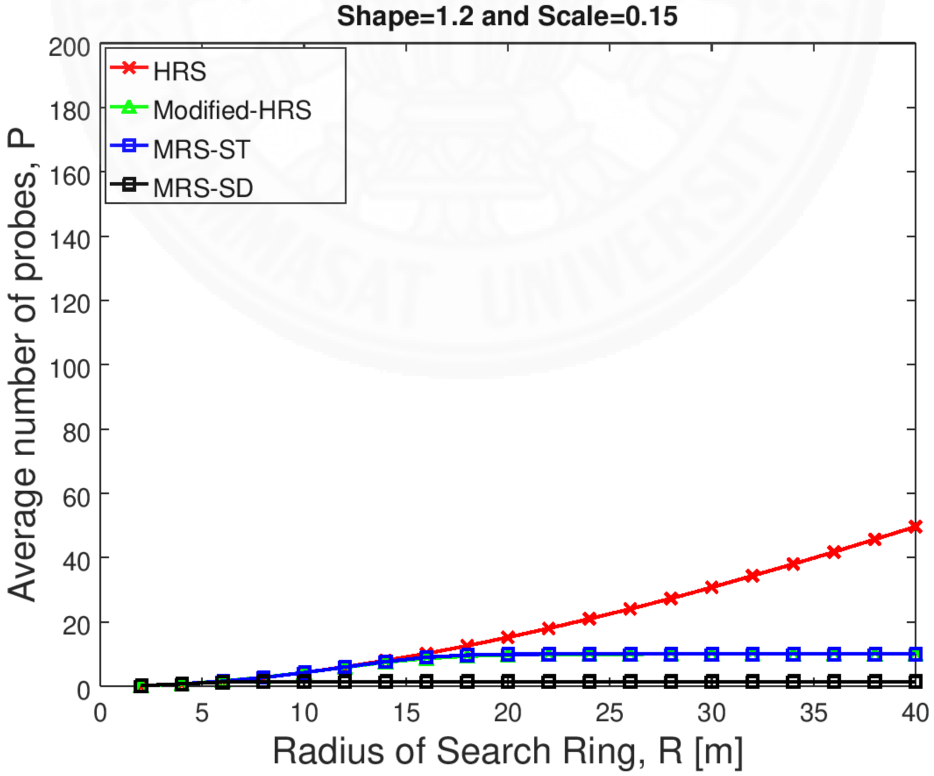

Figure A.57 Average number of probes of different schemes when Shape = 1.2, Scale = 0.15, social threshold = 0.5 and network width = 100 m

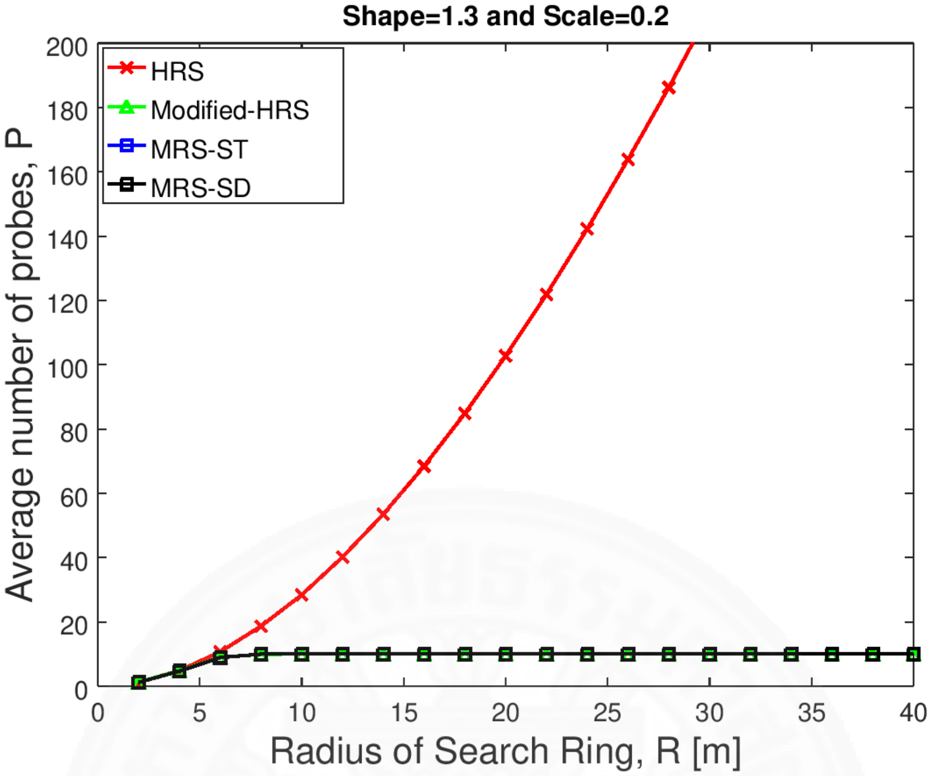

Figure A.58 Average number of probes of different schemes when Shape = 1.3, Scale = 0.2, social threshold = 0.2 and network width = 100 m

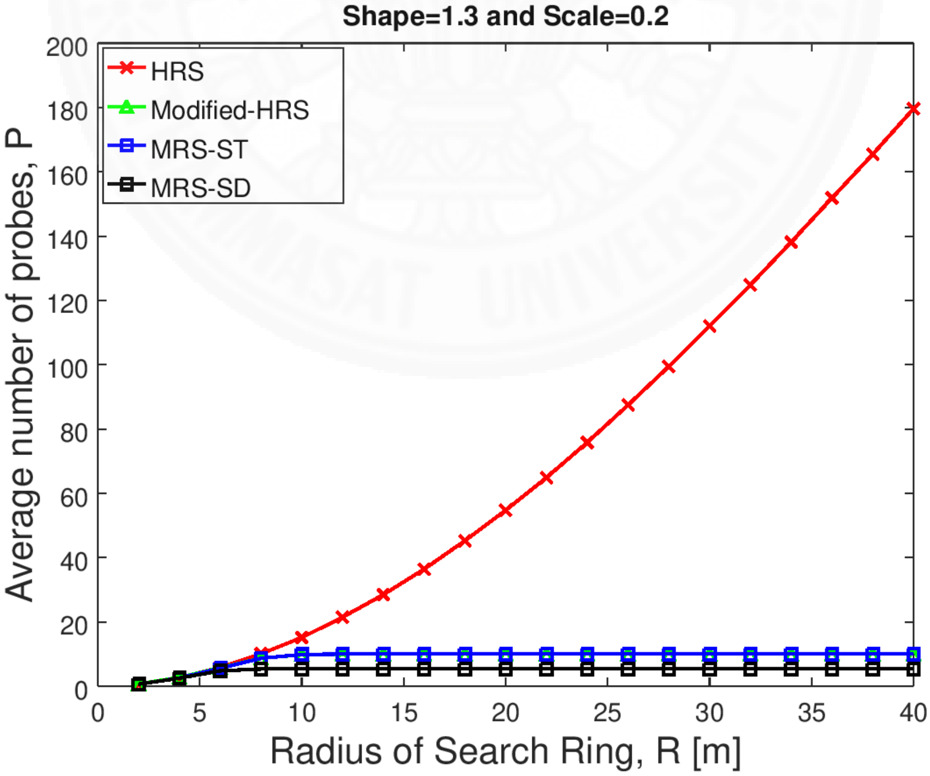

Figure A.59 Average number of probes of different schemes when Shape = 1.3, Scale = 0.2, social threshold = 0.3 and network width = 100 m

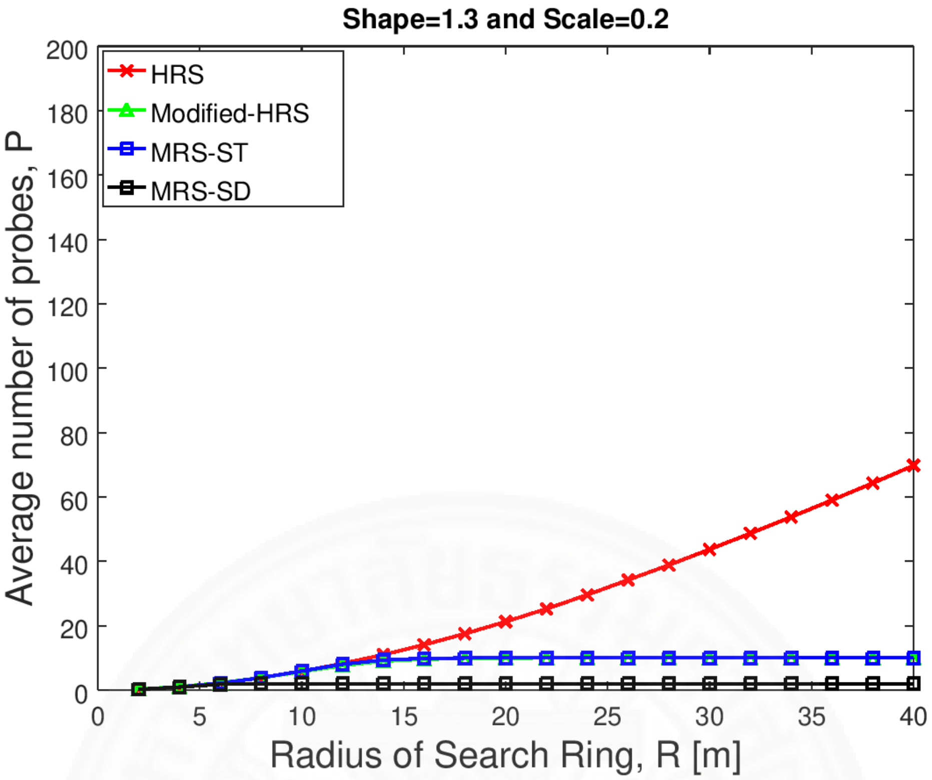

Figure A.60 Average number of probes of different schemes when Shape = 1.3, Scale = 0.2, social threshold = 0.5 and network width = 100 m

