Routing for Multi-hop Device-to-Device (D2D) Networks

DISSERTATION
zur Erlangung des Grades eines Doktors
der Ingenieurwissenschaften (Dr.-Ing.)

vorgelegt von
M.Sc. Farrukh Salim Shaikh

eingereicht bei der Naturwissenschaftlich-Technischen Fakultät
der Universität Siegen
Siegen 2021

Betreuer und erster Gutachter
Prof. Dr. Roland Wismüller
Universität Siegen

Zweiter Gutachter
Prof. Dr. Mesut Günes
Universität Magdeburg

Tag der mündlichen Prüfung
22. April 2021

Dedication

To my mother and (late) father who always Love, Care, Effort and Pray for me

Acknowledgements

All the praise to Almighty Allah, who make me born perfectly both mentally and physically, and thus could I use His given wiseness and energy to work on my studies.

I am grateful to my supervisor Professor Dr. Roland Wismüller, who behaves exactly like a true father to care, guide and support in every manner. I have never seen such kind and nice mentor and teacher ever in my life. I believe that the title 'Doctor Father' would surely be made for him. It is must to thank Professor Dr. Mesut Günes, for being the second main reviewer of my dissertation. I would like to say special thanks to Dr. Mubashir Husain Rehmani and my younger brother Dr. Yasir Saleem, who always provide immediate suggestions and help whenever I ask them. It is also great honor for me that I have a contact with Mufti Naeem Memon, who always guide me and motivate me for the true path in order to be away from any kind of academic or personal life cheatings. Mr. Sajjad is also been thanked for being a source to get contacted with Mufti sahib.

During my entire study period, my mother talk to me daily on phone and always care and prays the most about my health and life. My (late) father, the hero of my life, being the most positive thinking person, motivates me the best whenever I feel distress. My wife, who shows best patience to stay away from me for such a long period while also taking care of children in the best manner. My elder brother Tariq Saleem, and my sisters for always praying by heart about my successful completion of studies. My lab-mate Syed Wajahat Abbas Kazmi was a source of getting refreshed every after 2-3 hours of study by making pause in terms of chit chat, so was the most productive time of my studies when we used to be together, and also our third lab person Hawzhin Hozhabr Pour who care like a real sister. The friendly environment created by all group members Andreas Hoffmann, Luis Victor Coutinho Menezes, Marc Sauer, Regina Syska, Manfred Stettner and Alexander Kordes deserve many thanks. Dr. Muhammad Hassan Khan and Dr. Aamir Shahzad for being social, friendly and helping. Special thanks to Shah

Nawaz khan who helped me to get settled in living and academics, in my initial months after arriving Germany.

For sure, it is must to acknowledge the scholarship from HEC Pakistan administered by DAAD Germany, which give the opportunity to pursue my studies.

Abstract

In recent years, device-to-device (D2D) communication has attained significant attention in the research community which enables the users to exchange data directly with each other without the intervention of Base Station (BS). The advantages of D2D communication can be fully realized in multi-hop communication scenario. Establishing a multi-hop D2D route is crucial whenever the two nodes which want to communicate are not in the transmission range of each other. Routing in such multi-hop cellular D2D networks is a critical issue, since the multi-hop network can perform worse than a traditional cellular network if wrong routing decisions are made. This is because routing in these multi-hop networks needs to consider the challenges of node mobility, dynamic network topology, and network fragmentation, which are not major concerns for traditional cellular network.

This thesis mainly focuses on routing in multi-hop D2D networks and provides three main contributions as follows:

In first contribution, firstly, a discussion of various implementations, performance improvements and incentive mechanisms to support D2D communications is provided. Secondly, a detailed derivation and explanation of taxonomy of state-of-the-art routing algorithms for D2D networks is provided. It is worth mentioning that there are numerous works over the past two decades on routing for D2D networks with different naming conventions other than D2D communications. Thus, to the best of the knowledge, the provided taxonomy encompasses all possible routing algorithms. Each routing scheme consists of two main parts: routing metric, and route discovery mechanism. This work contributes in both parts by proposing a routing metric, MIIS, in second contribution and reactive and proactive centralize route discovery mechanisms in third contribution.

In second contribution, a novel routing metric, MIIS (Metric for Interference Impact and SINR) is proposed. Interference is an important parameter to consider in D2D communication, therefore, interference together with signal-to-interference-plus-noise-

ratio (SINR) are considered in the proposed routing metric, MIIS. The MIIS selects routes having higher SINR while being conscious about lower interference at the same time. The performance of MIIS is evaluated in a distributed D2D network implemented in OMNeT++ network simulator. Different MIIS variants are compared with two state-of-the-art schemes in terms of average hop count, routing overhead, packet loss ratio and end-to-end delay. The simulation results showed that all MIIS variants outperform the state-of-the-art schemes under various network topologies with varying number of nodes, nodes mobility and traffic load.

In third contribution, a novel route discovery mechanism of reactive centralized routing is proposed that takes the advantage of the presence of BS for establishing the D2D routes in which the route calculation and decision are taken by the BS for a given cell. The BS makes route decisions by gathering the information from all the nodes and constructs the network topology graph. The reactive centralized routing is also extended to proactive centralized routing. Both centralized routing schemes (i.e., reactive and proactive) significantly reduce the routing overhead as compared to distributed routing schemes by avoiding the flooding of route requests. The performance of reactive and proactive centralized routing have been evaluated through simulations by using MIIS and comparing with existing schemes in terms of varying number of nodes, nodes mobility and traffic load. The centralized routing schemes achieves much lower routing overhead, packet loss ratio and end-to-end delay.

Zusammenfassung

In den letzten Jahren hat die Device-to-Device (D2D)-Kommunikation in der Forschungsgemeinschaft große Aufmerksamkeit erlangt, die es den Benutzern ermöglicht, Daten direkt miteinander auszutauschen, ohne dass eine Basisstation (BS) eingreifen muss. Die Vorteile der D2D-Kommunikation können in einem Multi-Hop-Kommunikationsszenario voll ausgeschöpft werden. Die Etablierung einer Multi-Hop-D2D-Route ist immer dann entscheidend, wenn die beiden Knoten, die miteinander kommunizieren wollen, nicht im Sendebereich des jeweils anderen liegen. Das Routing in solchen zellularen Multi-Hop-D2D-Netzwerken ist ein kritisches Thema, da das Multi-Hop-Netzwerk bei falschen Routing-Entscheidungen eine schlechtere Leistung als ein traditionelles zellulares Netzwerk aufweisen kann. Dies liegt daran, dass das Routing in diesen Multi-Hop-Netzwerken die Herausforderungen der Knotenmobilität, der dynamischen Netzwerktopologie und der Netzwerkfragmentierung berücksichtigen muss, was bei traditionellen zellularen Netzwerken nicht der Fall ist.

Diese Arbeit konzentriert sich hauptsächlich auf das Routing in Multi-Hop D2D-Netzwerken und liefert drei Hauptbeiträge wie folgt:

Im ersten Beitrag wird erstens eine Diskussion verschiedener Implementierungen, Leistungsverbesserungen und Anreizmechanismen zur Unterstützung der D2D Kommunikation geliefert. Zweitens wird eine detaillierte Herleitung und Erläuterung der Taxonomie von State-of-the-Art-Routing-Algorithmen für D2D-Netzwerke bereitgestellt. Es ist erwähnenswert, dass es in den letzten zwei Jahrzehnten zahlreiche Arbeiten zum Thema Routing für D2D-Netzwerke mit unterschiedlichen Namenskonventionen gibt, die sich nicht auf D2D-Kommunikation beziehen. Daher umfasst die bereitgestellte Taxonomie nach bestem Wissen und Gewissen alle möglichen Routing-Algorithmen. Jedes Routing-Schema besteht aus zwei Hauptteilen: der Routing-Metrik und dem Mechanismus zur Routenfindung. Diese Arbeit trägt zu beiden Teilen bei, indem sie im zweiten Beitrag eine Routing-Metrik, MIIS, und im dritten Beitrag reaktive und proaktive zen-

tralisierte Routenfindungsmechanismen vorschlägt.

Im zweiten Beitrag wird eine neuartige Routing-Metrik, MIIS (Metric for Interference Impact and SINR), vorgeschlagen. Interferenz ist ein wichtiger Parameter, der in der D2D-Kommunikation berücksichtigt werden muss. Daher werden in der vorgeschlagenen Routing-Metrik MIIS Interferenzen zusammen mit dem Signal-zu-Interferenz-plus-Rausch-Verhältnis (SINR) berücksichtigt. MIIS wählt Routen aus, die ein höheres SINR aufweisen, während gleichzeitig eine geringere Interferenz berücksichtigt wird. Die Leistung von MIIS wird in einem verteilten D2D-Netzwerk evaluiert, das im OMNeT++-Netzwerksimulator implementiert wurde. Verschiedene MIIS-Varianten werden mit zwei State-of-the-Art-Schemata in Bezug auf die durchschnittliche Hop-Zahl, den Routing-Overhead, die Paketverlustrate und die End-to-End-Verzögerung verglichen. Die Simulationsergebnisse zeigen, dass alle MIIS-Varianten die State-of-the-Art-Schemata unter verschiedenen Netzwerktopologien mit unterschiedlicher Knotenanzahl, Knotenmobilität und Verkehrslast übertreffen.

Im dritten Beitrag wird ein neuartiger Routenfindungsmechanismus für reaktives zentralisiertes Routing vorgeschlagen, der den Vorteil des Vorhandenseins von BS für die Einrichtung der D2D-Routen nutzt, wobei die Routenberechnung und -entscheidung von der BS für eine bestimmte Zelle übernommen wird. Die BS trifft Routenentscheidungen, indem sie die Informationen von allen Knoten sammelt und den Netzwerktopologiegraphen konstruiert. Das reaktive zentralisierte Routing wird auch zum proaktiven zentralisierten Routing erweitert. Beide zentralisierten Routing-Schemata (d. h. reaktiv und proaktiv) reduzieren den Routing-Overhead im Vergleich zu verteilten Routing-Schemata erheblich, indem sie das Flooding von Routenanfragen vermeiden. Die Leistung von reaktivem und proaktivem zentralisiertem Routing wurde durch Simulationen unter Verwendung von MIIS evaluiert und mit bestehenden Schemata in Bezug auf unterschiedliche Knotenanzahl, Knotenmobilität und Verkehrslast verglichen. Die zentralisierten Routing-Schemata erreichen einen wesentlich geringeren Routing-Overhead, eine geringere Paketverlustquote und eine geringere Ende-zu-Ende-Verzögerung.

Contents

Chapter 1

Introduction

A cellular network establishes direct single-hop communication between the user nodes and a base station (BS). This direct connection provides the best services for delay-sensitive communications, but suffers from high data traffic load due to the limited amount of available spectrum resources [KH12]. The increase in the network capacity requirements due to the high data traffic load results in a reduction of the overall network coverage. One way to handle this issue is to increase the number of BSs which is very expensive [Ima+06]. By using the low transmission power, two devices can reuse the spectrum band which might already been used by some other cellular device or D2D pair(s), by utilizing the concept of space division multiple access. Thus, the third Generation Partnership Project (3GPP) identifies device-to-device (D2D) communication as a potential candidate technology to handle the network capacity/coverage problem [YGW15].

3GPP Release 12 approved that two devices in close proximity to each other can communicate directly. This direct communication can be applied in every possible kind of network scenarios. For example, the devices can be both under the network coverage (in-coverage scenario), or one device can be outside the network coverage (partial-coverage scenario), or even both devices can be outside the network coverage (out-of-coverage scenario) [Thi14; Thi15]. This alleviates the problem of network capacity/coverage to some extent. Two hop communication is approved by 3GPP in Release 13-15, which further minimizes the network capacity/coverage problem [Thi18]. In Release 13, 14 and 15, to enable network services by a device which is out of network coverage, the device can use another nearby device as a relay which is within network coverage. It can be deduced from the proliferation of D2D communication that multi-hop communication will be a part of standard in the near future. The advantages of D2D communication can be fully realized in the multi-hop communication scenario since the single-hop communication is usually limited to a specific geographic area. This restriction is imposed (for a while) only to ensure minimum interference to other users in the network.

D2D communication can be used both for public safety and commercial purposes. Most of the works have focused on providing D2D communication in case of natural disasters when the cellular network services are either partially or fully unavailable, while very few works considered human-made disasters like fires, accidents, terrorist attacks etc. Tata and Kadoch [TK14a] highlight the fact that many firefighters die because they cannot get out of the fire spot. This is because they are unable to communicate due to network congestion caused by the peak usage of the network in the locality. Authors of [YGW14] point the attention towards the terrorist attacks. Most of the terrorist attacks are targeted in urban areas in order to have higher impact and causalities. This leads to networks being overloaded or damaged. D2D communication provides an alternative communication in case of such network congestion or network unavailability. Due to the low costs and high data rates provided by LTE D2D, Federal Communications Commission (FCC) has endorsed it as the next generation public safety network in the USA [Lie+16].

In D2D communication, the users communicate with each other in an ad hoc manner using single-hop or multi-hop. This communication can happen both with and without the support of the cellular network infrastructure. According to different studies, reduced delay and energy consumption in the single-hop communication and improved network coverage in the multi-hop communication have been promised by D2D communications. Other performance improvements in both single-hop and multi-hop D2D communications include higher data rate, Quality of Service (QoS), spectrum efficiency, network capacity and availability of service and more balanced network load. Since multi-hop D2D communication requires intermediate devices to relay the data, therefore to motivate devices to assist in relaying data, a number of incentive mechanisms are proposed. Such performance improvements and incentives are discussed in Sections 2.6 and 2.7 in detail.

A number of works advocate the usefulness of multi-hop D2D communications in various network conditions/scenarios [NSV17; BYG15; MNB16; Qin+16]. For example, the work in [NSV17] proposed a Multi-hop D2D-based Broadcast (MDB) service to enable broadcast in a target area without having limitation of any cell boundaries. Multi-hop communication supports the services to scale to a large geographical area while keeping the advantages of D2D communication. The authors argue that the existing broadcast communication channel i.e. Multicast Broadcast Single Frequency Network (MBSFN) in LTE for delivering the services like mobile TV, is inflexible due to some circumstances. For example, the broadcast message is sent to all users in a cell and cannot be geofenced to some specific area. Moreover, the MBSFN consumes the capacity in downlink channel, even if there are no transmission requirements at all.

The integration of cellular and multi-hop network provides not only guaranteed QoS and reliability like a traditional cellular network, but also has the flexibility and adaptability like a multi-hop network [Li+13]. Routing in such multi-hop cellular D2D networks is a critical issue, since the multi-hop network can perform even worse than traditional cellular network if wrong routing decisions are made [TS08]. This is because, routing in these multi-hop networks need to take care of the node mobility, dynamic network topology, and network fragmentation, which did not exist in traditional cellular networking. An efficient routing scheme provides an enhanced performance, such as higher network capacity and reduces interference [SS04]. The detailed discussion on the performance improvements promised by routing protocols for multi-hop D2D networks, is provided in next chapter's sections (see Section 3.1, 3.2 and 3.3).

With the introduction of multi-hop communications, users can communicate in one of the four modes: (i) single-hop D2D communication (ii) multi-hop D2D communication (iii) multi-hop Device-to-Infrastructure (D2I)/Infrastructure-to-Device (I2D) communication, and (iv) traditional cellular communication. A pictorial view of multi-hop D2D, D2I and I2D communication is shown in Fig. 1.1.

There are three broad categories of D2D routing: multi-hop D2I/I2D routing, multi-hop D2D routing and ad-hoc routing for D2D networks. In multi-hop D2I/I2D routing, the communication is always governed by BS. In multi-hop D2D routing, communication could or could not be governed by BS. When communication is not under the control/supervision of BS, the routing behaves exactly as an ad-hoc routing and any ad-hoc routing protocol can be used with or without modification, depending upon the requirements. The only difference between ad-hoc routing and unsupervised D2D routing is in the usage of spectrum frequency bands. D2D nodes can use both the licensed and/or the unlicensed bands while ad-hoc nodes can only use unlicensed bands. When communication is governed by BS or when D2D communication takes into consideration the presence of BS and other cellular nodes in the network, such routing is considered purely as the multi-hop D2D routing. Taxonomy and state-of-the-art routing algorithms proposed for multi-hop D2D, D2I/I2D and ad-hoc routing for D2D networks

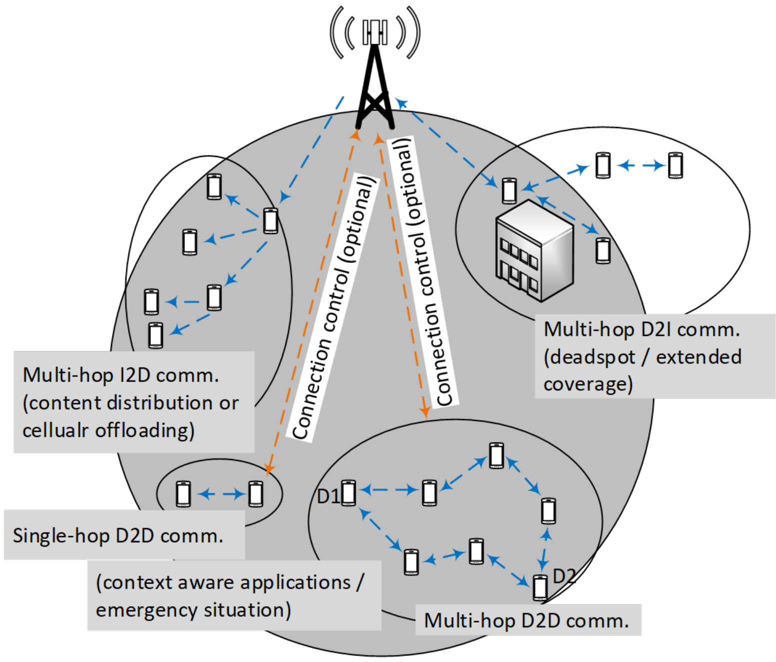


Figure 1.1: Modes of multi-hop D2D communication.

are discussed in Section 3.1, 3.2 and 3.3, respectively.

1.1 Problem Statement

In order to understand the importance of the need of having new routing protocols to meet the unique characteristics of D2D communications, we provide an evolution of the routing protocols from wired networks to multi-hop cellular D2D networks as follows. The routing protocols have been first devised for wired networks in order to establish communication among nodes which are not directly connected to each other with the same physical medium. The distance vector routing (DVR) and link state routing (LSR) have been proposed as the main routing approaches in this context. In DVR, nodes share their distance vector information with neighbors to maintain next hop-node for each destination. The DVR suffers from slow convergence and routing-loops problem, which limits its applicability to a small area. In LSR, each node floods in the whole network, the complete status of its directly connected links. In this way, by knowing the link state information of all nodes, each node can draw a complete network topology graph for routing decisions [Cha15].

The emergence of the Internet necessitates the optimization of routing, hierarchical routing is proposed to make routing decision based on network addresses instead of host addresses. The inter-domain routing is used to route packets between different networks and the intra-domain is used within a network to route packets to the required destination node.

The proliferation of wireless networks necessitate the need of new routing protocols due to the unreliable nature of the wireless links. The Destination-Sequenced Distance-Vector Routing (DSDV), Optimized Link State Routing (OLSR), Ad-hoc On-Demand Distance Vector (AODV) and Dynamic Source Routing (DSR) are some well known routing protocols proposed for wireless networks, which are derived from routing protocols for wired network, i.e., DVR and LSR. The DSDV is a proactive routing protocol that periodically maintains a route to every other node in the network, while avoiding routing loops at the same time. The AODV is a reactive routing protocol that finds the route only when required. For some special types of networks, such as wireless sensor networks, where nodes gather information and send to a centralized node called sink node, cluster-based routing has been proposed for such data gathering. The nodes are organized into groups in order to forward consolidated data to the sink node [Cha15].

Firstly, all these routing protocols do not take interference into consideration under channel reuse in underlay mode, while interference consideration is of paramount importance in D2D communication. Secondly, all these routing protocols are distributed in nature, where all nodes take the route decision autonomously using local and/or global information. There is no routing protocol that takes the benefit of the presence of centralized control entity (e.g., BS) for centralized route decisions. The development of D2D technology, with its promising performance improvements, necessitates the need of new routing metric that can take interference into consideration under channel reuse, as well as new routing protocols that can take advantage of BS for making route decisions.

This thesis aims to bridge this gap by proposing a novel routing metric and a novel route discovery mechanism. The proposed novel routing metric, MIIS selects routes with higher SINR while being conscious about lower interference, operating in underlay mode. The proposed novel centralized route discovery mechanisms, reactive centralized routing and its extension to proactive centralized routing, take the advantage of the presence of BS for establishing the D2D routes in which the route calculation and decision are taken by the BS for a given cell.

1.2 Contribution

The contribution of this dissertation is multi-fold, which is discussed as follows:

- A discussion of various implementations, performance improvements and incentive mechanisms to support D2D communications is provided. Moreover, in-depth survey of all state-of-the-art D2D, D2I/I2D and ad-hoc routing schemes for D2D networks along-with their taxonomy is provided. A clear differentiation between multi-hop D2D, D2I/I2D and ad-hoc routing for D2D networks is provided. A comparative analysis of routing schemes is also made using various metrics, such as the type of relay and the type of spectrum used.

- A novel routing metric, MIIS (Metric for Interference impact and SINR), is proposed that selects routes with higher SINR while being conscious about lower interference. A route decision formula is also proposed that not only avoids the routes having the lowest bottleneck MIIS values but also maintains the lower hop count value.

- A novel route discovery mechanism, reactive centralized routing, is proposed that takes the advantage of the presence of BS for establishing the D2D routes in which the route calculation and decision are taken by the BS for a given cell. The reactive centralized routing is also extended to proactive centralized routing. Both centralized routing schemes (i.e., reactive and proactive) reduce the routing overhead as compared to distributed routing schemes to a dramatic level by avoiding the flooding of route requests.

1.3 Publication List

- Farrukh Salim Shaikh and Roland Wismüller. "Routing in Multi-hop Cellular Device-to-Device (D2D) Networks: A Survey". In: *IEEE Communications Surveys & Tutorials* 20.4 (2018), pp. 2622-2657.

- Farrukh Salim Shaikh and Roland Wismüller. "Interference-Conscious Routing in Multihop D2D Communications". In: *2nd International Conference on Computer and Communication Systems (ICCCS).* 2017, pp. 146-151.

- Farrukh Salim Shaikh and Roland Wismüller. "Centralized Adaptive Routing in Multihop Cellular D2D Communications". In: *2nd International Conference on*

Computer and Communication Systems (ICCCS). 2017, pp. 158-162.

1.4 Outline of the Thesis

The dissertation is organized as follows.

- **Chapter 2** builds an understanding of D2D communications and highlights its importance and necessity in cellular communication by providing detailed discussion on D2D performance improvements, incentives and implementation scenarios. It covers the topics that were not well classified in D2D communications like various technologies that resembles D2D communications.

- **Chapter 3** reveals that all state-of-the-art routing algorithms relates to one of the three D2D categories. The chapter then provides an extensive in-depth survey of state-of-the-art routing algorithms and classify them based on their objectives and requirements. A routing scheme consists of two main parts, i) routing metric and ii) route discovery mechanism. This thesis contributes in both parts.

- **Chapter 4** presents a novel routing metric, MIIS that selects routes with higher SINR and lower interference. It also presents a route decision formula with an illustrative example that not only avoids the routes having the lowest bottleneck MIIS values but also maintains the lower hop count value.

- **Chapter 5** presents a novel route discovery mechanism that takes the advantage of the presence of BS for establishing the D2D routes in which the route calculation and decision are taken by the BS for a given cell. It presents the algorithms and examples for the operation of proposed centralized routing schemes.

- **Chapter 6** finally concludes the dissertation and presents some future research directions.

The relation of our publications with this dissertation is as follows. Most of the contents in Chapters 2, 3 and some future research directions in Chapter 6 have been published in the paper "Routing in Multi-hop Cellular Device-to-Device (D2D) Networks: A Survey". The proposed routing metric in Chapter 4 has been published in the paper "Interference-Conscious Routing in Multihop D2D Communications" and route discovery mechanism in Chapter 5 has been published in the paper "Centralized Adaptive Routing in Multihop Cellular D2D Communications".

Chapter 2

Overview on D2D Communications

This chapter provides detailed overview on D2D communications in many perspectives. The first section discusses various technologies which resembles with D2D communications. The D2D communications has been categorized based on three characteristics which is discussed in section 2.3. Implementation scenarios and the unique challenges in D2D communications are presented in sections 2.4 and 2.5. Finally, section 2.6 discusses single and/or multi-hop network performance improvements and the incentives to users by using D2D communications.

2.1 History

The idea of D2D communication dates back to nearly four decades, when opportunity driven multiple access (ODMA) was first proposed for extending the network coverage. Different techniques with their specific names have been proposed so far, for the direct (single and multi-hop) communication of cellular users under various network scenarios [Cav+05]. All the techniques have been seamlessly integrated into D2D communications. A brief description about all such popular techniques is provided below:

ODMA

The initial idea of extending the coverage area of the network to more than one hop, named as opportunity driven multiple access (ODMA) is first proposed by South African scientists in 1978 [Inc]. The idea was then discussed by the 3GPP standardization committee in 1999 [Thi99].

MCN

In multi-hop cellular network (MCN), cellular users not only forward the data of BSs as in ODMA, but also forward data of other nodes for inter-device communications [LH00].

IMCDN

In integrated multi-hop cellular data network (IMCDN), large number of fixed relay nodes are intelligently placed to efficiently deliver data from cellular users to the BS, regardless of the cellular user positions. The relay node is named as routing node (RN) and cellular user node is named as mobile data terminal (MDT) in the original text. The objective is to efficiently balance the load among the BSs, instead of power saving or high mobility support (as are the objectives in mobile ad hoc networks (MANETs)). Mobile switching centre (MSC) acts as central controller. All link layer and network layer decisions are made at the MSC. This reduces the topology management tasks from the BSs and RNs, which helps in making the network simpler, power efficient and cost effective. The upstream packets are always destined at BS and the downstream packets are always originated from BS [LL03; LL06].

ICN

In integrated cellular networks (ICNs), operator installed fixed relay nodes and/or cellular users are used to forward the data of heavy loaded BS to another less loaded BS. When there is a high traffic load and BSs have no additional cellular resources to fulfill new resource requests, BS finds a multi-hop route to a less loaded BS in case of a new resource request from a node. The fixed relay node is named as traffic diversion station (TDS) and cellular user node is named as mobile host (MH) in the original text.

Throughout this chapter, we use the same naming notations as used in the original research papers, however, it is important to remember that all the proposed schemes under different naming conventions can be directly used with D2D communications.

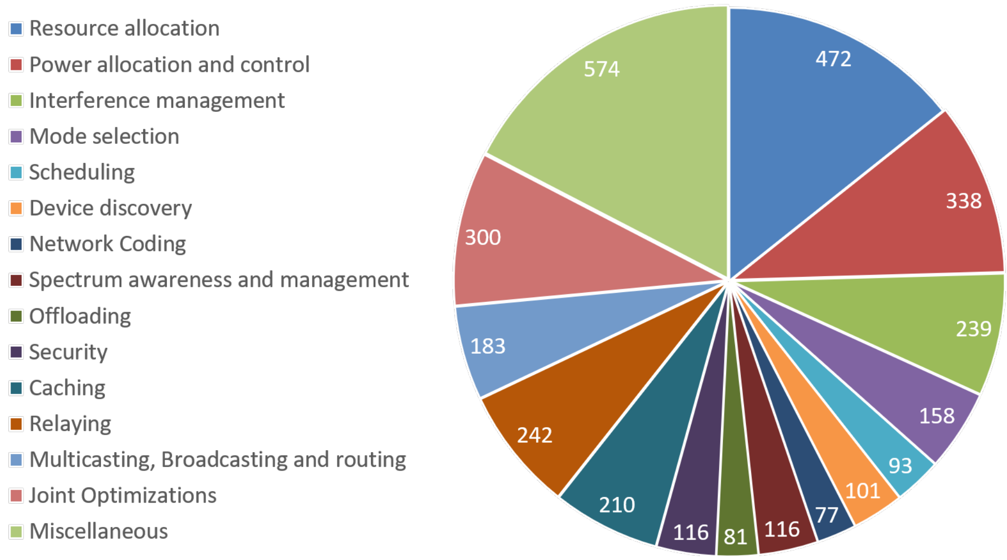


Figure 2.1: Number of publications in various D2D domains.

2.2 A glimpse on various D2D domains

A number of survey/review papers have been published to discuss the basics of D2D communications, and to discuss various other D2D research domains. Table 2.1 to 2.6 demonstrate the efforts of most of the existing survey papers related to D2D. In addition, a survey on the total number of approximate 3300 publications on D2D communications till November 8, 2019 has been carried out, and the approximate number of publications in various domains is shown in Fig. 2.1. To the best of our knowledge, there was no survey on routing in D2D networks. Thus, in the next Chapter, this thesis provides the first comprehensive survey which discuss the routing in multi-hop cellular D2D networks.

2.3 Classification of D2D communications

This section classifies D2D communications into three main characteristics, i.e., type of communication, number of hops and type of spectrum. These characteristics are further classified into sub-categories which are illustrated in Fig. 2.2 and discussed below.

2.3.1 Type of Communication

There can be two types of D2D communications, i.e., either supervised when under the control of the BS, or unsupervised when node is out of the coverage of the cellular

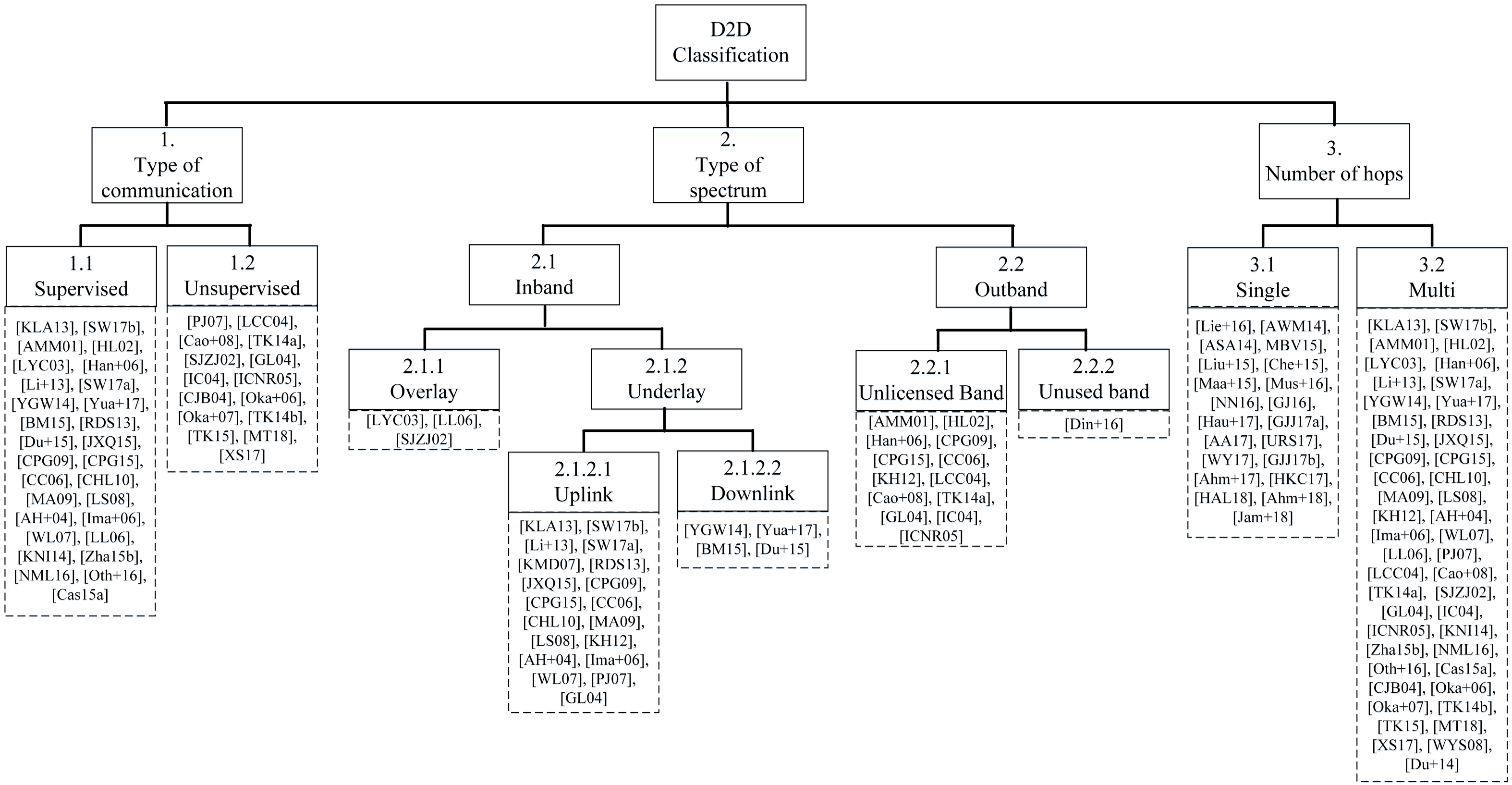


Figure 2.2: Classification of D2D communications.

network. Node under the coverage of the BS can also be tuned to work in unsupervised mode by not utilizing the services of the BS.

2.3.1.1 Supervised communication

In supervised communication, the BS controls the communication, and guarantees performance and security by complete control over the control plane and the data plane [MCC14], [TUY14]. In control plane, BS authenticates the devices and set appropriate encryption for privacy. Connection establishment and maintenance is also the responsibility of BS. Due to global network knowledge, issues in unsupervised (ad hoc) communication like synchronization, collision avoidance and free spectrum detection can be easily handled by the BS at the control plane. In data plane, resource allocation or spectrum management by the BS ensures that UEs do not have the burden of handover in case of information brokerage. Mobility management is also the responsibility of BS at the data plane. All these services are not possible in infrastructure-less (or purely ad-hoc) networks like WiFi Direct or Bluetooth. Additionally, large scale network communications is also not suitable for the infrastructure-less networks.

There are two types of supervised communication: network-based communication and network-assisted communication. In network-based communication, all the devices are under the full control of network. In network-assisted communication, devices can take decisions autonomously, however their decisions are based on the measurements provided by the network.

2.3.1.2 Unsupervised communication

Currently unsupervised communication is allowed to D2D devices only when infrastructure network is unavailable. In unsupervised mode, the network is stand-alone and works exactly like ad-hoc networks. Such network does not need any expensive infrastructure for communications. Moreover, the network is also quite flexible, and does not have any restrictions due to unavailability of any centralized management and control. For example, in ad-hoc network, where all nodes works autonomously, failure of any node have negligible effect on the overall network performance while in infrastructure based network, failure of a central processing node, results in total network failure. Similarly, in case of overload on the nodes in ad-hoc network, the network performance is slightly degraded, however overload on the central node in the infrastructure-based network results in significant service degradation and limited service availability.

2.3.2 Type of spectrum

D2D devices can communicate in either of the two types of spectrum i.e. inband or outband. These types of spectrum are discussed in detail below. The type of spectrum used in state-of-the-art topology based routing algorithms is listed in Table 3.5.

2.3.2.1 Inband

In inband communication, devices use available cellular channels opportunistically. The use of same spectrum enforce easier cooperation among D2D and cellular networks. BSs have higher control over the interference between the coexisting D2D and cellular networks, thus QoS can be guaranteed. The same cellular interface is utilized for D2D communications, so every device can use inband spectrum. There are two techniques to use the inband communications: overlay and underlay.

Overlay In this technique, spectrum resources are dedicated for D2D communications and separate spectrum are scheduled for both the cellular and the D2D networks. This ensures no interference with cellular devices. If many D2D communications opportunities are possible, the same spectrum can be reused spatially within D2D communications.

Underlay In this technique, spectrum resources are reused for D2D communications opportunistically. This increases spectral efficiency by exploiting the spatial diversity. However, interference mitigation involves detailed investigations both at the BS and the D2D UEs. Underlay has two types of spectrum: uplink and downlink. In frequency division duplex (FDD) mode, the reuse of downlink and uplink spectrum needs different considerations.

Downlink The reuse of downlink spectrum has very stringent requirements because the D2D UEs might severely interfere the cellular UEs which is not tolerable. On the other hand, D2D UEs also receive severe interference from the BS due to the high transmission power of BS. Therefore, this D2D communication is usually possible near the cell edges. D2D UEs are also affected by the interference from other D2D UEs of the same cell, and from the BS and D2D UEs of other cells.

Uplink In this type of communication, D2D UEs get most harmful interference from the cellular UE (CUE). D2D UEs are also affected by the interference from other

D2D UEs of the same cell, and from the CUEs and D2D UEs of other cells. Conversely BS is interfered by all D2D UEs of same and other cells. However BSs are very powerful and can handle interference efficiently. The use of uplink in D2D communication is the most widely used technique in the literature due to its numerous advantages. This is preferred to use for D2D communications because:

- D2D UEs have reduce impact on BS and thus interference tolerance is acceptable to some extent.
- The uplink band is underutilized and thus have more free resources.
- UEs radio interface is by-default designed to send data in Uplink [Lin+14]. Thus it would be complex if UEs had to send data in downlink band which requires OFDMA transmitter. Moreover, SC-FDMA transmitter enjoy low peak-to-average power ratio (PAPR).
- 3GPP also recommends to use uplink band for D2D communications [Thi14].

However, there are few constraints in SC-FDMA (uplink band). The resource blocks (RBs) in frequency domain should be contiguous and must use the same modulation scheme [JL13]. Morever, the SC-FDMA receiver is also complex because of single carrier transmission.

2.3.2.2 Outband

In outband communication, devices use unlicensed spectrum instead of cellular spectrum. Outband communication has several advantages in D2D communications which are summarized below:

- Precious cellular resources are preserved.
- No interference with the cellular resources.
- Simultaneous D2D and cellular communication is possible.
- No considerations of frequency, time and power are required while scheduling outband communication.

However, on the contrary, outband communication has some limitations as well which are summarized below.

- It consumes double power consumption due to using two interfaces. Thus, special techniques are required to minimize the power consumption.
- The second radio interface needs to be coordinated which needs investigation of inter-technology architectural designs.
- It causes some delay due to increased processing because protocols are not same and thus packets are decoded and encoded again. However, we assume processing delay is very small as compared to communication delay in inband communication.

Outband communication would be carried out either on license free band that is Industrial, Scientific and Medical (ISM) band or an opportunistic reuse of licensed bands, as permitted by FCC.

Unlicensed Due to the free license spectrum, a number of works use wireless LAN spectrum for direct communication among the users. The unlicensed spectrum is usually used for D2D communications in networks having low number of nodes. This is because in case of high node density, the cross-interference with other outband users is uncontrollable and hence QoS provisioning could not be guaranteed.

Unused It is permitted by the FCC to use the licensed channels (usually the TV white spaces) opportunistically provided that it does not interfere with the licensed users (called primary users) holding the license for certain time and frequency. Normally in BS-assisted D2D communication for the open access of TV white space, BS senses the available unused licensed spectrum in the cell using efficient spectrum sensing techniques. Subsequently, the unused available channels can be advised to the D2D UEs to be used for D2D communications [Din+16].

2.3.3 Number of hops

A communication can either be single-hop or multi-hop. In single-hop communication, two devices are in the proximity of each other and directly communicate without needing any relay. In multi-hop communication, a device which want to communicate with another device or BS is not in the proximity of destination node, therefore it needs atleast one intermediate node to assist it in relaying its data to another device or BS. As discussed in Subsections 2.6.1 to 2.6.3, single-hop and multi-hop have their own pros and cons. The advantages of single-hop communication is reduced delay and increased energy efficient. However, it is not also possible to have single-hop communication when the devices which want to communicate are not in the proximity of each other. The main advantage of multi-hop communication is increased network coverage. However, it incurs additional delay due to higher number of transmissions by relay nodes.

2.4 Implementation Scenarios for D2D communications

There are a number of use case scenarios where D2D communication is the best choice for implementation, however we discuss three major scenarios, which are provided below:

2.4.1 Natural disaster

Different types of natural disasters have been listed in order of the magnitude of fatality in [Adi15]. A smartphone disaster recovery system (SDRS) protocol [Adi15] is proposed to communicate with the BS, or otherwise establish D2D communication (using LTE-Direct) in case of natural disasters. An emergency communication protocol for D2D communications has been proposed in [Gom+14] which establishes a cluster like network topology of D2D users. A node called as chief D2D node (usually the first node in the network) is responsible for creating and maintaining the D2D network. However, the high energy consumption of the chief node in maintaining the topology has not been considered. Multi-hop D2D communication for extending the network coverage has been proposed in [AHKJ16]. Study has shown that the network-level success probability increases with the increase in the number of relays against the varying values of the damage ratio caused by the natural disaster.

A survey on disaster response network for cognitive radio (CR) [Gha+14] provides many new ideas that the D2D communication networks can use to get benefit from. A few of them are discussed below:

2.4.1.1 Immediate services

A number of disaster response network (DRN) solutions exist, provided by various disaster response organizations. Such organizations are generally telecommunication operators, telecommunication equipment vendors, government and non-government organizations (NGOs). These organizations aim to enhance resilience against natural and man-made disasters, usually provide communication services within 24 hours to affected areas in the immediate aftermath of a disaster. Any delay in the response to the disaster may result in further loss of life, injury and damage. AT&T's national disaster recovery (NDR) program provides LAN, WiFi and voice (VoIP) connectivity within minutes of arrival with dedicated generators. This connectivity is possible via solution called emergency communication vehicles (ECVs) that uses satellite links. However the arrival of relief personnel / disaster response organizations at the affected areas always incur delay, and thus no connectivity is possible before that time. Furthermore, the deployment might incur additional delays due to the lack of network damages information, prior government and mobile operator agreement for spectrum utilization and custom clearance. Thus these external solutions fail to provide an immediate first-aid recovery to the affected areas.

Local personnel who are less affected by disaster can immediately start the first-aid relief operations for the affected persons using D2D communication. These persons benefiting from the auto-configuring capability of D2D devices can search the affected persons by discovering the proximate D2D devices. They can also check and communicate with their close relatives and other personnel by utilizing the multi-hop communicating capability of D2D devices. D2D devices can also communicate multi-hop to any of the nearby base stations or relief-centers.

2.4.1.2 Wide area coverage

National disasters usually spans wide geographical regions. For example Hurricane Katrina affects 230,000 sq.km area in the US in 2005. The relief personnel require wide area connectivity to coordinate relief services. The network coverage provided by all the available DRN solutions is limited. Due to the damaged civil infrastructure, it might take several days to provide relief in all affected areas. D2D network provides the best connectivity solution in disaster response network when the cellular coverage is partially unavailable or when the cell coverage does not provide connectivity over the complete emergency area. We are considering the case when only a limited amount of cellular sites are functional following the disaster event. A D2D network acts as a glue to repair a damaged cellular network by providing extended coverage. Such network could also replace damaged cellular sites in terms of proximity communications. Highly-flexible D2D devices can provide multiple services reusing the same cellular spectrum.

As DRNs often provide limited connectivity in some target areas, forming sparse networks. Thus, the incorporation of D2D devices with multi-hop support provides extended coverage with high bandwidth efficiency. This involves challenges like next hop selection, channel selection, end-to-end delay, mobility of users and interference avoidance.

2.4.1.3 Cost-effectiveness

The services provided rapidly following the disaster event are generally very expensive. Almost all solutions use cost-effective satellite backhaul system to provide connectivity. These services are usually replaced by less-expensive solutions in the later weeks once the situation is under control. Thus the overall deployment of all such solutions incurs high costs.

D2D network can be deployed without any extra cost. The normal smartphones of users are used as D2D end-devices to communicate directly with other D2D devices and to provide the services of a relay.

2.4.1.4 Self-Organization

It is worth noting that most DRN solutions lacks the capability of self-organization. The operating environment in the disaster area is unpredictable due to dynamicity in user demands, network topology and spectrum availability.

