UNIVERSITI PUTRA MALAYSIA

STOCHASTIC GEOMETRY-BASED ANALYSIS OF RELAY-ASSISTED SPECTRUM SHARING FUTURE GENERATION WIRELESS NETWORKS

AMODU OLUWATOSIN AHMED

FSKTM 2021 13

STOCHASTIC GEOMETRY-BASED ANALYSIS OF RELAY-ASSISTED SPECTRUM SHARING FUTURE GENERATION WIRELESS NETWORKS

By

AMODU OLUWATOSIN AHMED

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

November 2020

DEDICATIONS

Towards the benefit of mankind.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

STOCHASTIC GEOMETRY-BASED ANALYSIS OF RELAY-ASSISTED SPECTRUM SHARING FUTURE GENERATION WIRELESS NETWORKS

By

AMODU OLUWATOSIN AHMED

November 2020

Chairman: Mohamed Othman, PhD
Faculty: Computer Science and Information Technology

Many technologies are set to revolutionize the efficiency of humans and devices communication. Three of the trending technologies envisaged to provide huge prospects towards the realization of the fifth-generation cellular systems are machine-to-machine (M2M) communication, device-to-device (D2D) communication and cognitive radio networks (CRNs). M2M facilitates the autonomous communication of smart devices while D2D facilitates direct connectivity between devices in proximity. Cognitive radio aids effective utilization of wireless spectrum as cognitive devices could opportunistically access the spectrum of licensed users. Similarly, relays improve the transmission coverage between nodes which in turn reduces the outage probability (OP) and increases the transmission capacity (TC) of the spectrum sharing network. These metrics can be effectively studied using stochastic geometry (SG): a mathematical tool for deriving insights into the performance of wireless networks of different spatial configurations. Motivated by these, this thesis is aimed at addressing three of the research gaps related to spectrum sharing systems (D2D and CRNs) assisted by relays using SG.

The coexistence of a massive number of machine-type devices (MTDs) with D2D and cellular users is set to heighten the interference levels within the cellular architecture. On the other hand, D2D devices would require relays whenever they are farther apart to improve the outage performance. However, limited battery or the non-altruistic nature of certain users may deter them from helping other users to relay data. Motivated by the recent specifications of MTD devices, the first contribution in this thesis conceptualizes that MTDs can relay data for D2D devices that are not in proximity. In this context, a probabilistic model is introduced for the availability of M2M devices. Thorough investigations are made on the TC, TC gains and trade-offs involved for both underlay and D2D-overlay modes. Using SG, the successful transmission probabilities for all associated links are derived to determine the TCs in these scenarios and present computable expressions for the TC gains achieved. Furthermore, an exposition is provided on how

the density and transmit power of MTDs in the network affect the D2D TC performance. Results show that the deployment of MTD devices as relays improves the TC as compared to when only traditional RNs are used. Similarly, higher peak TCs are achieved at 23dB MTD transmit power. Overall, a lower transmit power (15dB) yields better performance. Thus, high MTD density can be leveraged to improve the D2D TC when so many D2D transmissions occur within the system and when these devices are farther apart.

The literature on the performance analysis of energy harvesting cognitive radio networks focused on a dual and multi-hop secondary architecture. Also, the available literature on a multi-hop primary architecture was not studied in the context of radio frequency energy harvesting which makes the impact of a multi-hop primary network on the outage performance of a dual-hop energy harvesting CRN largely unknown. Thus, the second contribution in this thesis exploits SG and the advancements in wireless energy harvesting to develop a framework for the outage probability analysis of energy harvesting underlay CRNs. In this model, N-hop primary users are equipped with constant energy source while secondary users harvest energy from the transmissions of primary devices. The transmit power of secondary users is regulated to ensure it does not violate the target end-to-end OP constraint of the N-hop primary network. Potential relays that have harvested sufficient energy are eligible to relay data for other secondary users within the network. This model reveals the impact of the number of primary hops on the relay selection region and harvested energy (which is generally unknown). Also, an expression for the total outage probability which encapsulates the impact of N-primary hops is derived. The impacts of other relevant parameters on the outage probability are shown in detail. Results show that the multi-hop primary network reduces the secondary outage probability by regulating the number of transmitting energy harvesting relays within the network.

Interference cancellation has long been known as an effective approach to reducing the impact of interference in wireless networks. However, the interplay between interference cancellation and energy harvesting and how both can be used within the same architecture to improve the outage performance in cognitive radio networks is unknown. This motivates the third contribution where interference cancellation is incorporated in the outage analysis of a Poisson distributed wireless energy harvesting cognitive relay network. Based on a predefined interference threshold, devices within the primary network are assumed to be able to cancel a fraction of the strongest interferers in the entire network. To achieve this, the coefficient of cancellation is adapted into the SG analysis to reduce the level of interference. The rationale is to further help the secondary network to meet up with the primary outage constraint by reducing some of the interference experienced by primary receivers. Analytical results show that this significantly reduces the secondary OP which in turn improves the network performance based on a set cancellation threshold and residual interference power. However, this is at the cost of reducing the energy harvesting success probability of the relays within the secondary network which depends on the primary density as interference from such devices would be cancelled.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

ANALISIS BERASASKAN GEOMETRI STOKASTIK BERASASKAN GEGANTI SPEKTRUM PERKONGSIAN RANGKAIAN NIRWAYAR GENERASI MASA DEPAN

Oleh

AMODU OLUWATOSIN AHMED

November 2020

Pengerusi: Mohamed Othman, PhD
Fakulti: Sains Komputer dan Teknolologi Maklumat

Pelbagai teknologi digunakan bagi mengrevolusi kecekapan komunikasi antara manusia dan peranti. Tiga teknologi tren yang dirancang untuk memberikan prospek yang besar ke arah mencapai sistem selular generasi kelima adalah komunikasi dari mesin ke mesin (M2M), komunikasi peranti ke peranti (D2D) dan rangkaian radio kognitif (CRN). M2M meningkatkan komunikasi autonomi peranti pintar manakala D2D memudahkan sambungan terus antara peranti berdekatan. Radio kognitif membantu penggunaan spektrum tanpa wayar secara berkesan, di mana peranti kognitif boleh mengakses spektrum pengguna berlesen secara oportunis. Begitu juga, geganti meningkatkan liputan penghantaran antara nod yang seterusnya mengurangkan kebarangkalian gangguan (OP) dan meningkatkan kapasiti penghantaran (TC) rangkaian perkongsian spektrum. Metrik (or parameter) ini boleh dikaji secara berkesan menggunakan pendekatan geometri stokastik (SG): alat matematik untuk mengukur prestasi rangkaian tanpa wayar dalam konfigurasi spatial yang berlainan. Bermotivasikan pernyataan di atas, penyelidikan ini membentangkan tiga sumbangan kepada analisis prestasi sistem perkongsian spektrum tanpa wayar generasi masa hadapan yang dibantu geganti (termasuk D2D, M2M, dan CRN) menggunakan SG.