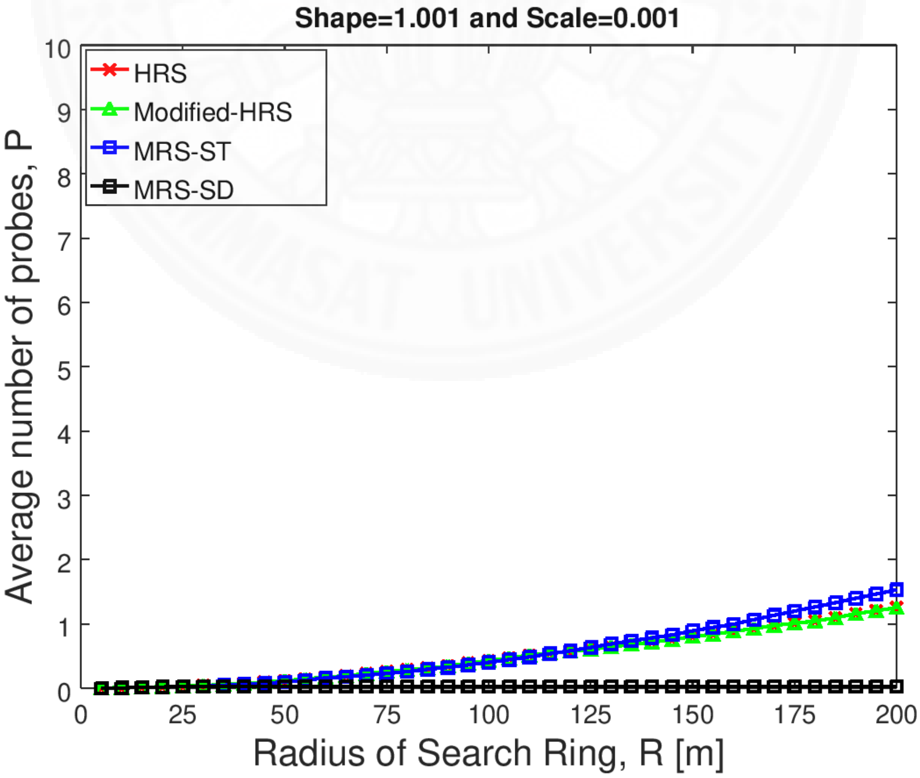

Figure A.61 Average number of probes of different schemes when Shape = 1.001, Scale = 0.001, social threshold = 0.2 and network width = 500 m

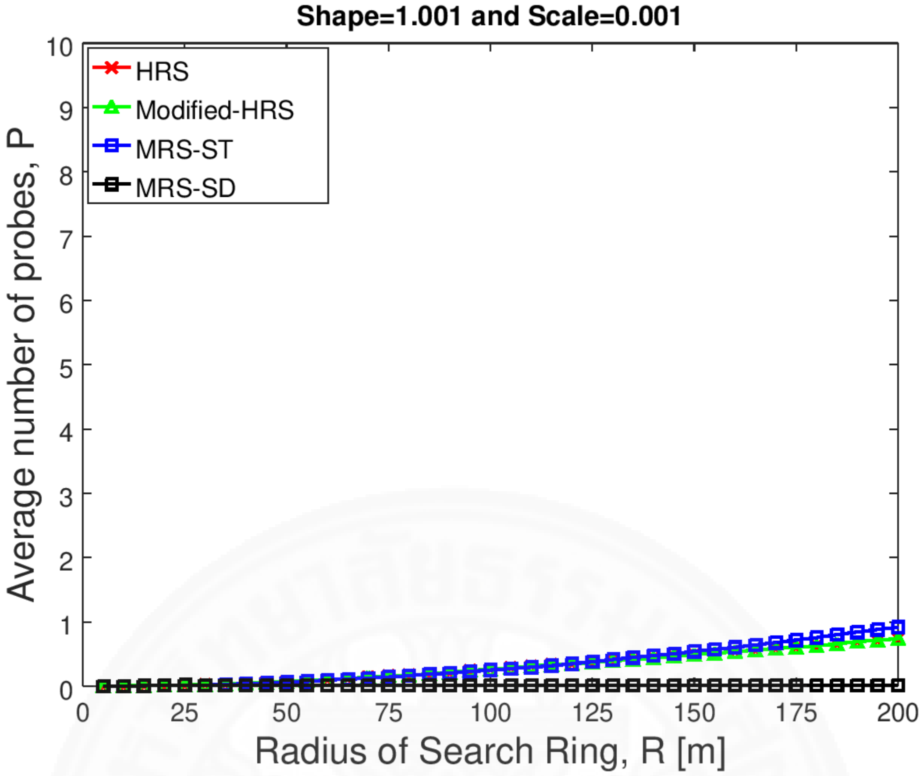

Figure A.62 Average number of probes of different schemes when Shape = 1.001, Scale = 0.001, social threshold = 0.3 and network width = 500 m

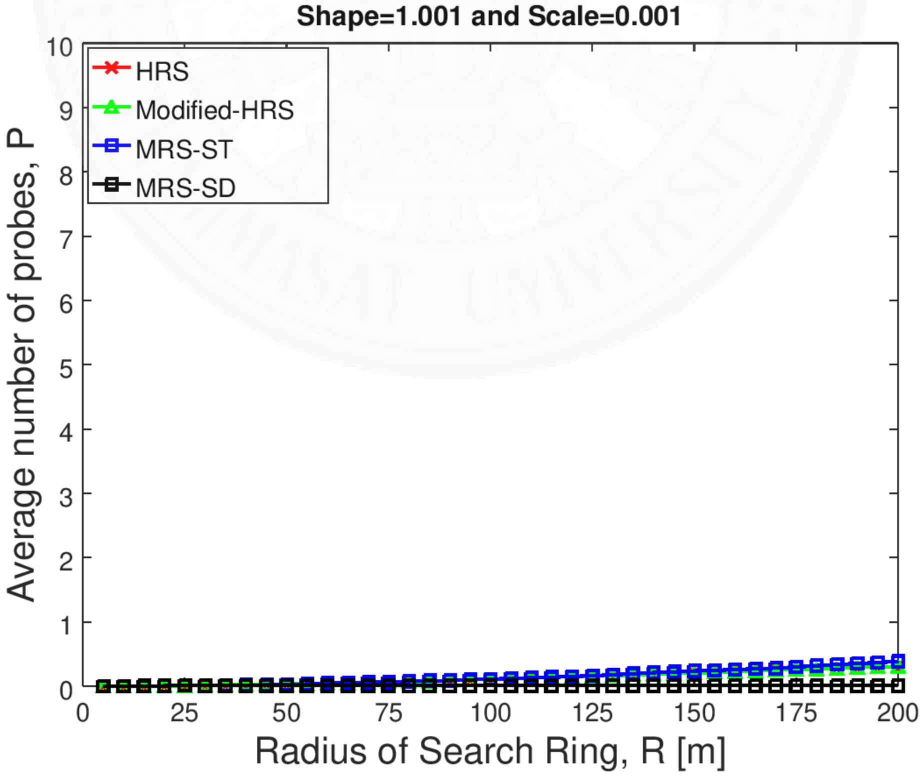

Figure A.63 Average number of probes of different schemes when Shape = 1.001, Scale = 0.001, social threshold = 0.5 and network width = 500 m

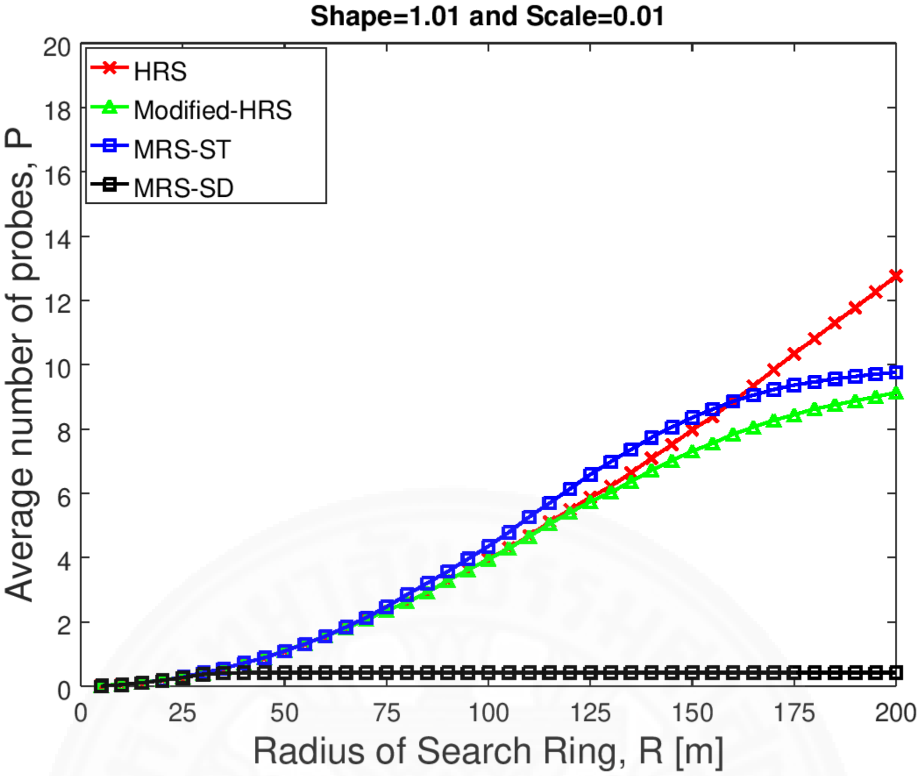

Figure A.64 Average number of probes of different schemes when Shape = 1.01, Scale = 0.01, social threshold = 0.2 and network width = 500 m

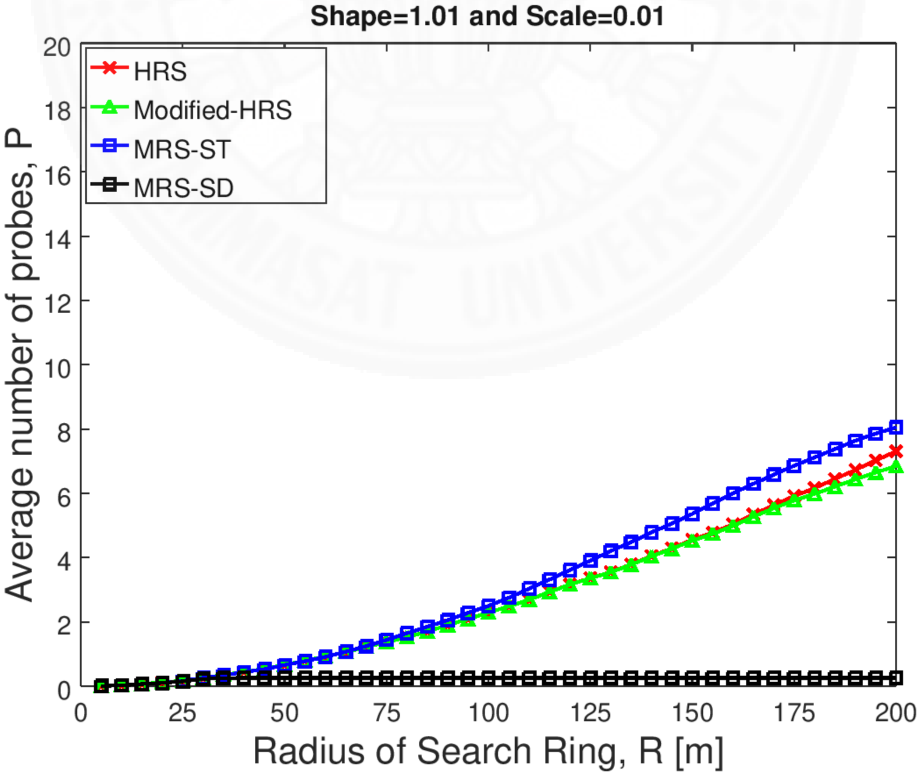

Figure A.65 Average number of probes of different schemes when Shape = 1.01, Scale = 0.01, social threshold = 0.3 and network width = 500 m