D2D communication provides flexible reconfigurations by observing the operating environments. Such operating information can be accumulated through local sensing, individually and by cooperation among neighbor devices. Thus, local sensing is expected to play a vital role. D2D devices can then select appropriate strategies to achieve specific goals. These self-organizing capabilities are especially valued in the context of DRN, where immediate communication is required with little or no information about the operating environment and which may change unpredictably. Auto-configuration capability of D2D devices helps in quick adaption to the changes in operating environment. This also helps in minimizing time consumption in the initial configurations.

2.4.2 Public safety

D2D communication has mainly emerged to offload the high data traffic from the cellular network, and to provide pubic safety communication services in case of natural or man-made disaster. Most of the works have focused on providing D2D communications in case of natural disasters when the cellular network services are either partially or totally unavailable [BYG15; MSS15; TK15; MMH15; MGC14; Li+15; Fod+14; AHK13; Gor+14; YK12; Yaa14; Gor+13; SKJ16; One+13; Hun+13; MAD13]. Very few works considered human-made disasters like fires [Cas+15b; TK14a], accidents, terrorist attacks [YGW14] etc. Tata and Kadoch [TK14a] highlight the fact that many firefighters die because they cannot get out of the fire spot. This is because they are unable to communicate due to network congestion caused by the peak usage of the network in the locality. Castel et al. [Cas+15b] analyze the LTE-D2D as a potential candidate standard for communication between the indoor body-to-body link (by considering firefighters as an example). Yuan et al. [YGW14] point our attention towards the terrorist attacks. Most of the terrorist attacks are targeted in urban areas in order to have higher impact and causalities. This leads the networks to be overloaded or damaged. D2D communication provides an alternative communication in case of such network congestion or network unavailability.

2.4.3 Expected and unexpected events and crowds

D2D technology is able to fulfill the communication needs in case of both the ‘expected’ (planned) and the ‘unexpected’ events and large crowds. The planned events could be pre-organized seminars, conferences, social or personal parties, parades, road skating or other sport events in stadiums, where the time and the crowd volume could be pre-estimated. Public speech or huge sales event are also planed events, however it is hard to estimate the exact number of people in such events. The unexpected events could be traffic jam or rally, where both the duration and the number of people involved are hard to predict. Thus, D2D is a quite flexible technology that can survive and provide communication services for all types of planned (normal) and the unplanned (emergency) events and crowds.

The above adaptability of D2D in such diverse scenarios is one of the very big advantage to the telecommunication operators. For providing better services, operators need to investigate the network requirements like number of users and user mobility of each location independently. For example Train/Bus stations have higher number of users and high user mobility, while academic institutions or offices have also high number of users but comparatively low mobility. Shopping markets have high user mobility but varying number of users in various times, and residential areas have low number of users and low mobility. Thus, by using D2D communication technique, network operators may alleviate some of the burden of detailed network planning due to the D2D ability to provide communication services in any kind of network requirements.

2.5 Unique Challenges

D2D communications is still in its infancy. A number of open issues and problems are there which need serious attentions. This section discusses such challenges.

Inter-operator or Multi-operator D2D operation

Without inter-operator support, the applicability of D2D communications is very limited. In multi-operator D2D operation; which spectrum to use and how to coordinate and control UEs operations are key issues to solve.

Co-existence and interference management

Interference management between the coexisting D2D networks and between D2D networks and cellular networks needs detailed investigations. Furthermore, resource allocations for D2D network within a single cell or across multi cells also needs serious attention. Although massive amount of research on this issue has already been performed, however this issue needs further considerations.

Mobility management

In case of mobility, new D2D handover criterion in addition to traditional handover is required. D2D-aware handover and D2D-triggered handover are some initial solutions in this domain which also needs investigation.

Dual mobility

In traditional cellular communications, one communicating entity that is the BS is always fixed and the other communicating entity that is the UE is mobile. However, in D2D communications, both communicating entities are the UEs and thus both are mobile. This affects both shadowing and fast fading (increased Doppler effect). Thus mobility is more difficult to manage in small coverage scenarios than with respect to their respective large coverage areas of the BS [Lin+14].

Extent of transfer of control from Network operators to Users

Transferring the network control to users is a big topic of discussion by the telecommunication operators. Since losing control over the users is never the desire of telecommunication operators. Thus further studies are required to investigate optimal solutions for splitting the control functionality between the network and the UE [Lin+14].

Impact on WAN as a whole

Mostly, all cellular technologies are designed to optimized eNB (evolved Node B) - UE links. However finding the impact of these techniques on WAN also need considerations [Lin+14].

Impact in Complex Heterogeneous Networks

In the presence of macro cell, micro cells, home cells and fixed relays, the impact of the wide deployment of D2D communications also needs further considerations [AWM14].

2.6 Performance improvements using D2D communications

In traditional cellular communication systems, it is hard to fulfill all the inter-dependent network performance metrics requirements. For example, in interference-limited systems, the coverage of the cell decreases with the increase in the number of users. Thus, there is always a trade-off between the capacity and cell coverage. With the introduction of D2D communication, drastic performance gains are achieved in various network metric and there is no longer a strict trade-off between most of the network requirements. Three types of gains are promised by D2D communications [Fod+12] which are proximity gain, hop gain and reuse gain. The proximity gain assures high data rates, low energy consumption and delay by taking advantage of the proximity of the other device. The reuse gain indicates the reuse of cellular spectrum for D2D communications. The hop gain is achieved by using a single-hop for D2D communications instead of two-hops, an uplink and a downlink resource in cellular mode. This allows the flexibility to use any available channel (i.e., uplink or downlink) for D2D communication. We now discuss the performance improvements that could be achieved in both the single-hop and multi-hop D2D communications.

2.6.1 Single-hop Performance Improvements

When two devices directly communicate with each other (i.e., single-hop communication), the two performance improvements that can be achieved are reduced delay and increased energy efficiency.

2.6.1.1 Reduced delay

Direct single-hop link between the two devices in D2D communication ensures reduced delay as compared to the minimum two-hop link in traditional cellular network.

2.6.1.2 Increased energy efficiency

Instead of using higher power by each device to communicate with BS in traditional cellular communication, D2D devices use lower power due to smaller distance between each other in D2D communications which increases the energy efficiency of D2D devices.

2.6.2 Multi-hop Performance Improvements

When two D2D devices want to communicate are not in the vicinity of each other, other D2D devices are used as relays, which makes a multi-hop communication between the two D2D devices. The performance improvement achieved in multi-hop communication is increased coverage.

2.6.2.1 Increased coverage

In multi-hop D2D communication, D2D devices which are out of the coverage or in the dead spot regions could use other D2D devices as relays to communicate with the infrastructure network or to communicate with other end-users, resulting in overall network expansion and increased network coverage.

2.6.3 Single and Multi-hop Performance Improvements

In addition to the above performance improvements which are applicable either only to single-hop or multi-hop. There are many other benefits which are applicable to any kind of network either established using single-hop or multi-hop D2D communications, which are discussed below:

2.6.3.1 Quality of Service

Devices in the proximity of each other, notice high signal to interference and noise ratio (SINR) as compared to the traditional links with the cellular network. However, the devices must use an efficient interference mitigation scheme in order to be aware of and mitigate the interference [MNB16]. Field tests [CPG11] also demonstrated the improved end user QoS in the cell-overlaid and in the handover areas.

2.6.3.2 Data rate

Devices in close proximity can use higher order modulation and coding schemes which leads to sufficiently high data rates [Lie+16], [Qin+16].

2.6.3.3 Spectrum Efficiency

The hop gain immediately doubles the spectrum usage because of saving one spectrum resource in each D2D communications. The reuse gain further improves the spectrum efficiency by the effective use of scarce cellular spectrum. Multiple D2D links can again reuse the same spectrum by exploiting the spatial diversity. For multi-hop D2D communication, Babub et. al [BYG15] have verified through results that the spectral efficiency increases with the increase in number of hops (upto four hops considered in simulation).

2.6.3.4 Network Capacity

Network capacity refers to the number of users (or specifically the amount of traffic) the network can handle simultaneously. As we know that Capacity = Bandwidth $\times$ Spectral Efficiency; and we also know that maximum bandwidth is usually given/fixed for a network, therefore the increase in the spectral efficiency results in the overall increase in the network capacity. It also increases the overall system capacity by bypassing blocked base stations [GL04].

2.6.3.5 Network Load

D2D communication always reduces the load on the network. This not only offload the traffic from the BSs but also offload the backhaul and the wide area network, which further results in cost efficiency [Tul+14].

2.6.3.6 Availability of Service

In case of no/partial network service, D2D communication serves as a fall back solution which enable devices to communicate directly or via relay(s).

2.7 Incentives of relaying data

D2D communication is advantageous for both the operators as well as the users. It gives incentives to users for relaying the data of other users and is beneficial for network operators in terms of network performance enhancements.

To motivate the users to assist in relaying data of the BS and other users, various kinds of incentives are provided by the BS and the users. The network relays are those users which relay data for the BS, and D2D relays are those users which relay data for other users. A number of incentive mechanisms have been proposed in literature [LG15; Zha+15a; MPL15; Tia+16].

2.7.0.1 Incentives provided by BS to network relays

In compensation of the consumed resources of the user offering the services as relay, following benefits could be provided by the BS to users involved in relaying data.

2.7.0.2 Monetary incentives

Financial benefits like extra balance, discount on monthly bills, or some cash prizes could be rewarded to the users involved in relaying the data of BS.

2.7.0.3 Service incentives

Package promotions, increased bandwidth and/or bonus minutes or SMSs can be rewarded.

2.7.0.4 Incentives provided by other D2D users

If a user is outside the coverage of the BS or is at some dead spot location, it can utilize the services of other users, either to connect to the infrastructure network (i.e., BS), or to connect with other users in a multi-hop manner. A number of research works focusing on incentivizing the users to act as relay are present in literature. Some of the attractive incentives are:

2.7.0.5 Direct bandwidth exchange

The user who uses the service of a relay node transfers the bandwidth (or could be amount) to the relay node immediately. The transferred bandwidth will be equal to the bandwidth that is consumed by relay node in servicing as relay plus extra bandwidth. This extra bandwidth is the reward of the resources (battery, processing, time and storage) consumed during relaying operations. However, if the relay node already has sufficient resources such that it does not need any reward immediately, then the immediate bandwidth exchange will not be useful here.

2.7.0.6 Social-tie based

A user can relay the data of other users within his/her social circles (e.g, friends, relatives etc.) to benefit them. There is no financial or service benefit for the relay node in this approach, rather it is based on social relations with each other.

2.7.0.7 Reputation based

In this approach, reputation level is maintained according to the participation in relaying service. Thus, for users having very low reputation of relaying, others might avoid providing relaying service. However, false reputation and selfish behavior of users are the main downsides of this approach. In false reputation, the users misrepresent their reputation level. This problem could be avoided in supervised communication where BS can track of the reputation of each user, while in unsupervised communication, the problem is not easy to be dealt with. In selfish behavior, a users calculates meetings with deviations for the user which has to provide relay service, and if the meetings are quite often, then provide the relay services. This is to ensure that the user also gets the same reward of service from the user currently providing the relay services. Such behavior creates uncertainty in relay services and therefore such devices are better to be off. Complete selfishness in which users demand some returns at the same instant does not create uncertain relay situations and therefore such devices are better than those discussed before.

2.7.0.8 Token-based

In this approach, tokens are used as virtual currency [Mas+13]. Tokens are required in order to use the relaying service of other users and tokens are transferred on getting service from other users. The tokens received by a user can be used later when a user requires relaying service from other users. Tokens are used only for D2D communications, they cannot be used as an alternate of the money. This necessitates either to buy tokens from the operator (operator benefit) or to earn tokens by servicing as a relay (motivates users to relay data). The price of token needs to be set such that it does not make burden to buyers, but it is still attractive for users to provide service for relaying data for getting the same tokens. Thus, the decision of using this approach depends on (a) service gains comparative to traditional communication by receiving data through a relay (from the perspective of service node) and (b) if the future benefits outweigh current resource costs it incurs for relaying data for others users (from the perspective of relay node). Results suggest that relaying cooperation is maximized when (a) the users have high relay energy budgets, (b) the users are highly mobile (e.g. on vehicles) and (c) there are moderate number of tokens.

2.8 Summary

This Chapter provided a review on D2D communications. The chapter started with the history of D2D communications, and reveal that the concept of D2D communications is not new and does exist with different naming conventions from several decades. The first idea was proposed with the name of ODMA (Opportunity Driven Multiple Access). The most popular and yet active technology that verily resembles D2D is MCN (Multi-hop Cellular Network). The Chapter then continued by providing a glimpse on surveys on different domains of D2D communications. A figure showing the total number of publications under various D2D topics is also presented to have a global view of D2D communications. The classification of D2D communications based on versatile characteristics is also the most important, to understand the variety of modes that D2D communication can work. Finally, the importance and necessity of D2D in cellular communication is provided, by detailed discussion on D2D performance improvements, incentives and implementation scenarios.

In the next chapter, we will survey all the existing routing algorithms that are proposed for or can be used for establishing multi-hop route in D2D communications. The routing algorithms have been broadly categorized into three categories. Each category has been sub-classified into different classes based on their objectives or network structure used. A detailed discussion on each routing algorithm have been provided with comparison based on various relay types and spectrum type used.

Table 2.1: Comparison of existing surveys/reviews in D2D communications.

Citation	Publication Year	Discussed Topics	Description
[AWM14]	2014	Generally discuss D2D communications	This is the first survey paper on D2D communications that provides detailed literature review based on inband (underlay and overlay) and outband spectrum band. Use-case, platform, performance metrics with achieved results, evaluating and analytical tools under each category is tabled and discussed.
[ASA14]	2014	Generally discuss D2D communications	A very short overview on challenges for interference mitigation using mode selection, resource allocation and power control for cooperative D2D communications.
[MBV15]	2015	Generally discuss D2D communications	The survey provides deep insight in various D2D research domains, which include but not limited to mode selection, interference management, power consumption and energy efficiency, relay functionality and 3GPP standardization activities.
[Liu+15]	2015	Generally discuss D2D communications	This paper surveys centralized and distributed interference management schemes for in-band and out-of-band D2D communications, and also tabled and discussed the existing radio resource management schemes. Prototypes and experiments for the implementation of D2D communications, 3GPP standardization and candidate radio technologies for D2D communications are also discussed.

Table 2.2: Comparison of existing surveys/reviews in D2D communications (contd...).

Citation	**Publication Year**	**Discussed Topics**	**Description**
[Che+15]	2015	Channel measurements and models in D2D communications	The paper provides the current state of the research on D2D channel measurements in various different scenarios like macro-cell/micro-cell outdoor-to-outdoor (O2O), outdoor-to-indoor (O2I), indoor-to-indoor (I2I) for urban, suburban, rural, office, shopping mall, and urban-road/highway vehicle-to-vehicle (V2V), and line-of-sight (LOS)/non-line-of-sight (NLOS) scenarios. The paper also surveys state-of-the-art research work on D2D channel models for various scenarios.
[Maa+15]	2015	Offload techniques in wireless access and core networks	In this paper, D2D is compared with RAN technologies like WiFi and small (femto) cell, in terms of various criteria like QoS, coverage and data rate etc. D2D is also compared in terms of strength and weakness with mobility and interworking protocols (like Mobile IP (MIP)/Proxy MIP (PMIP) used by Interworking WLAN (I-WLAN), and IP Flow Mobility (IFOM)) and with core network offload approaches (like Selective IP Traffic Offload (SIPTO) by implementing a Traffic Offload Function (TOF)).
[EZP15]	2015	Data offloading in heterogeneous access Networks	A brief overview on various offloading approaches in unlicensed band, licensed band and hybrid of both. D2D communications has been considered in the hybrid class in this paper.

Table 2.3: Comparison of existing surveys/reviews in D2D communications (contd...).

Citation	Publication Year	Discussed Topics	Description
[Mus+16]	2016	Separation framework for cooperative and D2D Communications	The control and data plane separation architecture (SARC) have been proposed as an enabler for coordinated multipoint (CoMP) and D2D communications in the context of 5G. Various SARC proposals have been discussed to alleviate the problems related to energy efficiency, mobility management, interference management and capacity maximization.
[NN16]	2016	Interference management in D2D communications	The paper provides detailed discussion about interference mitigation strategies in D2D communications based on two broad categories, co-tier (same tier i.e. between two D2D users) and cross-tier (different tier i.e. between D2D user and cellular user/BS) interference. Based on the quantitative comparison, and on the strength and weakness/limitations of the literature work, future research directions are also discussed in order to include D2D communications in 5G cellular networks.
[GJ16]	2016	Generally discuss D2D communications	The paper discusses in detail various features of 5G networks that can be integrated in D2D communications. Open challenges in D2D communications are also discussed at the end.
[Hau+17]	2017	Security in D2D communications	The paper classifies and provides detailed discussion on the security and privacy preserving approaches in D2D communications, along with their addressed attacks. Relationship in terms of contradicting and supporting requirements between security and privacy are also identified.

Table 2.4: Comparison of existing surveys/reviews in D2D communications (contd...).

Citation	Publication Year	Discussed Topics	Description
[Dou+17]	2017	Network coding in D2D communications	A new paradigm of network coding, instantly decodable network coding (IDNC) for D2D communications is surveyed in this paper. The paper first compares IDNC with random and opportunistic coding and then compares the types of IDNC schemes like strict, generalized and order-2 IDNC using various criteria. In the second part of this paper, the use of IDNC for centralized and distributed D2D communications is discussed in detail.
[GJJ17a]	2017	Security in D2D communications	The paper provides detailed overview on various challenges for D2D communications along-with the overview on security algorithms for D2D communications.
[AA17]	2017	Generally discuss D2D communications	A detailed literature review on centralized and distributed schemes for mode selection, interference and resource management, and power control for inband D2D communications has been provided.
[URS17]	2017	Generally discuss D2D communications	A very short overview on the classification of D2D communications based on control and frequency perspective. A brief view of D2D hypothesis and analysis techniques is also presented.
[WY17]	2017	Security in D2D communications	The paper compares the advantages and disadvantages of state-of-the-art security solutions proposed in literature, according to the security architecture and requirements.

Table 2.5: Comparison of existing surveys/reviews in D2D communications (contd...).

Citation	Publication Year	Discussed Topics	Description
[GJJ17b]	2017	Green communication in cellular networks	In addition to other aspects discussed in the perspective of green networking, D2D communication has also been considered a competent technology of 5G. A short review of some example works to enhance energy efficiency in mechanisms like mode selection, resource allocation and interference mitigation in D2D communications have been discussed.
[Ahm+17]	2017	Resource management in D2D communications	Resource management in D2D communications has been overviewed in terms of system performance objectives like throughput maximization, battery life etc. The different kinds of optimization problems (like mixed integer linear programming, stochastic programming etc.) and their solution types (like heuristic, evolutionary etc.) to optimize the D2D communication performance are also discussed.
[HKC17]	2017	Security in D2D communications	This paper identifies and categorizes security solutions using layer-based approach, in order to provide better understanding and design of D2D communications security.
[HAL18]	2018	Energy consumption models in D2D communications	This paper provides a brief overview and analysis on the power consumption models of the UEs and of the various types of BSs (maco, pico, femto etc.) in D2D networks. The analysis has been carried out using LTE and WiFi radio access technologies (RATs).

Table 2.6: Comparison of existing surveys/reviews in D2D communications (contd...).

Citation	Publication Year	Discussed Topics	Description
[Ahm+18]	2018	Socially-aware D2D communications	The paper first provides an overview on technical challenges and applications of D2D communications without taking into account any social connections. The paper then exploit the online and offline (neighbors, colleagues etc.) social connections while considering both the selfish and the selfless users behaviors, and discusses in detail the technical issues and application with social-awareness.
[Jam+18]	2018	Generally discuss D2D communications	A comprehensive survey which provides state-of-the-art and open research issues of challenges which include interference management, mode selection, power control, mobility management, device discovery, economic aspects, security/privacy, and the integration of D2D with 5G technologies.

Chapter 3

The State-of-the-art Routing Schemes for D2D Networks

The routing in D2D networks helps in establishing an efficient multi-hop communication route between the devices or user equipment (UE) where a single-hop direct connection is not possible. The classification of routing algorithms will help to select a routing algorithm based on varying user and network requirements. This thesis comprehensively discusses each routing scheme in order to have a clear understanding of the ongoing works. For convenience, some general acronyms and their definitions along with the acronyms of routing algorithms (topology based) used in this survey are listed in Table 3.1 and Table 3.2 respectively.

3.1 Multi-hop D2D Routing

The single-hop D2D communication limits the users to communicate with only nodes in the proximity. Therefore, if a user wants to communicate with another user out of its communication range, multi-hop D2D communication is the best choice. In multi-hop D2D routing, a route has been established between two nodes which are not in the proximity of each other. The route decision could be (a) centralized, where the route decision would be solely taken by a centralized entity (like BS, if both the end-nodes are under the coverage of the same BS), or (b) distributed, where the route decision could be taken autonomously by each node while taking into account the presence of other nodes (including the BS). Thus, the distributed routing does not face the problem of network failure due to a single processing element (i.e. BS) failure. Lastly, the route

Table 3.1: List of acronyms and their definitions.

Acronym	Definition
3GPP	Third Generation Partnership Project
ACK	ACKnowledgment
AODV	Adhoc On-demand Distance Vector
B-RREQ	Broadcast Route REQuest
BCH	Broadcast CHannel
CBR	Constant Bit Rate
CCH	Control CHannel
CoMP	Coordinated MultiPoint
CR	Cognitive Radio
D2D	Device-to-Device
D2I	Device-to-Infrastructure
DSR	Dynamic Source Routing
DTN	Delay/Disruption Tolerant Network
ESTOP	Early STOP
FDD	Frequency Division Duplex
I2D	Infrastructure-to-Device
I2I	Indoor-to-Indoor
IFOM	IP Flow Mobility
I-WLAN	Interworking Wireless Local Area Network
LOS	Line Of Sight
LSP	Link State Packet
MCN	Multi-hop Cellular Network
MIP	Mobile IP
NACK	Negative ACKnowledgment
NLOS	Non-Line Of Sight
O2I	Outdoor-to-Indoor
O2O	Outdoor-to-Outdoor
ODMA	Opportunity Driven Multiple Access
OLSR	Optimized Link State Routing
PAPR	Peak-to-Average Power Ratio
PERR	Path ERRor
PMIP	Proxy Mobile IP
ProSe	Proximity Services
PTR	PoinTeR
SARC	Separation ARChitecture
SIPTO	Selective IP Traffic Offload
SPR	Shortest Path Routing
TOF	Traffic Offload Function
UE	User Equipment
VC	Virtual Connection

decision could also be the hybrid of centralized and distributed routing.

The state-of-the-art multi-hop D2D routing schemes have been classified into incentive-based, security-based, content-based, location-based and flat topology-based routing.

The flat topology-based routing schemes have been further sub-classified based on the route discovery mechanism used, i.e., (i) reactive routing, (ii) proactive routing, and (iii) hybrid routing (both the reactive and proactive routing operate at the same time).

Reactive routing is used in networks having low number of data transmissions or low mobility or in networks having high node density and vice versa for proactive routing. The hybrid routing is used in large-scale networks where proactive routing is used to maintain neighborhood table for nodes in a zone within few hops, while reactive routing is used to find route outside that zone.

When confidentiality, authenticity and integrity of data are of utmost concern, security-based routing is used. If the objective is to share the frequently used data among users, the routing scheme is called content-based routing. The routing scheme in which the users are motivated to participate in relaying the data of other nodes by using some incentive, is called incentive-based routing. If the incentive is the social bond between the users, the routing is called social connection-based routing, and is considered as a sub-class of incentive-based routing.

The complete taxonomy of all state-of-the-art multi-hop D2D and D2I/I2D routing schemes is shown in Fig. 3.1. Each category has been numbered in order to have a quick referral from the text. In the figure, the name of category is followed by a two-column row, where references in the first (left) column shows the D2D routing schemes while the second column (i.e. column on the right) shows references for the schemes proposed for D2I/I2D routing. *It is very important to note that the category numbers assignment does not taken differently the D2D and the D2I/I2D routing schemes, therefore readers might notice gaps in category numbers while going through only D2D routing schemes or D2I/I2D routing schemes.*

3.1.1 Incentive-based Routing

The objectives of incentive based routing is to establish end-to-end communication among the devices by motivating the intermediate users to relay the data using different incentives. Social connection with other nodes is also used as a type of incentive to motivate other nodes to relay their data, and the routing is called social connection based routing.

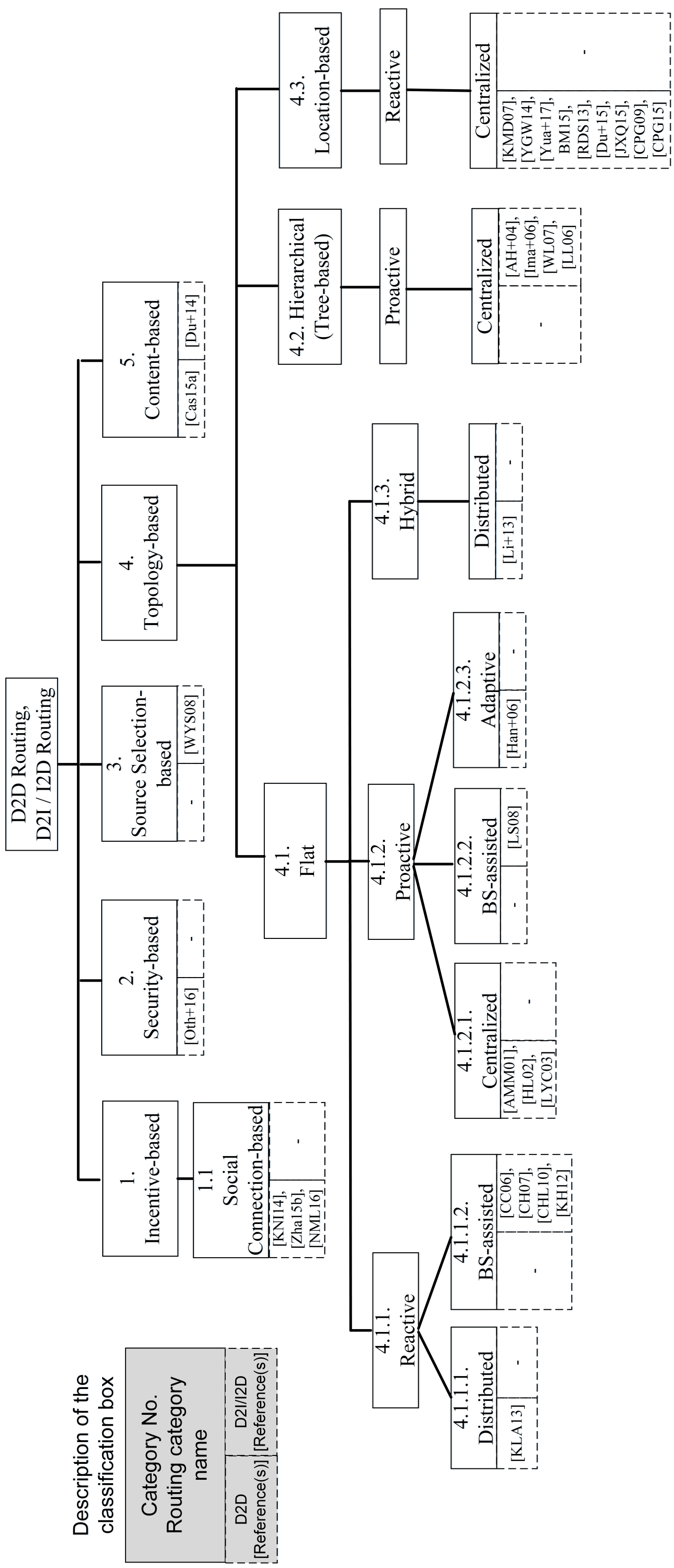


Figure 3.1: Taxonomy of state-of-the-art multi-hop D2D and D2I/I2D routing schemes.

Table 3.2: Acronyms of topology based routing algorithms.

Algorithm Acronym	**Algorithm Name**
ACMR	Adaptive Cellular and Multi-hop Routing
ARCE	Ad hoc Routing for Coverage Extension
BCR	Base-Centric Routing
CAR	Centralized Adaptive Routing
CBSR	Cellular Based Source Routing
ContouR	Contour Routing
CRL	CRoss Layer routing
CRSP	Combined Routing, channel Scheduling and Power control
DST	Distributed Spanning Tree
ERP	Efficient Routing Protocol
FPS	Fixed Power Scheme
FRS	Fixed Rate Scheme
HyLoMM	Hybrid Location-based Multiple Metric
IAC	Inhibit Access Control
IAR	Interference-Aware Routing
ICR	Interference-Conscious Routing
JRC	Joint Routing and Channel selection
JRS	Joint Routing and Scheduling
LBS-AOMDV	Load Balancing-based Selective - Ad-hoc On-demand Multipath Distance Vector routing
LDR	Light Dark Routing
LoMM	Location based Multiple Metric
LSSON	Large Scale Self Organizing Network routing
MCN	Multi-hop Cellular Network Routing
MCPR	Minimum Consumed Power Routing
MMRP	Multiple Metric Routing Protocol
MRC	Multiple Route Coding scheme
MR-D	Maximum-Rate towards Destination
MR-DA	MR-D Advanced
PAC	Priority Access Control
PIR	Power and Interference-aware Routing
PSF	Power-strength-based Selective Forwarding
RAR	Resource-Aware Routing
RCIL	Routing with Combined Interference and Link gain
RRR	Reception Range-aware Routing
xLoMM	x-hop location permissive Location based Multiple Metric

3.1.1.1 Social connection-based routing

In social connection based routing scheme, the relay node forwards the data based on strength of the social bond with the other nodes on the communication path. A relay node has given the independence to decide to relay the data or not. Thus, the probability of establishing an end-to-end communication path depends upon the social ties of intermediate relay nodes with each other. The state-of-the art schemes that uses social connection based routing are discussed below.

A centralized social-tie based routing scheme in which the route is determined by BS is proposed in [KNI14]. It is assumed that mobile users are connected with social ties and the network operators can extract the social ties between the users (by using some mobile apps, to find the contacts and activities of the user's online social network (OSN) accounts, e.g., Facebook, Twitter etc.). Thus, network operators can build social network graph which is used in conjunction with network connectivity graph to find the probability of data packet delivery under different percentages of possible D2D paths. Although the route decision is under the control of network operators, however, the unexpected user behavior, due to for example low remaining energy budget, makes the end-to-end delivery uncertain. The objective is to minimize the total communication cost (using the communication graph) while guaranteeing the delivery probability (using the social connection graph). Results showed that for the increasing probability of delivery, the communication cost also increases, while the percentage of D2D paths decreases.

A greedy algorithm is proposed to decrease the delay and the average-transmission path length (APL) in terms of number of hops by introducing long-range links (LLs) for multi-hop D2D communication networks [Zha+15b]. To reduce the computational complexity, the problem has been modeled as a coalition graph game. The LLs have been established by exploiting the social information. In social networks, community represents the group of persons having common interests. Thus, LLs have been established between the same community, as information sharing in intra-community is frequent. Results showed that by using LLs, the number of hops have been significantly decreased between source and destination nodes.

A group meeting aware routing (Groups-Net) protocol for delay tolerant data like video advertisements or non-critical application updates for multi-hop D2D networks is proposed in [NML16]. The routing protocol is aware of the social group meetings by using proximity traces, like classrooms, office buildings etc. Since normally the persons are involved in some specific schedules and routines, so it is expected to have group meetings with regularity or predictability. The forwarding algorithm forwards the data, if the next hop node had some meetings with the destination node in the near past. As opposed to the normal trend, the algorithm does not require social community group detection, and is argued to be an expensive and complex task. Results showed that Groups-Net is a promising strategy in large scale scenarios, where it reduced the overall network (or data) overhead.

A brief summary/comparison between the schemes proposed for social connection-based routing is as follows. Koutsopoulos et al. [KNI14] exploit the social ties between the mobile users to draw the social network graph. The social network graph is used in conjunction with network connectivity graph to find the probability of data packet delivery under different percentages of possible D2D paths. Zhao et al. [Zha+15b] groups the social ties having common interests into the community because the information sharing between intra-community is frequent. The long-range links have been established between the same community, which significantly reduce the number of hops and delay. Nunes et al. [NML16] exploit the schedules and routines of people to predict their group meetings, and the routing using this information is named as group meeting aware routing protocol (Group-Net). The Groups-Net is a promising strategy for delay tolerant data in large scale scenarios, and it reduces the overall network overhead.

3.1.2 Security-based Routing

Security of data in terms of confidentiality, authenticity and integrity of data are of critical concerns in this age of data communications.

A shortest hop based routing protocol ensuring confidentiality, authenticity and integrity is proposed in [Oth+16]. For confidentiality, each mobile station uses symmetric cryptography and shared a secret key with neighbor mobile node. A session key is generated between the source and destination nodes so that intermediate nodes can not intercept the data. The shared key shared between the neighbors nodes requires private key assigned from the BS. Thus, only authenticated nodes from BS can be the next hop node. For node anonymity, i.e. to prevent revealing the the real identity of the node, every node generates temporary identity (ID) by themselves using the private key of the BS. For integrity, a hash value is appended with the message, which is generated using the shared neighbor key and also the private key of the sender node.

The route discovery processed as follows. The source node sends the RREQ packet to each neighbor node using its temporary ID and the shared secret key with the neighbor node. The RREQ packet also contains the calculated hash value. Intermediate node on receiving the RREQ, decrypts the packet and check the hash value. On successful verification, a new hash value is generated and the RREQ is enrypted using the shared key with the next hp node. If the contents of the message within RREQ could be decrypted by the receiving node, then the node is the destination node. In case of receiving multiple RREQs, RREQ with the minimum hops is selected and the route reply is sent back to the source node. The same process of encryption using shard neighbor key and adding hash value is used for sending the RREP packet. The simulations have been performed on network simulator NS-2, and the results promise improve throughput and reduced routing overhead.

3.1.3 Topology-based Routing

The state-of-the-art topology-based routing schemes for multi-hop D2D communications have been categorized into location-based routing and flat topology-based routing, as discussed below.

3.1.3.1 Flat topology routing

When nodes in the network do not have any specific structure, nor have any location awareness mechanism then such arbitrary distribution of nodes is referred as flat topology network structure, and the routing is called flat topology routing. Flat topology routing has been divided into reactive and proactive routing, each with further sub-categories as listed in Table 3.3, and discussed below. The Table 3.3 also lists the performance parameters and simulation tool used in each scheme.

Reactive distributed routing In this type of routing, autonomous nodes find route only when required. The routing protocols proposed under reactive distributed routing are discussed as follows.

Kaufman et al. [KLA13] proposed a routing scheme which we named as power and interference-aware routing (PIR). In this scheme, a node sends the transmit power and interference information in the route request (RREQ) packet. The next hop node forwards the RREQ if (a) the SINR of an active cellular link do not fall below a certain allowed threshold value k, (b) the minimum SINR at the previous hop node could be achieved with a given power while taking into account the interference. This ensures that bidirectional communication is possible with the previous hop node. Destination node

Table 3.3: Comparison of topology based multi-hop D2D routing algorithms

Topology structure	Proactive / Reactive	Centralized / BS-assisted / Distributed	D2D Routing Algorithms	Performance parameters	Simulation Tool
Flat	Reactive	Distributed	PIR [KLA13]	Failure probability of discovering D2D link, Outage probabilty of D2D users and cellular users, Average number of hops, Power savings with D2D	MATLAB
	Proactive	Centralized	MCN [AMM01]	Throughput	GloMoSim
			BCR [HL02]	Throughput under BCR/UDP, FTP/TCP with/without mobility	GloMoSim
			CBSR [LYC03]	Delay, Packet delivery ratio, Routing overhead	NS-2
		Hybrid	LDR [Han+06]	No performance evaluation	-
	Hybrid	Distributed	ACMR [Li+13]	Delivery rate, Average delay, Overheads	NS-2
Location based	Reactive	Centralized	CRL [KMD07]	Total power spent per packet transmission, Dynamic call dropping probability, Number of nodes bathed with the interference, End-to-end delay, End-to-end throughput, Total incentives paid	-
			IAR [YGW14], [Yua+17]	D2D outage probability, Success probability, End-to-end delay, Throughput	-
			FRS and FPS [BM15]	Throughput	-
			MR-D [RDS13]	Outage probability, Average Hop Count	-
			MR-DA [Du+15]	Outage probability, Average Hop Count	-
			JRC [JXQ15]	Energy efficiency, Average hop count, Outage probability	NS-3
			LoMM & Hy-LoMM [CPG09]	Application and routing packet delivery ratio, Application throughput, Total energy consumed	NS-2
			xLoMM [CPG15]	Relative performance under various x-hop values	NS-2

on receiving the route request packet, replies following the reverse route order to confirm the existence of bidirectional route between the source and destination nodes. Dynamic Source Routing (DSR) [Joh03] is used for route discovery in which nodes which are near to the route also have the route information. This helps in easily repairing the route with the help of these nearby routes. In case of small pathloss environment, nodes lower their transmit power to minimize interference to BS which results in route with multiple hops. However there are some limitations in this work. The work is limited to single source of interference, multiple interfering nodes in case of multiple flows are not taking into consideration. To ensure that the interference is not above the threshold value, D2D nodes must need to coordinate either with the BS or with all other D2D nodes. This coordination is not explicitly mentioned in this work. Since such synchronization is usually the responsibility of BS, thus the proposed scheme would not be applicable for nodes outside the cellular network coverage.

Proactive centralized routing In proactive centralized routing, a centralized entity (for example BS) regularly gathers neighbor nodes information from all the network nodes, in order to always have a complete updated network.

One of the pioneer routing scheme, which efficiently utilize the services of BS for route decision is the multi-hop cellular network (MCN) routing [AMM01]. It is worth mentioning here that MCN is proposed by Lin and Hsu [LH00], however the routing for MCN is first proposed by Ananthapadmanabha et al. [AMM01]. In MCN routing, all the nodes notify the received power (Rx) of their neighbor nodes to the base station (BS). After collecting the neighbor information, the BS draws the network topology graph. When a node wants to send information to another node, it sends route request packet (RREQ) to the BS which contains the information of the destination node. BS sends either a reply packet (RREP) containing suitable route information to the requesting node or an error packet (RERR) if a route to the destination does not exist. Route information is also cached by nodes for reducing the BS overhead.

However, there are some serious limitations in this approach. The route updates are sent to the BS only when there is a considerable change in the received power (Rx) of the neighbor node. So, if there is a bad link which fluctuates then the immediate route updates will result in a high routing overhead which may severely degrade the network performance. On the other hand, when the network is stable, the same route will be used for a long time which puts burden on the specific set of nodes.

Base-centric routing (BCR) protocol which is a hybrid of demand-driven and table-driven routing is proposed in [HL02]. Neighbor nodes periodically exchange beacon messages with each other. The current link state information of neighbor nodes in the form of link state packets (LSPs) is also periodically unicast via multi-hop to the BS. In this way, BS uses table-driven method to maintain topology information of the whole network. Route to BS is known by the HELLO message periodically flooded by the BS. This route is used by LSPs, BROKEN_LINK error packets, and unicast path request (U-PREQ) messages.

In BCR, the nodes use the demand-driven approach to find the route to the required destinations. These nodes send U-PREQ to the BS, and if the route is not found, then broadcast route request (B-RREQ) like ad hoc on-demand distance vector (AODV) routing protocol. BS replies the complete route to the destination in the path reply (PREP) message. Since the PREP is unicast to the source node, therefore intermediate nodes in the path from the source node to the required destination node do not know this path. Thus the source node send pointer (PTR) message, which contains the information of path and hop count as received from the BS in the PREP message. This PTR message is not used in case of B-PREQ message. If an intermediate node finds a broken next hop link, it sends BROKEN_LINK and path error (PERR) messages to the base station and source node respectively.

The results show that BCR outperforms AODV, because path request messages are mostly unicast to the BS only, which significantly reduces the routing overhead. Without node mobility in the network, UDP performs better than TCP. However when mobility is enabled, paths are frequently broken which results in data loss. Thus throughput of UDP is lower than TCP because of not having any flow control and retransmission mechanisms. When the node mobility is enabled and the load is light, the throughput of AODV is higher than BCR. This is because, BS might provide disconnected path to the nodes.

One other variant of proactive centralized routing is cellular based source routing (CBSR) [LYC03]. In this proposal, each node periodically reports neighborhood table to the BS. The report contains each neighbor's load, link quality and HELLO packet receive time. The BS keeps $N * N$ matrix in which each node's link to every other node is maintained and includes an additional attribute of hop count in the table. The nodes send RREQ to find the routes and the BS replies with all available routes via RREP, or otherwise RERR in case of having no route. RERR is also sent by a node to inform about an error in the route suggested by the BS.

In a nutshell, the three schemes for centralized proactive routing are MCN routing, BCR and CBSR. In all these schemes, nodes periodically share HELLO packets with each other. In MCN, nodes notify their neighbors' received power (Rx) to BS and then update to BS only if there is a change in the neighbors' Rx. In BCR, all the nodes use their minimum power and communicate only to their neighbor nodes. Thus, nodes communicate to the BS also via multiple hops. The results have shown that both MCN routing and BCR can improve the network throughput in their considered network scenarios. In CBSR, each node reports their neighbors' load, link quality with the neighbor nodes and receive time of HELLO packet to the BS. The results have shown that CBSR can improve the network performance in terms of reduced delay and routing overhead and increased packet delivery ratio.

Proactive adaptive routing Proactive adaptive routing is an adaptive routing technique that adapts between proactive centralized routing and proactive distributed routing, based on the network constraints.

In this type of routing, a routing scheme called as light dark routing (LDR) [Han+06] is proposed that adapts to a changing network topology. It works in both centralized and distributed modes. LDR uses the same format and operations (for example RREQ packet format) as dynamic source routing (DSR) protocol. So in the absence of the BS the process continues as a DSR distributed routing protocol. In LDR, each node reports changes in the link state and traffic load to the BS which computes all routes in the network using latency metric and informs sub-routes information to the respective relay nodes. Nodes under the coverage of the infrastructure network report any changes directly to the BS in one hop. Nodes outside of the coverage report any considerable change to the BS via multi-hop using the help of some proxy node already under the coverage. Thus, a proxy node communicates with the out-of-the-coverage node in distributed fashion and with the BS in centralized fashion.

Hybrid distributed routing In hybrid routing, the nodes which are within the specific hop range always communicate proactively while farther nodes always communicate re-actively, this type of routing is also termed as zone based routing.

An adaptive cellular and multi-hop routing (ACMR) which uses zone routing technique and maintains the zone routing information based on optimized link state routing (OLSR) is proposed in [Li+13]. In ACMR, each node proactively maintains the routing table for p-hop neighbors using OLSR. Higher p-hop values improves network connectivity and coverage, and lower p-hop values reduce the complexity of route maintenance, communication overhead, bandwidth consumption and energy. The value of p is not constant and is variable with dynamic network topology. The ACMR protocol is proactive (table driven based) maintaining the topology of the network within p-hops, while reactive (on-demand) for more than p-hops. If the information about the destination is not available in the routing table, the source node sends route request (RREQ) packet. The RREQ packet is forwarded uptil $2 * p$ hops. If any node has information about the destination node, it sends route reply (RREP) packet back to the original sender, else will forward the RREQ. If the BS receive the RREQ, it will not further forward the RREQ and replies only if it has route information to the destination node. All nodes that forwards RREQ but not received RREP, will discard the RREQ information after timeout. If more than one RREPs are received by the source node, it keeps only one RREP and discard rest others.

Simulation results showed that ACMR minimizes the time delay for data packets, because (1) of restriction on the number of hops in ACMR (2) the load of base station is reduced by using the nodes as relays. There are three modes of communication in ACMR, multi-hop mode, cellular mode and hybrid mode (accessing BS through multi-hop relays). The impact of node density (to show connectivity of the network) and the movement speed (to show the frequency of topology changes) is evaluated for the multi-hop network. The cellular network packet delivery is affected by traffic load and channel bandwidth rather than the node density. Similarly cellular network has no impact of movement speed since all the movements are within the coverage of base station to guarantee the reliability of connection. Therefore there is no extra communication overhead in cellular network with the increase in the node density and movement speed.