Keberadaan sejumlah besar peranti jenis mesin (MTD) dengan pengguna D2D dan selular akan meningkatkan tahap gangguan di dalam seni bina selular. Manakala, peranti D2D memerlukan geganti setiap kali ia berada jauh untuk meningkatkan prestasi pemadaman. Walau bagaimanapun, bateri terhad atau sifat tidak altruistik pengguna tertentu boleh menghalangnya daripada membantu pengguna lain untuk menyampaikan data. Dengan menjangkakan pembangunan secara besar-besaran peranti jenis mesin MTD dengan spesifikasi terkini, sumbangan pertama dalam tesis ini berkonsepkan bahawa MTD boleh menyampaikan data kepada peranti D2D yang berjauhan. Dalam konteks ini, model kebarangkalian diperkenalkan untuk ketersediaan peranti jenis M2M. Siasatan

yang menyeluruh dibuat ke atas TC, keuntungan dan keseimbangan TC yang terlibat untuk kedua-dua mod iaitu underlay dan D2D-overlay. Menggunakan pendekatan SG, kebarangkalian penghantaran berjaya untuk semua pautan yang berkaitan telah diperolehi bagi menentukan TC dalam senario ini dan memperlihatkan ungkapan komputasi untuk mencapai TC. Tambahan pula, penerangan menyeluruh disediakan mengenai bagaimana ketumpatan dan kuasa penghantaran MTD di dalam rangkaian memberi kesan terhadap prestasi TC D2D. Hasil penyelidikan menunjukkan bahawa penggunaan peranti MTD sebagai relay meningkatkan TC berbanding ketika hanya tradisional RN yang digunakan. Begitu juga, TC memuncak capaian lebih tinggi pada daya penghantaran 23dB MTD. Secara keseluruhan, daya transmisi yang lebih rendah (15 dB) menghasilkan prestasi yang lebih baik. Oleh itu, kepadatan MTD yang tinggi dapat dimanfaatkan untuk meningkatkan D2D TC apabila begitu banyak transmisi D2D berlaku di dalam sistem dan ketika peranti ini semakin berjauhan.

Kajian literasi tentang analisis prestasi rangkaian radio kognitif tenaga-menuai memfokuskan pada seni bina sekunder dual dan multi-hop. Juga, kajian literasi yang tersedia mengenai seni bina multi-hop tidak dipelajari dalam konteks tenaga-menuai frekuensi radio yang menjadikan kesan "transmisi primer multi-hop" tidak diketahui mengenai prestasi pemadaman dua-hop tenaga-menuai CRN. Oleh itu, sumbangan kedua dalam tesis ini adalah mengeksploitasi pendekatan SG dan kemajuannya dalam pengambilan tenaga tanpa wayar untuk mengembangkan kerangka kerja bagi analisis kebarangkalian gangguan penuaian tenaga underlay CRNs. Pada model ini, pengguna utama $N-$hop dilengkapi dengan sumber tenaga yang berterusan sementara pengguna sekunder menuai tenaga dari penghantaran peranti utama. Kuasa penghantaran pengguna sekunder dikawal untuk memastikan ianya tidak melanggar sasaran hujung ke hujung OP untuk tujuan utama rangkaian $N-$hop. Alat geganti berpotensi untuk mengumpul tenaga yang mencukupi, layak untuk menyampaikan data kepada pengguna sekunder yang lain di dalam rangkaian. Seterusnya, kajian ini mendedahkan kesan bilangan hop utama ke atas kawasan pemilihan geganti dan tenaga yang dikumpul (yang biasanya tidak diketahui) menggunakan model yang dipelajari. Juga, satu ungkapan untuk kebarangkalian jumlah gangguan yang merangkumi kesan dari $N-$hops dihasilkan. Kesan parameter lain yang berkaitan dengan kebarangkalian. Hasil menunjukkan bahawa rangkaian primer multi-hop mengurangkan OP sekunder dengan mengatur jumlah transmisi relai "tenaga-menaui" dalam rangkaian gangguan ditunjukkan dengan terperinci. Sumbangan ketiga dalam tesis ini adalah menggabungkan pembatalan gangguan dalam analisis gangguan rangkaian penuaian tenaga kognitif tanpa-wayar dimana peranti disebarkan secara taburan Poisson.

Berdasarkan ambang gangguan, peranti dalam rangkaian utama diandaikan dapat membatalkan sebahagian kecil daripada gangguan terkuat di seluruh rangkaian yang sering menguasai gangguan dalam kedua-dua sistem. Bagi mencapai matlamat ini, pekali pembatalan disesuaikan semasa menganalisis untuk mengurangkan tahap gangguan. Rasionalnya adalah untuk membantu lagi rangkaian sekunder dalam menghadapi kekangan kendalian utama dengan mengurangkan beberapa gangguan sendiri. Hasil analitikal menunjukkan bahawa pendekatan ini dapat digunakan untuk mengurangkan pengurangan OP yang sekaligus meningkatkan prestasi rangkaian. Walau bagaimanapun, ini adalah bagi mengurangkan kebarangkalian kejayaan pengumpulan tenaga geganti dalam rangkaian sekunder kerana beberapa gangguan dari peranti utama akan dibatalkan. Pembatalan gangguan telah lama diperkenalkan sebagai pendekatan yang berkesan untuk mengurangkan kesan gangguan dalam rangkaian tanpa-wayar. Walau bagaimanapun, interaksi antara pembatalan gangguan dan pengambilan tenaga-kumpul dan bagaimana gabungan kedua-duanya dapat digunakan dalam seni bina yang sama untuk meningkatkan prestasi pemadaman dalam radio kognitif masih belum dikaji lagi.

ACKNOWLEDGEMENTS

All Praise is due to ALLAH *Subhanahu wata'ala* for all His Blessings and Guidance. May His Peace and Blessings be upon the noble Prophet Muhammad *Sollalahu 'alaihi wasallam*, his household, companions and those who tread their path.

My sincere appreciation goes to my supervisor, Prof. Dr. Mohamed Othman for his dedication towards my well being and research. Particularly, Prof. was available, supportive and considerate. I also appreciate his great concern for quality which has really shaped my perception. Many thanks to my supervisory committee members; Prof. Nor Kamariah Noordin for her encouragement and valuable suggestions, and Dr. Idawaty Ahmad for her comments and support. I would also like to thank the examination committee members for benefiting me with their knowledge.

My enrolment into this programme may hardly have been possible if not for the fact that I was blessed to be among those chosen for the Malaysian International Scholarship award in 2016. The Malaysian Ministry of Higher Education has invested much in my academic pursuit and did not fall short of providing the needed support for my studies. I would gladly love to appreciate this initiative and I hope my research output benefits the Malaysian community and the world at large.

A significant place in my entire life is held by my parents for their all-round support. I pray they are granted increased happiness and well-being in this life and the Next. Their financial support and that of Mr Sam Olumekun benefited me immensely. My parents' psychological support also kept me motivated. I thank my brother for his kind words and my spouse for her tremendous sacrifices and unwavering support.