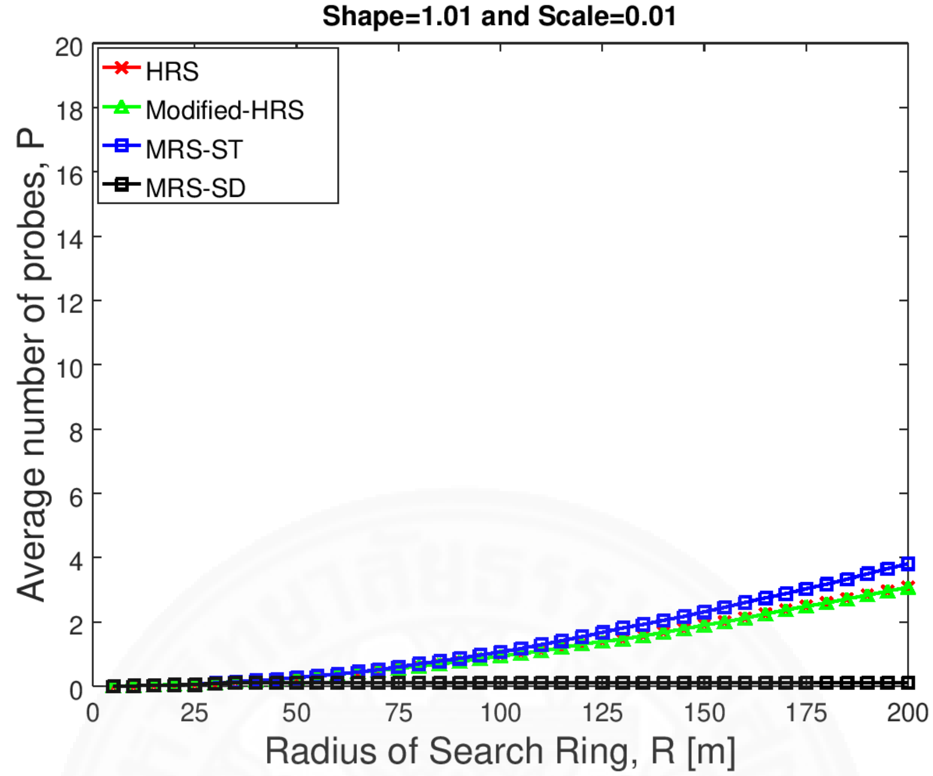

Figure A.66 Average number of probes of different schemes when Shape = 1.01, Scale = 0.01, social threshold = 0.5 and network width = 500 m

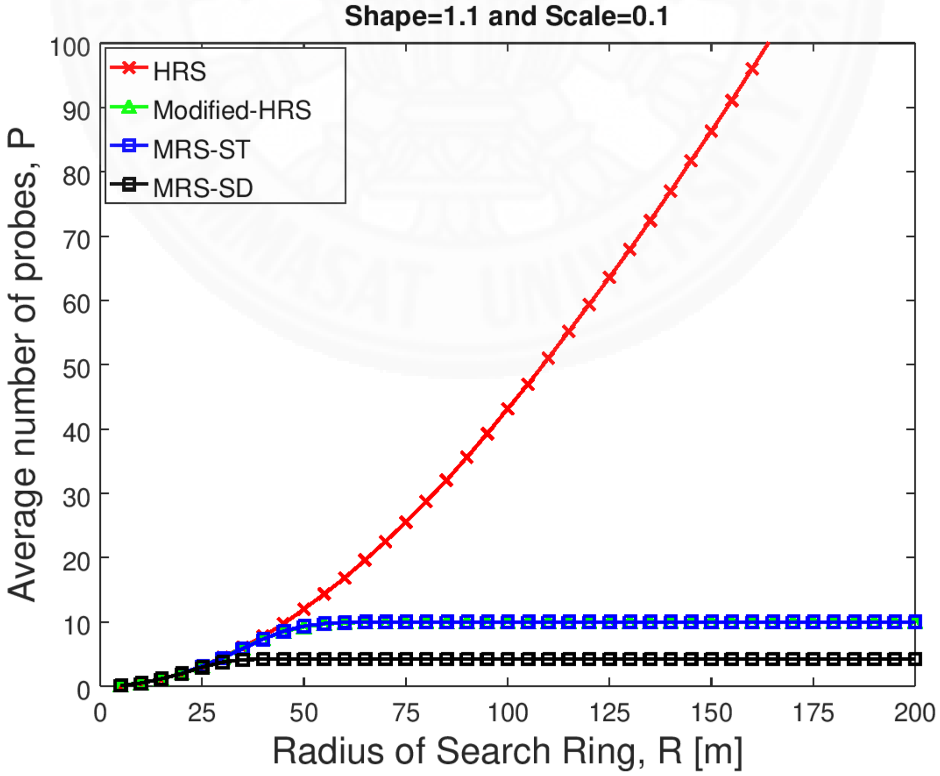

Figure A.67 Average number of probes of different schemes when Shape = 1.1, Scale = 0.1, social threshold = 0.2 and network width = 500 m

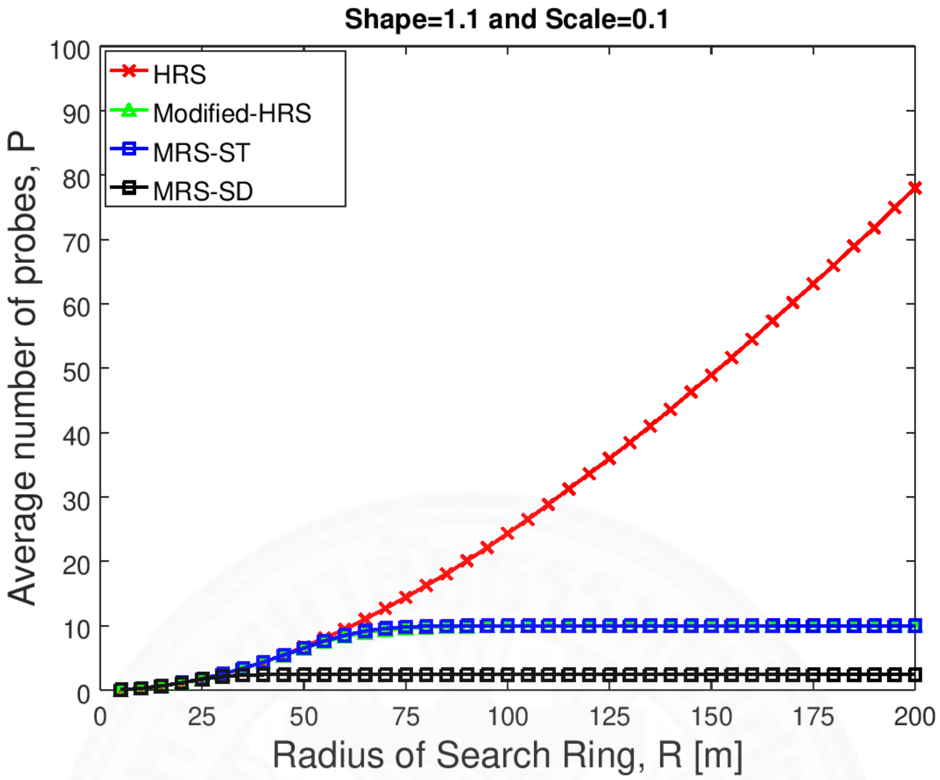

Figure A.68 Average number of probes of different schemes when Shape = 1.1, Scale = 0.1, social threshold = 0.3 and network width = 500 m

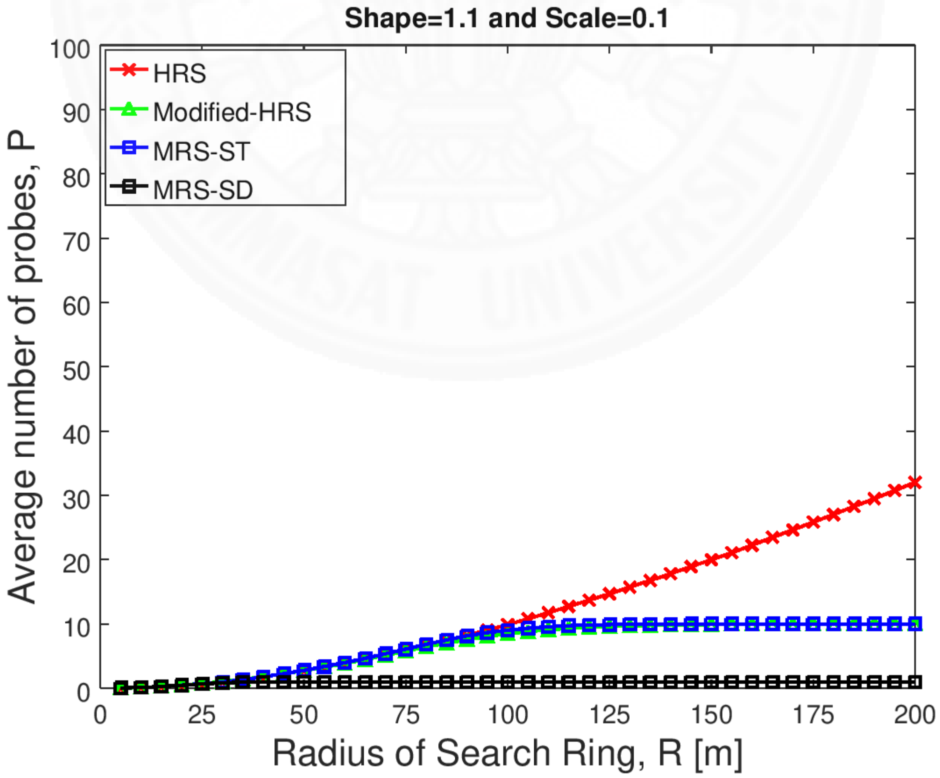

Figure A.69 Average number of probes of different schemes when Shape = 1.1, Scale = 0.1, social threshold = 0.5 and network width = 500 m