The communication overhead increases both in ACMR and OLSR with the increase in node density, movement speed and p-hop values. In all cases the communication overhead of ACMR is less than OLSR because of adopting zone based routing which limits the broadcast area. When p-hops are less than equal to 2, the routing table is maintained by just using HELLO packet while the communication overhead increases with the increase in p-hop values. In comparison to cellular network, the extra communication overhead to maintain proactively the topology of the network still not guarantee the up-to-date state of the network due to high network dynamics which lead to reduction in packet delivery. On the other hand, the spatial frequency reuse results in increasing the packet delivery rate. Thus the overall packet delivery rate is higher than the cellular network but fluctuating.

3.1.3.2 Location-based routing

Location based routing protocols depends on location servers (or some other central entity) to know the location of the destination node. The route decision is taken by nodes autonomously using the location information (i.e. distributed routing strategy), except in [KMD07], where the decision depends upon the BS (i.e. centralized routing strategy). It is important to note that all state of the art location based routing protocols are reactive in nature, apart from the fact that in real, every location based routing need to proactively maintain the location update. Due to this regular location update, location based routing protocols do not need entire network broadcast. It is also interesting to note that all location based routing protocols inherently assume that a given channel is used by only one D2D pair. This would probably be managed by location servers; however, it is not explicitly mentioned in any state-of-the-art work. A number of location based routing protocols are proposed, which are discussed below.

The work in [KMD07] proposed a cross layer routing (CLR) algorithm with multiple constraints. The algorithm incorporate MAC layer's interference levels and physical layer's propagation channel conditions into the routing layer's decisions. The constraints are categorized as node constraints and path constraints. The constraints imposed on the selection of intermediate relay node are the sufficient neighborhood connectivity, dynamic call dropping, interference to other nodes and cooperation. The path constraints are the throughput and delay. All these are detailed as follows.

(i) Cooperation metric: Full cooperation is not assumed and the cooperation is incentivized by a charging and rewarding policy. When a call initiation request is received by BS, it uses broadcast control channel (CCH) to forward the cooperation request which contains the incentive amount, source and destination address to the nodes. Only interested nodes reply via CCH.

(ii) Interference metric: Interference management is done using the power control mechanism. By knowing the distances between the source, destination and the nodes which get interfered by the communication, it is ensured to maintain minimal interference in the network.

(iii) Dynamic call dropping and connectivity metric: Dynamic call dropping due to mobility of nodes or emergency call situation is incorporated, which selects a neighbor node around the particular depleted node as relay node. The availability of an alternate relay node is ensured by having sufficient number of neighbor nodes around the depleted intermediate relay node. Thus intermediate relay node was selected if it has k number of neighbor nodes where $k>\theta(logn)$, where n is total number of neighbor nodes in the network. If $k<0.074(logn)$, it means network is asymptotically disconnected and $k>5.1774(logn)$ means connectivity probability is approaching one.

(iv) End-to-end throughput: End-to-end throughput is ensured by maintaining minimum threshold SINR at each intermediate relay. Interference at the node due to other communications assumes Rayleigh fading, because of prevalent fading factor in cellular networks instead of impractical commonly used distance-decay law.

(v) End-to-end delay: The transmission delay at each hop and the propagation delay constitutes the end-to-end delay which is minimized by selecting route having minimum number of hops.

The routing algorithm filters nodes sequentially from n nodes. Firstly set of cooperative nodes is constructed from n nodes. The nodes satisfying interference constraint are further shortlisted from the set of cooperative nodes. The resulting set of nodes are further shortlisted in terms of satisfying sufficient neighborhood connectivity, minimum required SINR and then the delay.

Interference aware routing (IAR) which constructs route from source to destination, using nodes on the cell edges is proposed in [YGW14], [Yua+17]. Firstly, the route sends data towards nodes in the edge, then the data travels along the cell edge towards the direction of destination; and then finally data is forwarded from cell edge to the destination. Each stage of the IAR utilizes Shortest Path Routing (SPR). Therefore routes in IAR are longer than direct shortest path, but this IAR path has overall lesser interference. The algorithm uses the downlink band for D2D communications and the outage probability of cellular communication due to D2D communication is also calculated. Some limitations in IAR scheme are as follows. The work assumes that it knows the location of the cellular UEs whose spectrum are being reused by the D2D nodes and thus avoids interference among the cellular UEs and D2D UEs. Moreover, it can be easily seen that when the distance between the source and destination nodes is small, the shortest path routing is better in terms of both the interference and delay.

The work in [BM15] shortlists the feasible D2D links which are reliable (by maintaining minimum required SINR) and avoids harmful interference to the cellular users. The routing algorithm considered two different scenarios, fixed rate scheme (FRS) and fixed power scheme (FPS). In FPS, each link achieves a different rate based on the SINR at the receiver. Thus the maximum throughput path is not necessarily the shortest path. In FRS, a threshold SINR is maintained at each link, and the end-to-end throughput is calculated by dividing the rate achieved at an individual link with the number of hops.

Thus with the given SINR, the optimal path is usually the shortest path in terms of number of hops in the fixed rate scheme. The FRS-Improved (FRS-I) is proposed in [MGM17]. In FRS-I, the link outage is calculated by taking into account the channel fading effect between D2D pairs; and between D2D pair and cellular network. The actual (calculated) interference could be higher when taking channel fading into consideration. Thus, the overall throughput increases after accounting the link outages. The fixed rate schemes are preferred because same modulation and coding scheme can be used on all links.

The results show that the throughput is multiple times higher than the one achieved with one hop communications. However, it is assumed that only one D2D link could be active under a particular frequency channel in a given area. The algorithm uses downlink band for D2D communications and interference to cellular users is avoided by assuming that each D2D node has complete knowledge about the location and channel information of cellular nodes.

In Maximum-Rate towards Destination (MR-D) routing algorithm [RDS13], D2D UEs use uplink band for communication. The interesting work in this paper is to avoid interference without calculating the total interference impact at any node. This is because due to underlay approach, nodes farther from primary cellular nodes and Base Station provides higher data Rate (SIR ratio) than those which are nearer. Thus just by taking into account the Rate requirement, it avoids interference.

In downlink band, the route formed by the MR-D algorithm goes towards the cell edge which increase hop count. MR-D advanced (MR-DA) is proposed [Du+15] to reduce the number of hops by directing the traffic towards the next hop which is in the direction of destination. Two set of nodes $\Phi1$ and $\Phi2$ are defined. $\Phi1$ is the set of nodes towards the direction of destination and $\Phi2$ towards the opposite. If there is no next hop neighbor node possible in the direction of destination i.e. if $\Phi1 = null$ then $\Phi2$ is used.

A heuristic routing algorithm and a channel selection strategy is proposed [JXQ15]. The algorithm uses the downlink band and assumes that every node knows the channel and location information of every other cellular node, D2D node and BS. The algorithm selects the optimal channel that provides the best channel gain and the minimum interference. With the given channel, the next hop node is selected based on the combination of two weighted factors, the first is the energy efficiency of the current hop (up to the next hop) and the second is the direct transmission rate from next hop to final destination.

The work in [CPG09] proposed location based multiple metric (LoMM) routing protocol that guarantees packet delivery by discovering complete route from source to destination. The multiple metric weighted cost function includes the number of hops, traffic load and energy consumption. Congestion is calculated by using delay in the reception of periodic beacon messages, and the traffic load for bursty traffic is finally calculated by the cumulative weight of current congestion and previous load (as opposed to delay in packet reception as in CBR). The energy efficiency is maximized based on fair distribution of energy among all nodes (instead of power control mechanisms). LoMM by exploiting location information avoids intermediate nodes that are farther from the destination (BS) which reduces the candidate relaying nodes. This reduces the signaling overhead and energy consumption while increasing the application throughput. However results showed that it is 95% less probable (comparing to ad hoc MM routing) to find a next hop node in the direction of destination.

Hybrid LoMM (HyLoMM) is proposed in [CPG09] which is combination of LoMM and adhoc MM routing. HyLoMM first uses LoMM routing and if the route is not found then use the ad hoc MM routing. However HyLoMM has less application throughput.

The x-hop location permissive LoMM (xLoMM) allows x-hops that are not in the direction towards the destination. Optimal value of x-permissive hops that reduces network flooding and energy cost while maintaining end-to-end performance is investigated in [CPG15]. It is found via simulations under a certain given scenario that with the increase in cell radius, higher x-hop values are required. However values of x-hop above four does not improve performance but only increase the signaling load. The xLoMM has also been tested in three different location areas: line of sight (LOS), street (Non LOS) and intersection . Interesting results are found in the intersection, where LOS propagation is used with four road segments, among which two road segments progress towards the destination. These two road segments that progress towards the destination node, increase the route diversity and the end-to-end performance while also increasing signaling load and energy consumption.

In the following text, a summary and/or comparison between the various strategies which have been proposed under location-based routing is provided, in order to have clear understandings of the importance of each strategy. In all location-based routing, nodes depend on location servers to find the location of the destination node, thus proactively maintains the location update. In CLR, the BS decides the route based on multiple node and path constraints. The results have shown that CLR can improve network performance in terms of various performance metrics. In all the location based routing (except CLR), each node takes the route decision autonomously. The IAR constructs route using nodes near the cell edges, thus have longer routes than direct shortest path, but have lower D2D outage probability when distance between the end-nodes is greater than cell radius. When distance between nodes is lower than cell radius, SPR (shortest path routing) is preferred. The FRS and FPS schemes can improve the network throughput under fixed power or fixed rate (in terms of maintaining threshold SINR at each link) scenario.

The MR-D scheme avoids the interference by taking into account the rate requirements, and thus enhanced the outage probability. The MR-DA scheme is an advanced version of MR-D, which reduces the number hops by directing the traffic towards the next hop node which is in the direction of destination. In joint routing and channel selection (JRC) algorithm, after selecting a channel having minimum interference and best channel gain, the next hop is selected based on the energy efficiency and data transmission rate. In LoMM, location awareness is used by nodes to avoid intermediate nodes that are farther away from the destination node. Thus, LoMM reduces the number of RREQ packets (signaling overhead) which improves the application throughput. In hybrid LoMM (HyLoMM), if an LoMM routing fails to find a route, MM routing is used, which improves the application packet delivery ratio (PDR). Another technique to improve the PDR is x-LoMM. In xLoMM, x-hops are allowed that are not in the direction of destination node. Although this increases the signaling overhead (in comparison to LoMM) but it reaches almost 95% of the PDR of MM.

3.1.4 Content-based routing

Content-based routing is normally used to establish routes for sharing the frequently used data among users, like viral videos etc. Thus the route does not depend upon the destination node, but is established based on the contents of the information being shared.

A group-based approach for content-based routing is proposed in [Cas+15a]. In this approach, peer-to-peer (P2P) nodes in the network forms multiple groups. In each group, one peer is selected as group owner (GO) after negotiation with other peer nodes in the group. One peer is selected as a relay client, that acts a bridge between two (or more) groups using a different MAC identity at each group. Other nodes are normal P2P clients. After the formation of groups, nodes can share their contents with other nodes in the network. It is assumed that each content is provided by exactly one node, and once that node is disconnected, the content also becomes unavailable.

The routing table that contains information about route to each content in the network is called as content routing table (CRT). There are two steps to build the CRT, content registration and content advertisement. In content registration, a client advertises a new content by sending message to the GO. The GO registers the content and replies acknowledgment (ACK) to the client. In content advertisement, GO advertises the content internally by sending a broadcast message to all the nodes in the group so that all the nodes update their CRT. The relay client replies with an ACK message to the GO. In order to advertise the content to other groups, the relay client forwards the advertisement message to the GO of other group. The GO of the other group also replied with ACK for confirming the reception of the advertised message. It then broadcast the message within its group and the process continues till all the groups and their nodes update their CRT. Thus, based on the ACKs, all the GO and relay clients have confirmed information about the available contents. So when a node needs some contents, it first checks its CRT and in case of no entry, send content request to its GO. Results showed that the application layer throughput increases with the increase in offered load. However with the increase in the number of hops, the channel contention also increases resulting in overall decreased throughput.

3.1.5 Summary and Insights

As we know that the well-known DSR (Dynamic Source Routing) and AODV (Ad-hoc On-demand Distance Vector routing), both are distributed reactive routing protocols, however their route discovery process are different. Similarly, under some categories discussed above, more than one routing protocols are found in literature which differs based on their (i) route discovery process, and/or (ii) routing metric, and/or (iii) objective or network performance criteria. Therefore, a summary and/or comparison between the various strategies which have been proposed under the same category is provided (at the end of each category), in order to have clear understandings of the importance of each strategy.

There are some schemes proposed for communication among users in vehicles. As an example, consider a cluster-based routing scheme proposed for multi-hop D2D communication in vehicular network in [Rie17]. With BS assistance, the clustering based on communication range and mobility (CCRM) is used to simplify the network topology, by dividing the large scale network into clusters of different connecting probabilities, movement direction and speed. A node that can maintain for long duration; the highest number of connection with other nodes is selected as cluster head. The routing is then used to enable multi-hop communication within clusters, between inter-connected clusters and among the isolated clusters. It has been noticed that the network topology for vehicular routing is quite different from normal D2D network topology, therefore we neither cite nor discuss any other routing protocol for vehicle-to-vehicle (V2V) communication.

It is very interesting to note that all the muti-hop D2D routing schemes use only D2D relays for communications as shown in Table 3.4. For further readings, it would be interesting to go through the diverse types of spectrum used by the multi-hop D2D routing schemes as shown in Table 3.5.

3.2 Multi-hop D2I/I2D Routing

In multi-hop D2D routing, the route is established between the two user end-nodes, while in multi-hop D2I/I2D routing, multi-hop route is established between the node and the network service entity, i.e. BS. The BS serves as a common source in the downlink and common destination in the uplink communications. The BS periodically broadcasts the pilot signals which is received by all the nodes in the network. The received signal strength (RSS) of the pilot signal is used in most of the schemes as link cost with the BS, which is used for routing decision. Thus due to the assistance from BS in form of pilot signals for link cost calculation, this type of routing is more information-rich which is major difference from the multi-hop D2D routing [CC06].

In multi-hop D2I/I2D routing, a node can not only communicate with its own BS, but can also communicate with other BSs using relay nodes. This results in further load balancing, as nodes are no longer restricted to single cell only [Ima+06]. This type of routing has been further extended by relay nodes to forward the data of other nodes beyond the service area [CJB04].

The state-of-the-art multi-hop D2I/I2D routing schemes have been broadly classified (based on their objectives) into source selection based, content-based and topology based (reactive, proactive and tree-based) routing schemes. The source selection-based routing scheme is used when it is required to select a source node, from which the cellular resources can be snatched in order to allocate them to the new user request. The source node can then communicate via multi-hop to another BS as suggested by the current BS. This is to balance the load among multiple BSs and is done only if a multi-hop route is possible. Content-based routing is used to establish routes for sharing the frequently

Table 3.4: Type of relays used in topology based routing algorithms

Network	Algorithm	Topology			Relay type		
		Flat	Location based	Tree based	D2D Relay	Network Relay	
						Mobile	Fixed
D2D	PIR [KLA13]	✓			✓		
	MCN [AMM01]	✓			✓		
	BCR [HL02]	✓			✓		
	CBSR [LYC03]	✓			✓		
	LDR [Han+06]	✓			✓		
	ACMR [Li+13]	✓			✓		
	CRL [KMD07]		✓		✓		
	IAR [YGW14], [Yua+17]		✓		✓		
	FRS [BM15]		✓		✓		
	FPS [BM15]		✓		✓		
	MR-D [RDS13]		✓		✓		
	MR-DA [Du+15]		✓		✓		
	JRC [JXQ15]		✓		✓		
	LoMM [CPG09]		✓		✓		
	HyLoMM [CPG09]		✓		✓		
	xLoMM [CPG15]		✓		✓		
D2I/I2D	PAC [CC06]	✓				✓	
	IAC [CC06]	✓				✓	
	PSF [CH07], [CHL10]	✓				✓	
	RCIL [MA09]	✓				✓	
	ERP [LS08]	✓				✓	
	ContouR [KH12]	✓				✓	
	RRR [AH+04]			✓		✓	
	MRC [Ima+06]			✓			✓
	LSSON [WL07]			✓			✓
	JRS [LL06]			✓			✓
Ad-hoc	RAR [PJ07]	✓				✓	✓
	MCPR [LCC04]	✓			✓	✓	
	MMRP [Cao+08]	✓			✓		
	LBS-AOMDV [TK14a]	✓			✓		
	CRSP [SJZJ02]	✓				✓	
	ARCE [GL04]	✓				✓	
	DST [IC04], [ICNR05]			✓		✓	

used data among users.

Depending upon the network structure, topology based routing has been categorized into hierarchical routing and flat topology routing. The hierarchical (or tree-based) rout-

Table 3.5: Spectrum type used in topology based routing algorithms

Network	Routing Algorithm	Type of Spectrum			
			Inband		
		Outband	Overlay	Underlay	
				Downlink	Uplink
D2D	PIR [KLA13]				✓
	MCN [AMM01]	✓			
	BCR [HL02]	✓			
	CBSR [LYC03]		✓		
	LDR [Han+06]	✓			
	ACMR [Li+13]				✓
	CRL [KMD07]			✓	✓
	IAR [YGW14], [Yua+17]			✓	
	FRS [BM15]			✓	
	FPS [BM15]			✓	
	MR-D [RDS13]				✓
	MR-DA [Du+15]			✓	
	JRC [JXQ15]				✓
	LoMM [CPG09]	✓			✓
	HyLoMM [CPG09]	✓			✓
	xLoMM [CPG15]	✓			✓
D2I/I2D	PAC & IAC [CC06]	✓			✓
	PSF [CH07], [CHL10]				✓
	RCIL [MA09]				✓
	ERP [LS08]				✓
	ContouR [KH12]	✓			✓
	RRR [AH+04]				✓
	MRC [Ima+06]				✓
	LSSON [WL07]				✓
	JRS [LL06]		✓		
Ad-hoc	RAR [PJ07]				✓
	MCPR [LCC04]	✓			
	MMRP [Cao+08]	✓			
	LBS-AOMDV [TK14a]	✓			
	CRSP [SJZJ02]		✓		
	ARCE [GL04]	✓			✓
	DST [IC04], [ICNR05]	✓			

ing scheme can be used only in the presence of a central control entity. The flat topology based routing schemes have been further classified into two sub-categories: reactive routing and proactive routing. In proactive BS-assisted routing, nodes periodically update routing table, usually for delay sensitive or real-time applications. The objective is to instantly provide a multi-hop route with better BS channel capacity from node to the BS, when BS is overloaded or when the channel quality (or capacity) with BS is not good. In reactive BS-assisted routing, nodes find the route on-demand, by using their local (from neighbors) and global (pilot signal from BS) information. The tree-based routing is used when wireless network scalability is of major concern. All the schemes under each category use BS-assistance for their route decision.

The complete taxonomy of state-of-the-art multi-hop D2I/I2D routing schemes is shown in Fig. 3.1 and explained in the subsequent subsections. In Fig. 3.1, each category of D2I/I2D routing has been numbered in order to have a quick referral from the following text explanations. The category numbers assignment does not uniquely distinguish between D2I/I2D and D2D, and therefore the readers would notice gaps in the category numbers for only D2I/I2D routing.

3.2.1 Source Selection-based Routing

In source selection based routing, fixed relay nodes are used by the network operators to divert the traffic from the high loaded BS to a low loaded BS. When there is a high traffic load and BSs have no additional cellular resources to fulfill new resource requests, then in case of a new resource request from a node, BS updates its table listing the relay stations and their neighborhood mobile nodes with their bandwidth status. The source selection procedure (SSP) is then applied to find a node which can release the available cellular resources and switch to ad hoc mode using the relay stations (or called the traffic diversion stations or TDSs).

Three algorithms have been proposed for source selection procedures (SSPs) for the routing protocols in ICNs [WYS08]. The first SSP (SSP1) selects the node which has highest number of neighbor TDSs. However in such case, a node with highest number of neighbor TDSs is always selected which results in congestion. The second SSP (SSP2) selects node with the highest available average bandwidth of the neighborhood TDSs. Thus SSP2 can avoid blocking some specific nodes. However the request rejection rate (RRR) of SSP2 would be higher than SSP1 since some specific TDS could be favored due to its positioning among the available TDSs of the selected node.

The third SSP (SSP3) combines SSP1 and SSP2 and thus a lower RRR could be achieved than SSP1 and SSP2. To simplify the working of SSP3, the BS sorts the table according to the number of TDSs and the available free bandwidth. Thus node with highest number of TDSs and with highest available free bandwidth is simply selected. Location aware SSP (SSP-LA) further extends SSP3 and keeps track of the mobility of the mobile nodes and select the node which has the highest possibility of moving out of the home cell. The selected node is referred as the pseudo-source node or simply the source node and it could also be the same original source node which request the new cellular resources. Conclusively BS can use any proposed SSP algorithm depending on the number and bandwidth of TDSs to efficiently discover the relaying routes.

The SSPs are proposed for the voice calling traffic which has fixed bandwidth requirements, however the algorithm can also be used for data traffic by considering the required bandwidth for the data transmission with the available free bandwidth.

3.2.2 Topology-based Routing

Most of the routing protocols have been proposed based on the particular topology of the network. In general, there are three major categories of topology based routing protocols, which are hierarchical routing, location based routing and flat topology based routing protocols. However, for multi-hop D2I/I2D communications, state-of-the-art schemes have been categorized into hierarchical routing and flat topology based routing.

The categorization of all the state-of-the-art topology-based multi-hop D2I/I2D routing schemes with their performance parameters and simulation tool used are listed in Table 3.6, and discussed below.

3.2.2.1 Flat topology routing

When nodes in the network do not have any specific structure like tree or cluster, nor have any location awareness mechanism then such arbitrary distribution of nodes is referred as flat topology network structure, and the routing is called flat topology routing. As like normal wireless network, routing protocols in multi-hop cellular network are categorized as reactive routing and proactive routing. All the reactive and proactive routing schemes for multihop D2I/I2D communication are BS-assisted in nature.

Reactive BS-assisted routing When the route is updated only when required, such routing is called reactive routing. In reactive BS-assisted routing, when required, a node finds the route towards the destination while also using the global information provided by the BS. A number of schemes are proposed under this category, which are discussed in detail below.

A fast and reliable route discovery solution considering mobility of nodes is proposed in [CC06]. The work finds the next hop node among the neighbor nodes while minimizing route setup delay and flooding of control messages required for the route discovery. The pilot signal is periodically broadcast by the BS, and the received power of this signal (PL_{BS}) is used as a link cost by all the nodes in the network. Therefore the neighbor node having the minimum total path loss (from mobile node to neighbor node (PL_1) and from neighbor node to BS (PL_2)) is selected as the next hop node.

The three schemes, inhibit access control (IAC), priority access control (PAC) and hybrid of IAC and PAC are proposed in [CC06]. In IAC, the node sends RREQ with its measured PL_{BS}. Only those neighbor nodes having their measured power path loss from BS (PL_2) less than PL_{BS} reply with RREP after random backoff. This reduction in number of RREPs reduces collision of RREP messages and the route discovery time. This reduction is quite significant when the user density is high. The routing overhead in terms of number of RREPs is also reduced. In case of collision, RREPs are retransmitted according to classical exponential backoff algorithm. The work argues that the conventional schemes have more number of RREPs and thus more collisions with the increase in number of users which results in longer route discovery time.

In PAC, the priority is decided only on the base of the link cost between mobile node and neighbor node. Therefore the lesser the PL_1, the *faster* is the RREP sent by the neighbor node. When enough high priority RREPs are received, source node prevents further RREPs by sending an early stop (ESTOP) message. The time of sending ESTOP message depends on the relative density of users and is assumed one fourth the average number of neighbor nodes for the simulations. Thus PAC reduces the route discovery time by sending an early ESTOP. This reduction is quite significant when the user density is high, because more number of neighbor nodes would have better link quality. However, in PAC the number of RREP collisions are higher due to absence of inhibit access control. Since the link cost PL_{BS} is not required in PAC, therefore PAC can be applicable to simple ad hoc networks.

In hybrid scheme, the two schemes work in conjunction and the priority is calculated by the multiplication of two path loss costs PL_{BS} (i.e. $PL_2 < PL_{BS}$) and PL_1 (lower path loss has higher priority). In all schemes, neighbor nodes reply with PL_1, and the node having minimum total path loss PL_1 and PL_2 is selected as next hop.

All the proposed schemes perform cross layer design taking into account physical layer, MAC layer and network layers. In the physical layer, the received signal strength is used to compute the path loss costs. The processes of inhibit access control (IAC) and priority access control (PAC) to reduce the number of collisions and make the discovery process faster is performed at the MAC layer. The network layer selects the appropriate next hop and the appropriate time to send ESTOP based on the information received from lower layers. Conclusively, IAC scheme finds the most reliable path and hybrid scheme finds the shortest discovery time. However, all the proposed schemes are limited to two hop paths only. In case of more than 2 hops, end-end route is not guaranteed. Furthermore in PAC, neighbor nodes nearer to the mobile nodes have lower path loss, and selecting such node results in higher number of total hops.

A power-strength-based selective forwarding (PSF) mechanism to efficiently flood route requests (RREQs) during the route discovery process, is proposed in [CH07; CHL10]. Each node uses received power strength of BS, to decide to be act as relay or not. This helps in reducing the signal overhead and interference during the route discovery process. The power threshold to ensure minimum connectivity probability is solved analytically. A detailed description of the complete PSF mechanism is as follows. The BS periodically sends cell access parameters on the broadcast channel (BCH). The sending UE calculates the distance (d) with the BS using Friis free space formula by using the average received power and the transmit power of BS.

For establishing multi-hop route, the signaling overhead by the mobile nodes induces interference among the nodes. The effect is negligible in mobile adhoc networks (MANETs) but is nontrivial in the multi-hop cellular D2D networks due to high transmission power of the cellular nodes. This consumes network resources and drains the battery of the standby nodes. Thus design of a routing algorithm with low signal overhead is crucial. Therefore, value for the maximum number of hops (N_{opt}) is specified to limit the RREQ flooding. The value of N_{opt} depends on the maximum allowed interference, permissible end-to-end delay requirement or in other words the maximum route discovery time. Each hop distance (d_{opt}) based on the N_{opt} relay UEs would be $d_{opt} = d/(N_{opt} + 1)$. The connectivity probability at each hop (P_s) must be greater than threshold probability (P_s, min) and is set by the network operator and it depends on N_{opt}, the transmission radius (R) of RREQ and the UE density (m/A), where m is the number of UEs in the cell under investigation and A is the cell area. This hop limiting routing is known as power efficient routing (PER) in literature.

The signaling overhead is further reduced by the proposed power-strength-based selective forwarding (PSF), by selecting only those candidate UEs located between the distance r (d_{opt} - Δd) and R (d_{opt} + Δd). This is the overlapping shaded area bounded by the two transmission circles of the UE and BS. The value of Δd is calculated by BS from given values (Ps, N_{opt}, A, m) and the distance d reported by the sending UE, which determine the transmission power of each RREQ (P_{RREQ}). The BS informs the value of P_{RREQ} to all the UEs. The value of Δd is highly dependent on UE-density and it affects the connectivity probability P_s. The higher values for Δd may increase the number of forwarding participants (Backer UEs) as well as the radio interference, while smaller values result in lower connectivity probability which could results in unsuccessful route discovery. An analytical model is proposed to find the optimal value of Δd. Finally, only those UEs which are within the specified distances will forward the RREQ packet.

However exact location estimation by the UEs is not easy, hence two approaches are proposed to implement the concept. In the first approach, the UE will forward the RREQ if the received power from the previous node is greater than P_r and less than P_R. But in this approach, a high number of RREQs are possible, since it could not specify any overlapping area with the UE after next. In second approach, the UE calculates its position based on the distance from the sending UE and the BS. The distances are calculated from their respective received powers. However this approach requires the sending UE to also broadcast its beacon signal for distance calculation by the intermediate UEs. The results show that the signaling overhead in terms of number of RREQs is considerably reduced while ensuring minimum connectivity probability. However mobility of nodes is not considered in this work. The proposed solution involves high number of computations which further limits its scalability.

Contour routing protocol uses received signal strength indicator (RSSI) as a measure of location prediction to communicate with the BS. Due to fluctuations in the RSSI, the location of a static destination node (BS) could be predicted within a donut-shaped region [KH12]. The algorithm neither uses GPS nor cellular triangulation for locating the node. GPS consumes a lot of power and is inaccurate in indoor environment. Cellular triangulation requires complicated synchronization among the BSs and is usually less accurate. The source node knows its own RSSI and the RSSI of destination node and thus the data packet proceeds towards the destination node in multi-hop using WiFi, by selecting next hop node having higher RSSI than the current node. Thus, the routing algorithm relieves the BS from the high traffic load. However the multi-hop communication is not suitable for delay sensitive data and for such application cellular communication is the only choice. A single copy of message is relayed hop by hop until it reaches the vicinity of destination node wherein multiple copies of a message is forwarded using limited flooding. This flooding is because of the fact that we cannot pinpoint the location of destination node using the RSSI, however a circular region with possible location could be identified. By controlling the contour region, the time instant to change single copy to multiple copy relaying could be adjusted. Results showed similar performance to flooding with reduced traffic overhead with the proposed routing algorithm.

The work in [MA09] proposed routing metrics and route discovery mechanism for communications with the BS using uplink band. Four routing metrics are compared to determine the one with the best throughput under varying number of users in a cell. Routing with shortest distance (RSD), routing with minimum interference (RMI), routing with best link gain (RBL) and routing with combined interference and link gain (RCIL). The cell is divided into three concentric disks numbered from 0 to 2. Nodes within the disk 0 could communicate directly with BS. The nodes in disk 1 and 2 could communicate with the BS with the help of nodes in inner disks. In the route discovery mechanism, only those nodes having higher link gain reply to the route request. It is found via simulation that the routing metric RCIL performs the best among all the four metrics. This is because, the RCIL is the combination of two other routing metrics RMI and RBL, wherein node having the best link and have minimum interference over the other nodes is preferred.

To sum up, the four main algorithms proposed under this category are Hybrid PAC/IAC, PSF, Contour and RCIL algorithms. In hybrid PAC/IAC, a node selects the next hop node having the minimum total path loss (i) from current node to next hop node and (ii) from next hop node to BS. In PSF, two-hop communication is assumed, and only those nodes participate in route discovery which are in between the UE and BS. PSF further shortlists the candidate next hop nodes by selecting only those UEs which locate between the distance (d_{opt} - Δd) and (d_{opt} + Δd). This is the overlapping shaded area bounded by the two transmission circles of UE and BS. The values of the hop distance (d_{opt}) and Δd are calculated by BS from the given values of distance with the BS (d), maximum number of hops (N_{opt}), connectivity probability (P_s), cell area (A) and number of UEs in the cell under investigation (m). Both hybrid PAC/IAC and PSF are proposed to reduce the signaling (or routing) overhead, which also reduce the average route discovery time.

In Contour routing, a single copy of message is relayed hop by hop until it reaches the vicinity of BS wherein multiple copies of message is forwarded using limited flooding. It is assumed that due to the fluctuations in RSSI, the exact location of the BS could not be identified and could be predicted within a donut-shaped (contour) region. By controlling the contour region, the time instant to change single copy to multiple copies could be adjusted. Thus contour routing reduces the burden over the BS by using multi-hop communication for delay tolerant traffic. In RCIL, the routing metric selects the route having the best link gain and having the minimum interference with the objective to get the best throughput under varying number of users in the cell.

Proactive BS-assisted routing When the route decision is made by each node individually however the central entity helps in providing some global information, the routing is said to be the BS-assisted routing. In proactive BS-assisted routing, nodes periodically update routes based on the their local observations as well as the global information provided by the centralized entity.

An Efficient routing protocol (ERP) for reliable communication with the BS is proposed in [LS08]. In ERP, if the channel quality (measured in terms of channel capacity) of a node with the BS is not good or the BS is overloaded, then the node chooses a relay node with a better BS channel capacity to forward data to the BS. A node first selects the neighbor nodes having sufficient buffer capacity, it then selects node having the highest channel capacity. For every data packet, the status of neighbor nodes is checked and the best next-hop node is selected, according to the adaptive routing algorithm. In the route/neighbor discovery process, BSs send beacon message periodically, which are used by nodes to determine the channel capacity with the BSs. The nodes also periodically broadcast HELLO message to neighbors to inform about their presence and the information about the BS channel capacity is also piggybacked in it. Due to piggybacking, no extra routing overhead incurred to inform about channel status in this discovery process.

Results showed that ERP can achieve higher throughput than AODV. This is because in AODV, all nodes use shorter hops paths which results in congestion and thus have more packet drops. While longer paths have more probability of link breakage due to nodes mobility, thus higher packet drops and overall less network throughput. While in ERP, always the next higher capacity relay node is chosen or otherwise is sent directly to BS, therefore have overall good network throughput. With respect to routing overhead, AODV routing overhead is significant with the increase in number of nodes which result in high congestion, while ERP does not have any significant overhead because of its simple neighbor discovery process. However ERP has been limited to two hops only in the simulation.

Table 3.6: Comparison of topology based multi-hop D2I/I2D routing algorithms

Topology structure	Proactive / Reactive	Distributed / Centralized / BS-assisted	D2D Routing Algorithms	Performance parameters	Simulation Tool
Flat	Reactive	BS-assist	PAC & IAC [CC06]	Average route discovery time, Average total received power	-
			PSF [CH07], [CHL10]	Successful connectivity probability, Total number of RREQs, Total transmission power required for RREQs	NS-2
			ContouR [KH12]	Average delay time, Traffic overhead, Delivery ratio	ONE
			RCIL [MA09]	Throughput	-
	Proactive	BS-assist	ERP [LS08]	Throughput, Routing overhead rate	NS-2
Tree based	Proactive	Centralized	RRR [AH+04]	Throughput	Numerical results
			MRC [Ima+06]	Number of control packets, Average packet error rate	-
			LSSON [WL07]	Average hop count	-
			JRS [LL06]	Percentage of traffic assigned to each cell (for load balancing)	MATLAB

3.2.2.2 Hierarchical routing

Hierarchical routing is the mostly widely used technique in the communication networks. Nearly all the existing wired networks use hierarchy in the form of 'network', 'subnet' and 'sub-subnet'. Using this hierarchy, routing in the internet use inter-domain routing, to forward the traffic based on only the 'network' address. After reaching the destination network, the intra-domain routing is used to forward the traffic to the destination node using the 'subnet' and 'sub-subnet' addresses. Thus, routing tables in hierarchical routing are summarized, since routing table entry for the 'network' is suffice for all the 'subnets' and 'sub-subnets' in the network.

However, in wireless networks, where most of the wireless nodes have limited amount of battery, maintaining wireless network hierarchy is quite energy-consuming. Anyhow, due to the appealing benefits of hierarchical networks, the wireless networks have two possible types of network hierarchy, which are 'clusters' and 'trees'. Accordingly, the hierarchical routing has also two types; the cluster based routing and the tree based routing. It is interestingly found that all the proposed hierarchical routing schemes for multi-hop cellular networks are the tree based routing.

In a tree-based routing scheme, the BS or the mobile switching center (MSC) acts as a root of the tree and manages the tree structure. In some works, BS acts as a simple destination node and the hierarchy is constructed by the mobile nodes in the network. The tree-based routing is preferred when network scalability is of major concern. The tree-based communication is worst if source and destination nodes are close to each other. All state-of-the-art tree-based routing protocols are proactive, since BS needs to regularly update the tree structure. The detailed description of these existing tree based routing schemes are as follows.

Andrew et al. [AH+04] investigate the effects of the traffic load or the intensity of nodes on the reception range of the nodes. It is found that with the increase in traffic intensity, the interference also increases which results in reduced reception range of the nodes and thus finally increase in the number of hops between the source and the destination nodes. The reception range of the BS is comparatively larger and is also affected by the traffic load however the effect is not such adverse as on the mobile nodes. The routing algorithm grows a tree initiating from the BS. The nodes are added with the increasing distance with the BS. The selection of relay requires that (in decreasing priority) (a) reception range distance is less than the maximum threshold distance (b) load is balanced (c) number of hops are minimized. The average throughput for each node is calculated based on the successful probability of transmission. The successful transmission requires that (a) a node transmit its own data with probability $p0$, (b) the next hop node j is not transmitting with probability $1 - pt(j)$ and (c) the interference at the next hop node (receiver) is low enough to meet the required SINR threshold with the probability $ps(j)$. Assuming all events to be independent, the user $i's$ throughput is calculated as $u(i) = p0(1-Pt(j))ps(j)$. However the work only considers a unidirectional traffic from mobile nodes to a single BS only, using uplink band with no fading or power adjustments.

The work in [Ima+06] proposed routing scheme for multiple route coding. The routing scheme consists of two phases. In proactive phase, routes between BS and relay nodes are proactively established and updated periodically. BS sends reference packets which is forwarded by the relay nodes until the maximum number of hops is reached. The maximum hop limit is defined which reduces the number of control packets. In this way, multiple trees rooted at the BSs are constructed by the relay nodes. Multiple trees increase the possibility of disjoint routes. In reactive phase, a user node establish route to the BSs on demand, when data transmission is required. The RREQ packets are generated by the mobile nodes which are forwarded until the BSs. The BSs replies with routes which are mutually disjoint that is each route does not share the relay nodes. This reactive approach further reduces the number of control packets. Results have shown the decrease in number of control packets and also reduce average packet error rate. However some limitations in the proposed scheme are as follows. The scheme assumes that dedicated relay nodes are used which forwards the data of only one source node at a time. Moreover, the work is limited to uplink transmissions only.

The Large Scale Self Organizing Network (LSSON) routing scheme that scales to large areas keeping relatively constant user density is proposed in [WL07]. The routing scheme constructs trees which are rooted and maintained by the BSs. Each node maintains a parent node for each tree. Cluster is finally formed by joining a cell with its 6 neighboring cells in hexagonal structure. Such clusters are maintained by roots by periodic updates from the nodes.

The hierarchical proactive routing scheme is employed with two tiers, the intra cluster routing and the inter cluster routing. The intra cluster or local routing is used when the message reaches in the cluster/cell which contains the destination node. The message is forwarded upstream to the BS via multi-hop, and then the BS finally broadcast the message directly to the destination node in one hop. The downstream message could be more than one hops if the destination node is out of the BS communication range. The inter cluster routing is used to forward the message between the cells (clusters). The message is placed on the tree of the next hop cell towards the destination node. When the message reaches the cluster which contains the destination node then the intra-cluster routing is continued ahead. Farthest neighbor node is selected for message forwarding in case of more than one available neighbor nodes towards the destination.

Nevertheless, this work uses strategic placement of fixed relay nodes, relieving mobile nodes from the routing overhead. Geographic location of BSs and destination node is also required to be known for the routing process. Stationary nodes are considered in the simulation. It saves cellular resources only in the upstream communication, since downstream communication is still carried out in classical one hop manner. Furthermore, it can be seen that the communication is worst if the source and destination nodes are very close to each other.

A joint routing and scheduling algorithm is proposed in [LL06]. The algorithm behaves differently both the for the uplink and the downlink transmissions. For uplink transmission, strategically placed static relay nodes (or routing nodes or RNs) runs the algorithm in a distributed manner. For downlink transmission, the algorithm works in a centralized manner, being used by the mobile switching center (MSC). The routing algorithm balances the traffic load among the bottleneck BSs (similar to balancing the load among intermediate nodes in the ad hoc network). Spanning tree rooted at the BS is used as routing topology based on the distance vector technique. Spanning tree is referred as layer and the number of layers equal to the number of BSs. Each non-root node maintains information about all available layers for routing purpose. Each layer table entry contains that layer ID, parent ID and its depth. A level-d node in the layer hierarchy has a depth d and is d nodes (hops) away from the root. Each RN periodically broadcast control packet so that the neighbor nodes updates its existence. When a new RN is added into the network, it finds neighbor nodes with smallest depth for each available layer. The new RN sets the neighbor node as the parent node and sets its depth to be the one plus the depth of the parent node in its layer table. When the load on an RN is high, it broadcast the depth of the layer to be infinite to behave like a leaf node, in order to avoid any further relaying packets.

For an upstream data packet the source node sends the data packet to any nearby RN and then the RN selects the layer according to the layer scheduling algorithm. In downstream transmission the MSC selects the serving RN and corresponding layer (means a BS) according to the layer scheduling algorithm. The intermediate RNs cannot change the serving RN and other header fields of the data packet. Each intermediate RN will forward the data packet only if it receives from its parent and the destination is one of its descendants RN in the respective layer. The MSC collects the load information of each layer from the respected BS, and then informs about the updated load status to all the BSs. The BS forwards to the RNs not only its load information but also of other layers being serviced by the MSC. This load information is the available channel capacity for a layer (BS). This information is used by the RNs to make layer scheduling decision. It is noted that if the available channel (overlay) capacity and packet size is same for all BSs (layers) then the round robin is the best scheduling algorithm however such setup is not used in real practice. The simulation results showed that the proposed numerical scheduling algorithm is suitable for heterogeneous networks as the algorithm performs well and the performance variation effect is unnoticeable under drastic changing traffic load.

To summarize, the four algorithms proposed under this category are RRR, MRC, JRS and LSSON. The RRR algorithm uses mobile nodes as the relay nodes, while MRC, JRS and LSSON use operator installed fixed relay nodes for their route decisions. The RRR routing investigates the effects of the traffic load on the reception range of the nodes. By utilizing the fixed relay nodes, cellular resources are saved in upstream communications in LSSON, the number of control packets and average packet error rate are reduced in MRC, and a stable algorithm that performs well, and the performance variation effect is unnoticeable under drastic changing traffic load, is proposed in JRS.

3.2.3 Content-based Routing

Content-based routing is normally used to establish routes for sharing the frequently used data among users, like viral videos etc. The BSs act as the file servers and multi-hop route are established to share the frequently used files among users.

The three different versions of content-based routing are proposed in [Du+14], D2D routing without peer-to-peer (P2P) share, D2D routing with direct P2P share (R-DPS) and D2D routing with coverage-based P2P share (R-CPS). In these routing, D2D nodes which download data from the file servers are called as subscribers. In order to increase average download rate and average throughput, it is desired that the subscriber nodes that download similar contents, share their data during transmissions. Such subscriber nodes are called as *peer* D2D subscribers.

In the first routing scheme i.e. D2D routing without P2P share, shortest hop route from each server to subscriber is established, regardless of sharing the same contents with different subscribers. In the second routing scheme i.e. the R-DPS scheme, the route formed by the first scheme is extended in order to share the contents of a subscriber with other subscribers. The extended route is used only if the number of hops 'from current subscriber to another subscriber' is less than the original number of hops 'from the other subscriber to its server'. This improves the overall network throughput by sharing the data packet with its peer. In the third routing scheme i.e. the R-CPS scheme, the broadcast nature of wireless nodes is used to make a route that cover all the subscribers. The neighbor nodes of a subscriber are the candidate nodes to search for route to other subscribers. If any such route is found, and the number of hops 'from the candidate node to the new subscriber' is less than the original number of hops 'from the new subscriber to its server', then this new route is used. It is important to note that (1) this new route do not pass through the subscriber node, as in R-DPS scheme, and (2) both subscribers receive data from the same server, which improve the average download rate.

The processes defined above for R-DPS and R-CPS schemes are repeated for every other subscriber to find the best optimum routes. In all these schemes, the cellular user spectrum that keeps interference to other users under a tolerable level is used.

3.2.4 Summary and Insights

In all state-of-the-art multi-hop D2I/I2D routing schemes, network relays are used to establish multi-hop routes as shown in Table 3.4, and thus the routing is also regarded as *network relay* routing. The fixed network relays are used only in tree-based routing, while the mobile network relays are used in all reactive and proactive BS-assisted routing. As an exception, a tree based routing scheme named 'reception range aware routing (RRR)' also uses mobile network relays for route decision. All the topology based (reactive, proactive and tree-based) routing schemes work in underlay mode and utilize uplink band for multihop D2I/I2D communication, except in JRS (a tree-based routing scheme) which uses overlay mode for communications. Such classification of routing algorithms based on the type of relay and spectrum used, will help to quickly select a routing algorithm as per the network model requirement. It is interesting to note that no scheme is proposed for finding an optimal route from BS to UE in underlay mode. Therefore, schemes for efficient delivery of data from BS to UE(s) in underlay mode should be explored.