Finally, I would like to appreciate Faculty of Computer Science and Information Technology, Universiti Putra Malaysia and everyone I have benefited from during my research journey for providing me with information and support that facilitated my research.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy.

The members of the Supervisory Committee were as follows:

Mohamed Othman, PhD
Professor
Faculty of Computer Science and Information Technology
Universiti Putra Malaysia
(Chairman)

Nor Kamariah Noordin, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Idawaty Ahmad, PhD
Senior Lecturer
Faculty of Computer Science and Information Technology
Universiti Putra Malaysia
(Member)

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 11 February 2021

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: ______________________ Date: ______________________

Name and Matric No.: Amodu Oluwatosin Ahmed (GS46681)

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

3GPP	Third Generation Partnership Project
5G	Fifth Generation Cellular Network
ASR	Average Sum Rate
BS	Base Station
CRN	Cognitive Radio Network
CSI	Channel State Information
CUE	Cellular User Equipment
D2D	Device-to-Device
DF	Decode and Forward
DUE	D2D User Equipment
EC	Ergodic Capacity
EH	Energy Harvesting
FDAF	Full Duplex Amplify and Forward
FDMA	Frequency Division Multiple Access
IC	Interference Cancellation
IoT	Internet of Things
LOS	Line-of-sight
LTE	Long-Term Evolution
LTE-A	Long-Term Evolution Advanced
M2M	Machine-to-Machine
OP	Outage Probability
PCP	Poisson Cluster Process
PDF	Probability Density Function
PPP	Poisson Point Process
PR	Primary Receiver
PT	Primary Transmitter
PU	Primary User
QoS	Quality of Service
RF	Radio-frequency
RFID	Radio-frequency Identification
SG	Stochastic Geometry
SINR	Signal-to-interference-plus-noise ratio
SIR	Signal-to-interference ratio
ST	Secondary Transmitter
SU	Secondary User
STP	Successful Transmission Probability
SWIPT	Simultaneous Wireless Information and Power Transfer
TDD	Time Division Duplexing
TC	Transmission Capacity
UAV	Unmanned Aerial Vehicle
UE	User Equipment
WSN	Wireless Sensor Network

CHAPTER 1

INTRODUCTION

1.1 Background

Wireless mobile communication systems have experienced a tremendous change in traffic within the last few years. This can be partly attributed to the emergence of smart hand-held devices and internet-based applications. In this respect, the advent of the fifth-generation wireless networks (5G) is expected to contribute tremendously towards meeting the unprecedented traffic demands while also providing improved quality of service (QoS) to users. 5G and the internet of things (IoT) are two trending areas that are shaping the wireless communication terrain. 5G has a place in commerce and other aspects of human lives. Particularly, a massive number of devices will be connected and new application scenarios will emerge [1]. For example, 5G should significantly improve the spectrum, energy and cost efficiencies compared to the technologies of the past. In this context, spectrum sharing has the potential of improving the spectrum efficiency as it allows devices to utilize the spectrum at the same time [2]. Another way to improve this spectrum efficiency in 5G is by adopting new communication techniques. Among these technologies are device-to-device (D2D) communication and cognitive radio networks (CRNs) [3].

The huge capacity demands of emerging wireless communication is another challenge that calls for efficient spectrum sharing mechanisms. For instance, the advent of machine-to-machine (M2M) communication and IoT calls for the coexistence between technologies such as the Long-Term Evolution (LTE) mobile communication standard [4]. Although these technologies are promising in terms of their prospects and applications, the need to improve spectrum utilization also increases the level of interference within the network which has a negative impact on the system performance if not well managed. Moreover, devices will need to communicate with each other to facilitate the interesting applications (such as smart communication) they are expected to deliver. However, their performances degrade within the channel when the level of interference is severe or due to pathloss when the devices are far apart. This motivates the need for relays to further improve the quality of communication by forwarding data from source devices to their destinations.

Two major metrics used to measure the performance of wireless communication and spectrum sharing systems are transmission capacity (TC) and outage probability (OP). These two metrics are closely connected as the former is a product of the density of active devices and the successful transmission probability (STP) while the latter adds up with the STP to give a total of 1 [5]. Similarly, stochastic geometry (SG) is one of the techniques that have been extensively deployed within the last two decades to answer questions that are pertinent to wireless networks involving randomly located transmitters and receivers [6]. This mathematical tool has been deployed to study metrics such as energy-efficiency, TC and OP. Particularly, the literature is rich in SG-based analyses of the TC and OP of wireless systems. In line with this, this research is directed at analysing and improving the performance (i.e., TC and OP) of relay-assisted spectrum sharing systems for future wireless communication (which includes D2D and CRNs) using SG analyses.

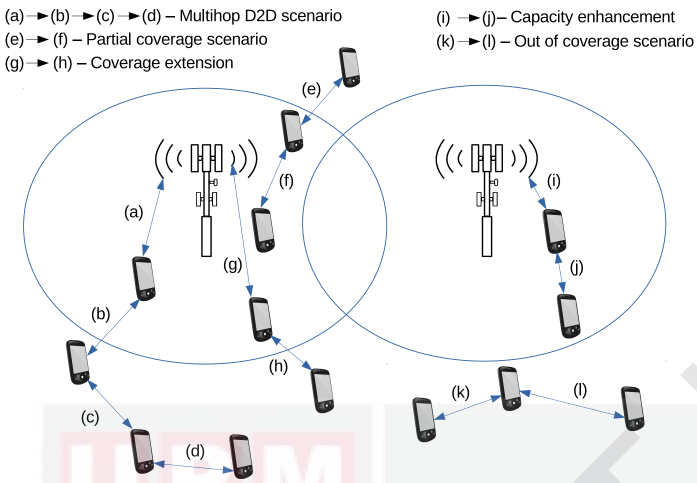

Figure 1.1: Typical relaying scenarios for relay-assisted D2D communication.

1.2 D2D communication

D2D communication has been identified as a favourable technology for increasing network capacity, user experience [7] and reliable connectivity of mobile devices [8]. It facilitates mutual communication between devices in proximity with little or no base station (BS) intervention [9, 10, 11]. Also, it is a major prospective technology for attaining energy efficiency in cellular networks [12]. In 5G networks, D2D communication is regarded as an enabling technology to achieve high spectral efficiency and ultra-densification [13, 8]. Furthermore, it enhances network throughput and reduces delay [14]. However, a major challenge in D2D networks within a cellular architecture is co-channel interference which occurs when the existing cellular transmissions interfere with D2D communication.

1.2.1 Relay-assisted D2D communication

D2D can play a life-saving role in applications such as disaster scenarios where the traditional BS becomes dysfunctional (see [15] for example), and it is very difficult to communicate with those outside of the disaster zones. In such cases, relay assistance can be highly propitious [16]. In relay-assisted D2D communication, the source and destination devices discover an idle node between them to establish mutual communication. The source node thus transmits data to the relay which decodes and forwards it to the destination node.