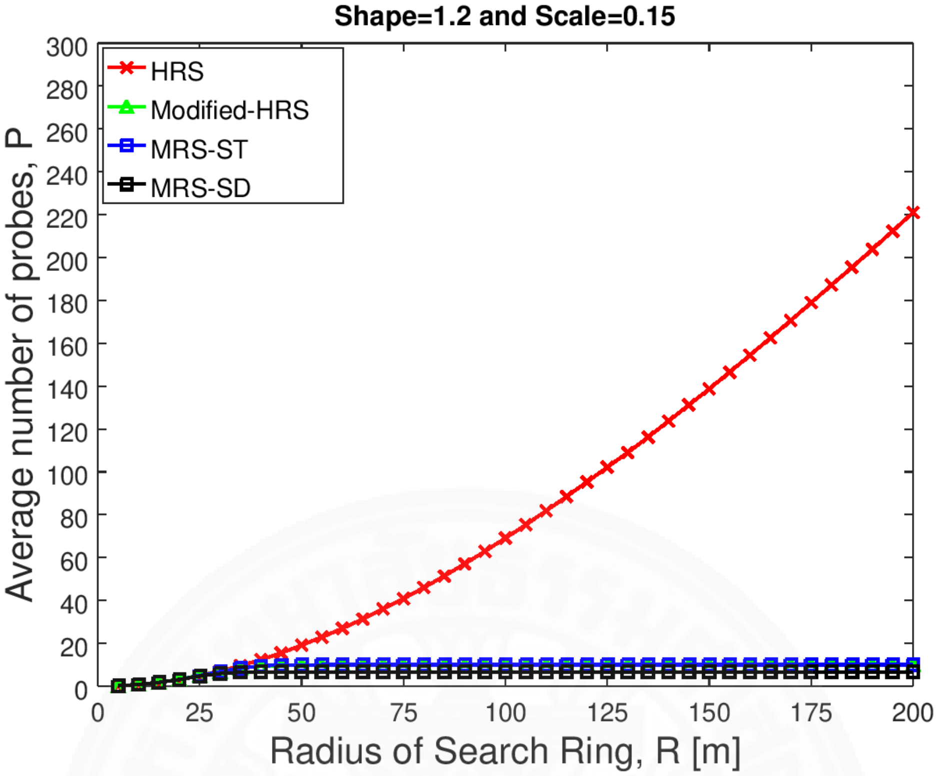

Figure A.70 Average number of probes of different schemes when Shape = 1.2, Scale = 0.15, social threshold = 0.2 and network width = 500 m

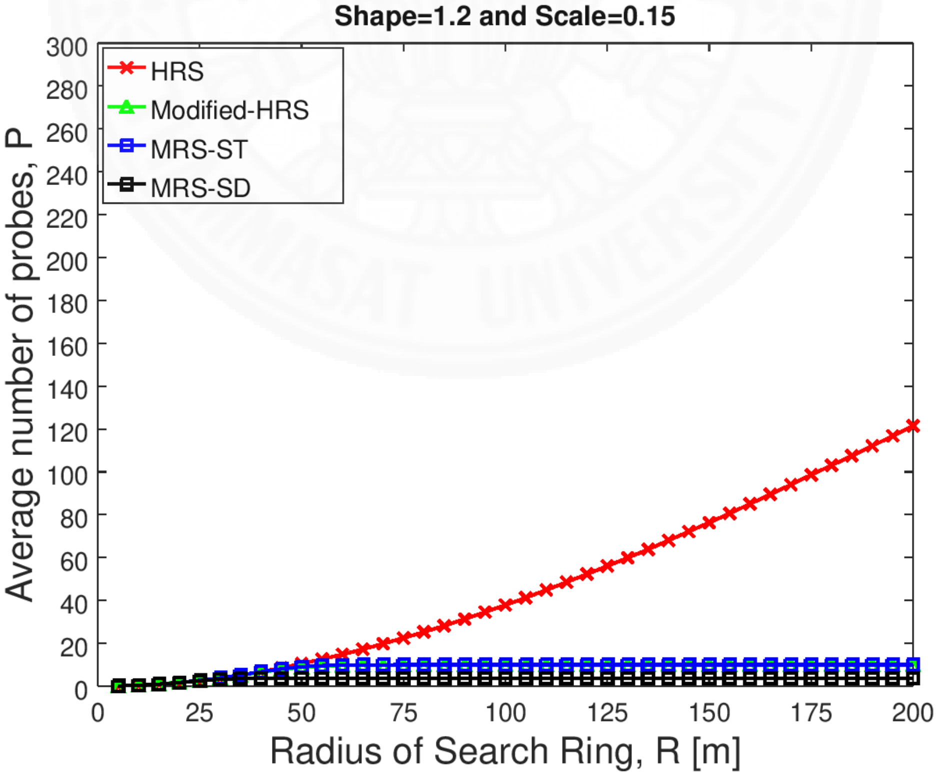

Figure A.71 Average number of probes of different schemes when Shape = 1.2, Scale = 0.15, social threshold = 0.3 and network width = 500 m

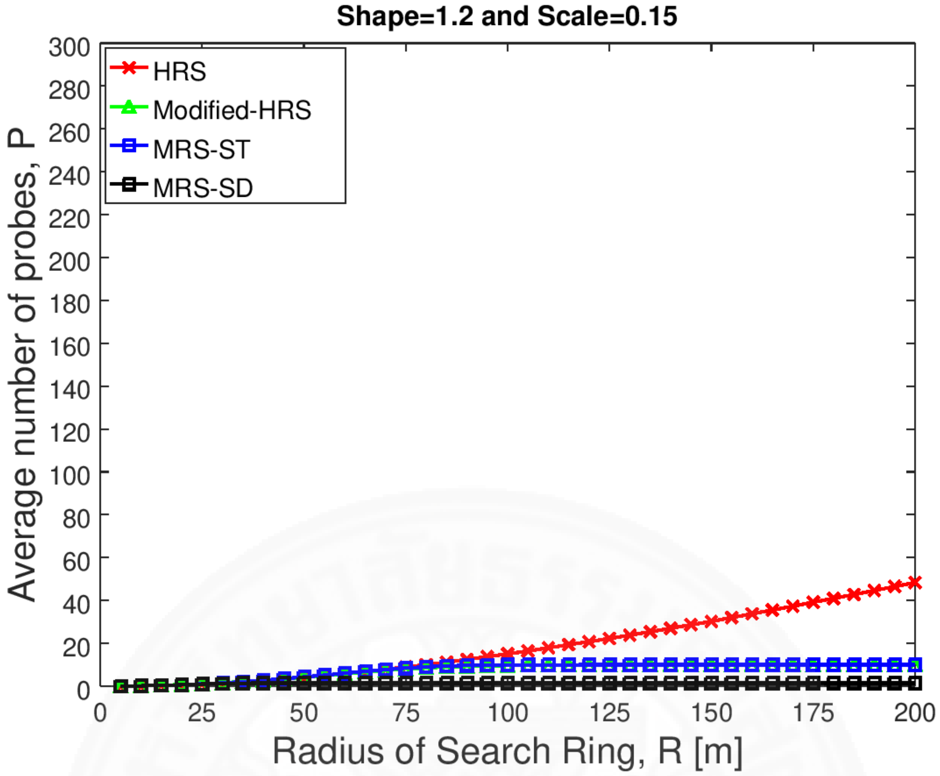

Figure A.72 Average number of probes of different schemes when Shape = 1.2, Scale = 0.15, social threshold = 0.5 and network width = 500 m

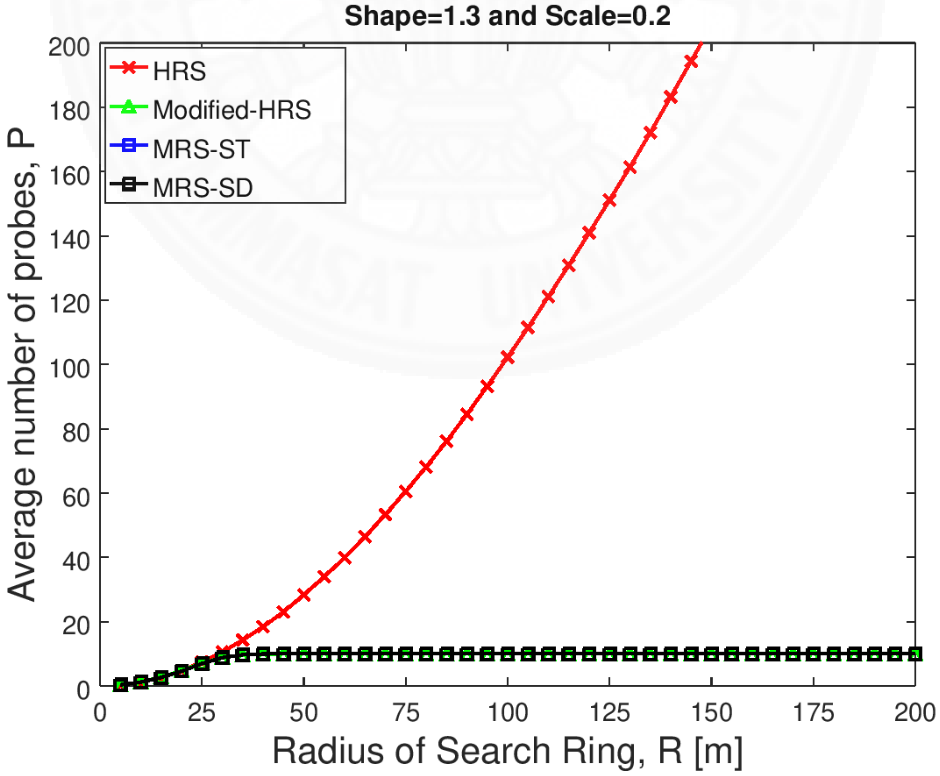

Figure A.73 Average number of probes of different schemes when Shape = 1.3, Scale = 0.2, social threshold = 0.2 and network width = 500 m