3.3 Ad-hoc routing protocols for D2D networks

When the cellular network services are either partially or totally unavailable in case of natural disasters (floods, earthquakes etc.), or when the network is overloaded or damaged in case of human-made disasters (fires, accidents, terrorist attacks etc.), or when the user is out of coverage or in dead-spot area, then the *ad-hoc routing* would be the *only* choice for multi-hop D2D communications. In case the user is inside the network coverage, and the routing decision does not take the advantage of the presence of centralized control entity, nor care for BS or any other on-going user transmissions, then such routing is also *purely* ad-hoc routing.

All the state-of-the-art ad-hoc routing protocols for D2D networks are distributed in nature, and can be classified as: incentive (or profit)-based, multipath coding-based,

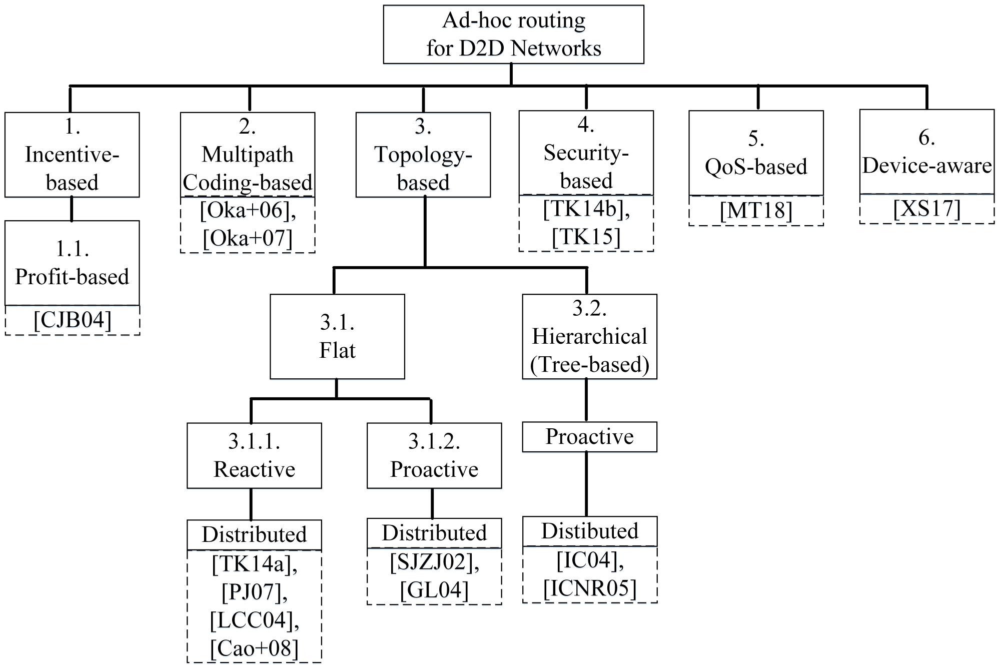


Figure 3.2: Taxonomy of state-of-the-art ad-hoc routing schemes for D2D networks.

security-based, QoS-based, tree-based, reactive and proactive routing.

The routing scheme in which the users are motivated to participate in relaying the data of other nodes by using some incentive (or profit), is called incentive (or profit)-based routing. When quality of service (QoS) cannot be compromised, for example in live video streaming, the routing scheme is called QoS-based routing. When data confidentiality is of utmost concern, the routing scheme is called security-based routing. If each node decide to participate or not in relaying the data based on its capabilities, the routing is called device-aware routing. For large size networks, tree-based routing is preferred. The reactive distributed routing is the most widely used routing type. In reactive distributed routing, routes are discovered only when required, which saves precious resources from unnecessary periodic route updates. The proactive distributed routing is used for delay-sensitive applications and updates routing table regularly in order to instantly provide the route when required without any delay.

A number of ad-hoc routing protocols have been proposed for D2D networks in literature. These routing protocols have been classified as shown in Fig. 3.2 and discussed in detail below. The performance parameters and the simulation tools used in the respective routing schemes are listed in Table 3.7.

Table 3.7: Comparison of ad-hoc topology based routing algorithms for D2D networks

Topology structure	Proactive / Reactive	Centralized / BS-assisted / Distributed	D2D Routing Algorithms	Performance parameters	Simulation Tool
Flat	Reactive	Distributed	LBS-AOMDV [TK14a]	Bandwidth consumption, Hop Count, Number of RREQs	MATLAB
			RAR [PJ07]	-	-
			MCPR [LCC04]	Average total consumed power, Average success rate, Average number of hops per path	Numerical results
			MMRP [Cao+08]	Delivery ratio, End-to-end delay, Routing overhead, Remaining energy capacity	NS-2
	Proactive	Distributed	CRSP [SJZJ02]	Transmit power, Throughput per BS	Numerical evaluations
			ARCE [GL04]	Route lifetime probability, Packet loss, Packet overhead	NS-2
Tree based	Proactive	Distributed	DST [IC04], [ICNR05]	Percentage of optimal total throughput	-

3.3.1 Incentive-based Routing

The objectives of incentive based routing is to establish end-to-end communication among the devices by motivating the intermediate users to relay the data using different incentives. Profit is one of the incentive that motivate the nodes to act as relay, and the routing is called profit based routing.

3.3.1.1 Profit-based routing

Routing algorithm that provides some cost to the intermediate nodes for providing their services as relay, with the aim to find a low cost route from source to destination is known as profit based routing.

A profit-based routing algorithm that maintains a multi-hop route to the BS when the profit of the BS and the relays are positive is proposed in [CJB04]. The algorithm aims at gaining profit instead of maximizing profit, nevertheless route with minimum number of hops are preferred because of high profit. On the other hand, the cost demand of each intermediate node depends on the respective power consumption, thus nodes on the route with higher number of hops have to consume comparatively less power. Therefore, in some case, the overall cost of route having high number of hops could be smaller than the route having lower number of hops.

Each node do not need to remember route to any other node but BS. The cost of uplink connection with the BS increases with the increase in distance with the BS. Thus if a route request failed then the source regenerate RREQ with higher revenue offer, as motivation. However there are some serious limitations in the proposed scheme. The energy consumption of nodes during control packets forwarding is not considered. Such forwarding of control packets might only waste the battery energy without any gain if the final route is not established using these nodes. Moreover nodes are assumed to be static and having equal amount of power. Each node waits for some time to gather enough RREQs before forwarding further. This induces high delay, but reduce the routing overhead. If a better RREQ is available after the wait time, then such RREQ is wasted. Furthermore unlicensed band is used for communication between relays. All the revenue-cost calculations are performed at the BS, thus the algorithm is BS dependent and cannot work autonomously.

3.3.2 Multipath Coding-based Routing

In single path routing, when a path fails, the communication is interrupted until a new path is established between the source node and the destination node. Therefore, to increase reliability, multipath routing is used which establish multiple paths (preferably disjoint paths) between source and destination. As the paths are disjoint, so if one or more paths fails, but not necessarily all, the communication can still be carried out however at lower rate. Thus, multipath routing provides better QoS and better resource utilization [SDJ15].

Multipath routing is used as one way for cooperation between the traditional cellular communication and the D2D communications by using multiple parallel paths between source and destination nodes, where the main data stream is split into streams of lower data rates and routed to the destination through cellular and ad-hoc D2D connections. [Jam11].

In [Oka+06] and [Oka+07] a multipath route coding scheme is proposed that encode a packet and divide it into sub-packets. Each sub-packet traversed along its route and finally the destination BS combine and decode the packet. This reduces the packet loss and the error rate by exploiting diversity gain. To further reduce the influence of the route loss and thus also the packet errors; disjoint routes are selected in multipath route coding scheme in which the forwarding nodes are not shared between the source node and the BS (destination). However, the number of control packets must be kept small [Ima+06]. To increase the diversity gain; more and more number of routes are discovered.

3.3.3 Topology-based routing

The state-of-the-art ad-hoc topology-based routing schemes for D2D networks have been categorized into flat routing and tree-based routing. All the topology-based schemes with their performance parameters and simulation tool used are listed in Table 3.7 and discussed next.

3.3.3.1 Flat topology routing

There are two broad categories of flat routing, i.e. reactive routing and proactive. All the flat topology-based routing schemes are distributed in nature, as discussed below.

Reactive distributed routing In reactive distributed routing, autonomous nodes find routes on demand. Th ad-hoc on-demand distance vector (AODV) routing is one of the famous routing protocol in literature that uses reactive distributed routing. The AODV has been modified in thousands of ways in different type of wireless networks, in order to fulfill their respective network requirements. For example, in order to have multiple paths to a destination node, AOMDV (ad-hoc on-demand multipath distance vector) is proposed. The routing protocols proposed under reactive distributed routing are discussed as follows.

Load balancing-based selective - AOMDV (LBS-AOMDV) routing [TK14a] is an extension of AOMDV. As like AOMDV, it establishes multiple loop-free and link disjoint paths, and to further reduce the routing overhead it limits the flooding by selecting only those nodes having links with given bandwidth threshold. In this way the real-time traffic demands could be ensured.

Resource aware routing (RAR) protocol that uses the reactive distributed routing technique is proposed in [PJ07]. Three performance metrics have been studied for the resource aware routing (RAR) considering energy efficiency and relay capabilities in [PJ07]. Two type of relay nodes have been used, fixed relay nodes which are installed and operated by the network operators, and mobile relay nodes which are normal mobile nodes that provide services of relaying. The first metric preferred routes having more number of fixed (dedicated) relay nodes than mobile nodes to take advantage of the unlimited energy of dedicated nodes. The BS waits for pre-defined duration after receiving first RREQ, for the possibility of getting more RREQs. In case of receiving more than one (shortest path) RREQ, BS chooses earliest arrived RREQ. The second metric avoids routes having nodes with minimal residual energy. This prolongs the network lifetime and circumvents network partitioning. Third metric considers the relay capabilities in terms of processing power and memory vacancy (buffer capacity). While using this metric, if BS receives a better RREQ later, then it sends additional RREP.

However there are no evaluations regarding the performance of the studied metrics, nor any new metric to improve the performance of cellular communications is proposed. Moreover the routing algorithm does not count number of energy-limited mobile relays compared to energy- unlimited fixed relays. This might results in higher number of mobile relays in a path and thus high consumption of the limited resources of the network e.g. energy. Furthermore no minimum threshold value for energy is specified for mobile relays, which might results in route failures. This is because of using those nodes whose energy is reaching to zero.

A cross layer design using time-based MAC and power aware routing algorithm is proposed in [LCC04], named as minimum consumed power routing (MCPR). The algorithm considers the minimum total transmission power among all probable routes. Each RREQ packet contains information about not only transmission power, but also receiving power and total consumed power along the route. All the control packets like RREQ and RREP are sent with maximum power and data packets are sent with adjustable minimum required power.

To prefer the routes with minimum required power, RREQ packet which is received with high power is forwarded with a very small wait interval, while RREQ having low power has to wait a large interval of time. The wait interval (Twait) is set such that the cumulative wait time for at least two hop nodes with high received power is smaller than the one having single hop with low received power. This is made possible with new timer-based MAC protocol, which modifies the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) for rebroadcasting RREQs. This ensures that long distance nodes will not forward the data packets earlier than the multi-hop nodes with smaller distances. Thus the final route has more number of hops compared to shortest path but has the high energy efficiency because of lower total consumed power.

If the destination is BS, the destination IP address is a predefined value and thus BSs do not need to advertise their IP addresses. If the RREQ is received by a BS, then the BS selects an MCPR path and forward upward to the controller. The controller selects an MCPR path among paths received from various BSs, and send RREP to the selected BS. If a mobile node receives RREPs from several BSs operating under different controllers, then a mobile select the one received first and send NACK to the remaining BSs.

The results have shown the superiority of proposed algorithms Timer-based MAC + MCPR over CSMA/CA + AODV and CSMA/CA + MCPR. Moreover the algorithm is scalable, since the algorithm runs on each mobile node in a fully distributed way.

Multiple metric routing protocol (MMRP) that integrates hop count, traffic load and energy consumption into the path cost calculations is proposed in [Cao+08]. The purpose is to explore path that minimize energy consumption and the number of hops while avoiding congestion at most favorable nodes. First extension of this protocol MMRP-I (MMRP-Improved) enables discovery of more optimal paths after the discovery of first path. Second extension of this protocol MMRP-A (MMRP-Adaptive) enables heterogeneous devices to set the path cost according to their classifications e.g. battery and bandwidth. The disadvantage of a single path cost metric is the overloading or depletion of resources in the hotspot (along the preferred paths). The proposed MMRP uses a simple linear combination of cumulative weight metrics. It modifies the traditional AODV protocol. Every node in the path updates the path cost field in the RREQ using the proposed cumulative weight metric while forwarding the RREQ. When destination node receives the first RREQ, it waits for some particular time to receive other possible RREQs.

In MMRP-I, if a node finds an RREQ message from the source with path cost better above some threshold than the previous one, then it rebroadcast the new RREQ. This increase the performance of the route in terms of delivery ratio and delay (because new RREQ probably have better delay option) at the expense of higher routing overhead and energy consumption. In MMRP-A, the value of path cost metrics could be set by the nodes themselves according to their classifications or real time system measurements/requirements. For example, a device with fixed power supply does not consider the energy metric. The results showed improved performance and overall less system resource consumption when appropriate weights metrics are used for the calculation of the path cost calculations. However, all the schemes assume constant bit rate (CBR) traffic and thus the approach is not directly feasible for bursty traffic.

To summarize, there are four schemes proposed for reactive distributed routing. The LBS-AOMDV scheme reduces the routing overhead by selecting only those nodes having links with given bandwidth threshold. In this way, the real time traffic demands could also be ensured. The RAR scheme considers energy efficiency and relay capabilities in routing decision. The RAR prefers to use operator installed fixed relay nodes over mobile relay nodes, and avoids routes having nodes with minimal residual energy. The MCPR selects route with minimum consumed power for improving the energy efficiency. The MMRP uses cumulative weight routing metrics like hop count, traffic load and energy consumption, for route decision. The value of path cost metric could be set by themselves according to their requirements. For example, a device with fixed power supply does not consider the energy metric.

Proactive distributed routing In proactive distributed routing scheme, autonomous nodes periodically update their routing tables in order to have constantly updated route information to every other node in the network.

A Combined routing, channel scheduling and power control (CRSP) scheme has been proposed in [SJZJ02]. The scheme jointly considers the physical, data link and network layers. The aim is to maximize the total network throughput by finding optimal solution for joint routing, scheduling and power control. The optimal solution depends on the information available about the network, the system constraints and the defined objective function. The paper assumes that complete channel state information is available which include path loss and shadowing information, known to both the transmitter and the receiver while fading information is available only to the receiver.

The only system constraint is to transmit $C * Tbits$ in $Tseconds$ where $Cbits/sec$ is the required capacity. The objective function is to minimize the total transmit power for a fixed amount of information transfer, where power is considered to be the only system resource. In general, every node knows about the traffic rate, induced interference, queue size, transmit power and the total induced interference (up to the destination). The information is shared between the neighbor nodes periodically and the then the optimal routes are calculated. The base stations are the terminal points of packets, and a zero cost is reported by the BSs to their neighbors. However there is one serious limitation in this paper. This paper assumes that a mobile station can participate in at most one data flow for a given time which is unrealistic for packet data service.

Ad hoc routing for coverage extension (ARCE) protocol is a proactive routing scheme proposed in [GL04]. The ARCE increases the capacity by bypassing the blocked BSs by simply not specifying the destination BS address in RREQ packet. BS will reply to RREQ only if having sufficient resources. To ensure sufficient route lifetime and to avoid frequent route updates, ARCE limits the maximum number of hops to five. Each node waits for maximum of 10ms to merge all the received RREQs into a single RREQ, which contain link information of all previous routes till that node. Therefore the size of RREQ and RREP is larger than packets of other source based routing. This increases time delay however reduces the overhead significantly. In contrast, if multiple RREQs are forwarded by a node then it increases the routing overhead while keeping delay to minimum. If the node is neighbor of the BS it forwards the RREQ only to the BS, or otherwise broadcast to all its neighbors.

BS assigns an associativity value to each link. The associativity value shows the freshness information received about the link and the link is deleted when the associativity value decreases to zero. BS receives multiple RREQs from many routes and update the link load and associativity value accordingly. The link load is calculated by taking into account all routes that use a particular link. Multiple disjoint routes can then be calculated based on link load and associativity value by using Dijkstra algorithm multiple times. Every time, BS increases the weights and then the Dijkstra algorithm is repeated to find a new route. BS informs about all the candidate routes to the source node via the primary route. The data packets contain the source route information. In case of any failed link, the intermediate node generates a route error (RERR). On reception of RERR, the source node deletes all routes using that particular link and then use alternate backup route. Simulation results showed the improved performance of ARCE with two additional backup routes. However further additional backup routes result in more overhead with no considerable performance gains since the routes used to break often. ARCE is not suitable for delay sensitive network due to RREQ delay at every hop. It is also not suitable for large scale network since the maximum number of hops are limited to five.

To summarize, the two schemes for proactive distributed routing are CRSP and ARCE. The CRSP scheme is proposed to maximize the total network throughput by finding optimal solution for joint routing, scheduling and power control. The ARCE scheme increases the network capacity by bypassing the blocked BSs.

3.3.3.2 Tree-based routing

In tree-based routing scheme, a hierarchy is maintained in the form of tree with BS usually acting as a root node. The tree-based routing is preferred when network scalability is of major concern.

A distributed spanning tree (DST) algorithm that avoids RREQ flooding problem and maintains the routes to the BS with minimum routing overhead has been proposed in [IC04], [ICNR05]. DST maintains a close to optimal spanning tree by using distributed topology trees. Maximum spanning tree is used to maximize the throughput. Each link capacity is updated based on measuring the response time from the periodic updates of the neighbor nodes. The refresh rate depends upon the frequency of the network changes.

There are two strategies proposed to update the child parent relationship. In the first strategy, a node cut the link with the parent and update the parent based on the periodic neighbor node probe packet. O (d log n) messages are generated where d is number of neighbor nodes, and n is the total number of nodes in the network. In the second strategy, parent node sends updates periodically and the link with the parent is cut if the rate falls below threshold. The first strategy has more overhead but is also more optimal.

By using the tree structure, the route discovery requires only O (log n) messages instead of O(n) as in flooding. For calculating maximum capacity path for m-th concurrent flow, the resources already consumed in m -1 flows are first subtracted. It is important to note that due to interference, not only adjacent links but also links adjacent to neighbor nodes are also blocked. Results show high network throughput which ensure the suitability of DST for large size networks. However there are two questionable things in the DST algorithm. Firstly, the reduction of routing overhead in comparison to RREQ flooding is not shown in results. Secondly, the periodic route updates are used, which are not suitable for highly dynamic networks since the outage probability of such networks is very high.

3.3.4 Security-based routing

The security of data in terms of confidentiality, authenticity and integrity of data are of critical concerns in this age of data communications.

In multiple path routing protocols, data splitting and data shuffling strategies are used in [TK14b; TK15] to encode the data, for making the data confidential. In conjunction with encoding, network coding (NC) scheme is used in [TK14b] and disjoint multi-path routing scheme is used in [TK15] in order to safe data from eavesdropper attacks. The data is splitted in chunks of six bits each, and then some random pattern synchronized by the source and destination is used to shuffle the data between different chunks. Each data chunk then travel through different paths to reach to the destination,. Results showed that an eavesdropper can never intercept the data completely in any of the given cases. However, interception of data is more higher in internal attack (i.e. when the eavesdropper is nearer to the source) than as compared to external attack. Moreover, the quantity of data interception is more lower, when data splitting and shuffling is used with NC in [TK14b] and with multipath routing in [TK15].

3.3.5 Quality of Service-based Routing

In communication networks, three mechanisms are generally used to ensure the quality of service (QoS). These are reservation, differentiation and over provisioning [MT18]. Among all the three mechanisms, reservation is the most commonly used strategy, in which the resources are allocated for a particular connection. In QoS based routing, the QoS guarantee not only cover the single hop, but instead cover the entire multi-hop route.

An admission control scheme with an on-demand quality of service routing (OQR) protocol is proposed in [Lin01] for the multi-hop cellular network, that establishes virtual connection (VC) between the source and destination. The process of establishing a QoS route is described as follows. The source node broadcasts the route request (RREQ) packet. All the neighbor nodes that received the RREQ packet, check the source address within the source list of packet to avoid routing loops and the sequence number to reduce redundancy. Long routes are difficult to maintain in dynamic environment thus time-to-live (TTL) field in the RREQ packet limits the number of hops and also controls the flooding traffic since unlimited packet flooding degrades the network performance. The admission control scheme guarantees the bandwidth for real-time applications by finding a feasible bandwidth route. Thus the required bandwidth for an application is mentioned in terms of number of time slots.

Each node calculates the link bandwidth by the intersection of the free slots of itself and the previous node. If the number of slots are not equal to required bandwidth slots then RREQ is dropped. The process of forwarding the RREQ packet continues and if the path bandwidth (or called end-to-end bandwidth) is met till the destination node then the RREP is replied to the original source. Multiple paths could be established to ensure more robust packet delivery. When enough RREQs are received by the destination node, then CLEAN_RREQ packet can be broadcasted by the destination node to clean the RREQ packets that are still roaming in the network in order to reduce the flooding overhead. RREP sent by the destination node will reserve the slots backward till the source node. In case of failure (for example slot is already booked or route breaks) at any node, a NACK (i.e. RESERVE_FAIL) is sent back to the destination node to clear all the reservations in between. If no route is available till the destination, the source node can be notified by a NACK (i.e. NO_ROUTE). If the source node do not receive any kind of response packet, then it can re-initiate the route request after a timeout.

Once a VC is setup, the source begins to send data packets. When data transfer is complete, the slots are released in order to be available for new connections. If this last packet is lost, then the slots may erroneously remain reserved, thus each slot is reserved for a timeout. If the route breaks while sending the data packet, a NACK (i.e. ROUTE_BROKEN) is sent by the nodes at the breakage point to both the source and destination in order to release the all the reserved slots in between, and also drops the data packets of this connection waiting in the queue. Results showed that the scheme greatly reduces the failure of the call setup and the routes are mostly very close to shortest paths.

3.3.6 Device-aware routing

In device-aware routing, each node decides to participate in relaying the data based on its capabilities. Thus, the routing can be easily deployed in network having devices with heterogeneous capabilities.

A device-aware routing and scheduling algorithm (DARA) is proposed in which each device decides how much data it can handle based on its processing power, remaining energy, and incentives [XS17]. A network utility maximization (NUM) formulation has been developed in order to incorporate device capabilities. A node after deciding to participate in forwarding the data (routing decision); activates the link for the next hop node (scheduling decision) and thus the algorithm involves both the routing and the scheduling decisions. The DARA has been compared to the traditional back-pressure algorithm wherein each device has to forward and schedule all the data it receives, even if a device does not have sufficient resources. The DARA has been implemented between the transport layer and the application layer and thus can be easily adjusted to any operating system of the mobile devices. The results from the test-bed have shown significant throughput improvement over the back-pressure algorithm.

3.3.7 Summary and Insights

In case of network congestion or network unavailability, an ad-hoc routing protocol is the only choice for multi-hop D2D communications. However, it is important to note that these distributed routing protocols can not ensure security as any other infrastructure-based centralized control entity can do.

There are many works in literature that do not propose any new routing scheme but instead use or check the suitability of existing routing schemes for D2D networks. Few of the works are discussed in detail as follows. Yuan et al. and Wang et al. use shortest path routing, and evaluate the collision and outage probability in multi-hop and conventional cellular communication scenarios [YGW15], [Wan+15]. As the location accuracy is complex and power consuming in cellular networks, therefore collision area (CA) is defined to mitigate interference from the BS and other D2D UEs [YGW15]. The shortest path routing (SPR) is used to explore the multi-hop path and find the collision probability for the intermediate nodes in the routing path. The probability for collision invokes the switching strategy between D2D and conventional cellular (CC) communications to minimize the interference. A collision area is defined as a circular area (CA) around an interfering node like BS. The radius of CA is variable and depends on the QoS requirements. Each node can check whether it is in CA or not through the pilot channel power from the BS. Thus the receiver node's SINR is greater than required SINR only if it is outside the range of CA. However interference from neighbor BSs is not considered. It is assumed that destination node is not within the communication range of CA which is unrealistic. It is also assumed that the algorithm avoids collision from other D2D UEs however CA is not defined for any other D2D UEs. Furthermore, the strategy is proposed only for downlink band, since it considers interference from BS but not from mobile nodes.

Shabany et al. proposed joined downlink rate allocation and routing algorithm to improve the throughput of the system [SS04]. Based on traffic pattern, the transmit power of the relays and BSs is adjusted which results in cell breathing. However, the proposed heuristic algorithm is limited to use two operator installed relays and two BSs while using unlicensed band for their data forwarding. The two famous ad-hoc routing protocols AODV and DSDV have been simulated in the cellular network environment to check the suitability in terms of data latency in [MMH15]. The NS3 simulator with LENA framework is used to evaluate latency of the AODV and DSDV in varying number of nodes. Bello and Zeadally identify the requirement of adaptable and scalable routing algorithms that can work in a complex and heterogeneous scenarios and in varying network sizes. The authors compare the advantages and limitations of three categories of routing, suitable for intelligent D2D communications in the Internet of things (IoT), which are stochastic, bio-inspired, and context-aware routing [BZ16].

It is worth mentioning that due to the diverse types of possible distributed routing schemes, the ad-hoc routing protocols can use any of the suitable relays for their data forwarding (unlike previous sections, where D2D relay is used for only D2D routing, and network relay for only D2I/I2D routing) as shown in Table 3.4. The same is true for the type of spectrum used as shown in Table 3.5.

3.4 Consolidation of taxonomy

This section precis the three broad categories of D2D routing i.e. multihop D2D routing, multi-hop D2I/I2D routing and ad-hoc routing for D2D networks as follows. In multi-hop D2D routing, either the communication is governed by BS, or the nodes take into consideration the presence of BS and other nodes in the network. In multi-hop D2I/I2D routing, the communication is always governed by BS. The multi-hop route is established between the node and the network service entity, i.e. BS. In case the user is inside the network coverage, and the routing decision does not take the advantage of the presence of centralized control entity, nor care for BS or any other on-going user transmissions, then such routing is purely ad-hoc routing. When the network services are either partially or totally unavailable, then the ad-hoc routing protocol is the only choice for multi-hop D2D communications. However, it is important to note that these distributed routing protocols can not ensure security as any other infrastructure-based centralized control entity can do.

The routing schemes under each category have been further sub-classified based on their objectives and topology structure used. All the classes of routing proposed under the three D2D categories have been consolidated into a single set of tables as shown in Tables 3.8 and 3.9. The tables present the purpose, application and/or working mechanism of every routing class, which highlights the necessity and importance of each class.

In the next chapter, we will discuss about the problem of burdening some specific set of nodes/routes due to single-criterion metric. Interference management having most critical concern in D2D communication is taken into consideration for the proposal of the routing metric. The observed interference and signal-to-interference-and-noise-ratio (SINR) have been used as routing metrics in interference aware routing. The observed interference results in a very long route, and the metric using SINR suffers from high number of hop count. A new routing metric has been proposed that avoids that cons of both type of interference metrics while keeping their pros like lower packet error ratio (PER) and higher throughput.

Table 3.8: Brief description of state-of-the-art classes of routing for D2D networks

Routing Class	D2D Category			Application and/or Working Mechanism
	D2D	D2I/I2D	Ad-hoc	
Incentive-based routing	✓		✓	The users are motivated to participate in relaying the data of other nodes by using some incentive.
Social connection-based routing	✓			The relay node forwards the data based on strength of the social bond (ties) with the other nodes on the communication path. It is considered as a sub-class of incentive-based routing.
Profit based routing			✓	It provides some cost to the intermediate nodes for providing their services as relay, with the aim to find a low cost route from source to destination. It is considered as a sub-class of incentive-based routing.
Security-based routing	✓		✓	When condentiality, authenticity and/or integrity of data are of utmost concern.
Content-based routing	✓	✓		To share the frequently used data among users, like viral videos etc. Thus the route does not depend upon the destination node, but is established based on the contents of the information being shared. In D2I/I2D networks, the BSs act as the file servers and multi-hop route are established to share the frequently used files among users.
Source selection-based routing		✓		It is used when it is required to select a source node, from which the cellular resources can be snatched in order to allocate them to the new user request. The source node can then communicate via multi-hop to another BS as suggested by the current BS. This is to balance the load among multiple BSs and is done only if a multi-hop route is possible.
Multipath coding-based routing			✓	To increase reliability, multiple disjoint paths between source and destination are established, that also provide better QoS and better resource utilization. Multiple parallel paths between source and destination nodes also helps in reducing the packet loss and the error rate by exploiting diversity gain.
QoS-based routing			✓	When quality of service (QoS) cannot be compromised, for example in live video streaming.
Device-aware routing			✓	If each node decide to participate or not, in relaying the data based on its capabilities. Thus, the routing can be easily deployed in network having devices with heterogeneous capabilities.
Hierarchical (or tree-based) routing		✓	✓	Can be used only in the presence of a central control entity. Normally, the BS or the mobile switching center (MSC) acts as a root of the tree and manages the tree structure, or the BS acts as a simple destination node and the hierarchy is constructed by the mobile nodes in the network. It is is used when wireless network scalability is of major concern. (i.e. For large size networks, tree-based routing is preferred.)

Table 3.9: Brief description of state-of-the-art classes of routing for D2D networks (contd...)

Routing Class	D2D Category			Application and/or Working Mechanism
	D2D	D2I/I2D	Ad-hoc	
Location based routing	✓			Nodes depend on location servers to find the location of the destination node, thus proactively maintains the location update.
Flat topology routing	✓	✓	✓	When nodes in the network do not have any specific structure like tree or cluster, nor have any location awareness mechanism then such arbitrary distribution of nodes is referred as flat topology network structure, and the routing is called flat topology routing.
Reactive distributed routing	✓		✓	Routes are discovered only when required, which saves precious resources from unnecessary periodic route updates.
Proactive distributed routing			✓	It is used for delay-sensitive applications. It updates routing table regularly in order to instantly provide the route when required without any delay.
Hybrid distributed routing	✓			Both the reactive and proactive routing operate at the same time. It is used in large-scale networks where proactive routing is used to maintain neighborhood table for nodes in a zone within few hops, while reactive routing is used to find route outside that zone. This type of routing is also termed as zone based routing.
Reactive BS-assisted routing		✓		Nodes find the route on-demand, by using their local (from neighbors) and global (pilot signal from BS) information.
Proactive BS-assisted routing		✓		Nodes periodically update routing table, usually for delay sensitive or real-time applications. The objective is to instantly provide a multi-hop route with better BS channel capacity from node to the BS, when BS is overloaded or when the channel quality (or capacity) with BS is not good.
Proactive centralized routing	✓			A centralized entity (for example BS) regularly gathers neighbor nodes information from all the network nodes, in order to always have a complete updated network.
Proactive adaptive routing	✓			Adapts between proactive centralized routing and proactive distributed routing, based on the network constraints.

Chapter 4

Interference-Conscious Routing Metric

This chapter focuses on Interference-conscious routing by proposing a routing metric, MIIS (Metric for Interference impact and SINR). MIIS considers Received Signal Strength (RSS) as well as is conscious about interference. It selects the routes having higher RSS and lesser interference. This chapter presents the mechanism and procedure of MIIS and evaluates its performance through simulations by comparing with existing works in terms of average hop count, routing overhead, packet loss ratio and end-to-end delay. The performance is measured for the effects of varying number of nodes, nodes mobility and traffic load. The simulation results show that MIIS outperforms existing works.

4.1 Introduction

The D2D communication refers to a direct communication of cellular devices with each other with or without the help of the BS. Most of the existing works focus on single-hop communication, however this limits the applicability of D2D communications. Therefore, facilitating multihop communication in D2D is an important factor to take into consideration. In multihop D2D networks, establishing a reliable multihop route is a critical issue. There are two cases when a route establishment is required between two end nodes. Firstly, when two D2D UEs want to communicate, but are not in the direct vicinity of each other. Secondly, when a UE does not have the infrastructural support. This might happen due to several reasons, for example, the infrastructure is destroyed due to an accident or natural disaster, or the UE is out of the network coverage or the UE is in dead-spot area. Therefore, intermediate UEs can be used to support in relaying to establish multihop communication paths between source and destination nodes/UEs. In case of providing the infrastructure network support to a UE, the destination node could be a BS or any ordinary node which have and can provide network services.

In D2D communication, interference management is a topic of most important concern. Two different metrics have been used in the literature for establishing a route having minimum interference. The first metric uses the observed average interference and selects those nodes for the route which have the minimum interference. The benefit of this metric is avoiding collision with CUEs (i.e., interfering sources) that minimizes the chances of packets loss. However, this metric suffers from very long route, since the metric tries to select nodes which are farthest from the CUEs.

The second metric selects nodes having the highest Signal-to-Interference and Noise Ratio (SINR) which is the ratio of Received Signal Strength (RSS) and interference (while neglecting noise as constant). The lower the interference is, the higher the SINR is. The higher RSS also results in higher SINR. The benefit of using SINR metric is higher data rate. In some existing works [RDS13], the performance improvement in terms of higher data rate using SINR metric is assumed mainly due to lower interference, while neglecting the effects of RSS. While in other works [JXQ15], only RSS is taken as the major factor for the improvement in SINR. Using SINR metric, each node selects the most closest node as its next hop node due to higher RSS which results in significantly higher number of hop counts in a route in a dense network. This high hop count route is typically unstable, due to frequent link breakages because of network dynamics (such as nodes mobility and topological changes). Thus, there is a need of a routing metric that can take advantage of the higher RSS (or the SINR) while avoiding its consequence.

A number of interference-aware routing schemes have been proposed in the literature, however none of them satisfies the network requirements of having better SINR and minimum interference at the same time. This work proposes a novel routing metric, MIIS (Metric for Interference impact and SINR). MIIS not only considers the RSS, but it is also conscious about the interference, therefore, MIIS selects the route having higher RSS and lesser interference.

4.2 Related Work

The state-of-the-art interference-aware routing schemes can be divided into three main categories. The existing schemes either (i) maintain the SINR and/or interference above/below a threshold value, or (ii) select a route having the lowest interference while maintaining SINR above a threshold value, or (iii) select a route having highest SINR (or highest data rate) while maintaining the interference below a threshold value. However, none of the state-of-the-art schemes enhance the network performance by selecting a multihop D2D route having the highest SINR as well as the lowest interference together. Among the existing schemes, the flat topology-based routing is considered only by Kaufman et al. [KLA13], in which the next hop is selected only if the bidirectional communication is possible and the interference at the BS due to this communication is below a threshold value. The routing scheme in [KMD07] is the only scheme that centrally maintains complete topology information of the network and selects only those neighbor nodes whose interference is below the threshold value. All other interference-aware routing schemes use distributed location-based routing strategy. The scheme proposed in [YGW14] establishes a route that passes through the cell edges which makes the route quite longer than the direct shortest hop path, but it has overall lesser interference. Maximum-rate towards destination (MR-D) routing scheme, proposed in [RDS13] selects the next hop node having highest data rate (and assuming to have the lowest interference also), by selecting a node which is farthest from both the BS and the cellular user. MR-D advanced (MR-DA) [Du+15] is the modification of MR-D for downlink band. In order to reduce the number of hops in MR-DA, the next hop node in the direction of the destination node is preferred over the node in the direction of cell edge. Fixed rate scheme (FRS) and fixed power scheme (FPS) are proposed in [BM15] for maximizing throughput. These schemes use only those D2D links in the route having minimum required SINR. The routing scheme proposed in [JXQ15] selects next hop having highest data transmission rate and energy efficiency. All the schemes in [Du+15; BM15; JXQ15] use downlink band for D2D communications, and avoid harmful interference to cellular node by making an unrealistic assumption that that each node has complete knowledge about the channels used by all cellular nodes. However, our proposed scheme does not require any kind of location information for making route decision.

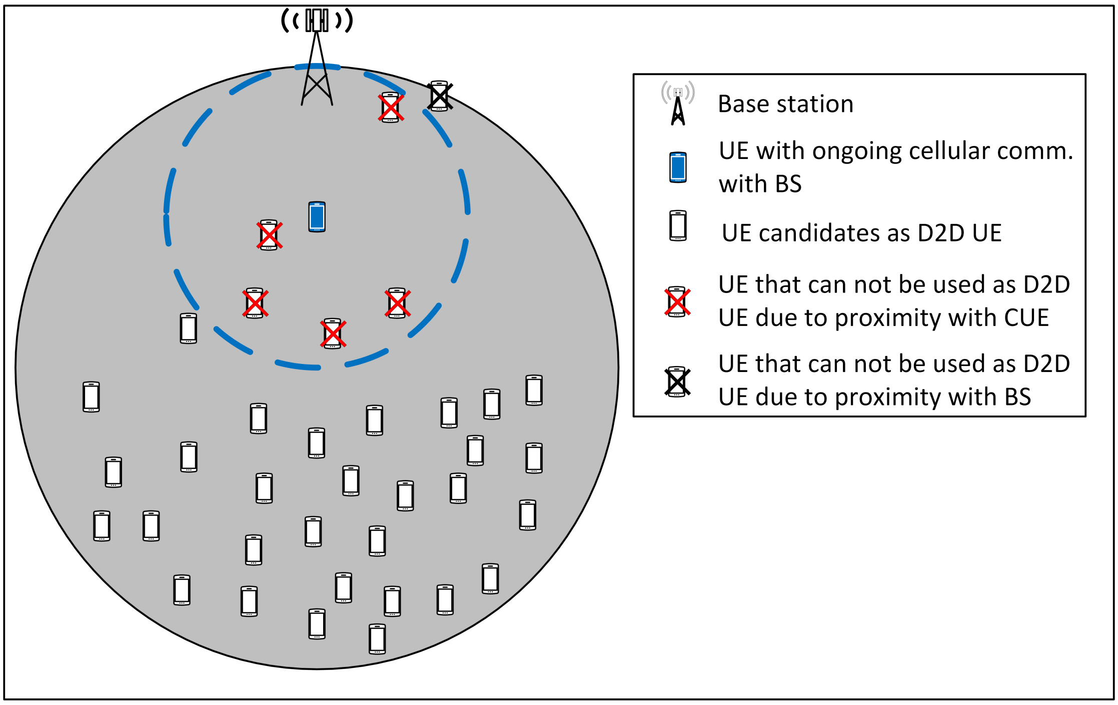


Figure 4.1: System model.

4.3 System Model

The system model considered in this thesis is presented in Figure 4.1. It consists of a single cell and comprised of three main entities: a BS, a Cellular User Equipment (CUE) and D2D UEs. BS coordinates and controls the communications among CUEs. CUE communicates with other CUEs using cellular communication through BS. D2D UE is also a CUE, however it can communicate with other D2D UEs directly, without the involvement of BS. The D2D UEs use inband (i.e. cellular spectrum) underlay mode in which the licensed cellular spectrum allocated to CUE is spatially reused by D2D UEs forming the network underlaying the existing cellular network. The uplink band is reused by D2D UEs, which requires following interference considerations. (i) CUE interference to D2D UEs, and (ii) D2D UEs interference to BS. The detailed discussion on specifically how inband, underlay, uplink band can be used for D2D communication or in general, how different types of spectrum can be utilized for D2D communication is provided in Chapter 2, Section 2.3.2.

As presented in Figure 4.1, a UE (in blue color) has ongoing cellular communication with BS on certain power. This UE is called CUE. The UEs (in white color) participate in D2D communications are called D2D UEs. However some D2D UEs (with red cross) are within the communication range of CUE, then they can not be used for D2D communications because they will receive harmful interference from CUE.

BSs periodically send beacon message to inform about their presence. The signal strength of this message is used by D2D UEs to estimate the distance with BS. The D2D UEs can then communicate at low power in order to avoid any harmful interference to BS. For example, consider the D2D UE (with black cross) that is shown near the BS in the top-right corner of Figure 4.1. The D2D UE is although outside the communication range of CUE, however since it is near to BS, so it can cause harmful interference at BS. Therefore, the D2D UE does not take part in D2D communication, after recognizing close proximity of BS, by estimating its distance with BS using beacon signal strength. However, since the exact distance with BS cannot be estimated due to variable power used by BS under different operating conditions, therefore it is assumed that if BS receive harmful interference from D2D UEs, then BS instructs the CUE to increase the transmit power in order to increase the overall SINR for the successful reception of CUE data at BS. With the increase in transmission power of CUE, its transmission range also increases, and thus D2D UE cannot be used for D2D communications because of receiving harmful interference from CUE.

A single channel used by CUE, is spatially reused by all D2D UEs in an underlay mode. Thus there is cross-interference between D2D UEs and CUE. However, since all D2D UEs use the same channel, and multiple D2D UEs might be simultaneously communicating at the same time, therefore Carrier Sense Multiple Access (CSMA) is used to avoid collisions.

It is assumed that the CUE and all D2D UEs use fix transmission power for their communication so that the interference behavior can be more accurately estimated. In order to calculate the value of interference at each D2D DUE, free space path loss formula is used. The interference is the value of Received Signal Strength (RSS) from CUE to the D2D UEs. If a D2D UE is within the communication range of CUE, then the RSS is high enough and no other communication can take place. However, when a D2D UE is outside the communication range of CUE, then the RSS from CUE is lower, hence, the same channel can be reused to establish simultaneous communication with other D2D UE. Thus, every D2D UE passively monitors the RSS from CUE, and if the average RSS from CUE is below some maximum threshold value (discussed next), it means that the D2D UE can participate in D2D communication. It is important to note that for the successful simultaneous communication with other D2D UE, the RSS from the D2D UE must be much higher than the interference (RSS from CUE). This ratio is calculated using Signal-to-Interference-and-Noise-Ratio (SINR). So, depending upon the modulation and coding scheme and other physical layer parameters, a minimum required SINR threshold is set. If the SINR between two D2D UEs is above the minimum required threshold value, then the communication will be successful.

The D2D-UEs communicate at lower power to keep the interference to a minimum. Thus, the D2D-UEs can communicate only at smaller distances due to the use of lower power which rises the need of multi-hop path from source D2D UE to destination D2D UE. In this thesis, D2D UE establishes routes in a distributed manner (in current chapter), as well as takes services of BS in route establishment (in Chapter 5).