Relay-assisted D2D significantly improves the network performance of traditional D2D communication [17] in terms of TC [18]. When the source and destination devices are not adjacent to each other, the application use-cases of D2D communication become more restricted [19]. Thus, a universal solution cannot be achieved by D2D communication without the intervention of relays [20]. For instance, when D2D pairs are farther apart, the OPs of D2D links will increase.

Moreover, nodes might not be able to reach other nodes due to constraints in transmit power [21] in a single-hop. In such cases, most traditional interference management schemes such as power control may not work. This motivates the need to enhance the range of communication, thereby reducing the OP [22]. Also, in poor coverage areas, relays can be used to improve network performance [23]. Thus, relay-assisted D2D communication has several benefits and use cases (see the scenarios in Figure 1.1 for example).

Device relaying can inherently bring to light the potential of cooperative communication to meet the growing demand for higher data rates and capacity in 5G cellular systems [24]. The use of relays facilitates multi-hop transmission which improves spectral reuse within the network. There are also 'promises' of higher data rate, improved QoS, network capacity and network load balancing. The ubiquity of D2D communication makes the incorporation of multi-hop D2D communication conceivable as a part of a future standard. This is because multi-hop D2D communication is not bounded to specific geographic locations like traditional D2D communication [25].

1.2.2 D2D communication modes

Considering how user devices can access the licensed or unlicensed spectrum, D2D communication can be classified into in-band (licensed) and out-band (unlicensed)[1]. The in-band D2D can be further categorized into underlay and overlay modes (see Figure 1.2). In the underlay mode, devices use the same spectrum for cellular and D2D communication, i.e., they share the same radio resources. One motivation for the consideration of inband D2D communication is that the licensed spectrum has a considerable level of control compared with the unlicensed band [14]. Asides this, [9, 14, 27] highlighted a number of benefits including improved spectral efficiency due to the exploitation of spatial diversity. Also, cellular devices can support inband D2D since the cellular frequency will be exploited. Furthermore, resource allocation techniques can be easily deployed to manage the network QoS.

Despite these benefits, inband D2D communication has its own drawbacks [27, 28]. A typical challenge in underlay D2D is interference which could be addressed when proper power control and interference management techniques are considered. However, these may require very complex resource allocation techniques [9]. In the overlay mode, D2D uses a dedicated spectrum orthogonal to that of cellular communication. The cellular resources could be underutilized and a typical user cannot perform simultaneous cellular and D2D transmission. The use of the overlay mode may poorly affect the QoS due to a high level of unmanaged interference resulting from other wireless technologies sharing the same spectrum [13, 27]. This interference cannot be controlled by the BS. Thus, the underlay D2D is more popular [9] and it is the focus of this research. Considering relay-assisted D2D communication, user devices can function in one of three modes: a cellular mode where they function as traditional cellular users (CUEs), D2D mode where they communicate in a D2D fashion, and relay mode where they relay data for other devices.

[1]In out-band D2D communication, the interference from D2D to eNodeB-UE is absent [26] as the frequency spectrum used by D2D does not overlap with the cellular spectrum [9].

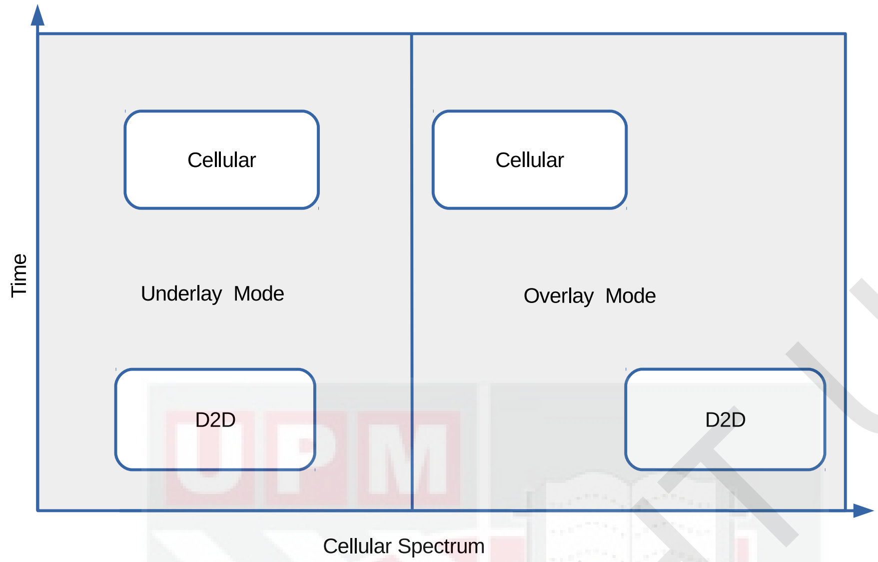

Figure 1.2: In-band D2D spectrum sharing modes.

1.2.3 Spectrum sharing in D2D networks

In the quest for effective utilization of the scarce cellular network resources, it is imperative that the wireless channel should be shared efficiently [29]. Spectrum sharing occurs when users/radio communication systems use the same spectrum resource. Sharing could occur in frequency, time and place (space) [30]. A fundamental component which affects spectrum sharing systems is the device density. In a dense relay-assisted D2D communication network, the chance of a more efficient spatial re-use is higher since the spectrum will be 'heavily' used by these systems across the entire network. However, for effective network performance, the QoS requirements of participating systems have to be met [31]. In this regard, the level of reliability in terms of success probability for specific data rates has to be given proper consideration.

On the other hand, the demand for spectral resources becomes higher. Also, a dense network will experience more interference which significantly affects network performance. The level of interference dictates what type of resource allocation mechanisms, mode control, and power control is required to guarantee the target signal-to-interference-plus-noise ratio (SINR) thresholds for different systems within the network. Therefore, a deeper understanding of the effect of device density on the network is crucial.

There are several models for spectrum sharing in relay-assisted D2D networks consisting of cellular devices, D2D devices, and relay nodes (RNs). As mentioned earlier, relay-assisted D2D has positioned itself as a potential approach to tackle some of the traditional challenges of D2D communication such as coverage. Also, efforts have been made to model and unveil its performance in diverse application use cases and physical layer configurations using mathematical tools such as SG.

1.3 Cognitive radio networks

Cognitive radio technology has the potential to improve the spectral utilization efficiency [1, 32, 33] by filling 'holes' in the wireless spectrum. It can address the problems of spectrum scarcity and requirements in future wireless communication systems [34]. This is because devices can effectively learn, sense and be 'cognitive' of parameters relating to the operation of the channel environment [35]. In applications like IoT, cognitive sensors can make the network more spectrally efficient [36]. CRNs can function in one of three modes: underlay, overlay and interweave. The transmit power of cognitive devices are controlled based on the channel state to meet up with the interference constraints in the underlay [37]. In the overlay, the power of secondary devices is used for secondary communication and relaying primary transmission [38]. Spectrum occupancy is periodically monitored and intelligently detected in the interweave mode. Also, communication is made over the spectrum holes in an opportunistic manner [38]. Among these modes, the underlay mode is known for its high spectral utilization efficiency [39]. Thus, this research focuses on the underlay spectrum sharing mode.