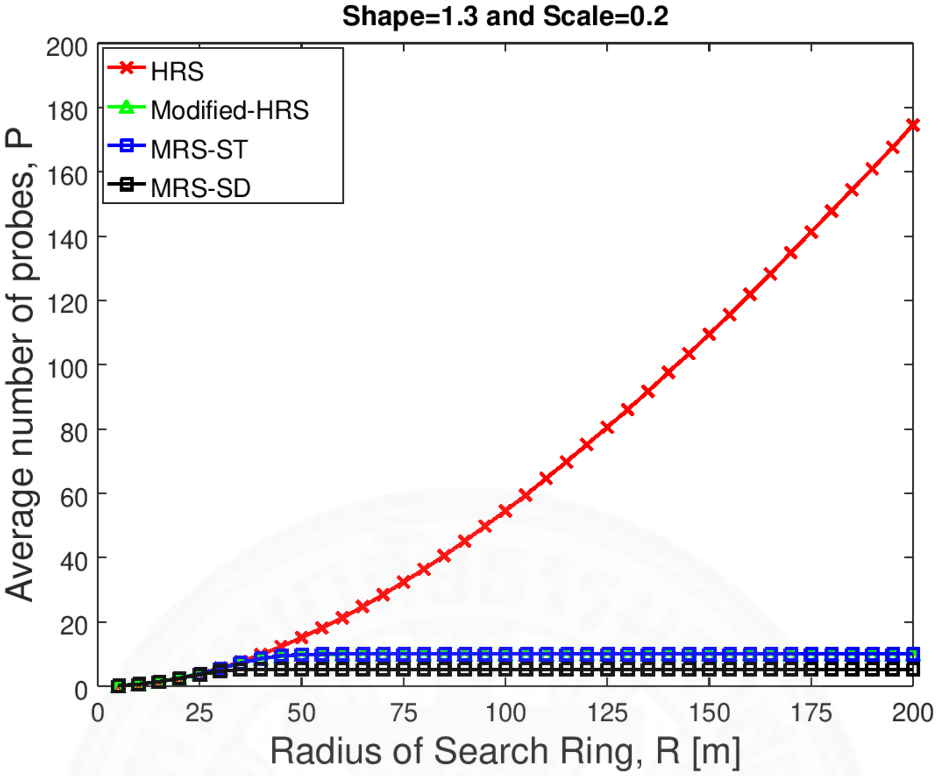

Figure A.74 Average number of probes of different schemes when Shape = 1.3, Scale = 0.2, social threshold = 0.3 and network width = 500 m

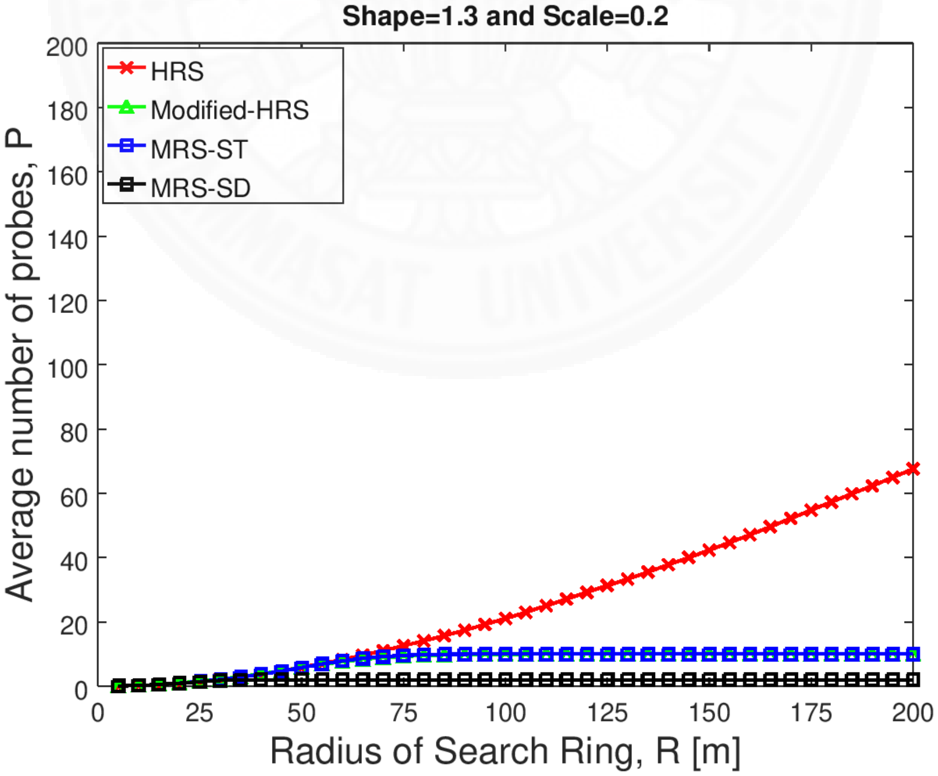

Figure A.75 Average number of probes of different schemes when Shape = 1.3, Scale = 0.2, social threshold = 0.5 and network width = 500 m

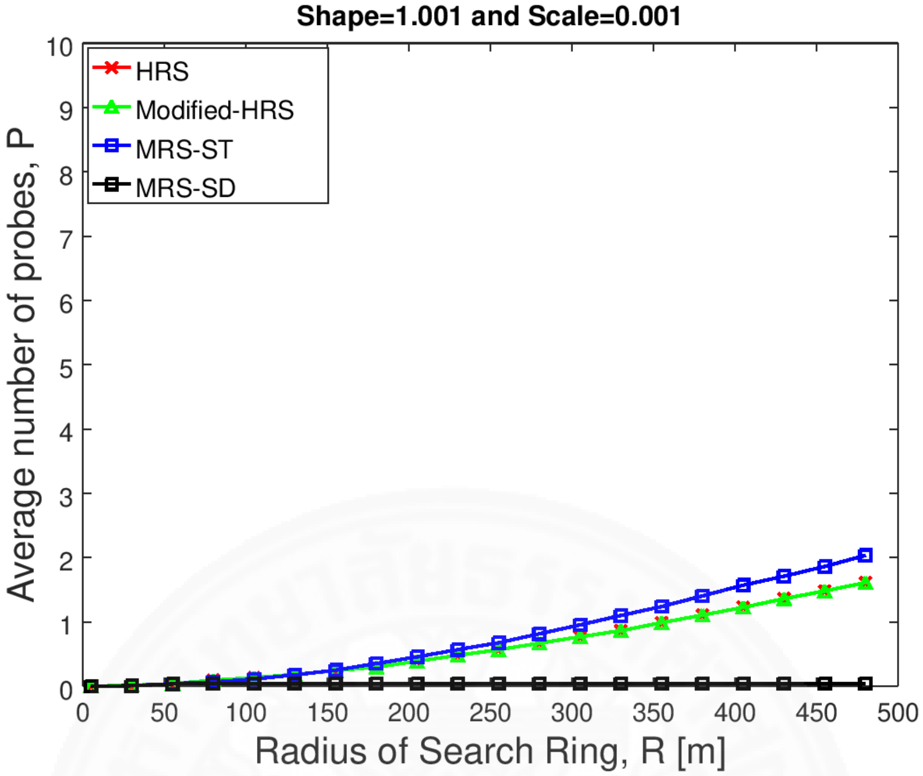

Figure A.76 Average number of probes of different schemes when Shape = 1.001, Scale = 0.001, social threshold = 0.2 and network width = 1000 m

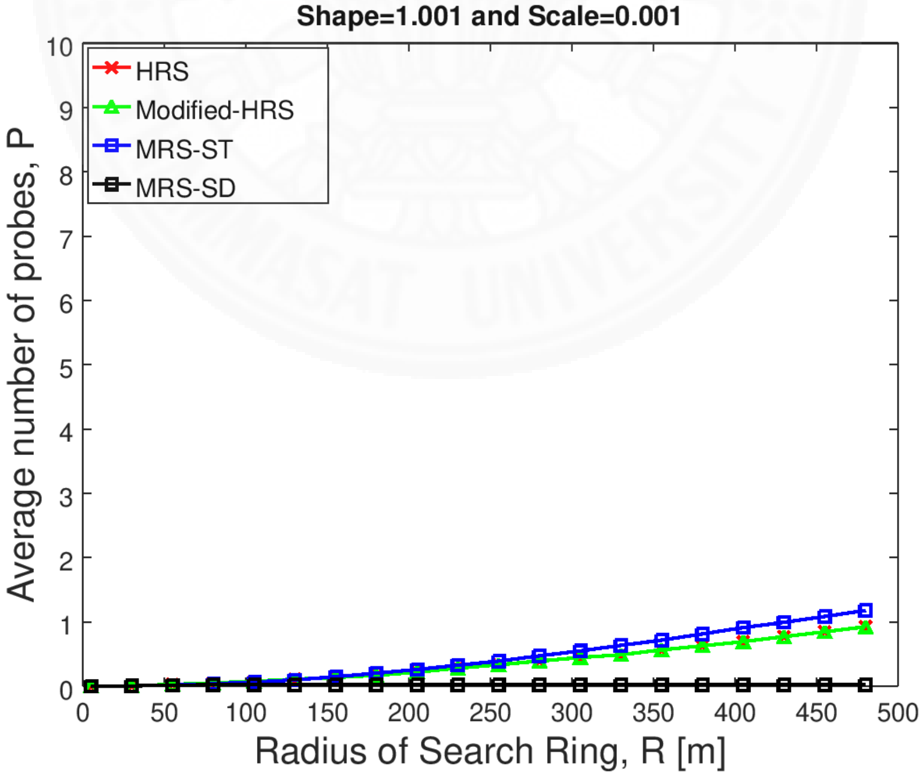

Figure A.77 Average number of probes of different schemes when Shape = 1.001, Scale = 0.001, social threshold = 0.3 and network width = 1000 m

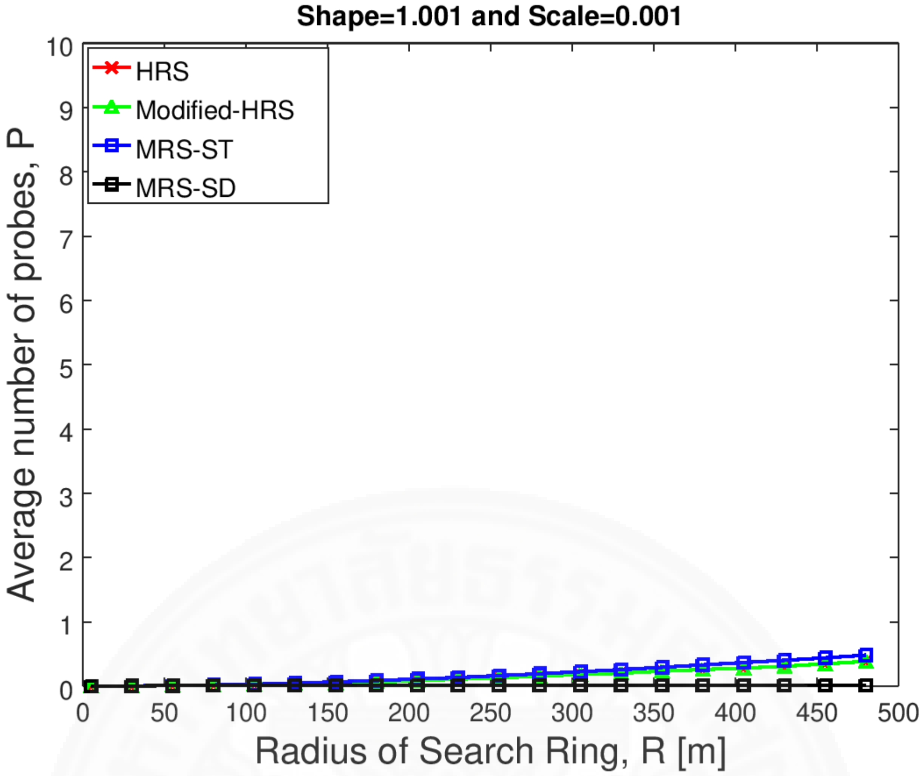

Figure A.78 Average number of probes of different schemes when Shape = 1.001, Scale = 0.001, social threshold = 0.5 and network width = 1000 m