4.4 Proposed routing metric

In most of the routing schemes, a single routing metric is used for making a route decision. This causes a set of routes to be preferred over others, which burdens the nodes used in these routes. Therefore, it is recommended to combine various atomic routing metrics to form a global metric in order to avoid performance trade-off among them. There are two common ways for making a global routing metric: weighted sum metric and lexicographic metric. In weighted sum metric, weights are assigned to the routing metrics according to their priority. In lexicographic method, routing metrics have been arranged in order of their importance [You+14]. In our work, we are using the former technique and propose a novel routing metric named as MIIS (Metric for Interference impact and SINR). This metric takes into account the interference in the network, and is a compromise between the interference and the SINR values. MIIS is defined as follows:

$$MIIS_{n,m} = (SINR_{n,m})^{\alpha} \times (\frac{1}{I_m})^{(1-\alpha)} \tag{4.1}$$

where n is previous hop node, m is current node, $SINR_{n,m}$ is the signal to interference and noise ratio from node n to m and is calculated as:

$$SINR_{n,m} = \frac{RSS_{n,m}}{\sigma^2 + I_m} \tag{4.2}$$

By putting the value of equation 4.2 in equation 4.1, while ignoring *noise* (σ^2) as constant, we will get:

$$MIIS_{n,m} = \frac{(RSS_{n,m})^{\alpha}}{I_m} \tag{4.3}$$

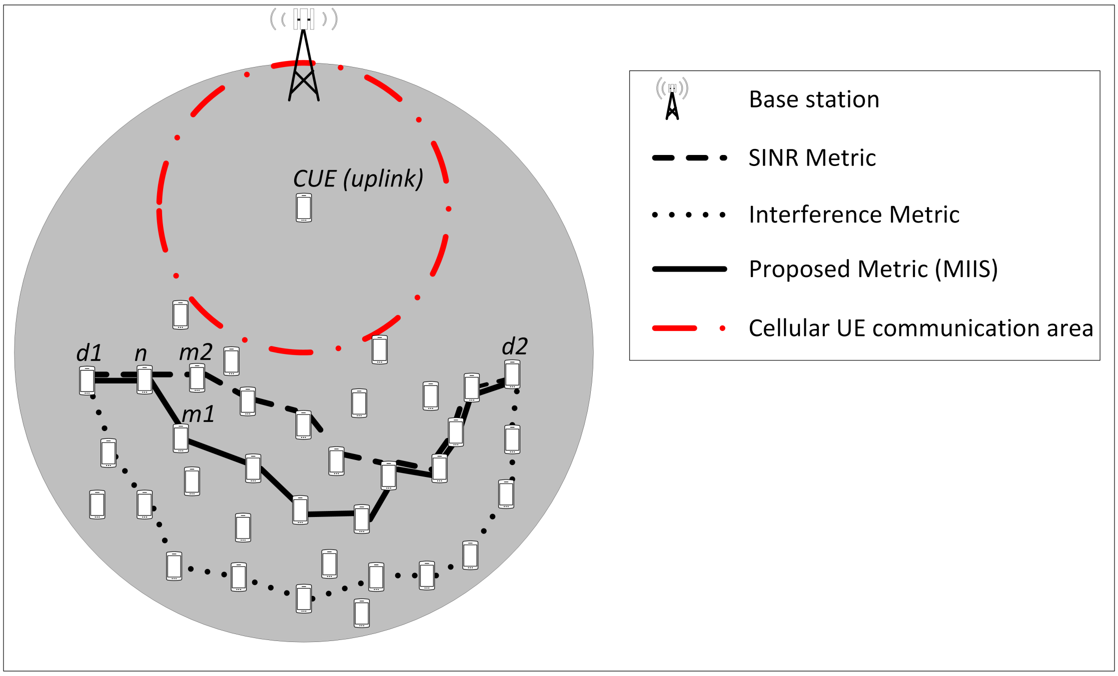


Figure 4.2: An example of the proposed routing metric scheme.

where I_m is the observed (cumulative) channel interference at the current node m from other nodes. It is calculated by accumulating the received signal strengths of nodes using the particular channel. $RSS_{n,m}$ is the received signal strength from previous node n to the current node m. To compute $RSS_{n,m}$ at the node m, the transmission power information must be sent by the previous node n to current node m. α is a weighting parameter where $0 \leq \alpha \leq 1$. Varying the values of α will variate the consideration of metric, i.e., when $\alpha = 0$, MIIS behaves as an interference metric, and when $\alpha = 1$, it behaves as SINR metric. Different values of α (i.e., $\alpha = \{0, 0.25, 0.5, 0.75, 1\}$) will be evaluated under varying number of nodes, mobility and traffic load. The suitable value of α might be different for different kind of network topology or operating conditions.

Figure 4.2 presents an illustrative example to explain our proposed routing metric. The source and destination nodes are labeled as *d1* and *d2* respectively, and the primary cellular UE (CUE) is shown with its communication range in dotted dashed circular red line. The CUE is the node which communicates with the BS in the traditional cellular communication system mechanism. All D2D nodes reuse the same uplink channel as already used by CUE for communicating with each other. We assume that when control information is shared by D2D nodes to BS, then in order for the BS to successfully receive the information, the channel used by CUE is specially reserved for D2D communication during that time. This is to avoid collision of D2D control packets with the CUE packets.

As we know that the closer the node is, the higher the SINR is. Therefore, when SINR metric is used for next hop selection, the next hop node is generally the closest neighbor node. The advantage of SINR metric is its high data rate, however the route suffers from the high hop count. This is because, SINR metric tries to select the most closest nodes as possible, which results in overall number of hops to be dramatically increased in case of dense networks. On the contrary, when interference metric is used, all the intermediate nodes are farthest from the interference source (i.e., CUE), resulting in a route as shown by dotted line. The interference metric can select the route with comparatively lower hop count than SINR metric. Thus, our proposed MIIS routing metric, finds a balance between the two metrics in order to find a route with lower hop count and better network performance (such as lower packet loss ratio and end-to-end delay).

To give an insight into the proposal, we elaborate the use of the proposed routing metric for the selection of next hop. The mechanism of next hop selection is different from the complete route formation mechanism, which we will discuss in Section 4.4.2. We consider the same Figure 4.2 for the calculation of this metric $MIIS_{n,m}$. Three D2D nodes labeled as n, $m1$ and $m2$ are shown in figure. All the D2D nodes are reusing the same uplink spectrum band as used by traditional cellular node labeled as $CUE(uplink)$. The node n wants to select one of the next hop among the two candidate nodes $m1$ and $m2$. Both the nodes $m1$ and $m2$ sense the interference on the uplink band and inform their channel state to the previous node n . The node $m1$ is farther from the node n, therefore has a low received signal strength $RSS_{n,m1}$. Moreover the node $m1$ is also farther from the interfering source CUE, and thus has also low interference I_{m1}. On the contrary, the node $m2$ is nearer to node n as well as to the interfering node CUE, and thus has higher received signal strength $RSS_{n,m2}$ as well as higher interference I_{m2}. Conclusively, since $m1$ has lower $RSS_{n,m1}$ and lower I_{m1}, while $m2$ has higher $RSS_{n,m2}$ and higher I_{m2}, thus the ratio i.e. $SINR_{n,m}$ could probably be same. Thus the SINR metric could select any one arbitrarily. However, our proposed metric, will not only check the SINR, but it is also conscious about the interference, therefore, our proposed metric selects the next hop node as $m2$, because of lower interference. By this, we can say that our proposed metric uses interference as a filtering criteria between the two nodes having equal SINR, but varying interference values. Similarly, in the reverse manner, the proposed metric will select a higher SINR node among the candidate nodes with similar interference values.

The selection of next hop node mechanism as discussed above is just for giving an insight of the proposed routing metric. The actual route discovery mechanism is quite different and is discussed below. We use the technique of Ad-hoc On-Demand Distance Vector (AODV) [PR99] for route discovery. The complete working mechanism after the integration of our proposed routing metric with the AODV routing algorithm is discussed below through route request and route decision mechanisms.

4.4.1 Route request

When a node needs to communicate with another node, it adds information about its observed interference over the given channel into route request (RREQ) packet and subsequently, broadcasts RREQ packet which is received by all its neighboring nodes. All the next hop neighbor nodes upon receiving the RREQ packet, calculate the SINR values by observing the RSS of the received RREQ packet and their observed interference over the given channel. This is to validate that the SINR is above the minimum required (threshold) SINR. To validate that SINR values are also above the threshold SINR for the links in the reverse direction (i.e. from current nodes to the previous hop node), the interference information of the previous hop node appended in the RREQ packet is used to derive the SINR using equation 4.2. This will ensure that bidirectional communication over the given link is possible while maintaining the threshold SINR.

The proposed routing metric MIIS value is calculated (likewise SINR), and appended in the RREQ packet, and is used to decide whether to forward RREQ by the next hop nodes. This process of adding interference and MIIS values in the RREQ packet will continue until the RREQ packet reaches the destination node.

The calculations involved in forwarding the RREQ and the contents of RREQ packet is illustrated using an example shown in Figure 4.3. The source node 1 wants to communicate with destination node 8. The source node 1 initiates the route discovery by broadcasting the RREQ packet. RREQ packets contain the following information: (1) average observed interference at current node for the given channel, (2) the minimum value of MIIS till the current node, and (3) the number of hops that RREQ packet has traversed. At the source node, the observed interference (I_1) is added in the RREQ packet. However, since no MIIS value is yet available, so the value is marked as unused (at the source node only). Moreover, since no hops has yet been traversed, so Hop field is also set to zero. The broadcast packet sent by node 1 is received by nodes 2, 4 and 6.

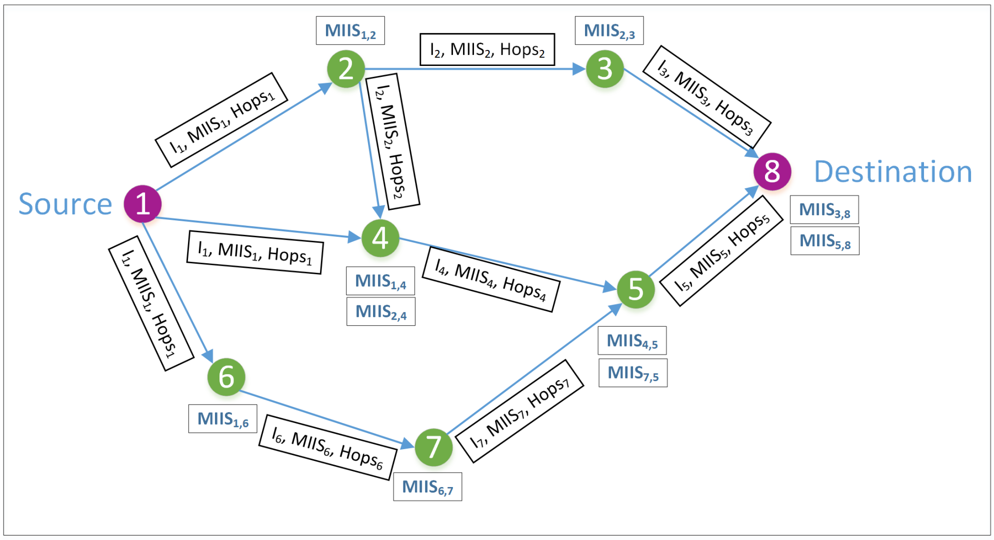


Figure 4.3: An example of RREQ packet contents and route calculations.

On receiving the RREQ packet, node 2 measures the Received Signal strength (RSS) from node 1 to node 2 ($RSS_{1,2}$) and then calculates the $MIIS_{1,2}$ using the received I_1 in RREQ packet and measured $RSS_{1,2}$ values. The number of hops is also incremented by 1. The calculated MIIS value, updated hop count and the average observed interference for the given channel at node 2 are appended into the RREQ packet and then broadcasted further. The same procedure is performed at nodes 4 and 6, to calculate MIIS value and then forward the RREQ further.

The RREQ broadcasted by node 2 is received by node 3 and node 4. At node 3, the received RREQ is the first RREQ, and so the same procedure applies as is on node 2. However, at node 4, this is the second RREQ. The first RREQ is already received from the source node directly. The node 4 has to decide whether to forward (i.e., broadcast) this newly received (i.e., second) RREQ or not, based on the received MIIS value. It is extremely important to understand how the MIIS values are calculated at this node. The node 4 already has an MIIS value from the previous RREQ packet (let's call it $previous\_MIIS$). The second RREQ packet also contains an MIIS value (let's call it $MIIS\_from\_RREQ$). In addition, the MIIS value from node 2 to node 4, i.e. $MIIS_{2,4}$ is also calculated (let's call it $current\_MIIS$). The bottleneck MIIS value (let's call it new_route_MIIS) is calculated for the new RREQ that is the minimum of $MIIS\_from\_RREQ$ and $current\_MIIS$. Now, if the value of new RREQ's MIIS i.e. new_route_MIIS is higher than the value of previous RREQ's MIIS i.e. $previous\_MIIS$, it means that the new RREQ is better than the previous RREQ, so this new RREQ is also forwarded further. Otherwise, it will be discarded. Note that the bottleneck value is the minimum MIIS value of the whole route. Since, in the above consideration, only two values are available, so minimum of the two has taken, while for route longer than two hops, the minimum MIIS value among all hops will be considered.

The same procedure of selecting RREQ is applied on all nodes as discussed above, and the final decision is made at the destination node (node 8). When the destination node 8 receives first RREQ, it starts a timer to wait for receiving more RREQs (for the selection of better route). Once the waiting timer expires, the destination node 8 checks all the received RREQ and selects the one having the highest bottleneck MISS value.

It is important to note that there is no delay at intermediate nodes for forwarding the RREQs. As soon as the first RREQ or later on, some better RREQ is received by an intermediate node, it forwards it immediately. This will although increase the overall routing overhead, but is infact giving more choices to the destination node. The destination node waits for some time in order to collect all possible RREQs, and then finally selects the one with the best value. Thus, there is delay only at the destination node for collecting all possible RREQs.

4.4.2 Route decision with hop count consideration

The higher the MIIS values is, the better the route is. When a node receives the first RREQ, it stores the MIIS and hop count values and broadcasts it further. If it receives another RREQ having higher MIIS and lower or same hop count values than the previously stored ones, it means that the new RREQ has better metric values (and the better route). Hence, it stores the new MIIS and hop count values by replacing the older values and broadcasts it as well. However, if the new RREQ has higher MIIS value but also higher hop count than the previously stored ones, then this newly received route might not be efficient. To address this problem, we propose a route decision formula that maintains a balance between higher MIIS and lower hop count values in the routes. Note that the MIIS value is calculated at each hop and the minimum MIIS value among all hops (i.e., the bottleneck MIIS value) is considered as the MIIS value for the route and is represented as $MIIS_{minR1}$ for route $R1$. The route decision formula is given as follows:

$$\textbf{If} \quad (\frac{hops_{R2}}{hops_{R1}})^{\beta} \geq \frac{MIIS_{minR2}}{MIIS_{minR1}} \quad \textbf{then} \quad R1 \quad \textbf{Else} \quad R2 \tag{4.4}$$

where $R1$ is the previously stored route and $R2$ is the newly received route from RREQ, $hops_{R1}$ and $hops_{R2}$ are the number of hops in the routes $R1$ and $R2$, and $MIIS_{minR1}$ and $MIIS_{minR2}$ are the MIIS values of routes $R1$ and $R2$ respectively. $\beta \in \{0, 1\}$ represents the hop count consideration (hcc). β=0 means without hcc, while β=1 means with hcc.

For ease of understanding, the operation of our proposed route decision formula is presented through four different cases.

Case 1. New RREQ with same MIIS value but different hop count: In this case, the RREQ having the lower number of hops will be selected. This case is referred as hop count optimization.

Case 2. New RREQ with different MIIS value but same hop count: In this case, the RREQ having the higher MIIS value will be selected. This case is referred as Interference and SINR optimization.

Case 3. New RREQ with same MIIS value and same hop count: In this case, the new RREQ will be discarded. This case is referred as routing overhead optimization.

Case 4. New RREQ with different MIIS value and different hop count: In this case, there will be no fixed behavior and the exact behavior depends on the calculation of proposed route decision formula.

The decision about the selection of particular route is presented using an example in Figure 4.4. The nodes shown in green color are the intermediate (relay) nodes, and the nodes in purple color, labeled as 1 and 8 are the source and destination nodes, respectively. The arrows between the nodes show the forwarding of RREQ packet to the neighboring nodes. The values on those arrows show the computed MIIS value between the current node and the next hop node. For simplicity and better understanding of our proposed route decision formula, we used some simple MIIS values for explanation.

As presented in Figure 4.4, route decisions are made at two intermediate nodes (node 4 and 5) and at the destination node (node 8). We can see that two RREQs are received at node 4, which fall under case 1 to make the RREQ selection decision. Node 5 received two RREQs that fall under case 4. Assuming $R1$ is the route having two hops and $R2$ is the route having three hops. By putting the values in the route decision formula in

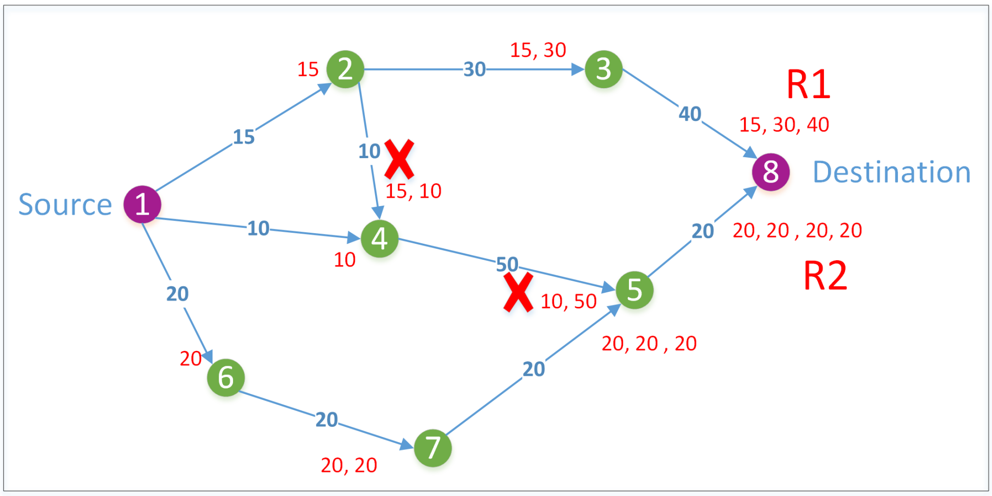


Figure 4.4: An example of RREQ packet forwarding and route decision.

Eq. (4.4), RREQ of route $R2$ is accepted that overrides the previously received RREQ of route $R1$. To provide some more insight, assume that the number of hops in $R2$ is 4 (while keeping all other variables constant), then by putting these values in the formula, RREQ of $R2$ is discarded in this case. Lastly, the destination node also receives such RREQs, and the route decision formula in Eq. (4.4) is applied to make the final route decision. By putting the values shown in Figure 4.4, route $R2$ is finally selected. Table. 4.1 presents the detailed route selection that is discussed above in the example.

At destination node, after receiving the first RREQ, it waits for certain time duration for more RREQs to arrive. After which, it informs the source node about the optimal route by sending the route reply (RREP) packet that follows the reverse route that the RREQ packet has traversed.

After receiving the RREP packet, the source node starts sending the data packets. Each hop node sends the MAC layer acknowledgment of successful reception of data packets to its previous hop. If the acknowledgment is not received (after retries if used), the next hop is marked as unreachable and all the nodes that use the particular next hop link for their routes are informed by broadcasting the route error (RERR) packet. On receiving the RERR packet by the source node(s), the source node(s) initiates the route discovery if required.

Table 4.1: Details of route selection of the illustrated example.

Route decision node	Route 1 ($R1$)			Route 2 ($R2$)			Case type	Selection
	$MIIS$ values	No. of hops	Minimum $MIIS$ value	$MIIS$ values	No. of hops	Minimum $MIIS$ value		
Node 4	10	1	10	15, 10	2	10	1	$R1$
Node 5	10, 50	2	10	20, 20, 20	3	20	4	$R2$
Node 5 (not exemplified in figure)	10, 50	2	10	20, 20, 20, 20	4	20	4	$R1$
Node 8	15, 30, 40	3	15	20, 20, 20, 20	4	20	4	$R2$

Table 4.2: Simulation parameters.

Parameter	**Value**
Number of D2D UEs	50
D2D UEs mobility	Static
Area	500m $\times$ 500m
Placement of nodes	Random
Traffic load (number of transmissions)	10
Traffic type	UDP-CBR
Packet size	1000 bytes
Total number of packets	50
Simulation time for each run	50s
Simulation runs	100

4.5 Performance Evaluation

4.5.1 Simulation Setup and Parameters

MIIS is implemented in OMNeT++ 5.4.1 with INET 4.0 framework. The number of D2D UEs vary from 50 to 100, the D2D UEs mobility vary from 0 meter/second to 2 meter/second, and the traffic load (number of transmission) range from 1 transmission to 25 simultaneous transmissions. The default number of D2D UEs is 50, having 10 simultaneous transmissions and no mobility. With the given fixed transmission power, the transmission range of UEs is 125 meters. All the results are generated with a confidence interval of 95%. Each simultaneous transmission refers to an end-to-end communication having a unique source-destination pair that is randomly deployed for each simulation. The MAC protocol used is Carrier Sense Multiple Access (CSMA). The simulation parameters are presented in Table 4.2.

4.5.2 Performance Metrics

- *Average hop count* is the average number of hops included in the established routes. A smaller average hop count is favorable [JXQ15; RDS13].
- *Routing overhead* is the number of control packets exchanged for route establishment. A lower routing overhead is favorable [RMP11].
- *Packet loss ratio* is the ratio of total number of lost packets to the total number sent packets. A smaller packet loss ratio is favorable [Abd+20].
- *Average end-to-end delay* is the average end-to-end delay of all the packets from source node to destination node. A smaller end-to-end delay is favorable [Sal+17; Sal+15b].

4.5.3 Comparison Schemes

The performance of MIIS is compared with two existing schemes: Maximum Rate towards Destination (MRD) [RDS13] and Joint Routing and Channel selection (JRC) [JXQ15]. MRD selects the intermediate nodes having the least interference from CUEs, hence it selects the intermediate nodes towards the edge of the cell. JRC selects the intermediate nodes having the stronger SINR, hence it selects the nearest nodes as intermediate nodes in the route.

It is important to note that both the schemes cannot be used for comparison in their true state. This is because, both the schemes are location-based routing schemes, requiring exact information about the current location of the all the nodes. However it is assumed in this thesis that knowing the exact locations of all the nodes in the network might not be feasible (or permitted) due to privacy concerns, so location awareness is not considered at all. Moreover, the location-based schemes select one candidate neighbor node as next hop node, and the process continues until the destination node is reached, this could result in selecting a route that reaches to a dead-end node (i.e. node having no next hop node in the direction of destination node). In addition, the location based schemes selects next hop node, based on their proposed metric, however the optimality of node with respect to complete route can never testified, i.e., the route with bottleneck values could not be avoided. Conclusively, as the location-based routing schemes are information-rich, wherein each node has complete information of location of all nodes in the network, and the route discovery also cannot avoid bottleneck links in the route, therefore MRD and JRC cannot be used in their true state (i.e., with location-awareness) in order to have fair comparison. Instead, the concept of the MRD and JRC is used for comparison.

Maximum Rate towards Destination (MRD)

The MRD algorithm is implemented without using the location information as follows. When a node i receives a RREQ packet, the RREQ packet contains the sum of interferences of all nodes (i.e. I_{sum}) and the hop count ($Hops$) in the route. The node i calculates the current interference (i.e., I_i), takes a sum of route interference I_{sum} and current interference I_i, and divides it with the hop count (i.e., $I_{avg} = (I_{sum} + I_i)/(Hops + 1)$). If the I_{avg} is lower than the average interference of previously received RREQ (i.e., I_{prev}), it means that the new route has overall lesser interference than the previous route, hence the new RREQ is also forwarded further. Otherwise, node i discards the current RREQ.

Joint Routing and Channel selection (JRC)

The JRC algorithm is implemented much similar to the MRD, however instead of lower average interference, higher average SINR value is better. When a node i receives a RREQ packet, the RREQ packet contains the sum of SINR values of all nodes (i.e. $SINR_{sum}$) and the hop count ($Hops$) in the route. The node i calculates the current SINR ($SINR_i$) from interference I_i, takes a sum of route SINR ($SINR_{sum}$) and current SINR ($SINR_i$), and divides it with the hop count (i.e., $SINR_{avg} = (SINR_{sum} + SINR_i)/(Hops + 1)$). If the $SINR_{avg}$ is higher than the average SINR of previously received RREQ (i.e., $SINR_{prev}$), it means that the new route has overall higher SINR than the previous route, hence the new RREQ is also forwarded further. Otherwise, node i discards the current RREQ.

4.5.4 Results and Discussions

In this section, MIIS with varying values of α={0, 0.25, 0.5, 0.75, 1} and β={0,1} is evaluated and compared with MRD and JRC. When the value of α is close to 0, MIIS gives more preference to interference metric, while when the value of α is close to 1, MIIS gives more preference to SINR metric. β=0 means without hop count consideration (hcc), while β=1 means with hcc. In our evaluation, MIIS with α=0 and β=0 behaves as interference-based scheme without hcc, while MIIS with α=1 and β=0 behaves as SINR-based scheme without hcc. MIIS with α=0 and β=1 behaves as interference-based scheme with hcc, while MIIS with α=1 and β=1 behaves as SINR-based scheme

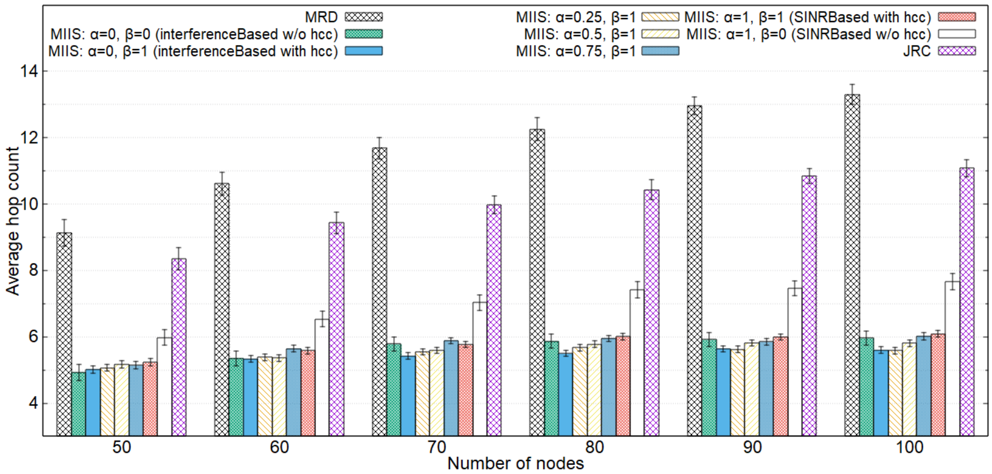


Figure 4.5: Average hop count for varying node density.

with hcc.

4.5.4.1 Effects of Node Density (Varying Number of Nodes)

This section evaluates the effect of node density (i.e., varying number of nodes) from 50 to 100 in the network. Figure 4.5 shows the average hop count for varying number of nodes for MIIS (different variants), MRD and JRC. All variants of MIIS outperform MRD and JRC by achieving lower average hop count (i.e., almost six). The effect of hop count consideration can be seen for interference-based MIIS without hcc and SINR-based MIIS without hcc that have higher average hop counts than interference-based MIIS with hcc and SINR-based MIIS with hcc, respectively. However, the SINR-based MIIS without hcc has comparatively much higher hops than SINR-based MIIS with hcc, because it tries to use as much closer nodes as possible to achieve higher SINR regardless of the hop count. JRC and MRD perform the worst among all and achieve much higher average hop count because of taking longer route in MRD and higher number of closer nodes in JRC. Overall, MRD performs the worst resulting in an average hop count of up-to around thirteen hops, i.e., around 216% higher than MIIS.

Figure 4.6 shows routing overhead for varying number of nodes. For all the increasing number of nodes, all variants of MIIS achieve very low and almost similar routing overhead, while for MRD and JRC, the routing overhead keeps increasing significantly.

Among all routing control packets, the flooding of RREQ packets is the main rea-

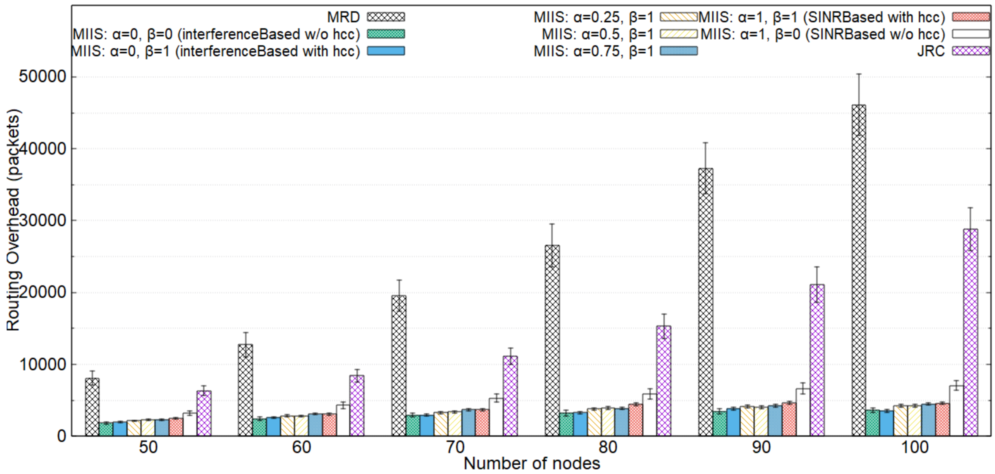


Figure 4.6: Routing overhead for varying node density.

son of routing overhead. The MIIS schemes limit the flooding of RREQ packets by maintaining a maximum value of the routing metric. The new RREQ is forwarded (i.e. broadcasted again) by intermediate nodes only if it contains higher value of MIIS metric (than previously processed RREQ). Thus, it restricts the flooding of RREQ packets and hence, the overall routing overhead is much smaller. The MRD and JRC select route involving higher number of hops, and therefore, the routing control packets are exchange among higher number of nodes, thus with the increase in number of nodes, routing overhead also keeps increasing significantly. The SINR-based MIIS without hcc (an MIIS variant) tries to use as much closer nodes as possible, resulting in comparatively much higher routing overhead than all other MIIS variants. Overall, MIIS performs the best, while MRD performs the worst. MIIS with α=0.5 is able to achieve around 1075% and 670% less routing overhead than MRD and JRC, respectively.

Figure 4.7 shows packet loss ratio for varying number of nodes. When the number of nodes in the network are 50, all schemes except MRD exhibit the similar packet loss ratio of around 14%, while MRD has much higher packet loss ratio of around 18%. As the number of nodes keeps increasing, the packet loss ratio of all MIIS variants keep reducing by taking the advantage of availability of higher number of nodes in the network. However, it is inverse for MRD and JRC, and when the number of nodes in the network increases, their packet loss ratio also keep increasing. This is because, MRD selects more nodes having lower interference, thus causing longer route. While JRC selects more and

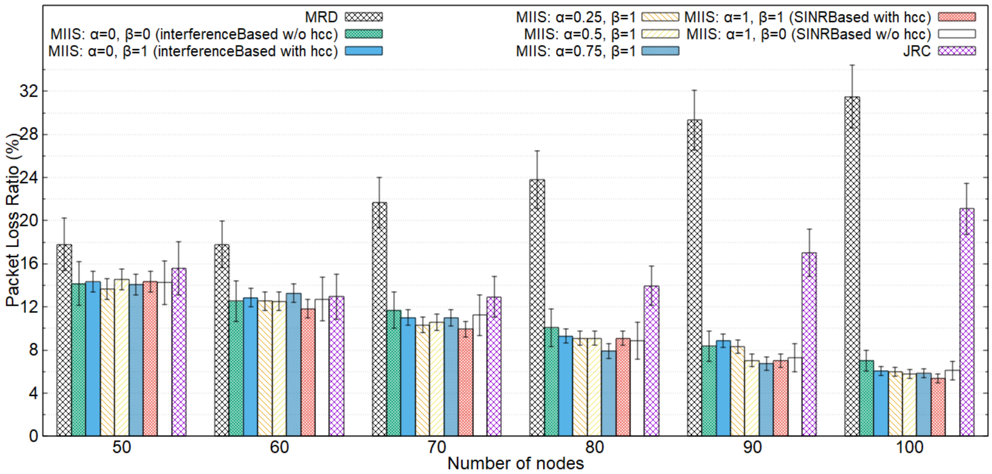


Figure 4.7: Packet loss ratio for varying node density.

more closer nodes to achieve higher SINR. The MIIS schemes without hcc have slightly higher packet loss ratio than their counterpart MIIS schemes with hcc. This is because since they use longer routes and routes having more closer nodes regardless of the hop count, therefore, incur more collisions among data packets, resulting in slightly higher packet loss ratio. Overall, MIIS performs the best, while MRD performs the worst and JRC performs the second worse. MIIS is able to achieve around 545% and 365% less packet loss ratio than MRD and JRC, respectively.

Note that higher packet loss ratio in MRD and JRC also contributes in their higher routing overhead. This is because, with more packet loss ratio, the route breaks more often thus have more route discoveries, resulting in significantly higher routing overhead in MRD and JRC as compared to MIISs' variants. Moreover, the higher hop count also contributes to higher routing overhead in MRD and JRC.

Figure 4.8 shows average end-to-end delay for varying number of nodes. When the number of nodes in the network are 50, all MIIS variants exhibit almost similar end-to-end delay of around 0.6 seconds, while the MRD and JRC exhibit slightly lower end-to-end delay of around 0.5 seconds. As the number of nodes keep increasing, the end-to-end delay of all MIIS variants keep reducing. This is because of selecting better routes by taking the advantage of availability of higher number of nodes in the network, causing routes having lower end-to-end delay. However, it is inverse for MRD and JRC, and when the number of nodes in the network increases, MRD selects longer routes and JRC selects routes having higher number of hops, that increase the delay of data packets.

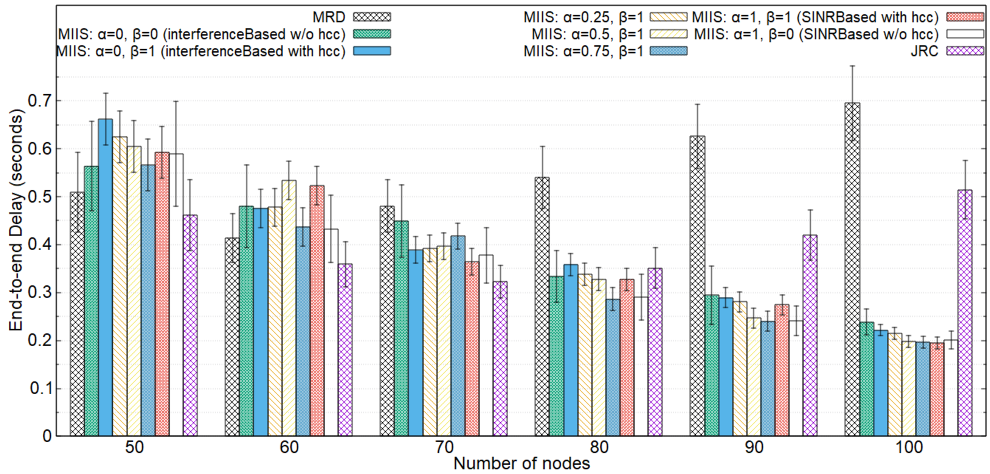


Figure 4.8: End-to-end delay for varying node density.

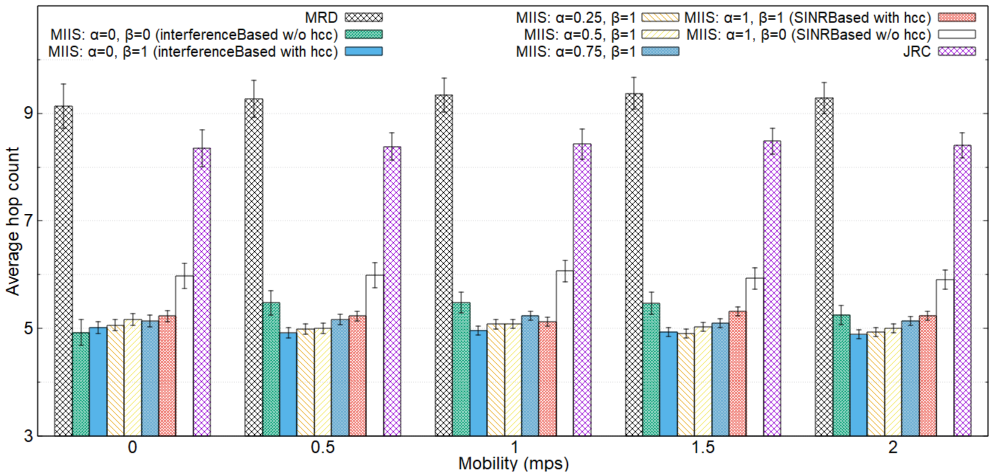


Figure 4.9: Average hop count for varying nodes mobiltiy.

MIIS with α=0.5 achieves the least end-to-end delay in most of the cases because it makes a balance between interference and SINR values for the selection of intermediate nodes in the route.

4.5.4.2 Effects of Varying Nodes Mobility

This section evaluates the effect of varying nodes mobility from 0mps to 2mps. Figure 4.9 shows the average hop count for varying mobility in the network. The average hop count of each scheme is almost constant for all varying speeds. This is because each scheme

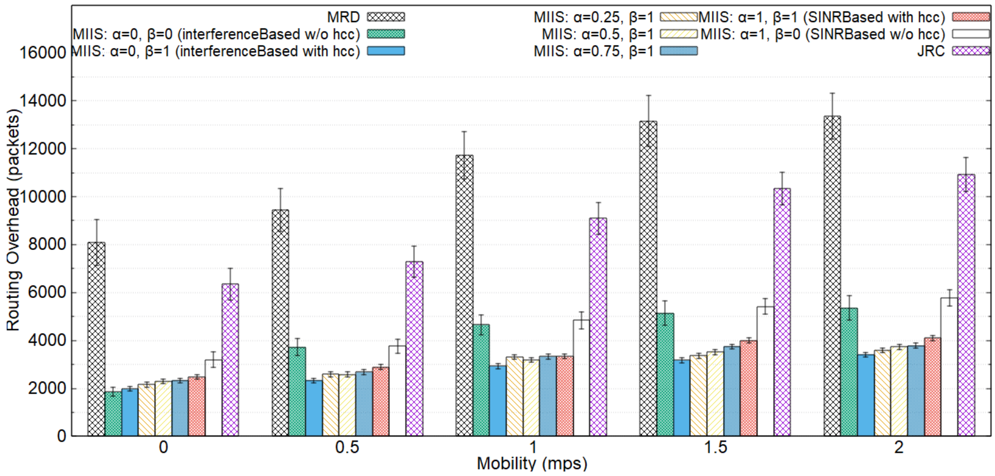


Figure 4.10: Routing overhead for varying nodes mobiltiy.

selects the routes based on the underlying routing metric and using the fixed number of nodes (i.e., fifty nodes). All MIIS variants outperform MRD and JRC schemes by achieving lower average hop count. They achieve average hop count of around five hops except for SINR-based MIIS scheme without hcc, which achieve average hop count of around six hops. SINR-based MIIS scheme without hcc tries to use as much closer nodes as possible to achieve higher SINR regardless of the hop count, so has comparatively higher hops than other MIIS variants. In general, MIIS schemes without hcc causes higher hop count than their counterparts with hcc, because of simply not caring for any hcc. JRC and MRD performs the worst as expected among all and achieve much higher average hop count because of taking longer routes in MRD and higher number of closer nodes in JRC.

Figure 4.10 shows the routing overhead for varying mobility in the network. The routing overhead for all schemes increases with the increasing mobility in the network. This is because for increasing mobility, although the average hop count is similar, however the routes break occur more frequently and hence, D2D UEs exchange more routing control packets for establishing new routes, causing higher routing overhead.

For increasing mobility, all MIIS variants with hcc achieve very low and almost similar routing overhead (or slightly increasing routing overhead with increasing values of α), while for MRD and JRC, the routing overhead is significantly high. For MIIS variants without hcc, the routing overhead is slightly higher than their counterpart MIIS with hcc but much lower than MRD and JRC.

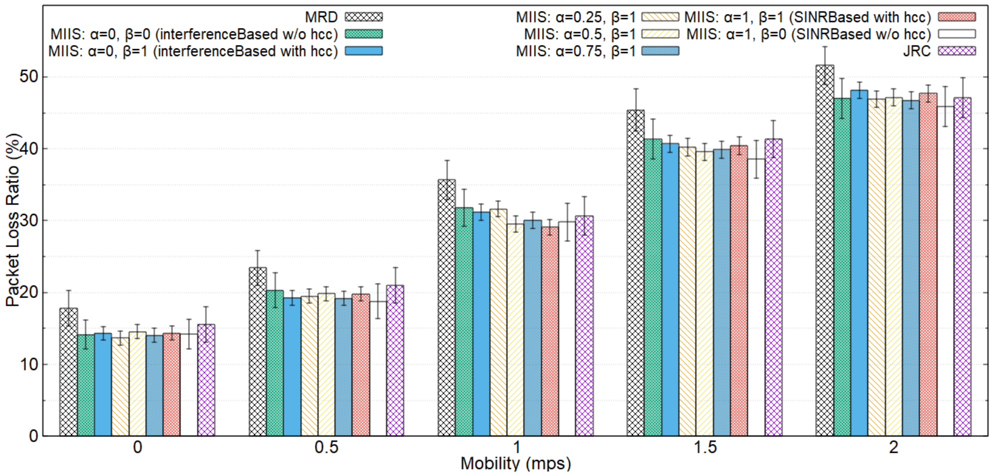


Figure 4.11: Packet loss ratio for varying nodes mobiltiy.

Note that the for MIIS with hcc, the routing overhead slightly increases for increasing values of α because when the value of α moves towards one, MIIS gives higher preference to SINR metric and hence, the established routes involves slightly higher hop count, and hence the routing overhead is naturally slightly higher.

Figure 4.11 shows the packet loss ratio for varying mobility in the network. The packet loss ratio of all the schemes keeps increasing because as the mobility increases, firstly, the chances of route breakages increase, and secondly, it might also be possible that with increasing mobility, no routes could be established. MRD has the highest packet loss ratio, while all MIIS variants and JRC have the similar packet loss ratio.

Figure 4.12 shows the average end-to-end delay for varying node mobility. The end-to-end delay for all the schemes increases with the increasing mobility. This is because of frequent route breakages due to high mobility which cause the nodes to establish the routes again before sending/relaying data packets. Moreover, for each varying mobility, the end-to-end delay of all the schemes is almost similar. This is because the number of nodes are fixed to 50 and as we have seen in Figure 4.8 that when number of nodes are 50, the end-to-end delay of all the schemes is similar. The end-to-end delay of MRD and JRC are lower than all MIIS variants. This is because since their packet loss is higher, therefore the lost packets are not involved in the calculation of end-to-end delay, hence their end-to-end delay are naturally lower.

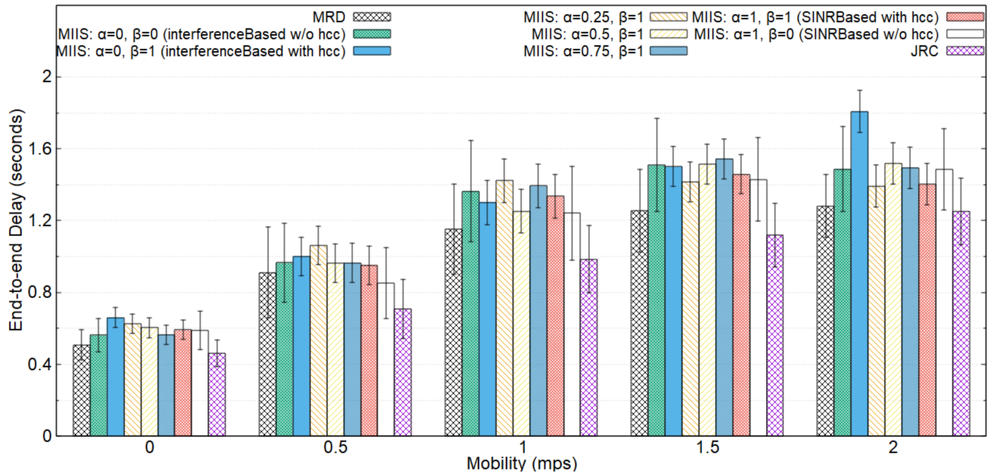


Figure 4.12: End-to-end delay for varying nodes mobility.

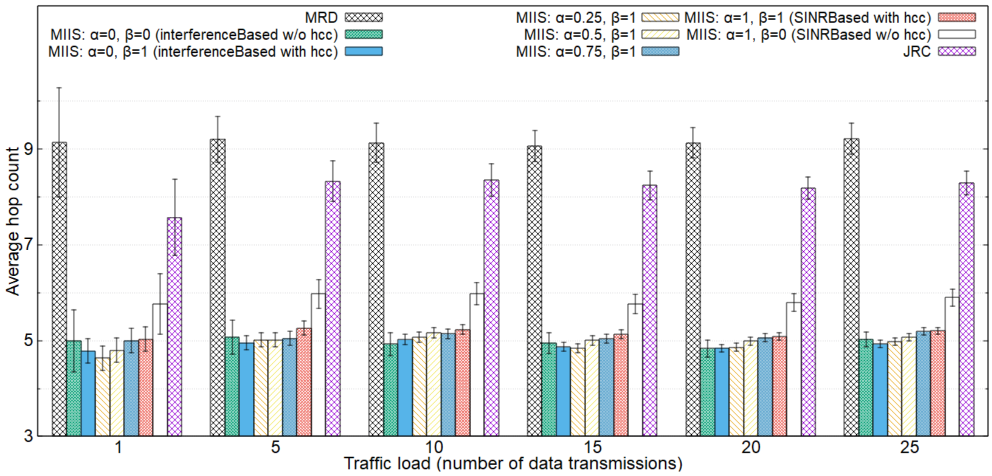


Figure 4.13: Average hop count for varying traffic load.