1.4 Other related technologies

Aside D2D communication and CRNs, other concepts considered in this thesis include M2M communication, Radio-frequency energy harvesting (RF-EH) and interference cancellation (IC). These technologies are described as follows:

1.4.1 Machine-to-machine communications

To meet the major technical demands for 5G in cellular networks, D2D communication will coexist with other paradigms such as M2M technology [40, 41]. M2M communication is distinguished by the autonomous interaction of a large number of intelligent machine devices to perform sensing, processing and actuation activities without human intervention [42, 43, 44]. These devices could be meters in smart grid, electronics and servers, and navigation sensors used for relaying information through a network. The main characteristic that sets M2M apart from other communication paradigm is the absence of human supervision [42, 43, 45, 46, 44]. The primary aim of M2M communication is to enable smart devices connect [47].

Current projections of M2M nodes (i.e., machine-type devices, MTDs) to be deployed in the future show that M2M could account for almost half of connected devices [48], reaching the order of millions. The massive number of machine devices [49] will be a major enabler of the IoT [50, 51]. Machines can connect to each other (in a D2D fashion) or connect to gateways to relay data to the BS using wired or wireless links [52]. Some interesting applications of M2M are smart meters, autonomous vehicular communication and e-health [42, 53, 54]. This fast-growing paradigm with billions of interconnected machines in different applications is imminent [55].

On a more general note, M2M plays a significant role in the realization of IoT applications. These include home automation, surveillance, transport, smart environment and healthcare [56]. A peculiar characteristic of this technology is its massive deployment which is predicted to be of the order of millions. This puts technical experts in a critical position to think of the major obstacles on the path to its practical realization and how these challenges can be effectively addressed. Generally, some of the most prominent techniques for addressing these challenges in relation to energy-efficiency, spectral-efficiency and reliable communication are RF-EH, cognitive radio technology and multi-hop data transfer.

1.4.2 Radio-frequency energy harvesting

Radio-frequency (RF) is an affordable and easily accessible energy source found in hand-held devices, television or radio towers, satellite transmitters, Wi-Fi routers and cellular mobile base stations [32, 56]. It is suitable for long-distance transmissions such as simultaneous wireless information and power transfer (SWIPT) [57]. RF can be used to charge low-power mobile devices such as electronic watches, mp3 player, hearing aid, wireless keyboard/mouse [58] and other wearable devices like google glasses [59]. RF-EH is a paradigm where RF signals serve as energy harvesting (EH) sources for wireless nodes [60]. It allows devices to harvest energy for information processing and transmission. As such, it can function within applications such as wireless sensor networks (WSN), e-health and radio-frequency identification (RFID) [58]

RF-EH for CRNs

Considering that cognitive devices consume a significant amount of energy during their operations (e.g., periodic sensing of the spectrum and decision making coupled with signal processing and data transmission), it is essential that an alternative source of power is considered for powering these devices [61]. Recently, harvesting ambient interference was found to be highly propitious for green communication. In simple terms, this means the interference will be 'harvested' and used to power devices within the network. Since it may be difficult to power all IoT devices using RF-EH, some researchers consider devices that perform special tasks or have a higher energy burden such as RNs as EH devices. Note that in scenarios like cognitive-based EH IoT networks, it is essential to preserve/respect the outage constraints of PUs (i.e., licensed users).

IoT devices in the unlicensed band could harvest energy from primary transmissions and devices that have harvested sufficient energy can function as relays. This cognitive communication is beneficial as it is more spectral-efficient and the high-density IoT devices increase the spatial reuse. CRN can be opportunistically powered to exploit underutilized network by harvesting the freely available energy without an energy supplement [62]. Moreover, cognitive devices can harvest energy to dynamically access the licensed band [63] which brings benefits in terms of energy and spectral efficiencies. To take these benefits, RF-EH CRN is considered in this thesis. From the two common architectures used in EH networks, power splitting and time switching architectures, the time switching architecture is adopted in this thesis (because of its simplicity [57, 58]).

Another important component required in the analysis of EH networks relates to the choice of energy harvesting conversion efficiency model, i.e., either linear or non-linear EH models. Particularly, the linear model is quite malleable for analysis using SG since a constant between 0 and 1 is used. This model is well used in the literature and it is also considered in this thesis. Although the non-linear EH model is more practical, it has a variable conversion efficiency which complicates the procedure for obtaining the energy harvesting success probability using stochastic geometry.

1.4.3 Multi-hop CRNs

Multi-hop communication finds unique applications in underlay CRNs as it helps to subvert issues relating to channel impairments [64]. In other words, the use of intermediate RNs in multi-hop relay networks can help to overcome issues of attenuation and fading to achieve reliability and network performance efficiency [58]. This improves the coverage and reliability of the network [32]. However, relays would also require energy to support their functionality. Note that replacing the batteries of some battery-constrained relays placed in toxic environments and walls might be difficult. Therefore, EH is a suitable, safe and cost-saving approach to power up relays [32] in such cases.

1.4.4 Interference cancellation

One of the main limitations of the cellular/ network performance is interference caused by 'human-designed' devices [65]. When devices and relays share the spectrum with primary users (PUs), this interference further aggravates. Similarly, in a scenario with dense network infrastructure, there exist an advantage of improved signal power which comes at the cost of an almost equal increase in interference; thereby limiting the spectral efficiency gains. Two major techniques used to tackle interference are interference avoidance/coordination and interference cancellation (IC). The former may not be as competitive as the latter when spectrum utilization is taken to account. This is because IC facilitates an aggressive spectrum reuse [66]. Thus, IC is a typical approach to mitigating interference in wireless networks where the desired information is demodulated and/or decoded. It is used with the estimate of channel states to cancel the interference from the received signal [65]. IC is a very competitive approach with respect to spectrum utilization [66].

1.5 Stochastic geometry

Evaluating the performance of wireless communication can be achieved using different approaches. One such approach is SG which has been used extensively within the last two decades to answer questions pertinent to wireless networks involving randomly located transmitters and receivers [6]. Particularly, the TC metric using SG has proven to be very useful as it reveals the network performance in relation to the number of successful transmissions of user devices of a particular density. Another widely studied performance metric for wireless communication using SG is the OP [67]. SG has also been handy for deriving the closed-form expression which captures the impact of the key parameters of interest and provides design guidelines to network designers and operators [68, 69]. The parameters of interest include the density of devices, their transmission power and the QoS expectation in terms of the SIR.

1.6 Problem statement

After an extensive review of the literature on relay-assisted future generation wireless spectrum sharing systems (which include D2D, M2M, and CRNs), it was observed that there is a need to develop new architectures and analytical models that improve on the successful transmission performances of these systems. Firstly, it was realized that the existing models on relay-assisted D2D communication have not considered the potential of using the newly specified MTD devices as relays to improve the transmission capacity of D2D devices. Also, a systematic SG-based analytical investigation on the impact of a massive number of MTDs on the TC performance of D2D communication assisted by randomly selected DUE and MTD relays is lacking in the current literature.