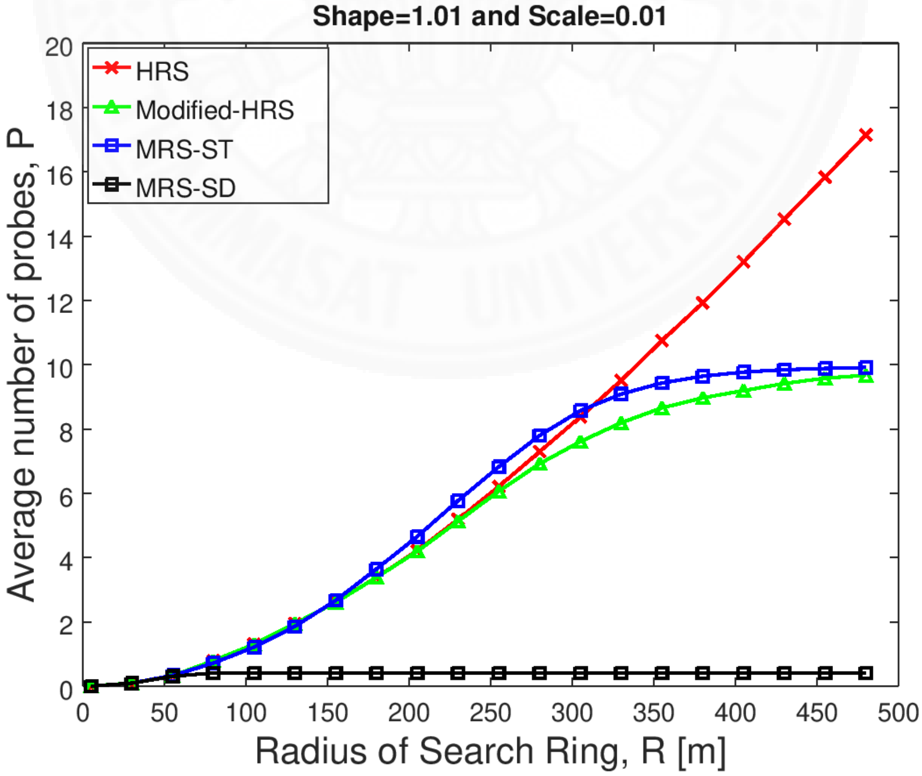

Figure A.79 Average number of probes of different schemes when Shape = 1.01, Scale = 0.01, social threshold = 0.2 and network width = 1000 m

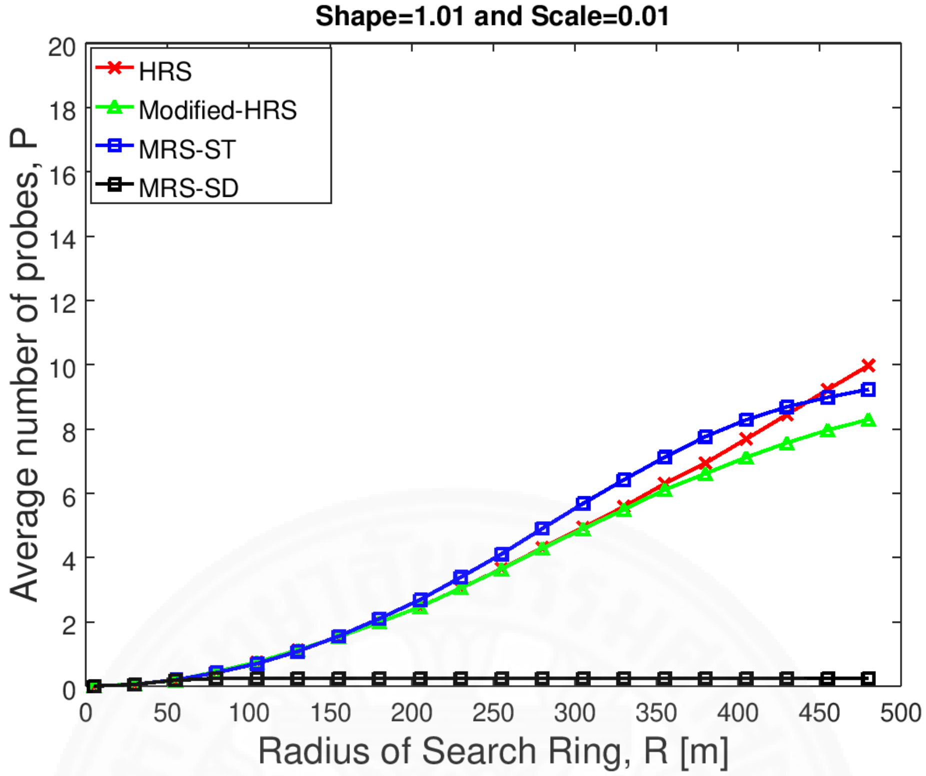

Figure A.80 Average number of probes of different schemes when Shape = 1.01, Scale = 0.01, social threshold = 0.3 and network width = 1000 m

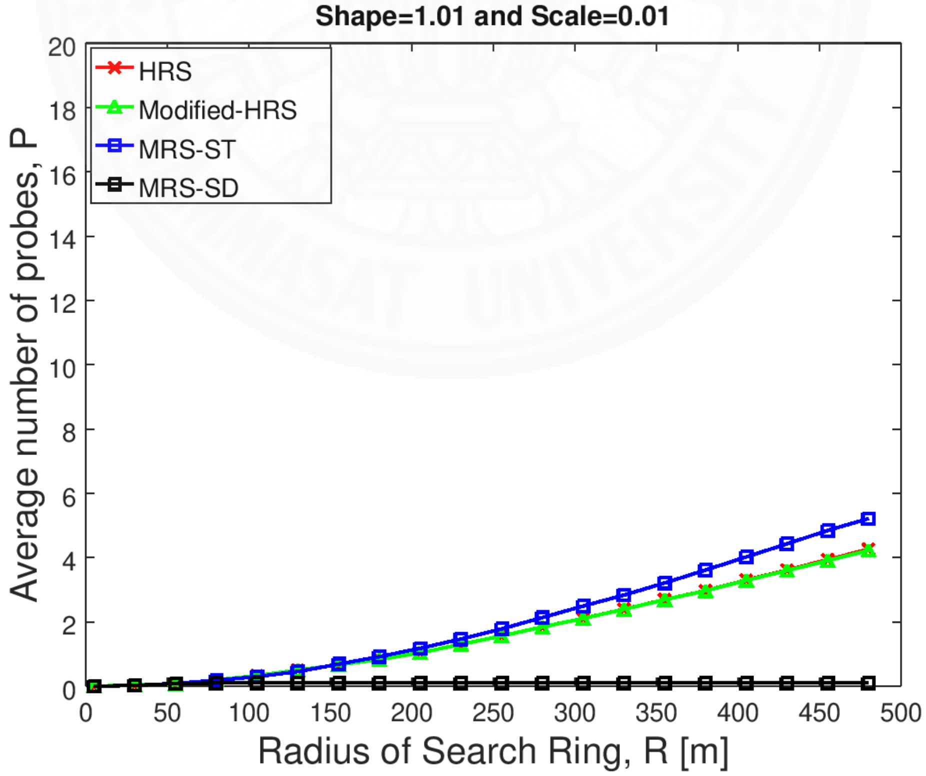

Figure A.81 Average number of probes of different schemes when Shape = 1.01, Scale = 0.01, social threshold = 0.5 and network width = 1000 m

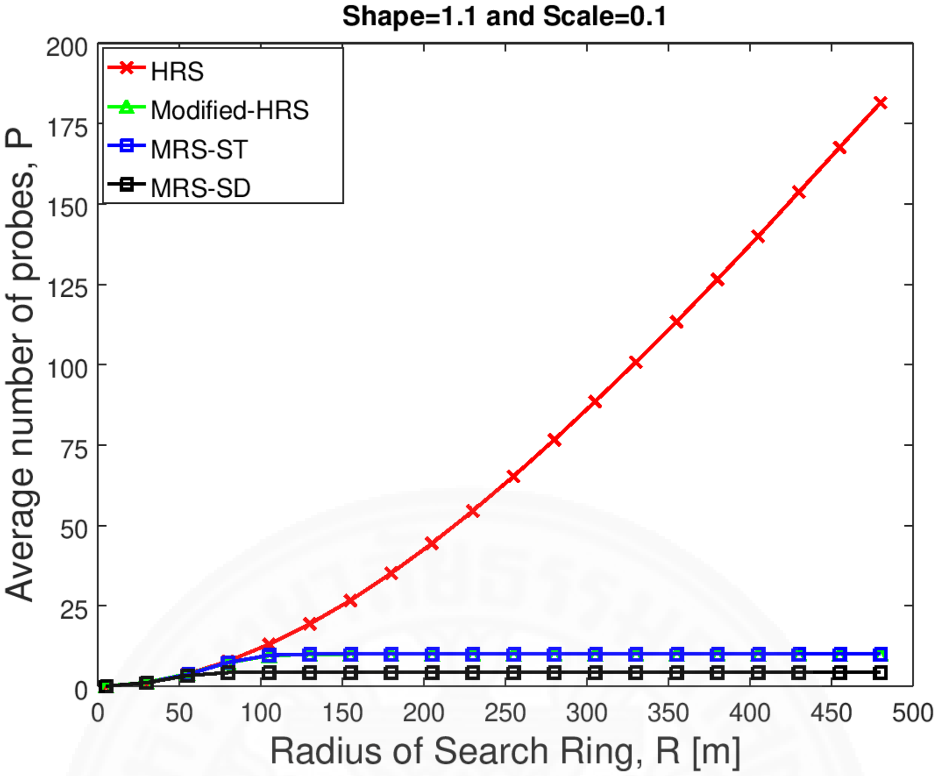

Figure A.82 Average number of probes of different schemes when Shape = 1.1, Scale = 0.1, social threshold = 0.2 and network width = 1000 m