4.5.4.3 Effects of Varying Traffic Load

This section evaluates the effect of varying traffic load (i.e., number of simultaneous data transmissions) from 1 to 25. Figure 4.13 shows the average hop count for varying traffic load in the network. The average hop count of each scheme is almost the same for varying traffic load. This is because each scheme selects the routes based on the underlying routing metric, hence, for all the data transmissions, since the underlying routing metric is the same, therefore average hop count is similar. All MIIS variants outperform MRD and JRC by achieving lower average hop count. They achieve average

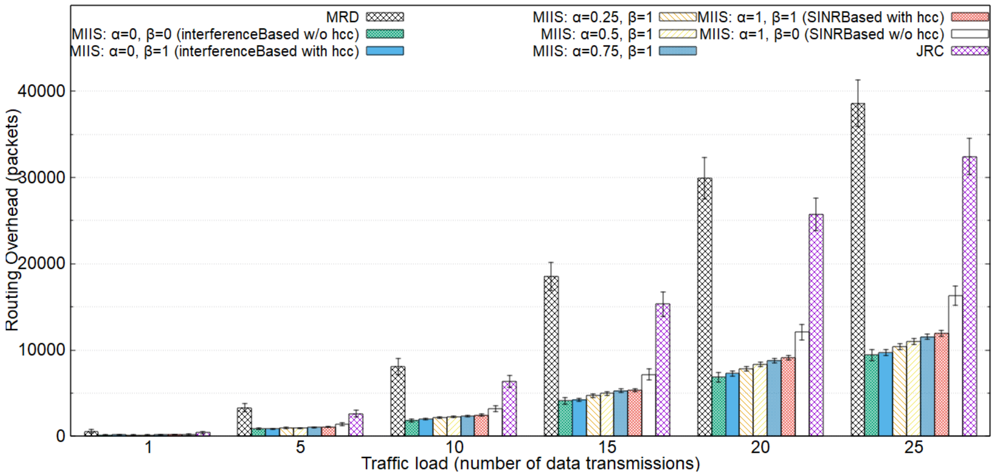


Figure 4.14: Routing overhead for varying traffic load.

hop count of around five hops except for SINR-based MIIS scheme without hcc, which achieve average hop count of around six hops. SINR-based MIIS scheme without hcc tries to use as much closer nodes as possible to achieve higher SINR regardless of the hop count, so have comparatively higher hops than other MIIS variants. JRC and MRD performs the worst as expected among all and achieve much higher average hop count because of taking longer route in MRD and higher number of closer nodes in JRC.

Figure 4.14 shows routing overhead for varying traffic load. When there is one data transmission, the routing overhead for all the schemes is negligible. With the increase in the traffic load, all MIIS variants achieve very low and almost similar routing overhead, while for MRD and JRC, the routing overhead keeps increasing significantly. This is because for varying traffic load, although the average hop count is similar, however the packet loss ratio increases with the increasing traffic load which also results in more route breakages. Hence, on route breakages, the D2D UEs exchange routing control packets for establishing new routes, thus causing higher routing overhead. Note that for MIIS, the routing overhead slightly increases for increasing values of α because when the value of α moves towards one, the MIIS gives higher preference to SINR metric and therefore, the established routes involves slightly higher hop count, and hence the routing overhead is naturally slightly higher.

Figure 4.15 shows packet loss ratio for varying traffic load. When the traffic load

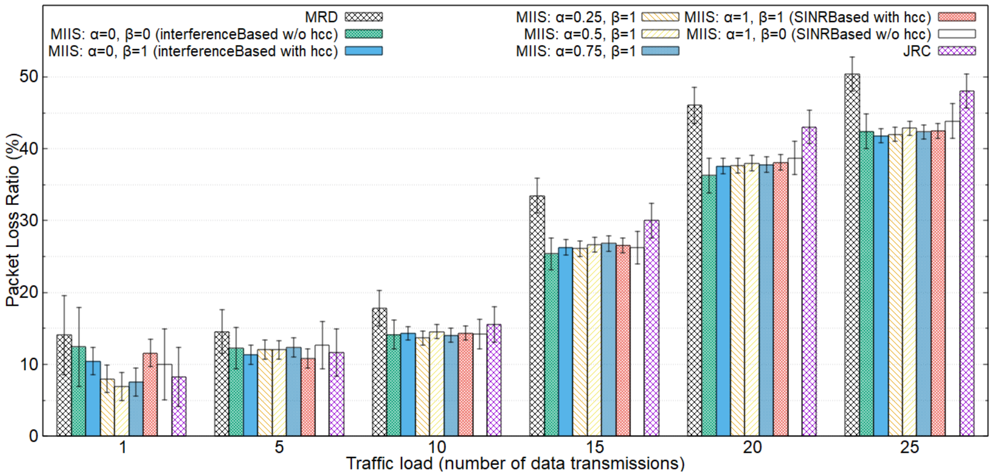


Figure 4.15: Packet loss ratio for varying traffic load.

(i.e., number of simultaneous data transmissions) increases, the packet loss ratio of all the schemes keep increasing because, firstly, there are higher chances of having the same set of intermediate nodes in multiple routes that causes contention and packets drop. Secondly, there is higher chance of collision among data packets causing packets to be dropped. There is an interesting behavior. The packets loss ratio of all the schemes remains almost constant until ten simultaneous transmissions, however increases linearly above ten simultaneous transmissions. This is because the network has the capacity to handle ten simultaneous transmissions, however the network performance starts degrading above ten simultaneous transmissions that causes higher packet loss. Overall, MRD and JRC have higher packet loss ratio, while all MIIS variants have lower and similar packet loss ratio.

Figure 4.16 shows end-to-end delay for varying traffic load. The end-to-end delay for all the schemes increases with the increasing traffic load. This is because a D2D UE can be involved as intermediate node in multiple routes, and therefore, if it receives data packets to relay from some routes while it is already relaying data packets of another route, it has to en-queue the packets. Moreover, for each varying traffic load, the end-to-end delay of all the schemes is almost the same. This is because the number of nodes are fixed to 50 and as we have seen in Figure 4.8 that when number of nodes are 50, the end-to-end delay of all the schemes are similar. Similar to packet loss ratio in Figure 4.15, the end-to-end of all the schemes remains almost constant until ten simultaneous trans-

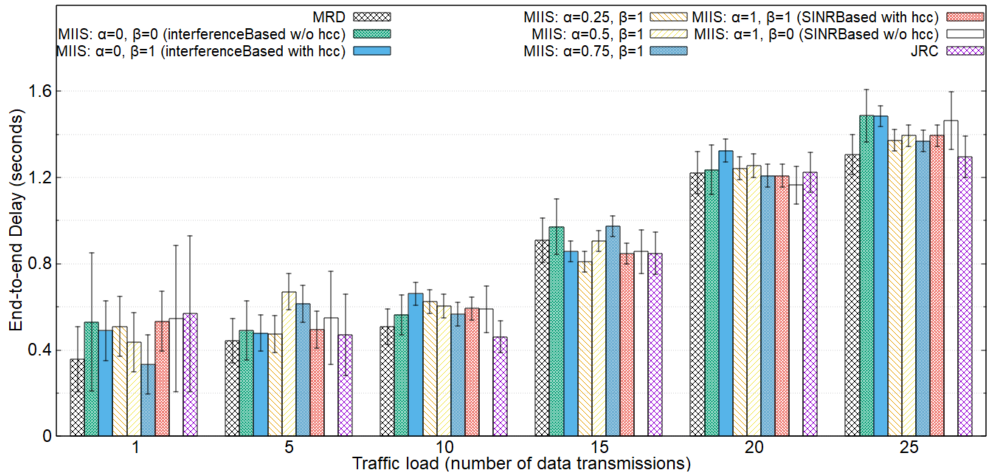


Figure 4.16: End-to-end delay for varying traffic load.

missions, however increases linearly above ten simultaneous transmissions. The reason is similar, i.e., the network has the capacity to handle ten simultaneous transmissions, however the network performance starts degrading above ten simultaneous transmissions and causes higher end-to-end delay. The end-to-end delay of MRD and JRC are lower than all MIIS variants. This is because since their packet loss is higher, therefore the lost packets are not involved in the calculation of end-to-end delay, hence their end-to-end delay are naturally lower.

4.5.5 Insights

The average hop count increases with the increasing number of nodes, however stays almost constant for varying nodes mobility and varying traffic load. This is very natural because when there are more number of available nodes, each scheme establishes routes according to them and causing the longer (and better in MIIS) routes having higher hop count. However, since the number of nodes are fixed (i.e., 50 nodes) in varying nodes mobility and varying traffic load, therefore the average hop count is similar for them. Overall, MRD performs the worst causing much higher hop count (i.e., around fourteen hops) while JRC performs the second worst (i.e., around eleven hops). All MIIS variants achieve very low and almost similar hop count (i.e., around six hops). The general trend of MIIS is that the average hop count slightly increases with the increasing values of α. Interference-based MIIS with hcc outperforms all the schemes by achieving the lowest hop count, while SINR-based MIIS without hcc causes slightly higher hop count than other variants of MIIS.

The routing overhead increases with the increasing number of nodes, nodes mobility and traffic load. However, there are different behavior observed for the schemes. MRD and JRC have significant increase in routing overhead (i.e., around 40k and 30k, respectively) with the increasing number of nodes and traffic load, while have slight increase in routing overhead (i.e., around 13k and 11k, respectively) with the increasing nodes mobility. All variants of MIIS have slight increase in routing overhead (i.e., around 4k packets) with the increasing number of nodes and nodes mobility, while have significant increase in routing overhead (i.e., around 10k packets) with the increasing traffic load (however, still much lower than MRD and JRC). The general trend of MIIS is that the routing overhead slightly increases with the increasing values of α (i.e., similar trend like average hop count). Interference-based MIIS with hcc outperforms all the schemes by achieving the lowest routing overhead, while SINR-based MIIS without hcc causes slightly higher routing overhead than other variants of MIIS. For increasing nodes mobility, Interference-based MIIS without hcc causes slightly higher routing overhead than other MIIS variants.

The packet loss ratio of all the schemes is almost similar and increases with the increasing nodes mobility and traffic load (MRD and JRC still having slightly higher packet loss ratio than all MIIS variants). For increasing traffic load, the packets loss ratio of all the schemes remains almost constant until ten transmissions (i.e., around 15% on average), however increases linearly above ten transmissions (i.e., around 30%, 40% and 45% packet loss ratio on average for fifteen, twenty and twenty-five transmissions, respectively). There is an interesting observation for increasing number of nodes (as discussed in Section 4.5.4.1). With the increasing number of nodes, the packet loss ratio reduces for all MIIS variants (i.e., upto 6%), while increases for MRD and JRC (i.e., upto 30% and 20%, respectively). SINR-based MIIS with hcc outperforms all the schemes in most of the cases by achieving the lowest packet loss ratio.

The end-to-end delay exhibit the similar behavior like packet loss ratio as discussed above.

To summarize, Interference-based MIIS with hcc is best suitable for scenarios where minimizing the routing overhead is more important and that can tolerate slightly higher packet loss ratio and end-to-end delay. While, SINR-based MIIS with hcc is best suitable for scenarios where minimizing the packet loss ratio and end-to-end delay is more important and that can tolerate slightly higher routing overhead.

4.6 Summary

A novel routing metric that selects routes having higher SINR while being conscious about lower interference at the same time, is proposed. The proposed scheme can be applied to in-coverage, partial-coverage and out-of-coverage network scenarios. It makes route decisions without using any kind of geographical location information and can operate under various network dynamics (such as high density, high mobility and high traffic load). The proposed scheme is compared with two existing schemes and can minimize the average hop count, routing overhead and packet loss ratio.

In the next chapter, the problem of high routing overhead is solved by utilizing the presence of BS for taking route decisions. The BS has the global view of the whole network and thus it can easily adapt whole network between different routing techniques based on different network circumstances. The reactive routing and proactive routing have shown lower routing overhead under specific network scenarios, and the BS takes advantage of each. Moreover, flooding of routing packets as in distributed networks is not required in presence of the central control entity, which reduces the routing overhead.

Chapter 5

Reactive and Proactive Centralized Routing Protocols

This chapter focuses on centralized routing techniques and proposed reactive and proactive centralized routing for establishing routes in D2D communications in which the routes are formed by BS for a given cell. The routes are established on-demand in reactive routing, while periodically in proactive routing. The centralized routing in comparison to distributed routing reduces the routing overhead by avoiding the flooding of route requests. This chapter presents the algorithms and procedures of reactive and proactive centralized routing. It evaluates their performance by using MIIS, our proposed routing metric in Chapter 4 through simulations in terms of average hop count, routing overhead, packet loss ratio and end-to-end delay by comparing with existing works. The performance is evaluated for the effects of varying number of nodes, nodes mobility and traffic load.

5.1 Introduction

In D2D communication, users forward data to each other without having any intervention from the infrastructure network/base station/operator. However, the communication can be governed by the base station (BS), in which case the BS will be responsible for authorizing and establishing the connection among D2D users. BS will also be responsible for maintaining a minimum required Quality of Service (QoS) level throughout the period of communication. In addition, mobility and handover management can also be easily managed by BS. If the communication is not under the control of BS, then

D2D communication behaves like an ad hoc network.

When two users that are not in the transmission range of each other want to communicate, multihop route is required to be established between them. We take advantage of the existence of BS for establishment and maintenance of a route. The supervision of BS helps in identifying the best route among all candidate routes due to the global network knowledge which is very difficult in distributed schemes (where nodes take decision autonomously) due to only limited local available information. It also helps in reducing the routing overhead significantly by avoiding the flooding of route requests (RREQs).

We propose reactive and proactive centralized routing schemes in which the BS establishes the routes on-demand or periodically, respectively. The centralized routing in comparison to distributed routing reduces the routing overhead by avoiding the flooding of route requests. The reactive routing provides lower routing overhead in high density networks with low traffic load. The proactive routing is preferred for other network scenarios. The system model for both reactive and proactive centralized routing schemes is the same as in Figure 4.1.

5.2 Related Work

Most of the works found in the literature for routing in multihop D2D networks do not take advantage of the presence of central entity for taking the route decision, and thus are distributed in nature. However, some centralized solutions exist for tree-based routing [WL07], location-based routing [CPGF16; Wu+16; Par16] and topology-based routing. In tree-based routing, all the existing schemes are proactive in nature, since a central node (i.e., BS) needs to be periodically updated in order to maintain the tree structure. In location-based routing, each node is assumed to inform about its current location to a location server. The location server is then responsible to provide the location of a destination node to the source node during connection establishment. In topology-based routing, the existing proactive centralized schemes include multihop cellular network (MCN) routing [AMM01], base-centric routing (BCR) [HL02], cellular-based source routing (CBSR) [LYC03] and light dark routing (LDR) [Han+06]. In proactive centralized schemes, each node continuously forwards the updated neighborhood table to the BS through hello packets either periodically or when there is a change in the topology. The BS then draws the network topology graph.

Due to high energy consumption in regular updates for all these three scheme, e.g., in tree-based routing for maintaining the tree structure, in location-based routing for sending location information to the server, and in topology-based centralized proactive routing for forwarding the periodic/on-demand hello packets and sending neighborhood table to the BS, such schemes are not suitable for most of the energy-conscious applications. Moreover, none of the topology-based centralized proactive routing scheme discussed the high routing overhead incurred due to regular updates. Although the routing overhead is discussed in CBSR, but it takes account of only route discovery packets like route request (RREQ), route reply (RREP) and route error (RERR), without considering the high overhead incurred in topology update packets like hello and neighborhood table status packets.

To the best of our knowledge, there does not exist reactive centralized topology-based routing scheme for D2D communications. We propose a novel route discovery mechanism, i.e., reactive centralized routing, which is further extended as proactive centralized routing that can reduce the routing overhead to a great extent. The proposed scheme takes advantage of reactive and proactive routing in different network conditions/scenarios which can enhance the network performance in terms of reduced routing overhead, lower packet loss ratio and delay.

5.3 Reactive Centralized Routing

In reactive centralized routing scheme, the BS is responsible for establishing and maintaining the routes between the nodes in its cell. Whenever a D2D UE wants to communicate with another D2D UE, it asks for a route from BS by sending a route request (RREQ) packet. The BS then checks whether it has up-to-date network topology graph. If yes, it calculates the route from network topology graph and send the route to source, destination and intermediate nodes. Otherwise, it enqueues the request and initiates neighbor discovery process by broadcasting the neighbor table request (NTREQ) packet to all nodes in the network. If another node request a route once neighbor discovery process is started, the BS also enqueues the request until the neighbor discovery process is completed.

Upon receiving the NTREQ, all nodes in the network schedule a neighbor discovery completion timer and start exchanging hello packets for neighbor discovery. The hello packet contains information required for the route establishment, such as the observed average interference from CUE and the transmission power in order to calculate the RSS at the neighbor nodes. On receiving hello packets, each node maintains the list of its neighboring nodes along-with their interference and other required information.

On expiration of neighbor discovery completion timer, the nodes are expected to have discovered all their neighbors and each node shares its neighbor table with BS by sending neighbor table reply (NTREP) packet.

After receiving neighbor tables from all the nodes, the BS constructs a complete network topology graph. This network topology graph will be valid until next *topologyLifetime* duration. The BS uses network topology graph to calculate routes for all the requested nodes. It then communicates each calculated route to all participating nodes (i.e., source, destination and intermediate nodes) by sending route reply (RREP) packets. On receiving RREP packets, the nodes add the received route to their routing table and update their next hop and previous hop nodes to reach source and destination nodes. The source node then starts data transmissions to the destination node.

At any time instant, if any participating node in an active route identifies a link break, it sends a route error (RERR) packet to the BS. The BS then immediately informs the source node about route breakage by sending route break (RBREAK) packet so that source node can promptly stop its current data transmission to avoid any further packet loss. The BS then calculate a new route for the affected source node using the route discovery mechanism discussed above and sends the newly calculated route to all participating nodes.

It is important to note that there is no flooding of control packets as in the distributed routing. Therefore routing overhead is minimal in centralized routing strategy.

Algorithm 1 presents the six main steps of route establishment in reactive centralized routing.

Algorithm 1: List of steps in reactive centralized routing

```
1 D2D UE sends RREQ to BS
2 if not up-to-date network topology graph then
    BS broadcasts NTREQ
  else
    goto step 5
3 Hello packet exchange by UEs (to update neighbors)
4 UEs send NTREP to BS
5 BS constructs network topology graph
6 BS calculate route and send RREP to all participating D2D UEs
```

For better understanding, an illustrative figure presenting the operation of route

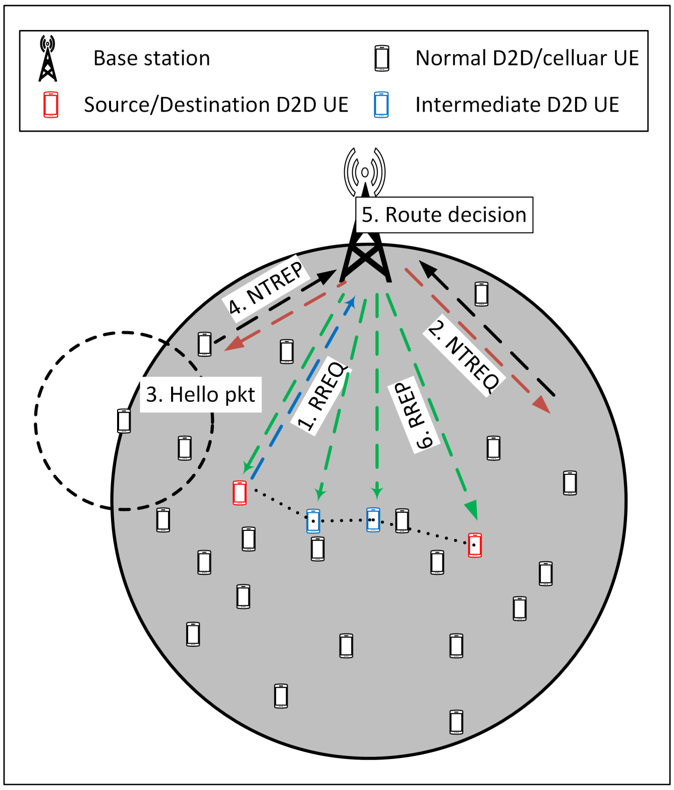


Figure 5.1: Reactive Centralized routing mechanism.

discovery procedure of reactive centralized routing is presented in Figure 5.1. The source D2D UE (red colored UE) sends RREQ (step 1) to BS in order to communicate with destination D2D UE (red colored UE). The BS broadcasts NTREQ (step 2) to whole network. All D2D UEs on receiving NTREQ, start exchanging Hello packets (step 3) and subsequently, send NTREP (step 4) to BS. The BS then calculates the route (step 5) and finally sends RREP (step 6) to all source, destination and intermediate nodes (red and blue colored UEs)

5.4 Proactive Centralized Routing

The reactive centralized routing is extended to proactive centralized routing. In proactive centralized routing, unlike reactive centralized routing in which the BS updates the network topology graph only when nodes request for route, the BS periodically keeps an up-to-date network topology graph. Hence, it broadcasts *NTREQ* packets periodically after each *topologyLifetime* duration. Similar to reactive centralized routing, the D2D

UEs upon receiving *NTREQ* start exchanging *Hello* packets to maintain neighbor table and then send *NTREP* packets to BS containing their neighbor tables. Upon receiving *NTREP* packets, the BS updates its network topology graph. In this manner, the BS has up-to-date network topology graph at periodic intervals and when a node asks for a route, it immediately calculates the route and sends the *RREP* to participate nodes. However, there could one issue. If any participating node in an active route identifies a link break and informs about it to BS through *RERR*, the BS either calculates a new route from its existing network topology graph, which might be stale and calculates the same problematic route as last time, or it waits for the network topology graph to be updated in the next cycle and then sends *RREP* to participating nodes that can increase the delay.

Algorithm 2 presents the six main steps of route establishment in proactive centralized routing.

Algorithm 2: List of steps in proactive centralized routing

```
   loop (after every topologyLifetime duration)
1:    BS periodically broadcasts NTREQ
2:    Hello packet exchange by UEs (to update neighbors)
3:    UEs send NTREP to BS
4:    BS constructs network topology graph
   end loop
5: D2D UE sends RREQ to BS
6: BS calculate route and send RREP to all participating D2D UEs
```

5.5 Performance Evaluation

5.5.1 Simulation Setup and Parameters

MIIS is implemented in OMNeT++ 5.4.1 with INET 4.0 framework. The number of D2D UEs vary from 50 to 100, the D2D UEs mobility vary from 0 meter/second to 2 meter/second, and the traffic load (number of transmission) range from 1 transmission to 25 simultaneous transmissions. The default number of D2D UEs is 50, having 10 simultaneous transmissions and no mobility. With the given fixed transmission power, the transmission range of UEs is 125 meters. All the results are generated with a confidence interval of 95%. Each simultaneous transmission refers to an end-to-end

Table 5.1: Simulation parameters.

Parameter	Value
Number of D2D UEs	50
D2D UEs mobility	Static
Area	500m × 500m
Placement of nodes	Random
Traffic load (number of transmissions)	10
Traffic type	UDP-CBR
Packet size	1000 bytes
Total number of packets	50
Simulation time for each run	50s
Simulation runs	100

communication having a unique source-destination pair that is randomly deployed for each simulation. The MAC protocol used is Carrier Sense Multiple Access (CSMA). The simulation parameters are presented in Table 5.1.

5.5.2 Performance Metrics

- *Average hop count* is the average number of hops included in the established routes. A smaller average hop count is favorable [JXQ15; RDS13].
- *Routing overhead* is the number of control packets exchanged for route establishment. A lower routing overhead is favorable [RMP11].
- *Packet loss ratio* is the ratio of total number of lost packets to the total number sent packets. A smaller packet loss ratio is favorable [Abd+20].
- *Average end-to-end delay* is the average end-to-end delay of all the packets from source node to destination node. A smaller end-to-end delay is favorable [Sal+17; Sal+15b].

5.5.3 Comparison Schemes

The performance of MIIS is compared with two existing schemes: Maximum Rate towards Destination (MRD) [RDS13] and Joint Routing and Channel selection (JRC) [JXQ15]. MRD selects the intermediate nodes having the least interference from CUEs, hence it selects the intermediate nodes towards the edge of the cell. JRC selects the intermediate nodes having the stronger SINR, hence it selects the nearest nodes as intermediate nodes in the route.

5.5.4 Results and Discussions

In this section, MIIS with varying values of α={0, 0.25, 0.5, 0.75, 1} and β={0,1} is evaluated and compared with MRD and JRC. When the value of α is close to 0, MIIS gives more preference to interference metric, while when the value of α is close to 1, MIIS gives more preference to SINR metric. β=0 means without hop count consideration (hcc), while β=1 means with hcc. In our evaluation, MIIS with α=0 and β=0 behaves as interference-based scheme without hcc, while MIIS with α=1 and β=0 behaves as SINR-based scheme without hcc. MIIS with α=0 and β=1 behaves as interference-based scheme with hcc, while MIIS with α=1 and β=1 behaves as SINR-based scheme with hcc.

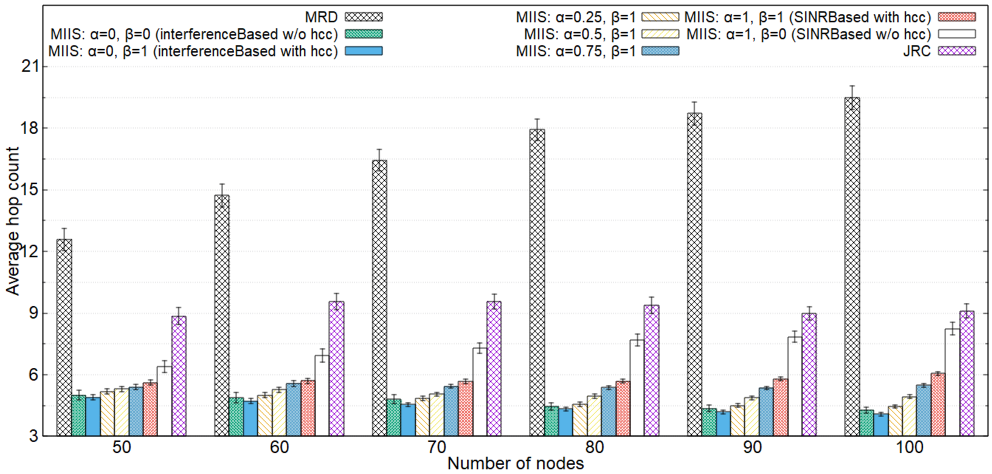
5.5.4.1 Effects of Node Density (Varying Number of Nodes)

This section evaluates the effect of node density (i.e., varying number of nodes) from 50 to 100 in the network. Figure 5.2 (a) and (b) show the average hop count of reactive and proactive centralized routing for varying number of nodes for MIIS (different variants), MRD and JRC. All MIIS variants outperform MRD and JRC by achieving lower average hop count (i.e., almost five hops).

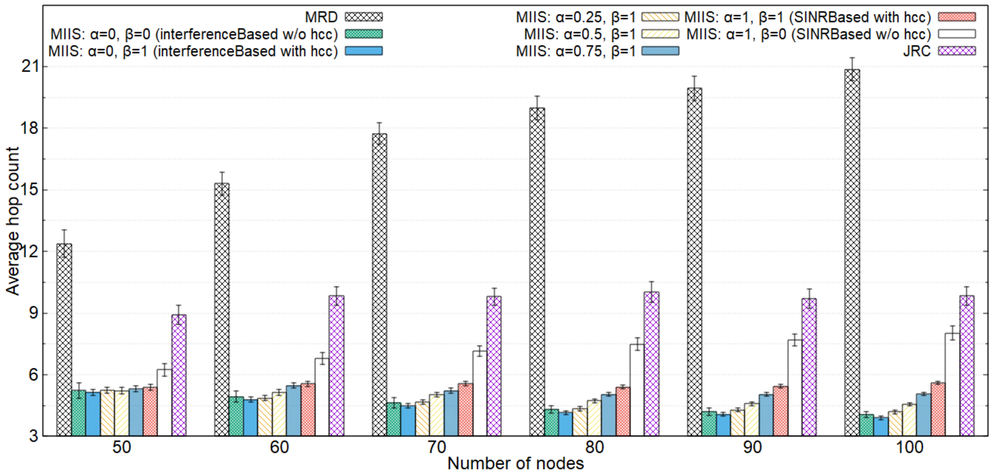
With the increase in the number of nodes in the network, the number of hops for all MIIS variants with values of $\alpha \leq 0.75$, tend to decrease a little. This is to take advantage of higher number of nodes and find routes with less number of hops. Conversely, the hop counts for MRD, JRC and SINR-based MIIS without hcc tend to increase with the increase in the number of nodes. This is because MRD takes more and more longer route with the availability of higher number of nodes in order to reduce interference. JRC and SINR-based MIIS without hcc select as much closer nodes as possible to achieve higher SINR, resulting in increase in number of hops with the increase in the number of nodes.

Overall, MRD performs the worst achieving an average hop count of up-to around twenty one hops (in proactive routing), i.e., around 457% higher than MIIS.

The average hop count does not have much effect of the centralized technique used, therefore reactive and proactive routing provide similar results. They result in higher average hop count than distributed reactive routing (presented in Figure 4.5). This is because, in distributed routing, the best route is usually not achieved due to the collisions of RREQ packets while flooding. These higher hops yet optimal routes from centralized routing significantly improved the performance in terms of packet loss ratio, end-to-end-delay and routing overhead, as will be discussed next.



(a) Reactive.

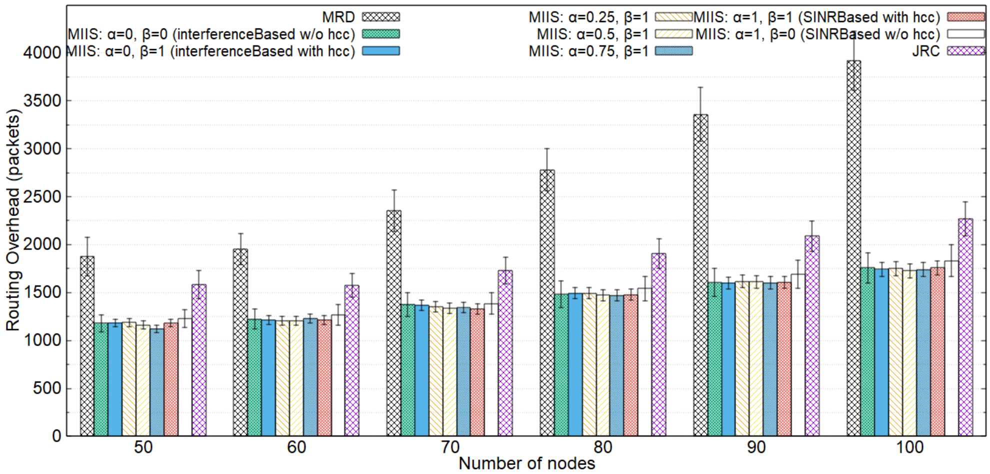


(b) Proactive.

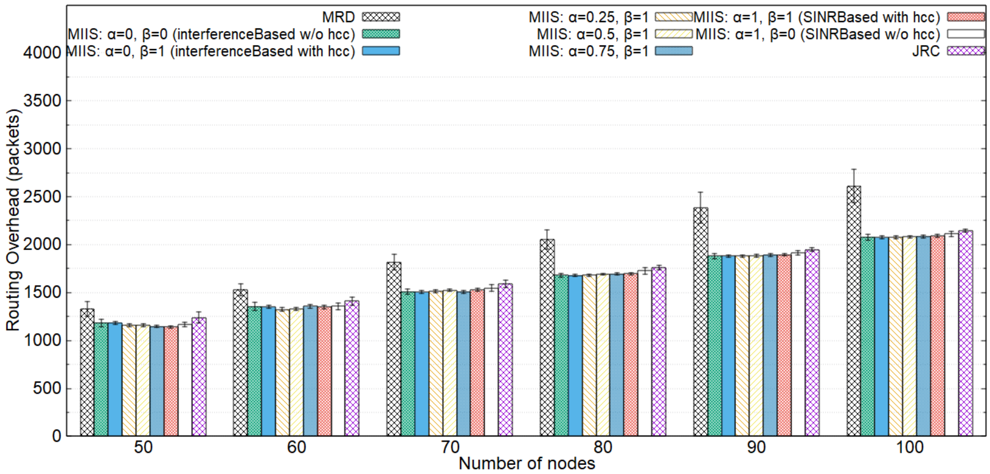
Figure 5.2: Average hop count for Reactive and Proactive Centralized Routing for varying node density.

Figure 5.3 (a) and (b) show routing overhead of reactive and proactive centralized routing for varying number of nodes for MIIS (different variants), MRD and JRC. With the increase in the number of nodes, the routing overhead also increases, as more number of nodes participate in the route discovery.

The routing overhead increases gradually with the increase in number of nodes in proactive routing. The proactive routing has higher routing overhead than reactive



(a) Reactive.



(b) Proactive.

Figure 5.3: Routing overhead for Reactive and Proactive Centralized Routing for varying node density.

routing, because proactive routing continuously update the routing tables regardless of whether any node needs a route or not. However, reactive routing updates the routing tables only when demanded by a node (provided the previous routing table is expired, if any). In summary, the proactive routing depends on the number of nodes and thus increases gradually, while reactive routing depends on the total number of data transmissions and thus total number of routes required, and so there is slow increase in its routing overhead.

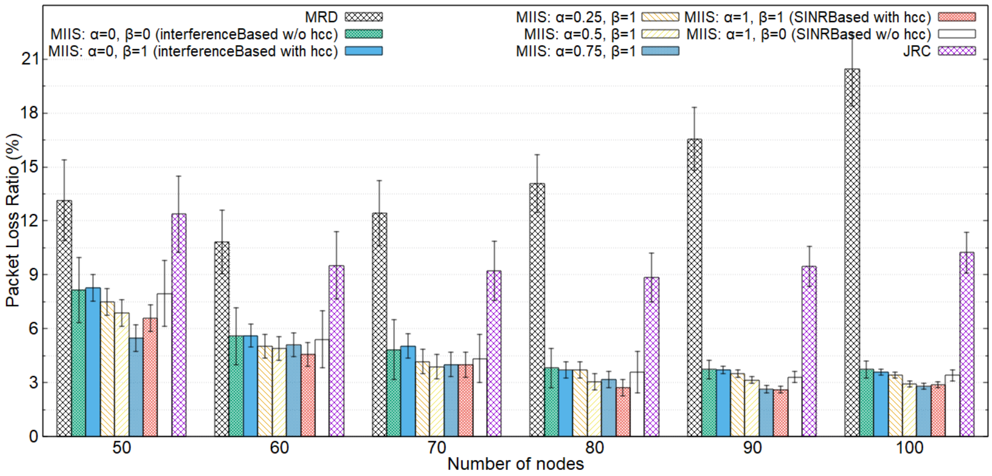
MRD and JRC use the availability of higher number of nodes to establish routes with lesser interference (causing longer routes) in MRD and more number of closer nodes having stronger SINR in JRC, which increase the total number of hops in the route, and also results in higher routing overhead. The effect on MRD and JRC is significant in reactive routing, however is insignificant in proactive centralized routing. This is because in reactive routing, the packet loss ratio (as discussed next) for MRD and JRC increases with the increasing number of nodes, resulting in more frequent route breakages, therefore the increase in routing overhead of MRD and JRC is very natural.

Figure 5.4 (a) and (b) show packet loss ratio of reactive and proactive centralized routing for varying number of nodes for MIIS (different variants), MRD and JRC. When the number of nodes in the network are 50, all MIIS variants exhibit the similar packet loss ratio of around 6% to 8%, while MRD and JRC has much higher packet loss ratio of around 12%. As the number of nodes keeps increasing, the packet loss ratio of all MIIS variants schemes keep reducing upto around 3%, by taking the advantage of availability of higher number of nodes in the network. The packet loss ratio of JRC also reduces upto around 9%. However, it is inverse for MRD and the packet loss ratio keep increasing upto around 21%. Thus, increase in the number of nodes, result in similar effect on the average hop count and the packet loss ratio.

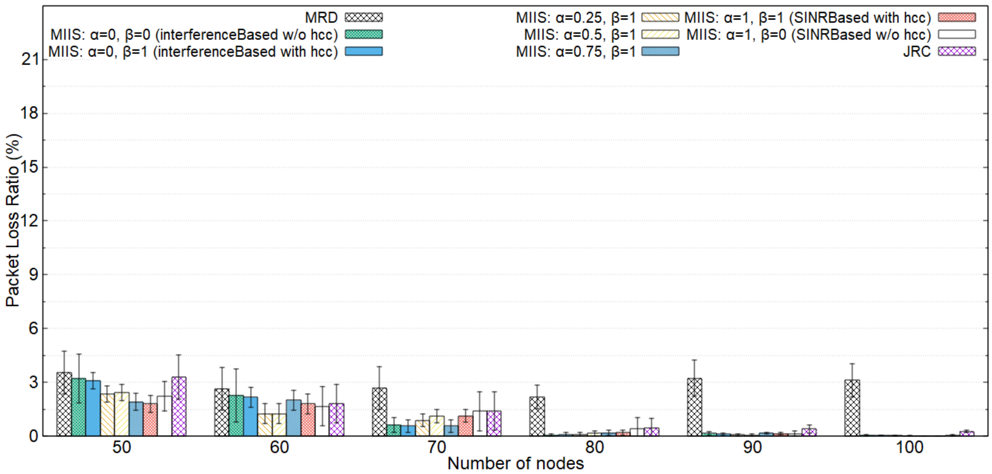
In reactive centralized routing, the MRD, with the increase in number of nodes, selects more and more number of nodes having lower interference, resulting in longer route and increases the probability of packet collisions, and hence causes higher packet loss ratio. Overall, MIIS performs the best, while MRD performs the worst. MIIS is able to achieve around 700% and 350% less packet loss ratio than MRD and JRC, respectively.

The trend of packet loss ratio of reactive routing is very similar to packet loss ratio in Chapter 4. However, the packet loss ratio in proactive routing is very less, which is a very surprising behavior. The possible reason of higher packet loss ratio in reactive routing might be because of non-coordinated route discovery which might overload the network, while is not the case in proactive routing due to coordinated route discovery.

Figure 5.5 (a) and (b) show average end-to-end delay of reactive and proactive centralized routing for varying number of nodes for MIIS (different variants), MRD and JRC. As the number of nodes keep increasing, the end-to-end delay of all schemes keep reducing. This is by selecting better routes by taking the advantage of availability of



(a) Reactive.

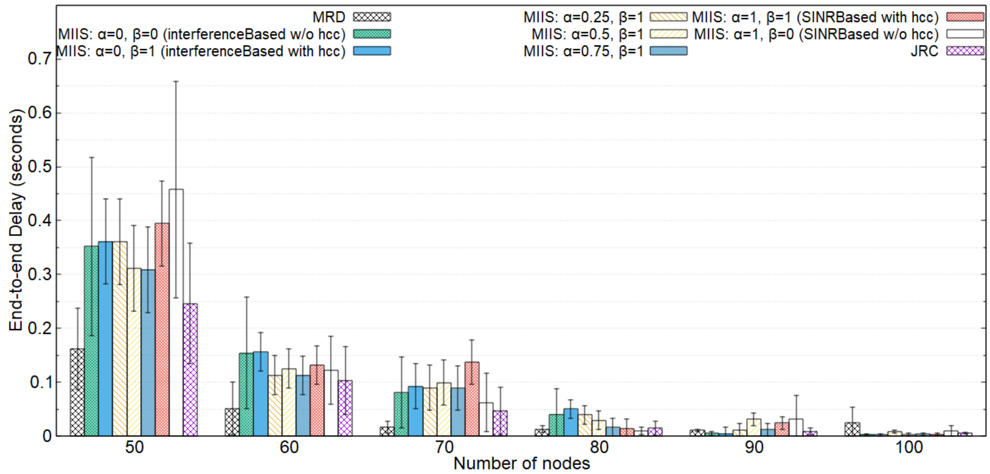


(b) Proactive.

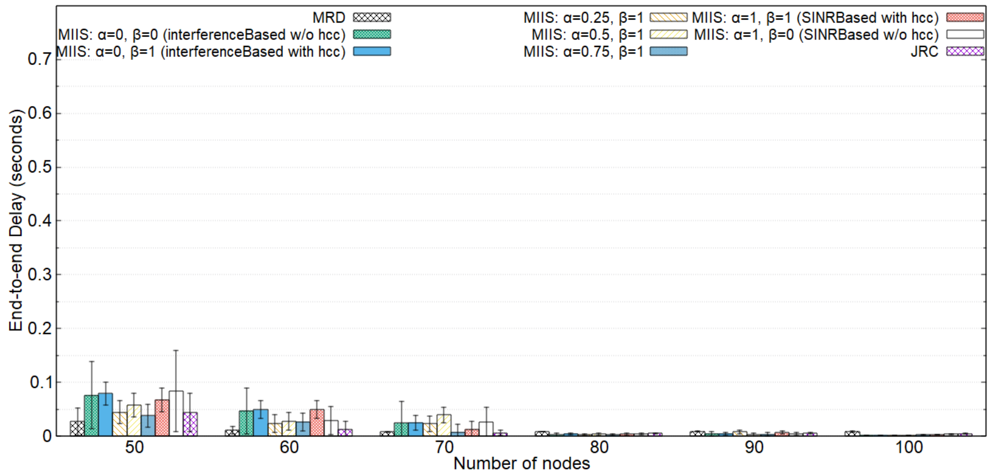
Figure 5.4: Packet loss ratio for Reactive and Proactive Centralized Routing for varying node density.

higher number of nodes in the network, causing routes having lower end-to-end delay.

The reactive routing has higher end-to-end-delay than proactive routing. This is because, when a node requires a route to the destination node, it request the BS, which further initiates the route discovery (if route not already available or routing table is not up-to-date), resulting in higher waiting time and thus the overall delay increases accordingly. Due to the same reason in reactive "distributed" routing, the flooding of RREQ packets in the whole network consumes high amount of time, which also results in



(a) Reactive.



(b) Proactive.

Figure 5.5: End-to-end delay for Reactive and Proactive Centralized Routing for varying node density.

significantly higher waiting time for the route and thus overall delay was also significantly higher (as discussed in Section 4.5.4.1). However, in proactive centralized routing, the BS maintains the up-to-date routing tables all the times, so whenever a node requires a route, it is provided immediately, causing lower waiting time for route and accordingly, lower end-to-end delay.

The end-to-end delay of MRD and JRC are lower than all MIIS variants. This is because since their packet loss is higher, therefore the lost packets are not involved in the calculation of end-to-end delay, hence their end-to-end delay are naturally lower.