The outage performance of EH-based relay-assisted random underlay CRNs has been recently investigated in the literature using SG-based models. However, the proposed model failed to consider the potential of increasing the spectral reuse of the primary network and the potential improvement that can be achieved using a multi-hop primary network. Similarly, trade-offs between the OP and EH success probability have also not been researched in the literature. Additionally, the impacts of the number of primary hops and other network parameters on the secondary outage performance, relay selection region and the harvested energy have not been investigated.

Although IC has been well-studied in different portions of the literature such as adhoc networks, none of the works in the literature has considered the potential of IC in an EH cognitive relay network (where meeting the primary outage constraint has a priority) despite that cancelling the interference experienced at the primary receiver has the potential to reduce the secondary outage performance.

1.7 Research questions

The research questions are summarized below.

1. Does the introduction of M2M relays have the potential to improve the TC of D2D communication?
2. How does the number of primary hops impact the secondary outage performance, relay selection region and harvested energy in an EH-based relay-assisted CRN with multi-hop primary transmissions?
3. How does the cancelled portion of the residual interference power impact the secondary outage performance, relay selection region and harvested energy in an EH-based relay-assisted CRN with strong interferer cancellation at primary receivers?

1.8 Research motivation

Spectrum sharing systems play significant roles in the development of future wireless generation communication systems as they improve the spectrum utilization between devices sharing spectral resources. However, interference becomes a major obstacle that negatively impacts the quality of communication. The use of relays is propitious for improving the performance of spectrum sharing systems for future wireless communication. It has the potential to facilitate data transmission among devices whenever the interference in the network is severe. Thus, improving the number of successful transmissions using relays is a current research focus in the literature.

Although, the introduction of relays and interference mitigation techniques can help to improve on the network performance, in certain cases, some devices are unwilling to relay data for others (in the case of D2D communication). Also, in cognitive radio networks with stringent primary outage constraint, it is essential to guarantee the QoS requirement while ensuring the secondary network does not have to significantly degrade its performance. To address these issues, new models are required to improve on the outage performance of cognitive radio networks. These motivate this research to aim at improving successful transmissions in relay-assisted spectrum sharing systems with D2D and CRN as the subjects of focus. These paradigms are studied using SG tools.

With the aforementioned in mind, an RF-EH scenario where SUs can harvest RF energy from other licensed users [70] is considered. This is considerable because a large number of machine devices will be deployed in future 5G and IoT networks. Such devices will generate much interference that could be exploited using wireless EH [57]. In scenarios where devices are energy-constrained, relaying data becomes another challenge as it is also an energy-consuming process. Hence, taking advantage of EH is a good option. The SUs in this case harvest energy from the interference of primary users (PUs). Using this as an energy source provides a better secondary throughput [71].

Additionally, the primary devices transmit in a multi-hop fashion (similar to [64]). Note that the primary distance in this model is short. This is because the current IoT devices are designed to be of low power which implies they should have a low transmission range. Such devices are typical examples of PUs. The projected future EH-based networks will be able to provide for a range of $5 - 100m$ [72] which could constitute the secondary network in this model.

1.9 Research objectives

This research aims at proposing new architectures and developing analytical models for improving the successful transmissions of devices transmitting information in wireless spectrum sharing systems assisted by relays. In particular, this will help to increase the transmission capacity and reduce the outage probability of spectrum sharing networks (i.e., D2D and CRN, respectively). The first objective represents that of the D2D network while objectives two and three relates to CRN.

1. To develop an analytical model for improving the TC of relay-assisted D2D communication using machine type devices as relays.
2. To develop an analytical model for EH-CRNs with multi-hop primary relays for improving the OP of energy harvesting cognitive relay networks.
3. To develop an analytical model for EH-CRNs with interference cancellation at primary receivers to improve the OP of energy harvesting cognitive relay networks.

1.10 Research contributions

This thesis contributes to the existing knowledge by improving the successful transmission performance of the relay-assisted spectrum sharing networks and revealing the associated trade-offs. These research contributions are as follows:

- It extensively reviews and classifies the existing works on the SG analyses of relay-assisted D2D communication.
- It proposes the use of machine type relays for improving the transmission capacity of relay-assisted D2D communication. As such, an analytical framework for the transmission probability of D2D communication with M2M coexistence is developed where machine type devices function as relays for D2D devices to improve the TC performance.
- It develops an analytical framework for the outage probability of energy harvesting cognitive radio network with multi-hop primary users to improve the outage probability of energy harvesting cognitive relay networks
- It designs an analytical framework for interference cancellation, enabled at the primary receivers, to reduce the outage probability of secondary users of energy harvesting cognitive radio networks.

1.11 Research methodology

This section presents the research methodology adopted in this thesis. The research steps taken from the problem statement to the performance evaluation are clearly discussed.

1.11.1 Notations

The notations used in this research are local to each section and are provided in each section to make it easier for the reader to follow. Similarly, to facilitate a well-structured and a smooth reading experience considering the three contributions, the system model for each research contribution is provided in the respective chapter. However, a general point of note is that all the networks involve devices sharing a spectrum and using relays to improve on their chances of successful transmission.

1.11.2 Research framework

The research framework is shown in Figure 1.3. It is divided into interrelated stages that follow in order. These stages include the research problem formulation, benchmarks re-implementation, proposed methods, analytical experiments and comparison with benchmarks.