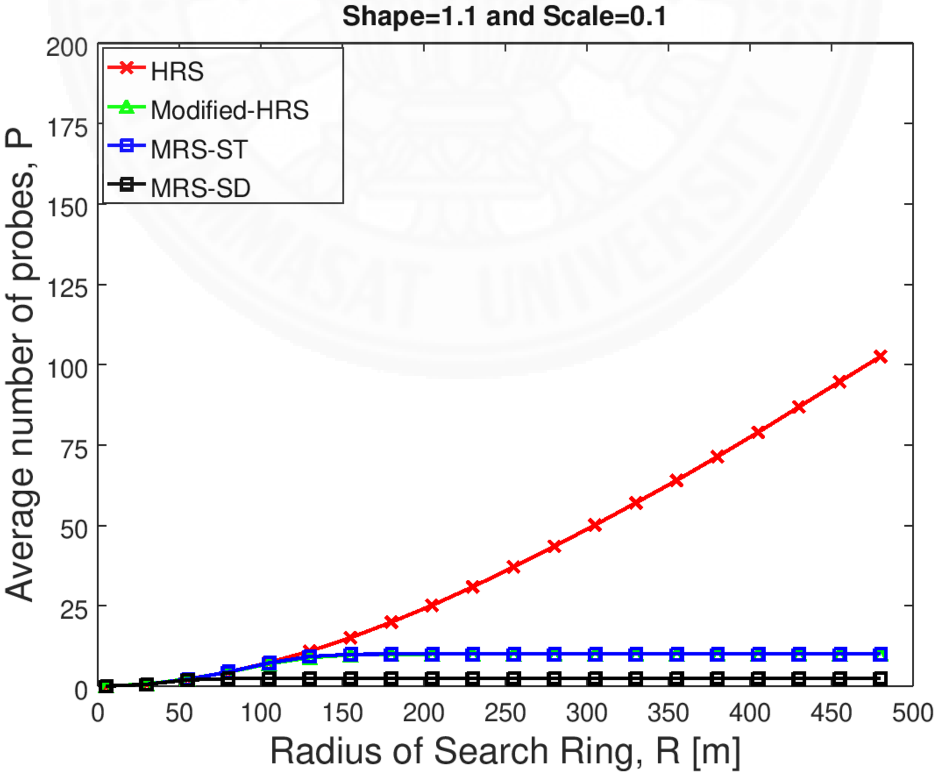

Figure A.83 Average number of probes of different schemes when Shape = 1.1, Scale = 0.1, social threshold = 0.3 and network width = 1000 m

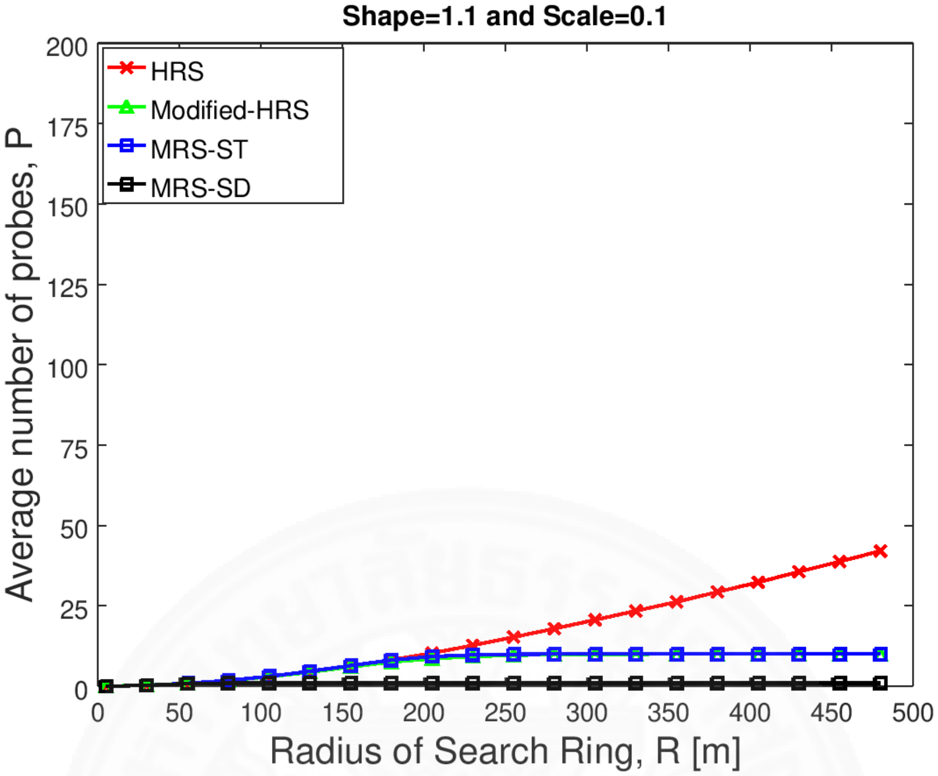

Figure A.84 Average number of probes of different schemes when Shape = 1.1, Scale = 0.1, social threshold = 0.5 and network width = 1000 m

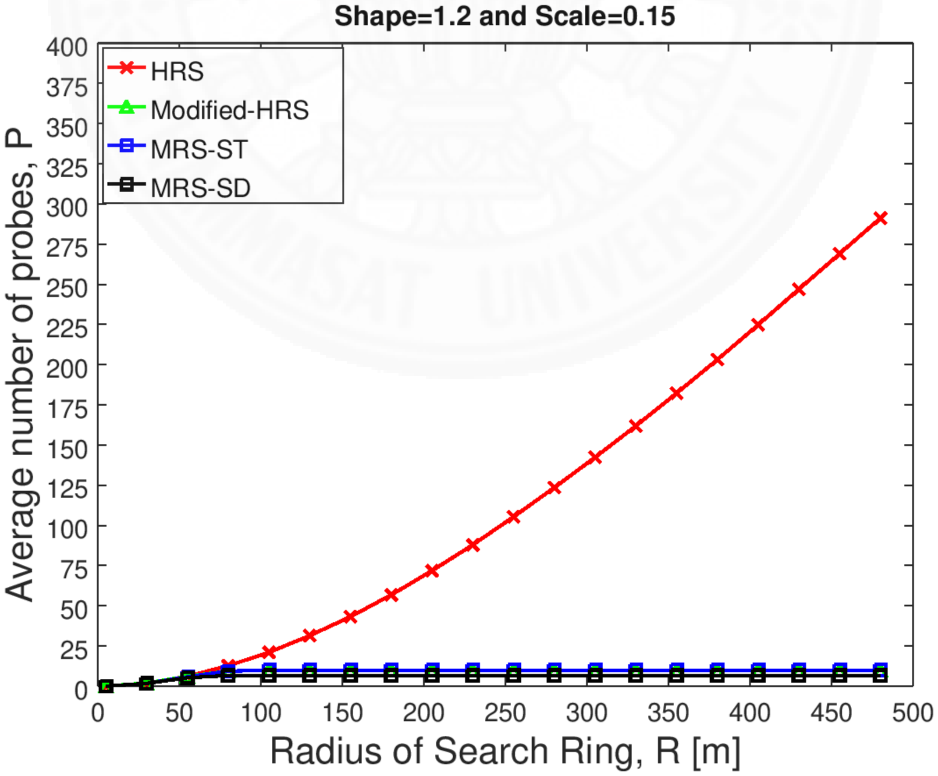

Figure A.85 Average number of probes of different schemes when Shape = 1.2, Scale = 0.15, social threshold = 0.2 and network width = 1000 m

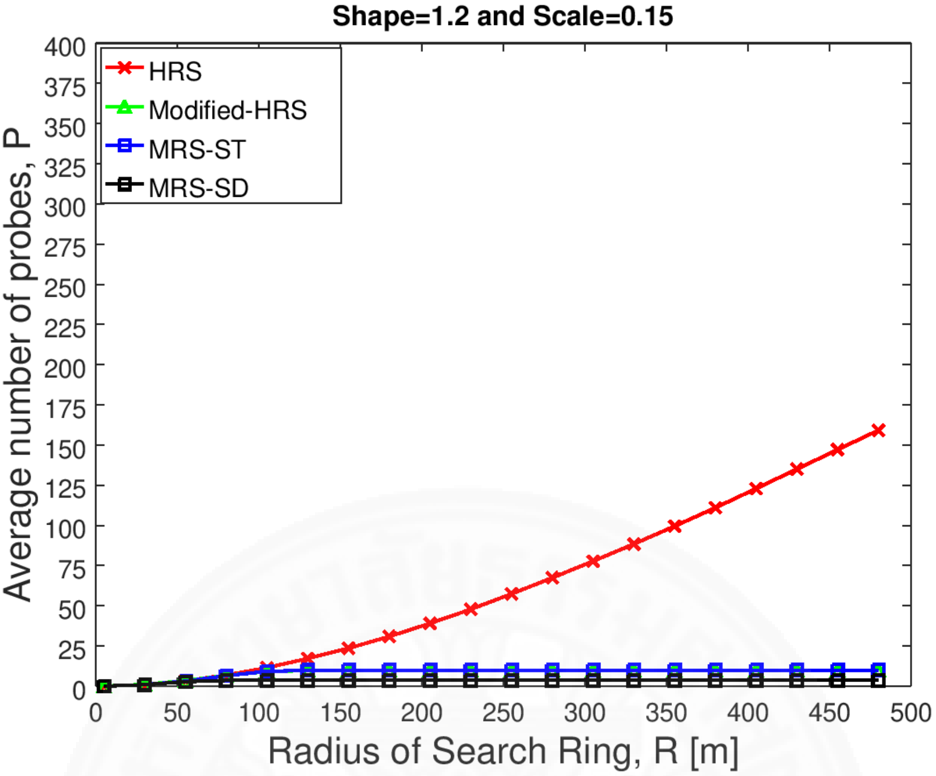

Figure A.86 Average number of probes of different schemes when Shape = 1.2, Scale = 0.15, social threshold = 0.3 and network width = 1000 m