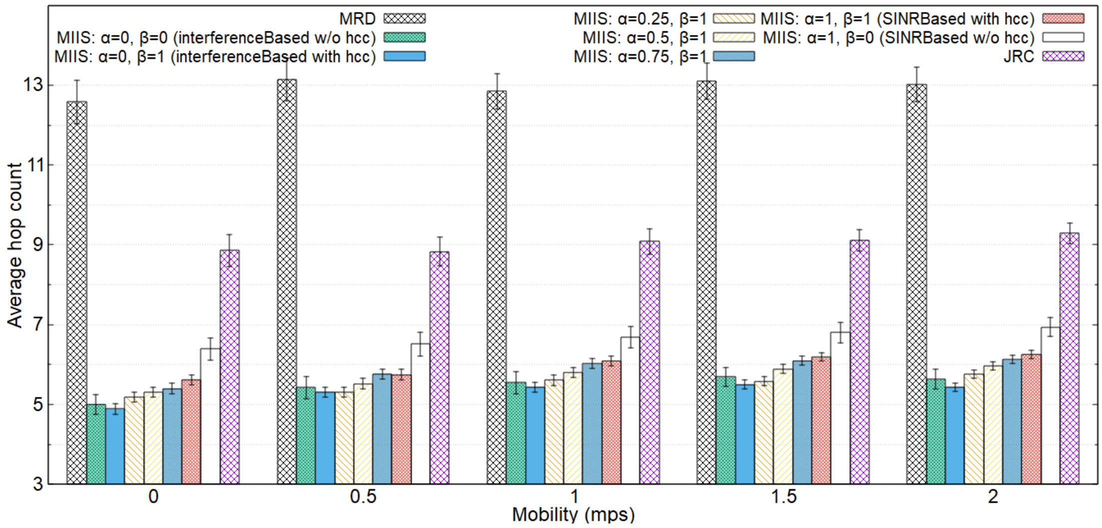
To summarize, note that end-to-end delay depends on many factors. The end-to-end delay decreases with the increase in number of nodes in the network. This is because, with the availability of more number of nodes, the same node is used by less number of routes, and thus the overall burden on each node for forwarding the data of other nodes is lesser, and hence data packets do not have to en-queue for longer time. The end-to-end delay also depends upon number of hops in the route, as higher the number of hops, the higher the delay incurred to reach the destination node. The end-to-end delay also depends on packet loss ratio, as higher the packet loss ratio is, the more the route breakages are, thus more waiting time to discover new route, and finally higher end-to-end delay, since it consists of route discovery time as well. Conclusively, it has been seen that with the increase in number of nodes, packet loss ratio decreases due to more better route options, all contributes to lessening the end-to-end delay.

5.5.4.2 Effects of Varying Nodes Mobility

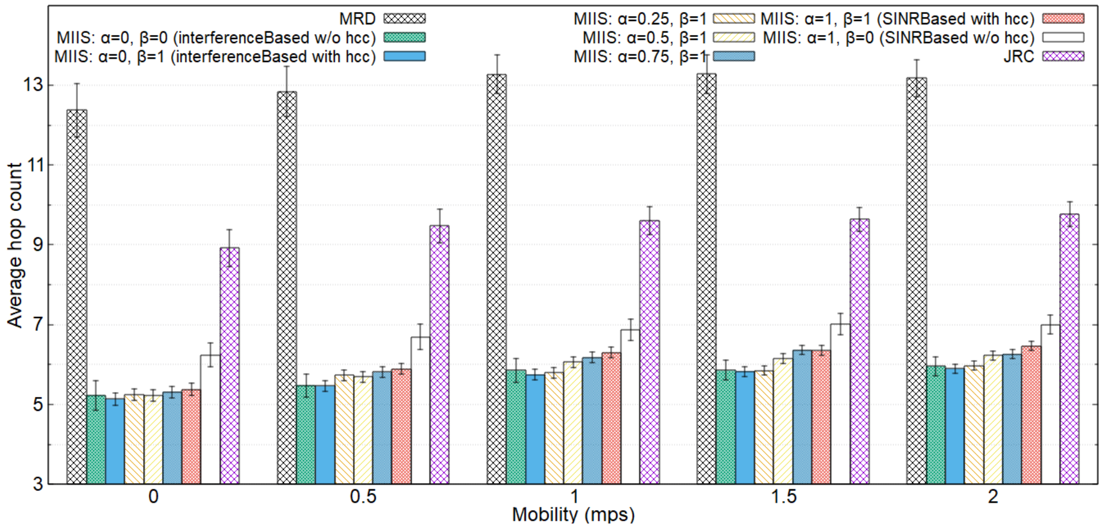
This section evaluates the effect of varying nodes mobility from 0mps to 2mps. Figure 5.6 (a) and (b) show the average hop count of reactive and proactive centralized routing for varying mobility in the network for MIIS (different variants), MRD and JRC. The average hop count of each scheme is almost constant for all varying speeds. This is because each scheme selects the routes based on the underlying routing metric, and using the fixed number of nodes (i.e., fifty nodes). All MIIS variants outperform MRD and JRC by achieving lower average hop count. SINR-based MIIS scheme without hcc tries to use as much closer nodes as possible to achieve higher SINR regardless of the hop count, so have comparatively higher hops than other MIIS variants. In general, all MIIS variants without hcc achieve higher hop count than their counterparts with hcc, because of simply not caring for hcc. JRC and MRD performs the worst as expected among all and achieve much higher average hop count because of taking longer route in MRD and higher number of closer nodes in JRC.

Figure 5.7 (a) and (b) show the routing overhead of reactive and proactive routing for varying mobility in the network for MIIS (different variants), MRD and JRC.

The routing overhead for all schemes increases with the increased mobility in the network. This is because for increasing mobility, although the average hop count is similar, however the routes breakage occur more frequently and hence, D2D UEs exchange more



(a) Reactive.

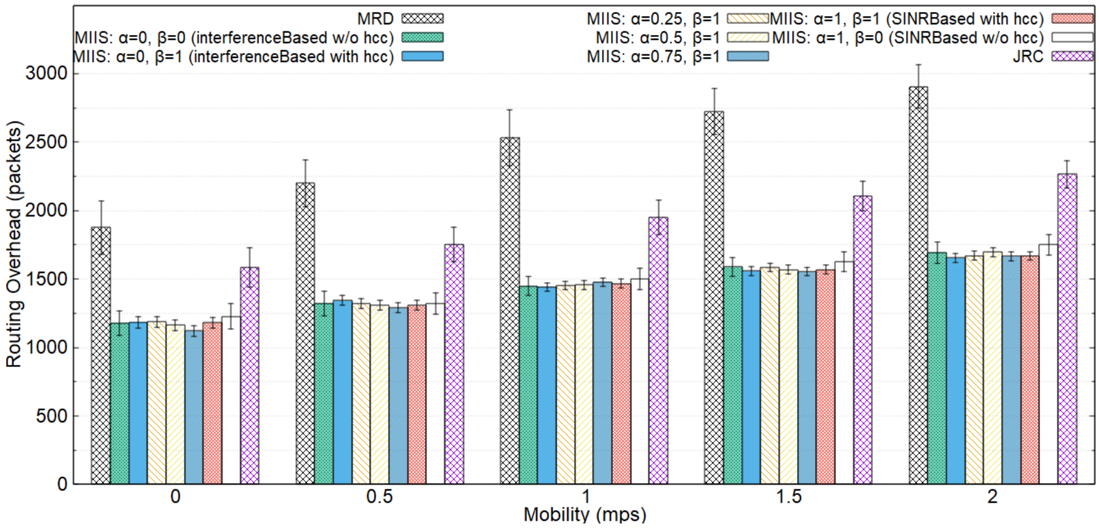


(b) Proactive.

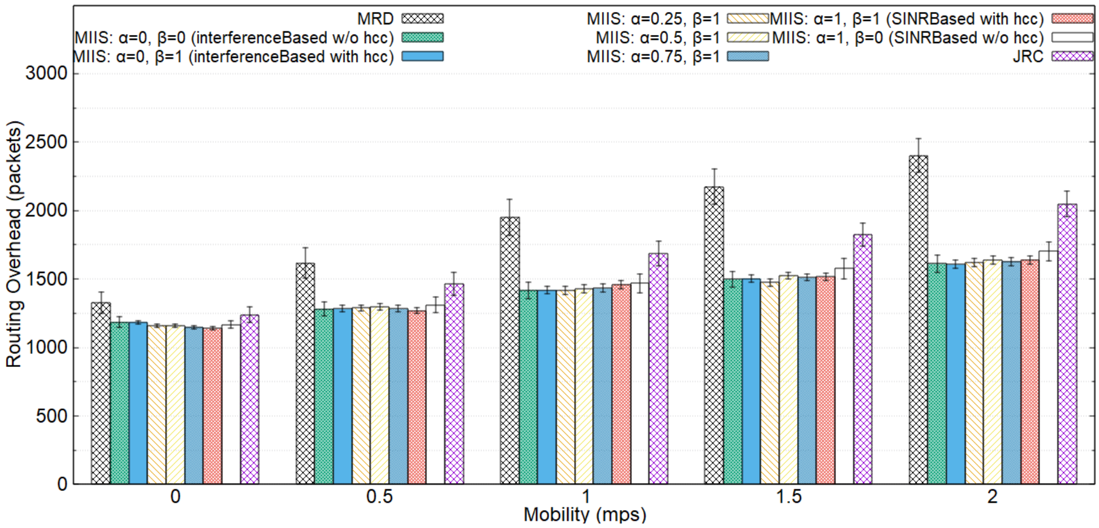
Figure 5.6: Average hop count for Reactive and Proactive Centralized Routing for varying nodes mobility.

routing control packets for establishing new routes, causing higher routing overhead.

For increasing mobility, all MIIS variants achieve very low and almost similar routing overhead, while for MRD and JRC, the routing overhead is significantly high. MRD and JRC use the availability of higher number of nodes to establish routes with lesser interference (causing longer routes) in MRD and more number of closer nodes having



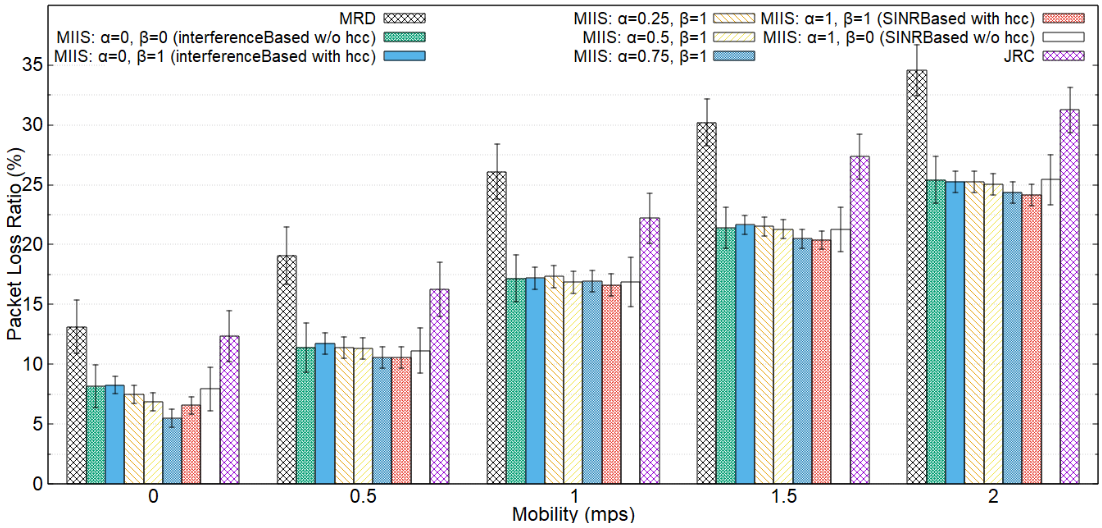
(a) Reactive.



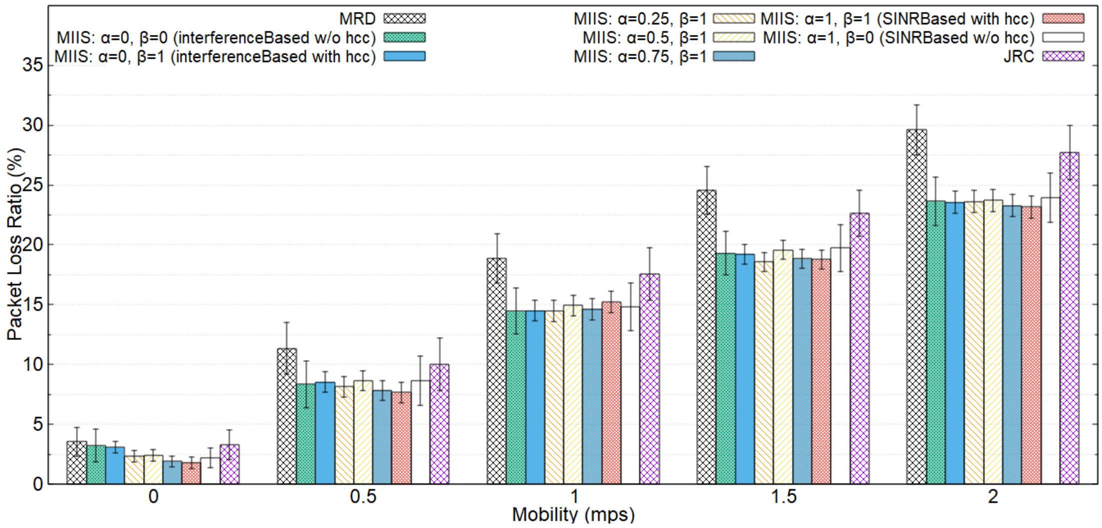
(b) Proactive.

Figure 5.7: Routing overhead for Reactive and Proactive Centralized Routing for varying nodes mobility.

stronger SINR in JRC, which increase the total number of hops in the route, and also results in higher routing overhead. The difference of MRD and JRC with the all MIIS variants is significant in reactive routing while it is insignificant in proactive routing. The quite similar behavior is observed in routing overhead for varying number of nodes in Section 5.5.4.1, which is because the higher packet loss ratio causes more frequent



(a) Reactive.



(b) Proactive.

Figure 5.8: Packet loss ratio for Reactive and Proactive Centralized Routing for varying nodes mobility.

route breakages, and hence higher routing overhead.

Figure 5.8 (a) and (b) show the packet loss ratio of reactive and proactive routing for varying mobility in the network for MIIS (different variants), MRD and JRC. The packet loss ratio of all the schemes keep increasing because as the mobility increases, the probability of connection failure with the next hop node increase, resulting in more packet losses and the breakage of routes.

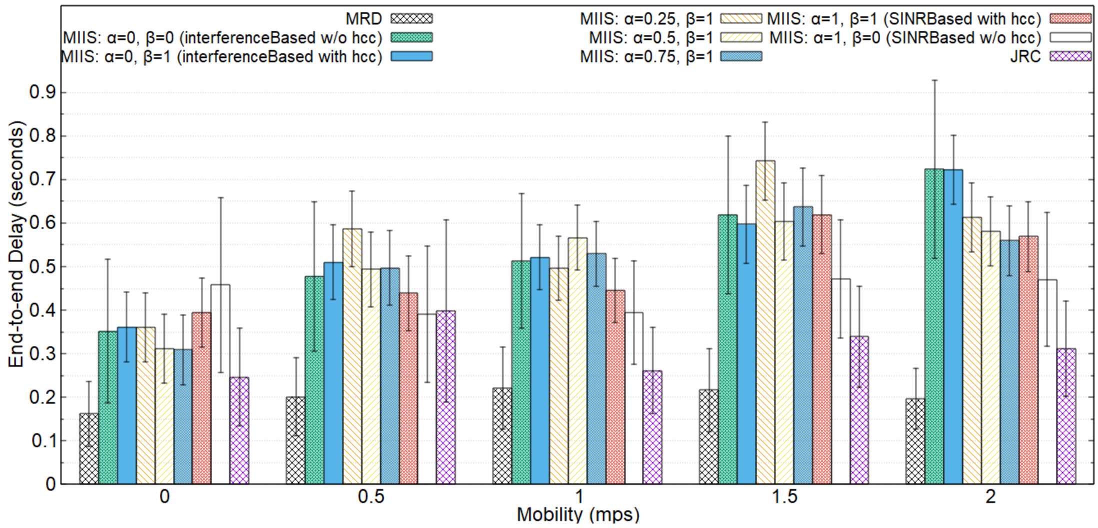
As MRD and JRC have higher hop counts than all MIIS variants in all types of scenarios, so due to more intermediate nodes, the packet collisions are also higher resulting in higher packet loss ratio for both the schemes.

The reactive and proactive routing exhibit similar effect with the increase in the network mobility, with proactive routing performs a little better than reactive routing.

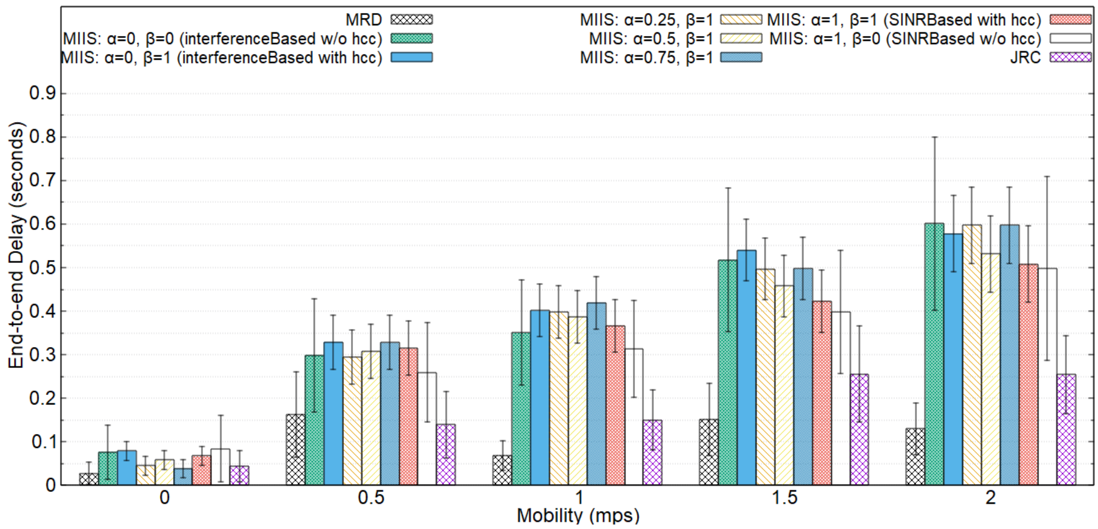
Figure 5.9 (a) and (b) show the average end-to-end delay of reactive and proactive routing for varying node mobility for MIIS (different variants), MRD and JRC. The end-to-end delay for all the schemes increases with the increasing mobility. This is because of frequent route breakages due to high mobility which cause the nodes to establish the routes again before sending/relaying data packets. Moreover, for each varying mobility, the end-to-end delay of all the schemes is almost the same. This is because the number of nodes are fixed to 50 and as we have seen in Figure 5.5 that when number of nodes are 50, the end-to-end delay of all the schemes is similar. The end-to-end delay of MRD and JRC are lower than all MIIS variants, because since their packet loss are higher, therefore the lost packets are not involved in the calculation of end-to-end delay.

5.5.4.3 Effects of Varying Traffic Load

This section evaluates the effect of varying traffic load (i.e., number of data transmissions) from 1 to 25, of reactive and proactive routing for MIIS (different variants), MRD and JRC. Figure 5.10 (a) and (b) show the average hop count of reactive and proactive routing for varying traffic load in the network. The average hop count of each scheme is almost constant for varying traffic load. This is because each scheme selects the routes based on the underlying routing metric. Hence, for all the data transmissions, since the underlying routing metric is the same, therefore the average hop count is similar. All MIIS variants outperform MRD and JRC schemes by achieving lower average hop count. All MIIS variants achieve hop count of around five hops except for SINR-based MIIS scheme without hcc, which achieve average hop count of around six hops. SINR-based MIIS scheme without hcc tries to use as much closer nodes as possible to achieve higher SINR regardless of the hop count, so have comparatively higher hops than any other MIIS variant. JRC and MRD performs the worst as expected among all and achieve much higher average hop count because of taking longer route in MRD and higher number of closer nodes in JRC.



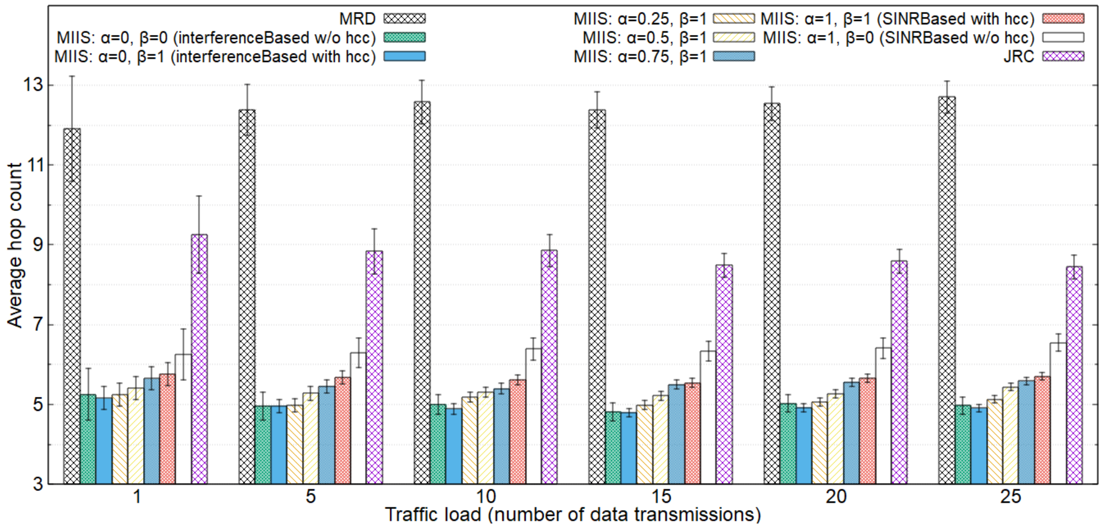
(a) Reactive.



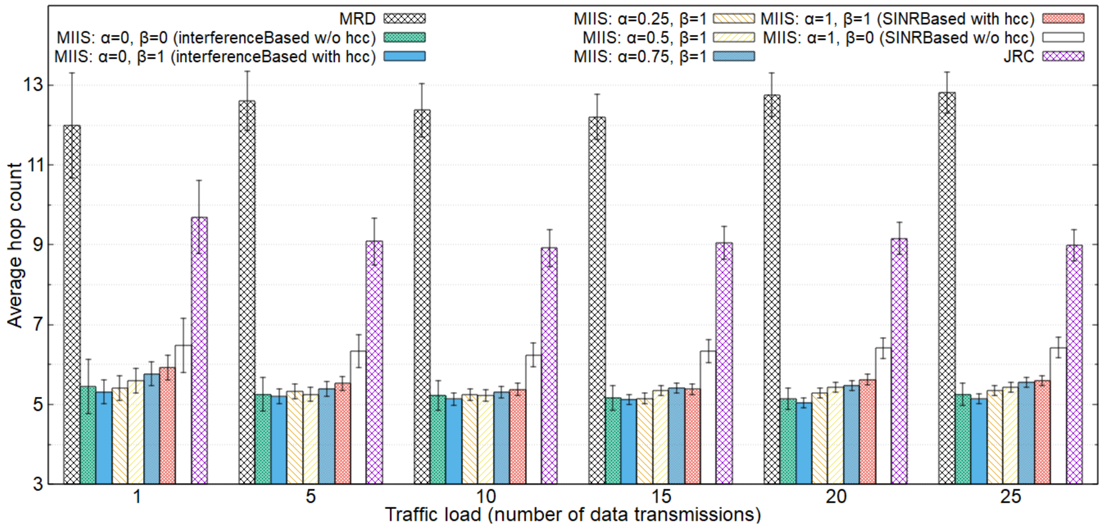
(b) Proactive.

Figure 5.9: End-to-end delay for Reactive and Proactive Centralized Routing for varying nodes mobility.

Figure 5.11 (a) and (b) show routing overhead of reactive and proactive routing for varying traffic load for MIIS (different variants), MRD and JRC. In reactive routing, when there is one data transmission, the routing overhead for all the schemes is negligible. With the increase in the traffic load, the routing overhead of all MIIS variants increase,



(a) Reactive.

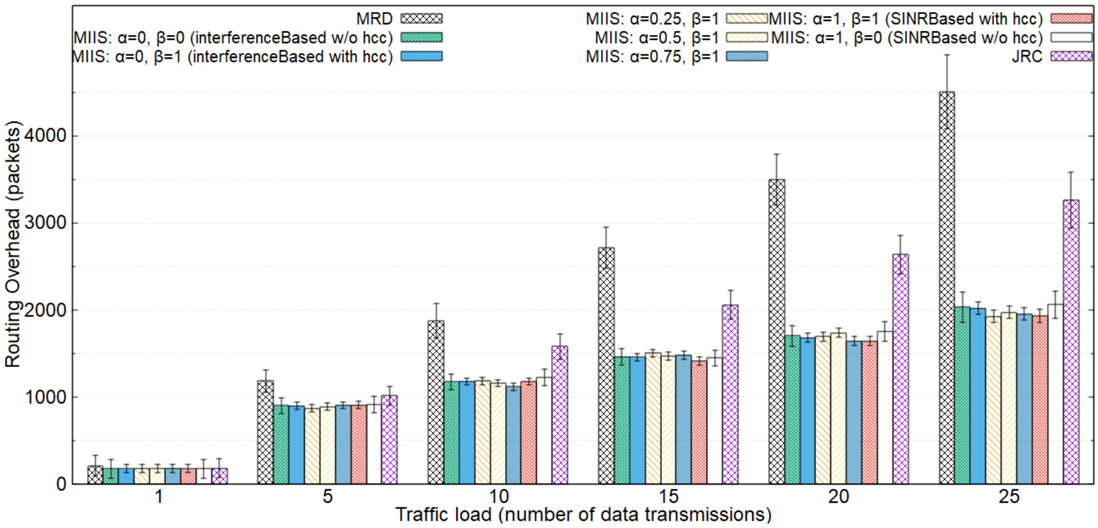


(b) Proactive.

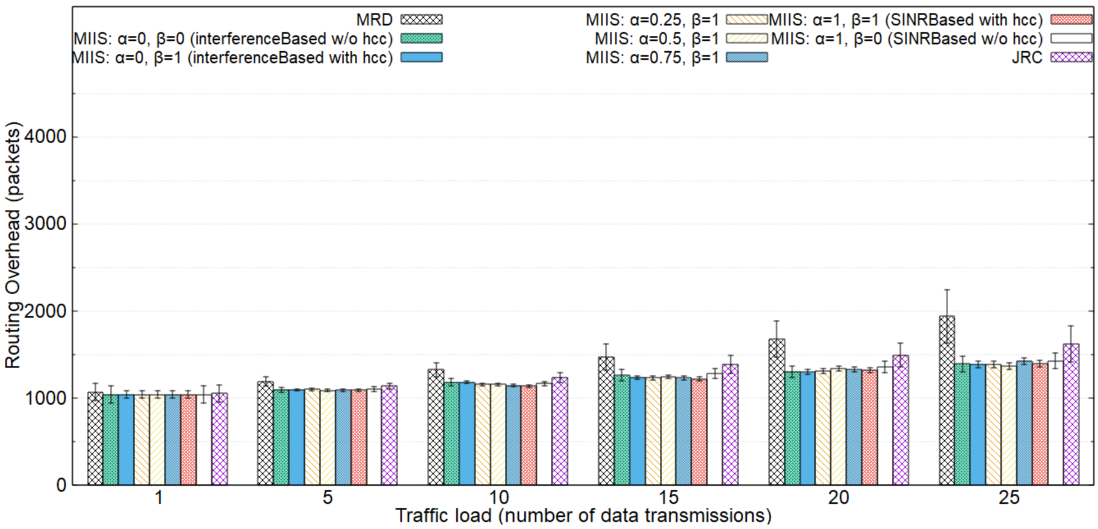
Figure 5.10: Average hop count for Reactive and Proactive Centralized Routing for varying traffic load.

with significant increase in routing overhead for MRD and JRC schemes.

In proactive routing, the routing overhead does not depend upon the traffic load, since the neighbor tables are periodically updated at the BS, irrespective of the traffic load. However, the increase in traffic load causes more collisions which result in frequent route breakages, and hence more routing overhead for establishing new routes.



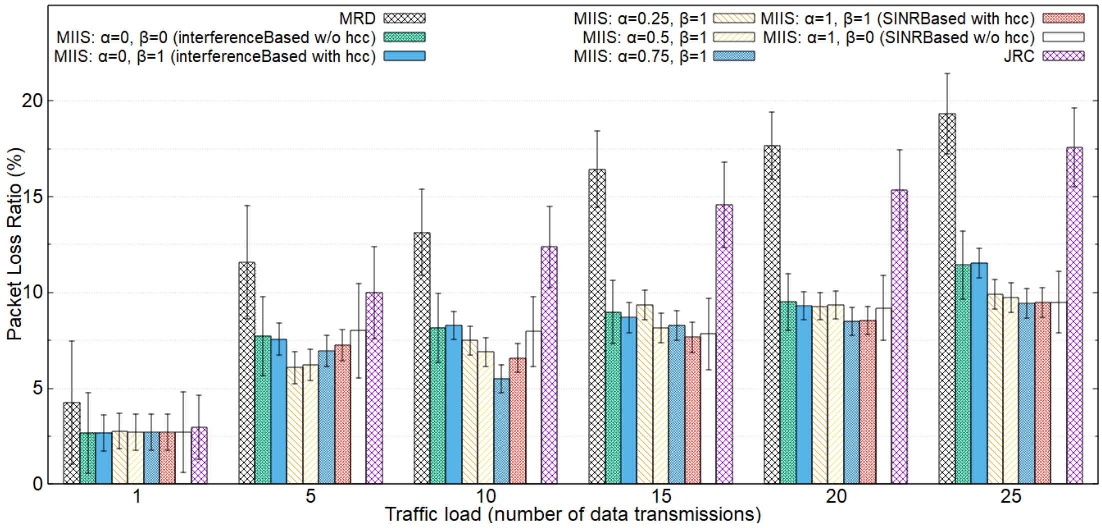
(a) Reactive.



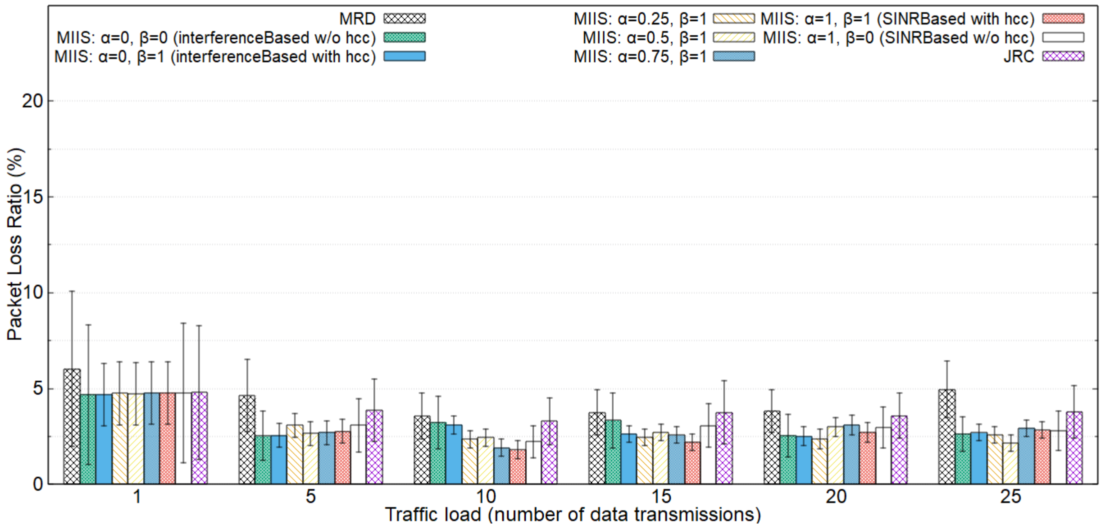
(b) Proactive.

Figure 5.11: Routing overhead for Reactive and Proactive Centralized Routing for varying traffic load.

Figure 5.12 (a) and (b) show packet loss ratio of reactive and proactive routing for varying traffic load for MIIS (different variants), MRD and JRC. In reactive routing, when the traffic load increases, the packet loss ratio of all the schemes keep increasing because, firstly, there are higher chances of having the same set of intermediate nodes



(a) Reactive.

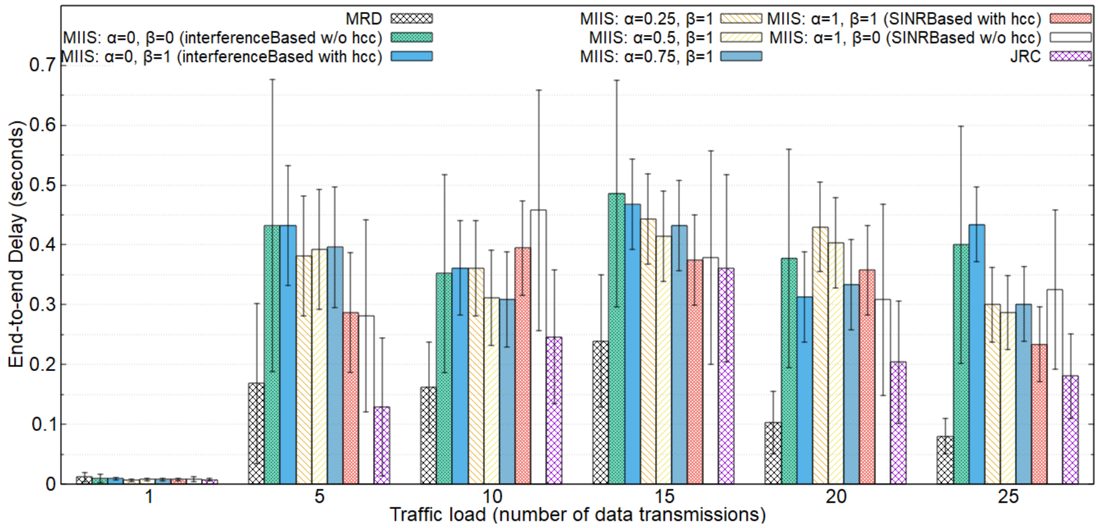


(b) Proactive.

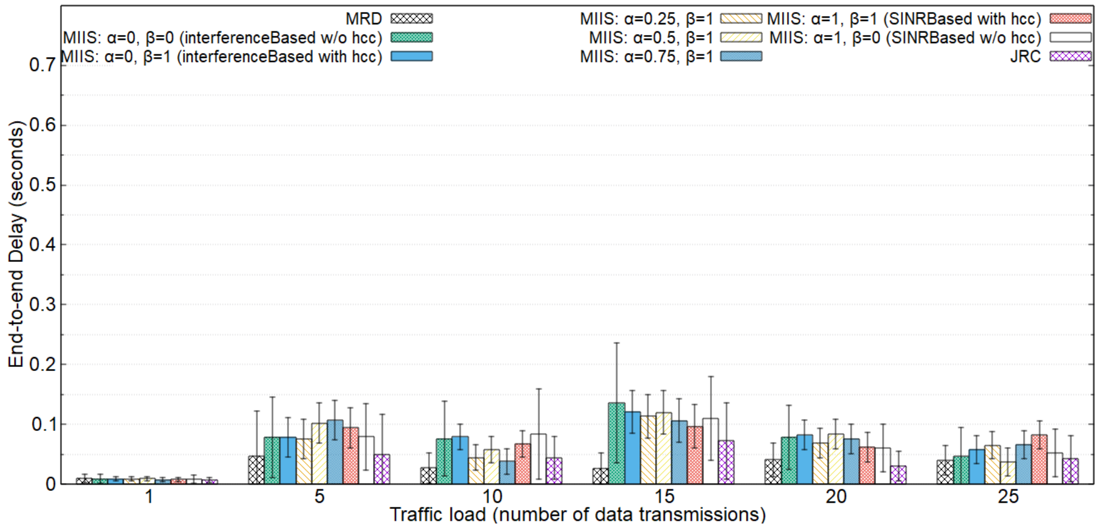
Figure 5.12: Packet loss ratio for Reactive and Proactive Centralized Routing for varying traffic load.

in multiple routes that causes contention and packets drop. Secondly, there is higher chance of collision among data packets causing packets to be dropped. Overall, MRD and JRC have higher packet loss ratio, while all MIIS variants have lower and similar packet loss ratio.

In proactive routing, the increase in traffic load does not have nearly any effect, and



(a) Reactive.



(b) Proactive.

Figure 5.13: End-to-end delay for Reactive and Proactive Centralized Routing for varying traffic load.

the packet loss ratio is between 3% to 5% for varying traffic load due to coordinated route discovery.

Figure 5.13 (a) and (b) show end-to-end delay of reactive and proactive routing for varying traffic load for MIIS (different variants), MRD and JRC.

The MRD and JRC have the least end-to-end delay than all MIIS variants. However, it does not mean that they are the best because since their packet loss ratio are higher, therefore the lost packets are not involved in the calculation of end-to-end delay.

In reactive routing, MIIS schemes have delays between 0.3 second to 0.5 second, and in proactive routing the delays are in and between 0.05 second to 0.15 second. The reason of higher delays in reactive routing, is due to the waiting time to get the route from the BS. No specific MIIS variant is prominent to have better performance than other, and all show the delays in between the some range.

The end-to-end delay of the all the schemes is the minimum when there is one transmission. This is because, when multiple pairs of routes are communicating simultaneously, a D2D UE can be involved as intermediate node in multiple route, and therefore, if it receives data packets to relay from some routes while it is already relaying data packets of another route, it has to en-queue the packets.

5.5.5 Insights

The reactive and proactive centralized routing show similar trends in the average hop count results. The average hop count of all schemes stays almost constant for varying nodes mobility and varying traffic load. For increasing number of nodes, the average hop count reduces for all MIIS variants having $\alpha \leq 0.75$, while increases for MIIS variants having $\alpha = 1$, JRC and MRD. Overall, MRD performs the worst causing much higher hop count (i.e., around twenty hops) while JRC performs the second worst (i.e., around ten hops). All MIIS variants achieve very low hop count (i.e., around six hops). The general trend of MIIS is that the average hop count slightly reduces with the increasing values of α. Interference-based MIIS with hcc outperforms all the schemes by achieving the lowest hop count, while SINR-based MIIS without hcc causes slightly higher hop count than other MIIS variants.

For reactive centralized routing, the routing overhead of all schemes increases with the increasing number of nodes, nodes mobility and traffic load. However, MRD has significant increase in routing overhead (i.e., around 225%) with the increasing number of nodes and traffic load. JRC has significant increase in routing overhead (i.e., around 165%) with the increasing traffic load. All MIIS variants have slight increase in routing overhead (i.e., around 550 packets) with the increasing number of nodes and nodes mobility, while have significant increase in routing overhead (i.e., around 1800 packets) with the increasing traffic load (however, still much lower than MRD and JRC).

For proactive centralized routing, all schemes have significant increase in routing overhead (i.e., around 925 packets) with the increasing number of nodes. However, all schemes have very slight increase (or almost constant) in routing overhead with the increasing nodes mobility and traffic load.

For reactive and proactive centralized routing, the packet loss ratio of all the schemes is almost similar and increases with the increasing nodes mobility and traffic load (MRD and JRC still having slightly higher packet loss ratio than MIIS). There is an interesting observation for increasing number of nodes (as discussed in Section 5.5.4.1). With the increasing number of nodes, the packet loss ratio reduces for all MIIS variants (i.e., upto 3% and 0% for reactive and proactive centralized routing, respectively), while increases for MRD (i.e., upto 20% and 3% for reactive and proactive centralized routing, respectively) and JRC (i.e., upto 10% and 0% for reactive and proactive centralized routing, respectively). SINR-based MIIS with hcc outperforms all the schemes in most of the cases by achieving the lowest packet loss ratio.

The end-to-end delay exhibit the similar behavior like packet loss ratio as discussed above.

To summarize, reactive centralized routing of all MIIS variants are best suitable for scenarios having varying number of nodes where minimizing the routing overhead is more important and that can tolerate slightly higher packet loss ratio and end-to-end delay. For all the other scenarios, proactive centralized routing of all MIIS variants are best suitable as they achieve the lowest routing overhead, packet loss ratio and end-to-end delay.

5.6 Summary

A novel route discovery mechanism of reactive centralized routing is proposed in this chapter that significantly reduces the routing overhead as compared to distributed routing schemes. The reactive centralized routing is extended to proactive centralized routing. In both centralized routing schemes (i.e., reactive and proactive), the BS gathered the information from all the nodes in order to construct the network topology graphs and to make route decisions while avoiding any kind of flooding. The performance of reactive and proactive centralized routing have been evaluated through simulations by using MIIS and comparing with existing schemes in terms of varying number of nodes, nodes mobility and traffic load. The centralized routing schemes achieves much lower routing overhead, packet loss ratio and end-to-end delay.

The next chapter concludes the dissertation, and discusses open issues, challenges and future research directions.

Chapter 6

Conclusion and Future Work

This chapter provides a short review of points discussed in this dissertation. The summary on the basics of D2D communications and on the detailed literature review of routing in D2D networks is provided. An overview of the proposed routing metric, route decision formula and route discovery mechanism is provided, followed by the conclusion drawn from the simulation results of the proposed techniques. Lastly, the discussion on future work provides possible improvements and new research directions based on the proposed work and the derived taxonomy.

6.1 Conclusion

This dissertation is focused on routing in multi-hop D2D networks. However, routing in multi-hop D2D networks is not explored much in the literature. Our first contribution is divided into two parts. In the first part, we provided a glimpse on how fast the D2D communication technology is emerging with the help of a figure showing the total number of publications and surveys under diverse aspects of D2D communication. It also presents the importance and necessity of D2D communication in cellular networks. The main contribution in this part is detailed discussion on D2D's performance improvements, incentives and implementation scenarios. In the second part, we provided a comprehensive survey of routing in multi-hop D2D networks. All the state-of-the-art routing schemes have been broadly categorized into three categories: multi-hop D2D routing, multi-hop D2I/I2D routing and ad-hoc routing for D2D networks. The routing schemes under each category have been further sub-classified based on their objectives and considered topology structure. It provided an in-depth analysis of the purpose, application and working mechanism of each routing category, highlighting their necessity and importance.

The second contribution of this dissertation proposed a novel routing metric, MIIS, that selects routes having higher SINR with specific consideration for lower interference. It makes route decisions without using any kind of geographical location information and can operate under various network dynamics (such as high density, high mobility and high traffic load). Different MIIS variants (by changing the values of tuning parameters α and β) are compared with two existing schemes through simulations. The performance evaluation showed that all MIIS variants outperform existing schemes in terms of average hop count, routing overhead and packet loss ratio under varying number of nodes, nodes mobility and traffic load. Interference-based MIIS with hcc (i.e., MIIS with $\alpha = 0$ and $\beta = 1$) is suitable for scenarios where minimizing the routing overhead is more important. While, SINR-based MIIS with hcc (i.e., MIIS with $\alpha = 1$ and $\beta = 1$) is suitable for scenarios where minimizing the packet loss ratio and end-to-end delay is more important.

The third contribution of this dissertation proposed novel route discovery mechanisms, reactive and proactive centralized routing schemes, that significantly reduce the routing overhead as compared to distributed routing schemes. In both reactive and proactive centralized routing schemes, the BS gathered the information from all the nodes in order to construct the network topology graphs and to make route decisions while avoiding any kind of flooding. In reactive centralized routing, the route discovery is performed on-demand, while in proactive centralized routing, the route discovery is performed at periodical intervals. The performance of reactive and proactive centralized routing schemes have been evaluated through simulations by using different MIIS variants and by comparing with existing schemes in terms of average hop count, routing overhead and packet loss ratio under varying number of nodes, nodes mobility and traffic load. The reactive centralized routing, under all experimented MIIS variants, is suitable in terms of minimizing the routing overhead for scenarios having higher number of nodes with low traffic load. While, for most of the other scenarios, proactive centralized routing is suitable as they achieve the lower routing overhead, packet loss ratio and end-to-end delay.

6.2 Future Works

Based on the three main contributions of this dissertation, the future works are also divided into three subsections. The first subsection provides research directions for our proposed interference-conscious routing metric. The second subsection provides research directions for our proposed centralized routing. The third subsection identifies future research directions based on the derived taxonomy of D2D routing schemes.