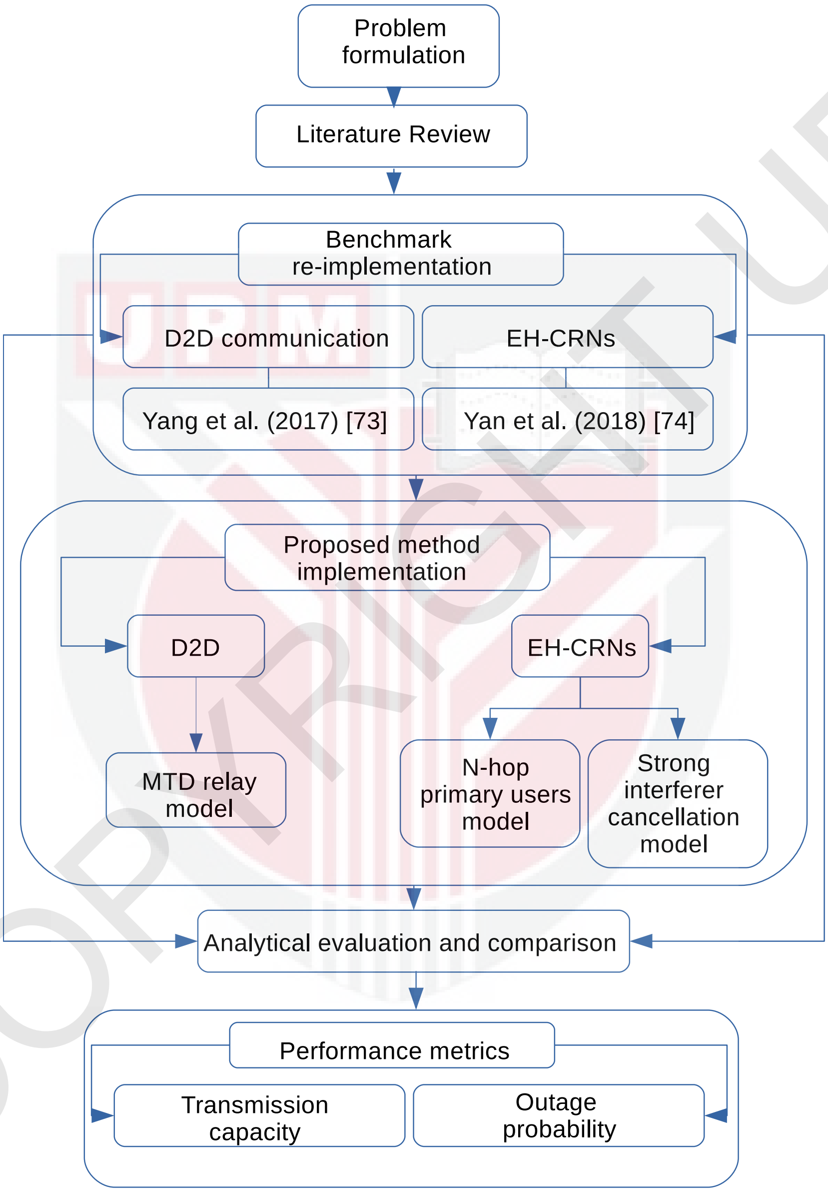

Figure 1.3: Research framework.

1.11.3 Problem formulation

The literature review on relay-assisted future generation wireless spectrum sharing systems reveals the need to improve on the successful transmission probability and tackle interference. To have a better understanding of SG, the fundamentals of this mathematical tool, its general principles and established theorems were studied to learn what problems could be solved using this tool and what metrics are considered.

Of particular interest is the model developed in [31] where the authors developed a framework for the transmission capacity of spectrum sharing systems which served as a basis for this research and many other works carried out in this area.

1.11.4 Benchmarks re-implementation

The first benchmark paper [73] adopted the model in [31] by considering the expected distance between D2D devices for a two-tier spectrum sharing scenario where D2D devices are assisted by traditional relays. The source codes were available online[2]. The d-s within the paper were matched with the code by changing the notations in the code to conform with the paper. Thereafter, the literature on this subject was extensively studied[3]. The next step was to extend this model to a three-tier model and thoroughly study how the use of M2M relays can be analytically adapted into such a model to improve the TC.

One of the challenges encountered was how to split $1 - \exp(\lambda_1 + \lambda_3)$ into two distinct probabilities that accommodate MTD relays and traditional D2D relays. This challenge was successfully tackled by developing a probabilistic model where the existence of MTD relays and traditional relays are tied to a global probability of one based on their individual existence probabilities. The details are given in Chapter 3.

The second benchmark [74] used a fundamental theorem in [31] to develop the OP of EH spectrum sharing systems. The paper was re-implemented and the exact results were obtained. Similarly, the analytical derivations were followed step-by-step to reproduce the analytical results in the paper. This follows what is shown in Appendix C of this thesis.

1.11.5 Proposed methods

The proposed methods focus on improving the successful transmissions (in D2D and CRNs) and addressing interference (in EH-CRNs). These objectives were achieved by introducing M2M relays to improve D2D transmissions, incorporating multi-hop primary transmissions in EH-CRNs, and applying strong-IC to EH-CRNs. The procedure for obtaining the analytical expressions in Chapter 3 is shown in Figure 1.4. For Chapters 4 and 5, the steps are shown in Figure 1.5.

[2]http://oa.ee.tsinghua.edu.cn/dailinglong/

[3]This led to the publication of two survey articles: the first on D2D communication and the second on relay assisted D2D communication using stochastic geometry (see the list of publications).

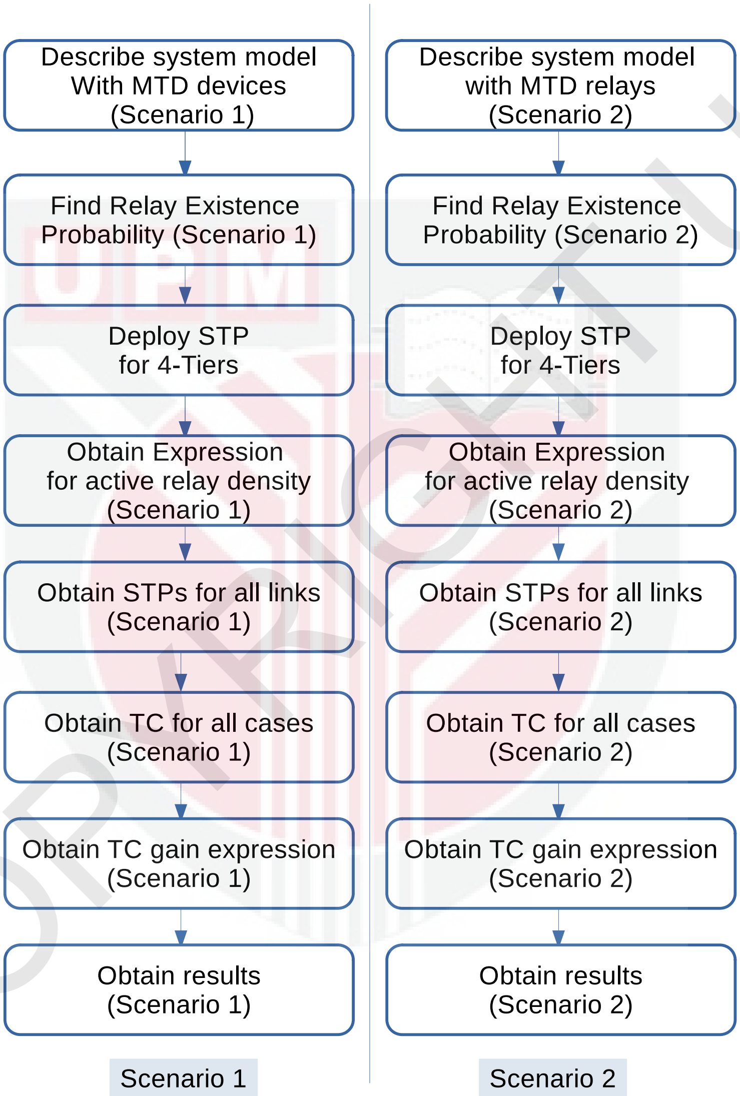

Figure 1.4: Procedure for the analysis in Chapter 3.