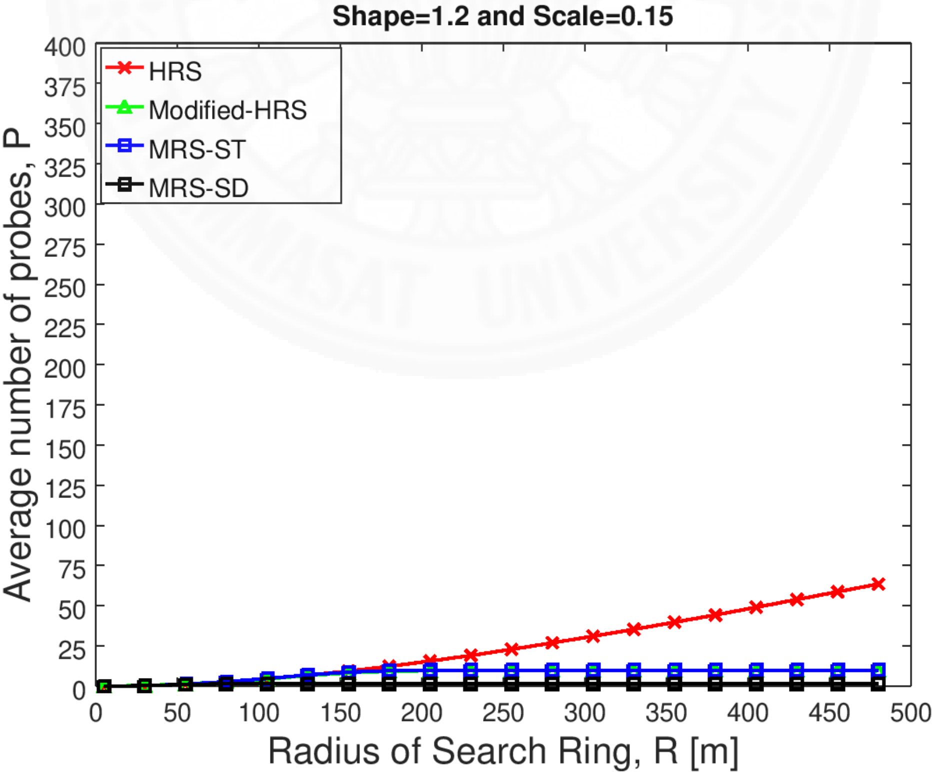

Figure A.87 Average number of probes of different schemes when Shape = 1.2, Scale = 0.15, social threshold = 0.5 and network width = 1000 m

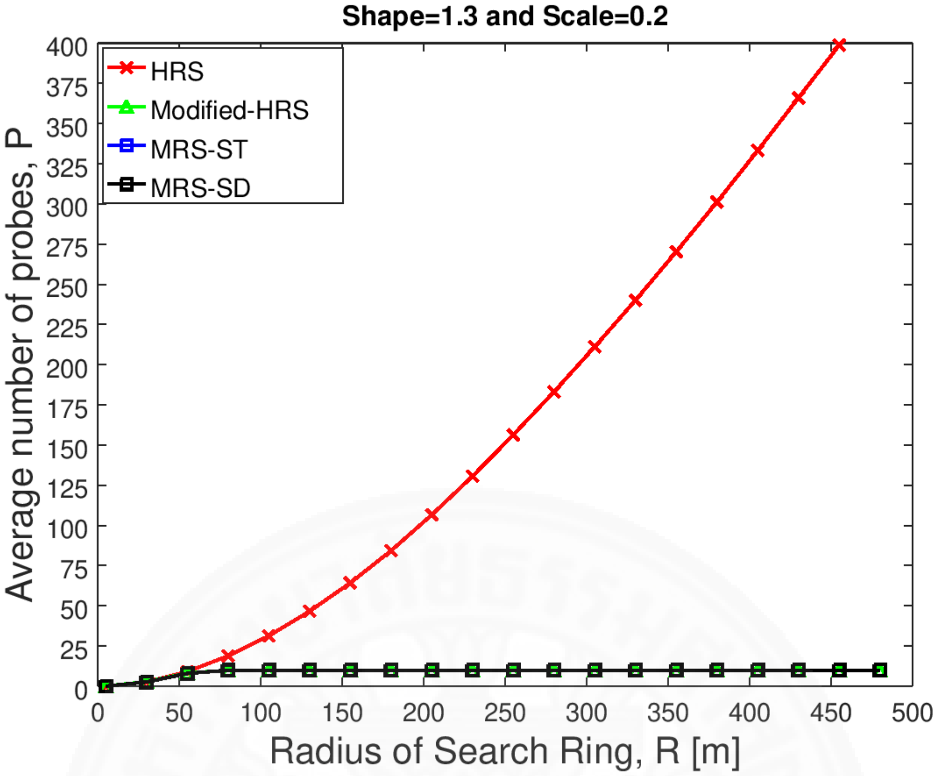

Figure A.88 Average number of probes of different schemes when Shape = 1.3, Scale = 0.2, social threshold = 0.2 and network width = 1000 m

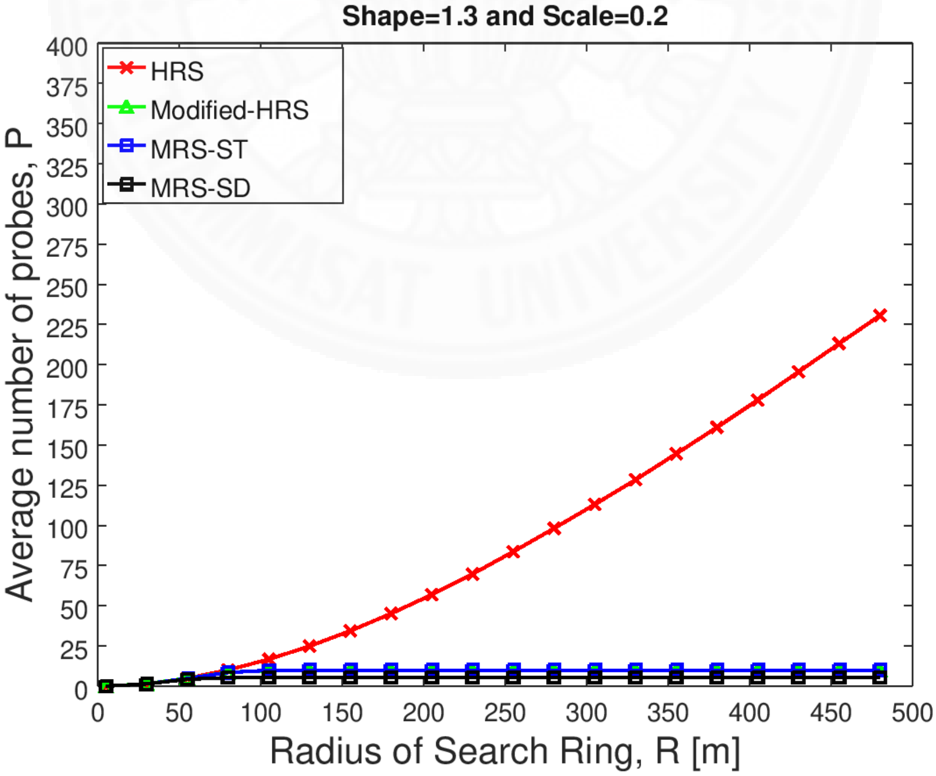

Figure A.89 Average number of probes of different schemes when Shape = 1.3, Scale = 0.2, social threshold = 0.3 and network width = 1000 m

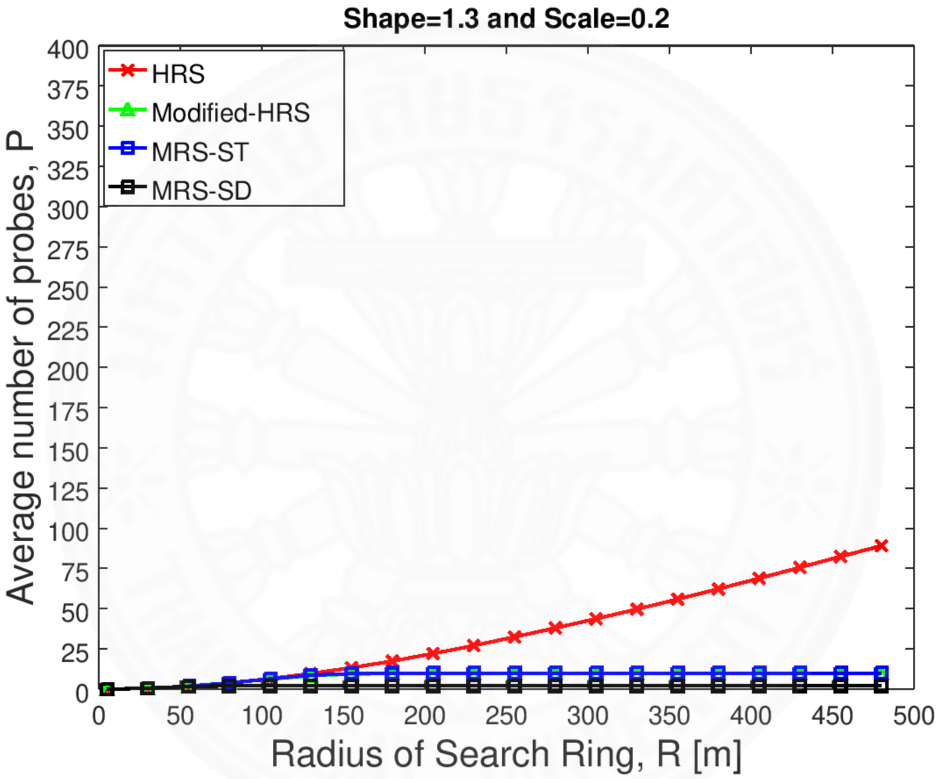

Figure A.90 Average number of probes of different schemes when Shape = 1.3, Scale = 0.2, social threshold = 0.5 and network width = 1000 m

BIOGRAPHY

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Publications

Journals

Khwakhali, U. S., Suksompong, P. Gordon, S. (2020), ”Midpoint relay selection using social trust and battery level to enhance throughput in cooperative device-to-device communications,” Sensors, Vol. 20, Issue 21, 6007, 2020; doi.org/10.3390/s20216007

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International Conferences

Bhattarai, A., Khwakhali, U. S., Paudel, S., Hom, N. K., Yang, F. (2020), ” Antenna Parameters Analysis of Patch Arrays at 2.4GHz Using ADS and TTR500 VNA,” 2020 Information Communication Technologies Conference (ICTC2020), Nanjing, China, May 29-31, 2020.

Khwakhali, U. S., Suksompong, P. Gordon, S. (2019), ”Adaptive Midpoint Relay Selection: Enhancing Throughput in D2D Communications,” 20^{th} IEEE/ACIS International Conference on Software Engineering, Artificial Intelligence, Networking and Parallel/Distributed Computing, SNPD 2019, Toyama, Japan, July 8-11, 2019. This is identical to the book chapter published in Studies in Computational Intelligence Series (SCIS).

Khwakhali, U. S., Gordon, S. Suksompong, P. (2019), Social-aware Relay Selection for Device to Device Communications in Cooperative Cellular Networks, in Proceedings of the 2017 International Electrical Engineering Congress (iEECON 2017), Pattaya Thailand, 8-10 March 2017.

Work Experience

Lecturer, Assumption University, Thailand, January 2018 to date

Lab Instructor/ Teaching Assistant, Sirindhorn International Institute of Technology (SIIT), Thammasat University, Thailand, January 2015 to date

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BSS Engineer, Nepal Satellite Telecom Pvt. Ltd., January 2010 to May 2012

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