6.2.1 Future Research Directions for Interference-Conscious Routing Metric

6.2.1.1 Backup routes to a destination

Backup routes are used for alternate route availability in case of primary route failure. Backup routes can be disjoint or non-disjoint. In disjoint routes, the nodes between the source and destination nodes are different than nodes in the primary route, while non-disjoint routes have one or more common nodes as in primary route. The disjoint routes are generally longer, however serve as better backup routes in case the primary route fails due to node/link failure. The non-disjoint routes are nearly of equal length as of primary route, however these backup routes might also fail in case of node/link failure in the primary route, as they share the same nodes/links [GL04]. It is an interesting direction to consider disjoint and non-disjoint backup routes for smooth operation of the network in the presence of frequent disruptions, as well as reducing the delay by avoiding searching for a new route in case of route breakage.

6.2.1.2 Multi-channel consideration

For simplicity, this thesis assumed single CUE and hence, a single channel reuse. The consideration of multiple CUEs and multiple channels reuse is an important and interesting direction to explore.

6.2.2 Future Research Directions for Centralized Routing

6.2.2.1 Node level decisions

Each node should be capable of autonomously deciding about participation in the route discovery. The node level decision (in comparison to the route level decision) will save not only precious resources consumed in forwarding the route discovery packets, but will also save time since it will be immediately known whether the route could use a particular node or not. There are various factors that can be considered in node level decision, as follows:

Energy awareness Based on the residual energy, the nodes can be classified as (i) normal relay nodes, (ii) non-relay nodes, and (iii) special relays nodes. Normal relay nodes are nodes having residual energy greater than *relayThreshold*. These nodes will always take part in the route discovery. The nodes having residual energy less than *nonRelayThreshold* are non-relay nodes which will never take part in the route discovery. The nodes which have residual energy between *nonRelayThreshold* and *relayThreshold* will take part in route discovery only when a special RREQ packet is received. We will discuss about special RREQ packet later in this section.

Traffic load awareness Based on the current and previous traffic load, the nodes should decide whether to participate in route discovery. For instance, if the current load is higher than *highLoadThreshold*, the node will not participate in route discovery. If the current load is less than *mediumLoadThreshold* and the previous traffic load was higher than *mediumLoadThreshold*, it means that the traffic load is reducing and hence, the node can accommodate new traffic. Thus the node will participate in the route discovery. Finally, if the current load is higher than *mediumLoadThreshold*, while the previous traffic load was lower than *mediumLoadThreshold*, it means that the traffic load is increasing, and the node will only participate in route discovery on receiving special RREQ packet.

Special RREQ packet In case of fully connected dense network, the overall routing overhead is generally dramatically high due to huge number of nodes participating in the route discovery. Since only a single route is primarily required between source and destination nodes, therefore participation of such high number of nodes in route discovery incurs high waste of the resources (e.g., battery energy, link bandwidth, processing time and buffer space). Moreover, the probability of collision of route discovery packets is also very high when high number of nodes participate. Therefore, to reduce the collisions and to save the precious resources of the nodes, restricted number of nodes should participate in route discovery. The restriction can be applied to nodes in terms of energy and traffic load perspective, as discussed previously. While using the energy and traffic load restrictions, after sending the first RREQ packet, if no route will be found within some specified time interval, then the second RREQ packet will be sent which will be considered as special RREQ packet. The nodes having residual energy between *RelayThreshold* and *nonRelayThreshold*, and the nodes having traffic load higher than *mediumLoadThreshold* will also participate in route discovery on receiving the special

RREQ packet. It is important to note that these restrictions and the special RREQ packet should be used only in highly dense network. This is because, if energy/load restrictions will be applied in sparse network, then finding a route will probably be impossible due to lower number of nodes in the network.

6.2.2.2 Variable route's timeout

In order to avoid using stale routes, route expiration (timeout) timers are generally used. However, using fixed route expiration timers might not be valid due to different link qualities and node mobility conditions. Therefore, every link should have a variable expiration timer, depending on for example current node mobility and link quality. Based on the variable expiration timers of the links, the route formed using those link will also have variable route timeouts. The route expiration will be the minimum value of the link expiration timer among all links in the route. A RREQ packet will contain the minimum required link expiration time. Hence, a node will only participate in route discovery if its link expiration timer (with the previous hop) is above or equal to the minimum required expiration time in RREQ. When more than one routes having similar metric values are available, the route with higher expiration timer can be used to break the tie.

6.2.2.3 Early stop message

In dense network, when sufficient number of route replies are received by the BS, then BS should broadcast an early stop (ESTOP) message to inform the nodes to stop sending the route replies. This message will save considerable amount of routing overhead by limiting the number of nodes replying to route requests. A similar approach has also been used in [CC06] which can be referred for more insights.

6.2.2.4 Reliable connectivity

If the multi-hop route is not possible, or an existing route is broken and no alternate route is available, then the BS should establish a traditional cellular connection between the source and destination node.

6.2.2.5 Route across multiple cells

Consideration of multiple cells is also an important direction to explore. In the infrastructure-based network, RREQ packet is sent to the BS. The BS on receiving the RREQ, checks the current network topology and if the destination is not found, it should forward the RREQ to its adjacent BSs. If the destination node lies within the coverage of any of the adjacent BSs, then the corresponding BS will reply with its complete current network topology. If the BS receive successful reply from any adjacent BS, then it should calculate the best path to the destination using topology information of both the BSs.

6.2.3 Future Research Directions based on Proposed Taxonomy

6.2.3.1 Opportunistic Routing

Opportunistic routing provides reliable delivery of packet from a source node to a destination node in sparse and disconnected networks. Although this routing technique is not suitable for delay sensitive applications but is found flexible and easily adaptable to high network dynamics. This is because opportunistic routing does not require any network topology information which is very expensive in highly dynamic networks. Instead, opportunistic routing uses the broadcast nature of nodes, thus the packet is received by all neighbor nodes, and only the opportunistically selected candidate relay nodes among the next hops nodes will forward the packet. The process continues until the packet reaches the destination node. Opportunistic routing has been classified into five broad categories [Cha15]. Among them, the concept of Geographic Opportunistic routing can be utilized in Location based D2D routing specifically, and the Link State aware Opportunistic routing (for improving network reliability) and Probabilistic Opportunistic routing (for supporting nodes mobility) in general, to leverage the D2D routing. Opportunistic routing also supports high amount of data transfers which along with other benefits is very appealing for D2D communications. Marin et al. [MCD17] provide a good example (as basis) of integrating the D2D and opportunistic networks.

6.2.3.2 Cooperative Routing

Cooperative communication is used to alleviate the multipath (channel) fading and to improve the communication reliability in wireless networks. It can be used in D2D communications to reduce the interference caused by D2D UEs. In cooperative communication, a node helps other nodes by exploiting the broadcast nature. It is called cooperative routing because it takes advantage of cooperative transmission at the physical layer [Ma+16; MA15]. Since interference mitigation is a critical problem in D2D communication, therefore this routing technique is a very good candidate to be used in D2D communication.

6.2.3.3 Network Coding-aware Routing

The Network coding-aware (NC-aware) routing technique uses omni-directional antenna to exploit broadcast nature of the wireless medium. NC-aware routing technique shows many performance improvements over traditional routing which includes improved throughput, higher reliability, lower data transmission rate, lower delay and minimum energy consumption [Far+14; Iqb+11; Nae+17]. Network Coding also proved its effectiveness in terms of achieving maximum information flow in D2D networks [Dou+17]. Thus, D2D routing can use this technique to get benefit from its performance improvements.

6.2.3.4 Multicast Routing

In highly dynamic networks, when high amount of data transfer to multiple destinations is required, in applications, such as video conferencing or mobile software updates; multicast routing shows improved QoS and energy efficiency in such scenarios [Jun+09]. In order to get benefit from the multicast routing technique in D2D networks, few schemes have been proposed [HB16; Pus+16; SR15]. However some efficient schemes that can perfectly integrate unique characteristics of D2D communication is still missing. Some general key-points to easily and efficiently design a multicast routing algorithm have been discussed in [Ram00].

6.2.3.5 White space-aware routing

The unused TV white spaces frequencies spectrum have been opportunistically exploited for cellular network in [Mad+15]. The results have shown improved network throughput. A number of routing protocols in Cognitive Radio Networks (CRNs) also take advantage of the presence of free (unused) TV white spaces and make spatial use for certain time and frequency to improve various network performance parameters [SSR15], [Sal+15a]. Since, the D2D communication is flexible to use a variety of frequency spectrum for their communications, as discussed in section 2.3, therefore it would be interesting to exploit TV white space spectrum in routing protocols for D2D networks. There are four white space paradigms: underlay, overlay, interweave, and hybrid [ARR16]. One future research direction is also to consider these four white space paradigms and propose routing schemes in future to exploit such white space paradigms for TV white spaces.

6.2.3.6 Routing for mm-wave D2D Communication in 5G Networks

Millimeter-wave (mm-wave) communications have shown great potential for providing efficient high speed data transmission for small distance communications. This is because mm-wave uses channels from 30 GHz to 300 GHz, which although have (i) limited diffraction capability, (ii) difficulty in communication signals passing through walls and (iii) difficulty in NLOS transmissions, but provides very high bandwidth. In order to cope with mentioned challenges associated with the extremely high frequency range and to provide high data rate using the highly available bandwidth, mm-wave D2D multi-hop routing protocols for 5G networks have been proposed [EMSM16; KM14]. The proposed schemes promise higher QoS for multimedia applications, however require mathematical modeling and are distributed in nature. Thus some simple and efficient routing protocols for mm-wave D2D networks which also take benefit from the presence of infrastructure network (e.g. [RPDM17]) are highly desired.

6.2.3.7 New research gaps identified by our proposed classification of D2D routing

Our proposed taxonomy of state-of-the-art research works provide a very good basis and foundation to identify the research gaps in D2D and D2I/I2D routing, where either no work or very small amount of work has been done, and thus further research investigations can be carried out. For example, social networks have been well exploited in D2D communication [Ahm+18], however socially-aware algorithms have not been utilized for D2I/I2D routing except for few works in D2D routing [KNI14; Zha+15b; NML16]. Similarly, an extensive research has been made for security solutions in D2D communications [Hau+17; GJJ17a; WY17; HKC17], however there is one only scheme proposed that takes advantage of the presence of BS for keeping confidentiality, authenticity and integrity of the data [Oth+16]. It is important to note that there is no work on D2I/I2D routing scheme that provides secure route. The idea of content-based routing is very appealing for D2D networks, where the route does not depend upon the destination node, but is established based on the contents of the information being shared. However, not enough work has been made neither for D2D nor for D2I/I2D routing. Last but not the least, no existing works take advantage of the 'location information' to establish route from node to BS or vice versa i.e. for D2I/I2D routing.

List of Figures

List of Tables

Bibliography

[AA17] Sher Ali and Ayaz Ahmad. “Resource allocation, interference management, and mode selection in device-to-device communication: A survey”. In: *Transactions on Emerging Telecommunications Technologies* (2017).

[Abd+20] Sami Abdellatif et al. “Service Oriented D2D Efficient Communication for Post-Disaster Management”. In: *2020 International Wireless Communications and Mobile Computing (IWCMC)*. IEEE. 2020, pp. 970–975.

[Adi15] Sasan Adibi. “A mobile health network disaster management system”. In: *7th International Conference on Ubiquitous and Future Networks*. 2015, pp. 424–428.

[AH+04] Lachlan LH Andrew, Stephen V Hanly, et al. “On routing in CDMA multihop cellular networks”. In: *IEEE Global Telecommunications Conference (GLOBECOM)*. Vol. 5. 2004, pp. 3063–3067.

[AHK13] Akram Al-Hourani and Sithamparanathan Kandeepan. “Temporary cognitive femtocell network for public safety LTE”. In: *IEEE 18th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*. 2013, pp. 190–195.

[AHKJ16] Akram Al-Hourani, Sithamparanathan Kandeepan, and Abbas Jamalipour. “Stochastic Geometry Study on Device-to-Device Communication as a Disaster Relief Solution”. In: *IEEE Transactions on Vehicular Technology* 65.5 (2016), pp. 3005–3017.

[Ahm+17] M Ahmad et al. “Resource management in D2D communication: An optimization perspective”. In: *Journal of Network and Computer Applications* 93 (2017), pp. 51–75.

[Ahm+18] Manzoor Ahmed et al. “A Survey on Socially-Aware Device-to-Device Communications”. In: *IEEE Communications Surveys & Tutorials* (2018).

[AMM01] R Ananthapadmanabha, BS Manoj, and C Murthy. “Multi-hop cellular networks: the architecture and routing protocols”. In: *12th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*. Vol. 2. 2001, G–78.

[ARR16] Fayaz Akhtar, Mubashir Husain Rehmani, and Martin Reisslein. "White space: Definitional perspectives and their role in exploiting spectrum opportunities". In: *Telecommunications Policy* 40.4 (2016), pp. 319–331.

[ASA14] Rawan Alkurd, Raed M Shubair, and Ibrahim Abualhaol. "Survey on device-to-device communications: Challenges and design issues". In: *IEEE 12th International New Circuits and Systems Conference (NEWCAS)*. 2014, pp. 361–364.

[AWM14] Arash Asadi, Qing Wang, and Vincenzo Mancuso. "A survey on device-to-device communication in cellular networks". In: *IEEE Communications Surveys & Tutorials* 16.4 (2014), pp. 1801–1819.

[BM15] Vinnu Bhardwaj and Chandra R Murthy. "On optimal routing and power allocation for D2D communications". In: *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*. 2015, pp. 3063–3067.

[BYG15] Leonardo Babun, Ali Ihsan Yürekli, and Ismail Güvenç. "Multi-hop and D2D communications for extending coverage in public safety scenarios". In: *IEEE 40th Local Computer Networks Conference Workshops (LCN Workshops)*. 2015, pp. 912–919.

[BZ16] Oladayo Bello and Sherali Zeadally. "Intelligent device-to-device communication in the internet of things". In: *IEEE Systems Journal* 10.3 (2016), pp. 1172–1182.

[Cao+08] Lijuan Cao et al. "Adaptive Multiple Metrics Routing Protocols for Heterogeneous Multi-Hop Wireless Networks". In: *5th Consumer Communications and Networking Conference (CCNC)*. IEEE. 2008, pp. 13–17.

[Cas+15a] Claudio Casetti et al. "Content-centric Routing in Wi-Fi Direct Multi-group Networks". In: *IEEE 16th International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*. 2015, pp. 1–9.

[Cas+15b] Thijs Castel et al. "LTE as a potential standard for public safety indoor body-to-body networks". In: *IEEE Symposium on Communications and Vehicular Technology in the Benelux (SCVT)*. 2015, pp. 1–6.

[Cav+05] Dave Cavalcanti et al. "Issues in integrating cellular networks WLANs, and MANETs: a futuristic heterogeneous wireless network". In: *IEEE Wireless Communications* 12.3 (2005), pp. 30–41.

[CC06] Hyun-Ho Choi and Dong-Ho Cho. "Fast and reliable route discovery protocol considering mobility in multihop cellular networks". In: *IEEE 63rd Vehicular Technology Conference (VTC Spring)*. Vol. 2. 2006, pp. 886–890.

[CH07] Ray-Guang Cheng and Jia-Yang Hung. "Power-Strength-Based Selective Forwarding (PSF) Mechanism for Multihop Cellular Networks". In: *IEEE Wireless Communications and Networking Conference (WCNC)*. 2007, pp. 3613–3618.

[Cha15] Nessrine Chakchouk. “A survey on opportunistic routing in wireless communication networks”. In: *IEEE Communications Surveys & Tutorials* 17.4 (2015), pp. 2214–2241.

[Che+15] Xiang Cheng et al. “Device-to-device channel measurements and models: a survey”. In: *IET Communications* 9.3 (2015), pp. 312–325.

[CHL10] Ray-Guang Cheng, Jia-Yang Hung, and Yao-Yuan Liu. “Power-strength-based Selective Forwarding (PSF) mechanism for multihop cellular networks”. In: *IEEE Transactions on Vehicular Technology* 59.7 (2010), pp. 3455–3467.

[CJB04] Young-June Choi, Jung Hyon Jun, and Saewoong Bahk. “Profit-based routing for centralized multi-hop wireless networks”. In: *IEEE 59th Vehicular Technology Conference (VTC Spring)*. Vol. 4. 2004, pp. 2131–2135.

[CPG09] Baldomero Coll-Perales and Javier Gozalvez. “Energy efficient routing protocols for multi-hop cellular networks”. In: *IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*. 2009, pp. 1457–1461.

[CPG11] Baldomero Coll-Perales and Javier Gozalvez. “On the capability of multi-hop cellular networks with mobile relays to improve handover performance”. In: *8th International Symposium on Wireless Communication Systems (ISWCS)*. 2011, pp. 207–211.

[CPG15] B Coll-Perales and J Gozalvez. “Contextual optimization of location-based routing protocols for multi-hop cellular networks using mobile relays”. In: *Telecommunication Systems* (2015), pp. 1–13.

[CPGF16] B Coll-Perales, J Gozalvez, and V Friderikos. “Context-aware opportunistic networking in multi-hop cellular networks”. In: *Ad Hoc Networks* 37 (2016), pp. 418–434.

[Din+16] Guoru Ding et al. “Cellular-base-station-assisted device-to-device communications in TV white space”. In: *IEEE Journal on Selected Areas in Communications* 34.1 (2016), pp. 107–121.

[Dou+17] Ahmed Douik et al. “Instantly Decodable Network Coding: From Centralized to Device-to-Device Communications”. In: *IEEE Communications Surveys & Tutorials* (2017).

[Du+14] Qinghe Du et al. “On P2P-Share Oriented Routing over Interference-Constrained D2D Networks”. In: *10th International Conference on Mobile Ad-hoc and Sensor Networks (MSN)*. 2014, pp. 138–143.

[Du+15] Qinghe Du et al. “Interference-controlled D2D routing aided by knowledge extraction at cellular infrastructure towards ubiquitous CPS”. In: *Personal and Ubiquitous Computing* 19.7 (2015), pp. 1033–1043.

[EMSM16] Nima Eshraghi, Behrouz Maham, and Vahid Shah-Mansouri. "Millimeter-wave device-to-device multi-hop routing for multimedia applications". In: *IEEE International Conference on Communications (ICC)*. 2016, pp. 1–6.

[EZP15] Golnoosh Elhami, Mona Zehni, and Mohammad R Pakravan. "A survey on heterogeneous access networks: Mobile data offloading". In: *23rd Iranian Conference on Electrical Engineering (ICEE)*. 2015, pp. 379–384.

[Far+14] Muhammad Zubair Farooqi et al. "A survey on network coding: From traditional wireless networks to emerging cognitive radio networks". In: *Journal of Network and Computer Applications* 46 (2014), pp. 166–181.

[Fod+12] Gábor Fodor et al. "Design aspects of network assisted device-to-device communications". In: *IEEE Communications Magazine* 50.3 (2012), pp. 170–177.

[Fod+14] Gabor Fodor et al. "Device-to-device communications for national security and public safety". In: *IEEE Access* 2 (2014), pp. 1510–1520.

[Gha+14] Saim Ghafoor et al. "Cognitive radio for disaster response networks: survey, potential, and challenges". In: *IEEE Wireless Communications* 21.5 (2014), pp. 70–80.

[GJ16] Pimmy Gandotra and Rakesh Kumar Jha. "Device-to-device communication in cellular networks: A survey". In: *Journal of Network and Computer Applications* 71 (2016), pp. 99–117.

[GJJ17a] Pimmy Gandotra, Rakesh Kumar Jha, and Sanjeev Jain. "A survey on device-to-device (D2D) communication: Architecture and security issues". In: *Journal of Network and Computer Applications* 78 (2017), pp. 9–29.

[GJJ17b] Pimmy Gandotra, Rakesh Kumar Jha, and Sanjeev Jain. "Green Communication in Next Generation Cellular Networks: A Survey". In: *IEEE Access* 5 (2017), pp. 11727–11758.

[GL04] Ingo Gruber and Hui Li. "A novel ad hoc routing algorithm for cellular coverage extension". In: *11th International Telecommunications Network Strategy and Planning Symposium. NETWORKS*. 2004, pp. 163–168.

[Gom+14] Karina Gomez et al. "Enabling disaster-resilient 4G mobile communication networks". In: *IEEE Communications Magazine* 52.12 (2014), pp. 66–73.

[Gor+13] Leonardo Goratti et al. "A novel device-to-device communication protocol for public safety applications". In: *IEEE Globecom Workshops (GC Wkshps)*. 2013, pp. 629–634.

[Gor+14] Leonardo Goratti et al. "Connectivity and security in a D2D communication protocol for public safety applications". In: *11th International Symposium on Wireless Communications Systems (ISWCS)*. 2014, pp. 548–552.

[HAL18] Marko Höyhtyä, Olli Apilo, and Mika Lasanen. "Review of Latest Advances in 3GPP Standardization: D2D Communication in 5G Systems and Its Energy Consumption Models". In: *Future Internet* 10.1 (2018), p. 3.

[Han+06] Xihai Han et al. “Light Dark Routing Protocol: An innovative Infrastructure-assisted Ad hoc Routing Protocol”. In: *IEEE Global Telecommunications Conference (GLOBECOM)*. 2006, pp. 1–5.

[Hau+17] Michael Haus et al. “Security and Privacy in Device-to-Device (D2D) Communication: A Review”. In: *IEEE Communications Surveys & Tutorials* (2017).

[HB16] Faezeh Hajiaghajani and Subir Biswas. “Device-to-device coupon distribution using economic routing utilities”. In: *IEEE 12th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*. 2016, pp. 1–8.

[HKC17] Othmane Nait Hamoud, Tayeb Kenaza, and Yacine Challal. “Security in device-to-device communications: a survey”. In: *IET Networks* 7.1 (2017), pp. 14–22.

[HL02] Yu-Ching Hsu and Ying-Dar Lin. “Base-centric routing protocol for multihop cellular networks”. In: *IEEE Global Telecommunications Conference (GLOBECOM)*. Vol. 1. 2002, pp. 158–162.

[Hun+13] Mythri Hunukumbure et al. “D2D for energy efficient communications in disaster and emergency situations”. In: *21st International Conference on Software, Telecommunications and Computer Networks (SoftCOM)*. 2013, pp. 1–5.

[IC04] Ioannis Ioannidis and Bogdan Carbunar. “Scalable routing in hybrid cellular and ad-hoc networks”. In: *IEEE International Conference on Mobile Ad-hoc and Sensor Systems*. 2004, pp. 522–524.

[ICNR05] Ioannis Ioannidis, Bogdan Carbunar, and Cristina Nita-Rotaru. “High throughput routing in hybrid cellular and ad-hoc networks”. In: *6th IEEE International Symposium on a World of Wireless Mobile and Multimedia Networks (WoWMoM)*. IEEE. 2005, pp. 171–176.

[Ima+06] Hitoshi Imai et al. “The effect of multipath hybrid routing protocol in multihop cellular networks”. In: *IEEE 17th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*. 2006, pp. 1–5.

[Inc] Intelligent Wireless Integrated Communications Systems Inc. *ODMA History*. Accessed: March 2021. URL: `http://www.iwics.com/Technology/ODMAHistory.shtml`.

[Iqb+11] Muhammad Azhar Iqbal et al. “Survey of network coding-aware routing protocols in wireless networks”. In: *Journal of Network and Computer Applications* 34.6 (2011), pp. 1956–1970.

[Jam11] Abbas Jamalipour. “Proxy discovery and resource allocation for cooperative multipath routing in cellular networks”. In: *IEEE Wireless Communications and Networking Conference (WCNC)*. 2011, pp. 552–556.

[Jam+18] Furqan Jameel et al. "A Survey of Device-to-Device Communications: Research Issues and Challenges". In: *IEEE Communications Surveys & Tutorials* (2018).

[JL13] Hung-Chin Jang and Yun-Jun Lee. "QoS-constrained resource allocation scheduling for LTE network". In: *International Symposium on Wireless and Pervasive Computing (ISWPC)*. 2013, pp. 1–6.

[Joh03] David B Johnson. "The dynamic source routing protocol for mobile ad hoc networks". In: *draft-ietf-manet-dsr-09. txt* (2003).

[Jun+09] Luo Junhai et al. "A survey of multicast routing protocols for mobile ad-hoc networks". In: *IEEE communications surveys & tutorials* 11.1 (2009), pp. 78–91.

[JXQ15] Zhao Jingyi, Li Xi, and Xu Quansheng. "Multi-hop routing for energy-efficiency enhancement in relay-assisted device-to-device communication". In: *The Journal of China Universities of Posts and Telecommunications* 22.2 (2015), pp. 1–51.

[KH12] Sun-Hyun Kim and Seung-Jae Han. "Contour routing for peer-to-peer DTN delivery in cellular networks". In: *4th International Conference on Communication Systems and Networks (COMSNETS)*. 2012, pp. 1–9.

[KLA13] Brett Kaufman, Jorma Lilleberg, and Behnaam Aazhang. "Spectrum sharing scheme between cellular users and ad-hoc device-to-device users". In: *IEEE Transactions on Wireless Communications* 12.3 (2013), pp. 1038–1049.

[KM14] Joongheon Kim and Andreas F Molisch. "Quality-aware millimeter-wave device-to-device multi-hop routing for 5G cellular networks". In: *IEEE International Conference on Communications (ICC)*. 2014, pp. 5251–5256.

[KMD07] Govindan Kannan, Shabbir N Merchant, and Uday B Desai. "Cross layer routing for multihop cellular networks". In: *21st International Conference on Advanced Information Networking and Applications Workshops (AINAW)*. Vol. 2. 2007, pp. 165–170.

[KNI14] Iordanis Koutsopoulos, Eugenia Noutsi, and George Iosifidis. "Dijkstra Goes Social: Social-Graph-assisted Routing in Next Generation Wireless Networks". In: *20th European Wireless Conference*. 2014, pp. 1–7.

[LCC04] Sun-Ho Lee, Eunjeong Choi, and Dong-Ho Cho. "Energy-efficient routing using timer-based MAC protocol in power-controlled multihop cellular networks". In: *IEEE 60th Vehicular Technology Conference (VTC Fall)*. Vol. 5. 2004, pp. 3201–3205.

[LG15] Peng Li and Song Guo. "Incentive mechanisms for device-to-device communications". In: *IEEE Network* 29.4 (2015), pp. 75–79.

[LH00] Ying-Dar Lin and Yu-Ching Hsu. "Multihop cellular: A new architecture for wireless communications". In: *19th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM).* Vol. 3. 2000, pp. 1273–1282.

[Li+13] Peng Li et al. "Adaptive routing protocol based on OLSR for hybrid multihop and cellular network". In: *International Conference of IEEE Region 10 (TENCON).* 2013, pp. 1–5.

[Li+15] Xu Li et al. "Drone-assisted public safety wireless broadband network". In: *IEEE Wireless Communications and Networking Conference Workshops (WCNCW).* 2015, pp. 323–328.

[Lie+16] Shao-Yu Lien et al. "Enhanced LTE Device-to-Device Proximity Services". In: *IEEE Communications Magazine* 54.12 (2016), pp. 174–182.

[Lin01] Chunhung Richard Lin. "On-demand QoS routing in multihop mobile networks". In: *20th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM).* Vol. 3. 2001, pp. 1735–1744.

[Lin+14] Xingqin Lin et al. "An overview of 3GPP device-to-device proximity services". In: *IEEE Communications Magazine* 52.4 (2014), pp. 40–48.

[Liu+15] Jiajia Liu et al. "Device-to-Device Communication in LTE-Advanced Networks: A Survey". In: *IEEE Communications Surveys Tutorials* 17.4 (2015), pp. 1923–1940.

[LL03] Hyunjeong Lee and C-C Lee. "An integrated multihop cellular data network". In: *IEEE 58th Vehicular Technology Conference (VTC Fall).* Vol. 4. 2003, pp. 2232–2236.

[LL06] Hyunjeong Lee and Yuan Li. "A hierarchical routing with load balanced scheduling in the integrated multi-hop cellular data network". In: *1st International Symposium on Wireless Pervasive Computing.* 2006, 6–pp.

[LS08] Ze Li and Haiying Shen. "An efficient routing protocol to increase the communication reliability of multi-hop cellular networks". In: *IEEE Military Communications Conference (MILCOM).* 2008, pp. 1–7.

[LYC03] Hui Li, Dan Yu, and Hui Chen. "New approach to multihop-cellular based multihop network". In: *IEEE 14th Proceedings on Personal, Indoor and Mobile Radio Communications (PIMRC).* Vol. 2. 2003, pp. 1629–1633.

[MA09] Hadi Meshgi and Bahman Abolhasani. "High throughput interference-based routing in multihop CDMA cellular networks". In: *14th International CSI Computer Conference (CSICC).* 2009, pp. 206–212.

[MA15] Fatemeh Mansourkiaie and Mohammed Hossam Ahmed. "Cooperative routing in wireless networks: A comprehensive survey". In: *IEEE Communications Surveys & Tutorials* 17.2 (2015), pp. 604–626.

[Ma+16] Chuan Ma et al. “Cooperative Spectrum Sharing in D2D-Enabled Cellular Networks”. In: *IEEE Transactions on Communications* 64.10 (2016), pp. 4394–4408.

[Maa+15] R. Maallawi et al. “A Comprehensive Survey on Offload Techniques and Management in Wireless Access and Core Networks”. In: *IEEE Communications Surveys & Tutorials* 17.3 (2015), pp. 1582–1604.

[MAD13] Martin Macuha, Darambazar Amgalan, and Thomas Derham. “Device-centric approach to improve resiliency of emergency communication”. In: *IEEE Region 10 Humanitarian Technology Conference (R10-HTC)*. 2013, pp. 124–129.

[Mad+15] Mukundan Madhavan et al. “Adapting Cellular Networks to Whitespaces Spectrum”. In: *IEEE/ACM Transactions on Networking* 23.2 (2015), pp. 383–397.

[Mas+13] Nicholas Mastronarde et al. “Learning relaying strategies in cellular D2D networks with token-based incentives”. In: *IEEE Globecom Workshops (GC Wkshps)*. 2013, pp. 163–169.

[MBV15] Pavel Mach, Zdenek Becvar, and Tomas Vanek. “In-Band Device-to-Device Communication in OFDMA Cellular Networks: A Survey and Challenges”. In: *IEEE Communications Surveys & Tutorials* 17.4 (2015), pp. 1885–1922.

[MCC14] Francesco Malandrino, Claudio Casetti, and Carla-Fabiana Chiasserini. “Toward D2D-enhanced heterogeneous networks”. In: *IEEE Communications Magazine* 52.11 (2014), pp. 94–100.

[MCD17] Radu-Corneliu Marin, Radu-Ioan Ciobanu, and Ciprian Dobre. “Improving Opportunistic Networks by Leveraging Device-to-Device Communication”. In: *IEEE Communications Magazine* 55.11 (2017), pp. 86–91.

[MGC14] Daniyal Munir, Jaheon Gu, and Min Young Chung. “Selection of UE relay considering QoS class for public safety services in LTE-A network”. In: *20th Asia-Pacific Conference on Communication (APCC)*. 2014, pp. 401–405.

[MGM17] Sireesha Madabhushi, Govind R Gopal, and Chandra R Murthy. “Optimal routing and data transmission for multi-hop D2D communications under stochastic interference constraints”. In: *23rd National Conference on Communications (NCC)*. 2017, pp. 1–6.

[MMH15] Pavel Masek, Ammar Muthanna, and Jiri Hosek. “Suitability of MANET Routing Protocols for the Next-Generation National Security and Public Safety Systems”. In: *Internet of Things, Smart Spaces, and Next Generation Networks and Systems*. Springer, 2015, pp. 242–253.

[MNB16] Leila Melki, Sameh Najeh, and Hichem Besbes. “Interference management scheme for network-assisted multi-hop D2D communications”. In: *IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*. 2016, pp. 1–5.

[MPL15] Nicholas Mastronarde, Viral Patel, and Lingjia Liu. "Device-to-device relay assisted cellular networks with token-based incentives". In: *IEEE International Conference on Communication Workshop (ICCW)*. 2015, pp. 698–704.

[MSS15] Kazushi Muraoka, Jun Shikida, and Hiroto Sugahara. "Feasibility of capacity enhancement of public safety LTE using device-to-device communication". In: *International Conference on Information and Communication Technology Convergence (ICTC)*. 2015, pp. 350–355.

[MT18] Andreas Mitschele-Thiel. "Quality of Service (in Mobile Networks)". Lecture Slides for course Advanced Mobile Communication Networks, Technische Universitat Ilmenau, Germany. 2018. URL: `https://www.tu-ilmenau.de/fileadmin/public/iks/files/lehre/mobilkommunikationsnetze/AMCN%20-%20QoS%20-%20ss18.pptx.pdf`.

[Mus+16] H.A.U. Mustafa et al. "Separation Framework: An Enabler for Cooperative and D2D Communication for Future 5G Networks". In: *IEEE Communications Surveys & Tutorials* 18.1 (2016), pp. 419–445.

[Nae+17] Ayesha Naeem et al. "Network Coding in Cognitive Radio Networks: A Comprehensive Survey". In: *IEEE Communications Surveys & Tutorials* (2017).

[NML16] Ivan O Nunes, Pedro OS Vaz de Melo, and Antonio AF Loureiro. "Leveraging D2D Multi-Hop Communication Through Social Group Meetings Awareness". In: *IEEE Wireless Communications* (2016).

[NN16] Mahda Noura and Rosdiadee Nordin. "A survey on interference management for Device-to-Device (D2D) communication and its challenges in 5G networks". In: *Journal of Network and Computer Applications* (2016).

[NSV17] Giovanni Nardini, Giovanni Stea, and Antonio Virdis. "A Fast and Reliable Broadcast Service for LTE-Advanced Exploiting Multihop Device-to-Device Transmissions". In: *Future Internet* 9.4 (2017), p. 89.

[Oka+06] Hiraku Okada et al. "Multi-route coding in wireless multi-hop networks". In: *IEICE transactions on communications* 89.5 (2006), pp. 1620–1626.

[Oka+07] Hiraku Okada et al. "A route selection scheme for multi-route coding in multihop cellular networks". In: *IEEE 66th Vehicular Technology Conference (VTC Fall)*. 2007, pp. 6–10.

[One+13] Evren Onem et al. "QoS-Enabled Spectrum-Aware Routing for Disaster Relief and Tactical Operations over Cognitive Radio Ad Hoc Networks". In: *IEEE Military Communications Conference (MILCOM)*. 2013, pp. 1109–1115.

[Oth+16] Salwa Othmen et al. "Anonymous and secure on-demand routing protocol for multi-hop cellular networks". In: *International Symposium on Networks, Computers and Communications (ISNCC)*. 2016, pp. 1–6.

[Par16] Jaesung Park. "Fast and Energy Efficient Multihop D2D Routing Scheme". In: *International Journal of Distributed Sensor Networks* (2016).

[PJ07] Yongsuk Park and Eun-Sun Jung. "Resource-aware routing algorithms for multi-hop cellular networks". In: *International Conference on Multimedia and Ubiquitous Engineering (MUE)*. 2007, pp. 1164–1167.

[PR99] Charles E Perkins and Elizabeth M Royer. "Ad-hoc on-demand distance vector routing". In: *Proceedings WMCSA'99. Second IEEE Workshop on Mobile Computing Systems and Applications*. IEEE. 1999, pp. 90–100.

[Pus+16] M Pushpalatha et al. "Power efficient multicast routing protocol for dynamic intra cluster device to device communication". In: *International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT)*. 2016, pp. 1853–1856.

[Qin+16] Hengjia Qin et al. "An Experimental Study on Multihop D2D Communications Based on Smartphones". In: *IEEE 83rd Vehicular Technology Conference (VTC Spring)*. 2016, pp. 1–5.

[Ram00] Maria Ramalho. "Intra-and Inter-domain multicast routing protocols: A survey and taxonomy". In: *IEEE Communications Surveys & Tutorials* 3.1 (2000).

[RDS13] Pinyi Ren, Qinghe Du, and Li Sun. "Interference-aware routing for hop-count minimization in wireless D2D networks". In: *IEEE/CIC International Conference on Communications in China-Workshops (CIC/ICCC)*. 2013, pp. 65–70.

[Rie17] Xiang Su Jukka Riekki. "A Cluster-based Routing Method for D2D Communication Oriented to Vehicular Networks". In: *IEEE International Conference on Systems, Man, and Cybernetics (SMC)*. 2017, pp. 2772–2777.

[RMP11] T Arvind Ramrekha, Grant P Millar, and Christos Politis. "A model for designing scalable and efficient adaptive routing approaches in emergency ad hoc communications". In: *IEEE Symposium on Computers and Communications (ISCC)*. IEEE. 2011, pp. 916–923.

[RPDM17] Salvatore Riolo, Daniela Panno, and Antonio Di Maria. "A new centralized access control for mmWave D2D communications". In: *13th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*. 2017, pp. 1–8.

[Sal+15a] Yasir Saleem et al. "Routing through efficient channel assignment in cognitive radio networks". In: *Handbook of Research on Software-Defined and Cognitive Radio Technologies for Dynamic Spectrum Management*. IGI Global, 2015, pp. 275–299.

[Sal+15b] Yasir Saleem et al. "SMART: A SpectruM-Aware ClusteR-based rouTing scheme for distributed cognitive radio networks". In: *Computer Networks* 91 (2015), pp. 196–224.

[Sal+17] Yasir Saleem et al. “Clustering and reinforcement-learning-based routing for cognitive radio networks”. In: *IEEE Wireless Communications* 24.4 (2017), pp. 146–151.

[SDJ15] Sandeep Kumar Singh, Tamal Das, and Admela Jukan. “A survey on internet multipath routing and provisioning”. In: *IEEE Communications Surveys & Tutorials* 17.4 (2015), pp. 2157–2175.

[SJZJ02] Christopher A St Jean, Ali N Zadeh, and Bijan Jabbari. “Combined routing, channel scheduling, and power control in packet radio ad hoc networks with cellular overlay”. In: *IEEE 55th Vehicular Technology Conference (VTC Spring)*. Vol. 4. 2002, pp. 1960–1964.

[SKJ16] Seung Beom Seo, Jae Young Kim, and Wha Sook Jeon. “Robust and fast device discovery in OFDMA-based cellular networks for disaster environment”. In: *18th International Conference on Advanced Communication Technology (ICACT)*. 2016, pp. 498–502.

[SR15] SB Sridhara and B Ramesh. “Energy efficient device to device multicast routing for wireless cellular ad-hoc network”. In: *International Conference on Applied and Theoretical Computing and Communication Technology (iCATccT)*. 2015, pp. 708–712.

[SS04] Mahdi Shabany and Elvino S Sousa. “Joint rate allocation and routing scheme in multihop cellular CDMA networks”. In: *9th International Symposium on Computers and Communications (ISCC)*. Vol. 1. 2004, pp. 442–447.

[SSR15] Yasir Saleem, Farrukh Salim, and Mubashir Husain Rehmani. “Routing and channel selection from cognitive radio networks perspective: A survey”. In: *Computers & Electrical Engineering* 42 (2015), pp. 117–134.

[Thi14] Third Generation Partnership Project (3GPP). “Study on LTE Device to Device Proximity Services; Radio Aspects”. In: *3GPP TR 36.843 version 12.0.1*. 2014.

[Thi15] Third Generation Partnership Project (3GPP). “LTE Device to Device (D2D) Proximity Services (ProSe) User Equipment (UE) radio transmission and reception”. In: *3GPP TR 36.877 version 12.0.0*. 2015.

[Thi18] Third Generation Partnership Project (3GPP). “Study on further enhancements to LTE Device to Device (D2D), User Equipment (UE) to network relays for Internet of Things (IoT) and wearables”. In: *3GPP TR 36.746 version 15.1.1*. 2018.

[Thi99] Third Generation Partnership Project (3GPP). “Opportunity Driven Multiple Access”. In: *3GPP TR 25.924 version 1.0.0*. 1999.

[Tia+16] Feng Tian et al. “Movement-based incentive for cellular traffic offloading through D2D communications”. In: *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. 2016, pp. 1–5.

[TK14a] Chafika Tata and Michel Kadoch. “Multipath routing algorithm for device-to-device communications for public safety over LTE heterogeneous networks”. In: *1st International Conference on Information and Communication Technologies for Disaster Management (ICT-DM)*. 2014, pp. 1–7.

[TK14b] CHAFIKA Tata and MICHEL Kadoch. “Secure network coding based data splitting for public safety D2D communications over LTE heterogeneous networks”. In: *Recent Advances in Computer Engineering, Communications and Information Technology* (2014), pp. 86–92.

[TK15] Chafika Tata and Michel Kadoch. “Secure Multipath Routing Algorithm for Device-to-Device Communications for Public Safety over LTE Heterogeneous Networks”. In: *3rd International Conference on Future Internet of Things and Cloud (FiCloud)*. 2015, pp. 212–217.

[TS08] Bogdan Timu and Pablo Soldati. “A joint routing-MAC model for cellular-relaying networks”. In: *IEEE 19th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*. 2008, pp. 1–6.

[Tul+14] Hugo Tullberg et al. “Towards the METIS 5G concept: First view on Horizontal Topics concepts, booktitle = European Conference on Networks and Communications (EuCNC)”. In: 2014, pp. 1–5.

[TUY14] Mohsen Nader Tehrani, Mustafa Uysal, and Halim Yanikomeroglu. “Device-to-device communication in 5G cellular networks: challenges, solutions, and future directions”. In: *IEEE Communications Magazine* 52.5 (2014), pp. 86–92.

[URS17] Sachin Umrao, Abhishek Roy, and Navrati Saxena. “Device-to-Device Communication from Control and Frequency Perspective: A Composite Review”. In: *IETE Technical Review* 34.3 (2017), pp. 286–297.

[Wan+15] Siyi Wang et al. “Outage probability for multi-hop D2D communications with shortest Path routing”. In: *IEEE Communications Letters* 19.11 (2015), pp. 1997–2000.

[WL07] Alan R Wolff and Chung-Chieh Lee. “Large scale routing in a multi-hop cellular network using a radial geometric approach”. In: *IEEE Wireless Communications and Networking Conference (WCNC)*. 2007, pp. 4446–4451.

[Wu+16] Yue Wu et al. “Device-to-device (D2D) meets LTE-Unlicensed”. In: *IEEE Communications Magazine* (2016).

[WY17] Mingjun Wang and Zheng Yan. “A survey on security in D2D communications”. In: *Mobile Networks and Applications* 22.2 (2017), pp. 195–208.

[WYS08] Yaowu Wu, Kun Yang, and Jianbing Shen. “Source selection routing algorithms in integrated cellular networks”. In: *IET Communications* 2.1 (2008), pp. 98–106.

[XS17] Yuxuan Xing and Hulya Seferoglu. "Device-aware routing and scheduling in multi-hop Device-to-Device networks". In: *Information Theory and Applications Workshop (ITA)*. 2017, pp. 1–7.

[Yaa14] Elias Yaacoub. "On the use of device-to-device communications for QoS and data rate enhancement in LTE public safety networks". In: *IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*. 2014, pp. 236–241.

[YGW14] Hu Yuan, Weisi Guo, and Siyi Wang. "Emergency route selection for D2D cellular communications during an urban terrorist attack". In: *IEEE International Conference on Communications Workshops (ICC)*. 2014, pp. 237–242.

[YGW15] Hu Yuan, Weisi Guo, and Siyi Wang. "D2D multi-hop routing: collision probability and routing strategy with limited location information". In: *IEEE International Conference on Communication Workshop (ICCW)*. 2015, pp. 670–674.

[YK12] Elias Yaacoub and Osama Kubbar. "Energy-efficient device-to-device communications in LTE public safety networks". In: *IEEE Globecom Workshops (GC Wkshps*. 2012, pp. 391–395.

[You+14] Moustafa Youssef et al. "Routing metrics of cognitive radio networks: A survey". In: *IEEE Communications Surveys & Tutorials* 16.1 (2014), pp. 92–109.

[Yua+17] Hu Yuan et al. "Interference-aware multi-hop path selection for device-to-device communications in a cellular interference environment". In: *IET Communications* (2017).

[Zha+15a] Yanru Zhang et al. "Contract-based incentive mechanisms for device-to-device communications in cellular networks". In: *IEEE Journal on Selected Areas in Communications* 33.10 (2015), pp. 2144–2155.

[Zha+15b] Yulei Zhao et al. "Social community aware long-range link establishment for multi-hop D2D communication networks". In: *IEEE International Conference on Communications (ICC)*. 2015, pp. 2961–2966.