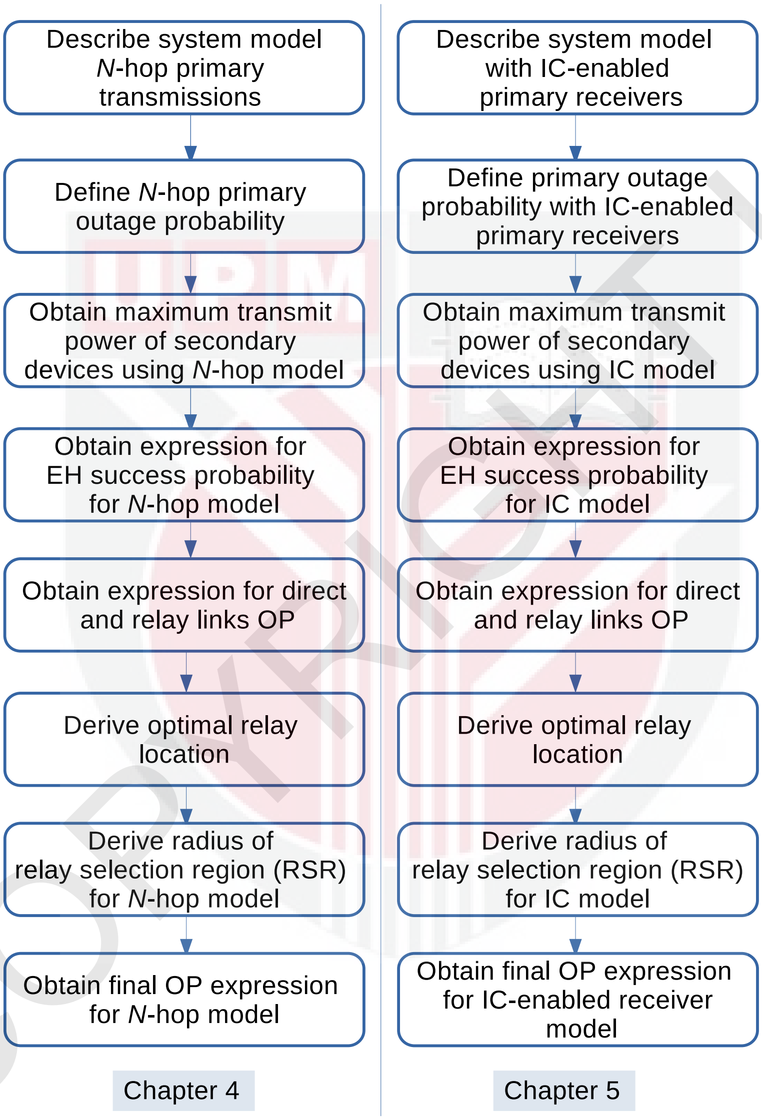

Figure 1.5: Procedure for the analysis in Chapters 4 and 5.

1.11.6 Analytical experiments

The analytical experiments in this research were carried out in MATLAB R2018a and MATLAB R2019b (student version). Note that since analytical results are derived, any version of MATLAB or any mathematical software should produce similar results with what was obtained in this research. The university PC with processor specification: Intel(R) Core(TM) i5-3470 CPU@ 3.20GHz (4CPUs), 3.2GHz was used to carry out the computations in this thesis. The network parameters follow from [73] (Chapter 3) and [74] (Chapters 4 and 5) while the IC parameters are taken from [75] which are the benchmarks used. The source codes for all the results published from this thesis (see list of publications) can be downloaded from the article page on the publishers website.

1.11.7 Performance metrics

The two performance metrics referred to in this thesis for evaluating the considered cellular networks are described below.

Transmission capacity

Transmission capacity refers to the number of successful transmissions that take place per unit area in a network, given a constraint in the OP [76]. TC measures the intensity of transmissions in space. It is motivated by fixing the OP to achieve a proper characterization of network performance. TC metric was initially developed for the analysis of the spread spectrum in adhoc networks. It has found a lot of applications in wireless networks (specifically in decentralized networks that are difficult to characterize) since then. TC has been studied in systems with respect to IC [77, 78, 75], scheduling and power control [79, 80], CRN [81, 82, 83], frequency spread spectrum [84, 85], multiple antennas [86, 87, 88, 76], etc.

Outage probability

Outage probability is an essential QoS parameter [89] used in wireless communication systems. OP is the probability that an end-to-end signal-to-noise ratio falls below a particular protection ratio in noise-limited systems [90]. It is thus an important performance measure in wireless networks [91]. In cognitive relay networks, the OP is affected by the transmission distance [92]. Note that in random networks, the distance between a relay in the secondary network and its destination is a random variable.

1.12 Research scope

This research focuses on using SG for the analysis of relay-assisted spectrum sharing systems which include D2D communication and cognitive radio networks. A homogeneous Poisson point process distribution (where devices are randomly located in the field of interest) is considered for all devices. Also, the systems studied are assumed to be assisted by relays. For ease of analysis, Rayleigh fading channel model is considered for the special case where the fading coefficient equals 4. This is due to its tractability and the potential to yield closed-form expressions. Moreover, it is a common assumption in stochastic geometry literature.

1.13 Thesis structure

This thesis is organized into six chapters. The description of each chapter is as follows:

Chapter 1 provides the background of this thesis. Therein, the concepts and motivation of spectrum sharing networks, relaying and relevant technologies such as D2D, M2M, and cognitive radio communication are introduced. The concept and significance of energy harvesting for cognitive radio networks and interference cancellation are introduced. Thereafter, the research problem, motivation, objectives, contributions and methodology are all provided. Following the approach considered in presenting most of the thesis published in stochastic geometry, the methodology is not considered a separate chapter for coherence of presentation. For each contribution, details on the system model, assumptions and notations are provided to make it easy to follow.

Chapter 2 introduces the role of stochastic geometry in the analysis of wireless networks. A detailed review of the literature on the focus of this thesis is provided. This includes the transmission capacity analysis of D2D communication and the outage analysis of cognitive radio networks with classifications. Strengths and limitations of these works are also provided. Thereafter, the chapter is summarized.

Chapter 3 is focused on the first contribution: transmission capacity analysis of relay-assisted D2D cellular networks with M2M co-existence. It describes the assumptions used, the network and the channel models for this contribution. Furthermore, derivations of the RN existence probability and relay distance expectation are provided. The generalized STP for spectrum sharing systems and pertinent lemma used in the analysis are given in this section as well. TCs of relay-assisted D2D communication with M2M coexistence for static and variable D2D link distance in the underlay and overlay are analyzed for Scenarios 1 and 2. Thereafter, the obtained results and discussions for both underlay and overlay modes are presented. A summary is provided at the end of this chapter.

Chapter 4 is dedicated to the second contribution: outage analysis of energy harvesting-based relay-assisted random underlay cognitive radio networks with multi-hop primary transmissions. In this chapter, the system model which includes the network model, channel model, and transmission and EH model is described. The secondary OP expression for the proposed network is also derived. Thereafter, results and discussions are presented and the chapter is summarized

Chapter 5 studies the outage analysis of energy harvesting-based relay-assisted random underlay cognitive radio networks with interference cancellation. Therein, a description of the system model that comprises the network model, channel model, and transmission and EH model is provided. Furthermore, the secondary OP expression for the proposed network is derived. Analytical results are discussed and the chapter's summary is provided.

Chapter 6 concludes this research by describing what has been achieved in the course of addressing the three main objectives set out in this thesis. The implications of the findings in this research within the context of wireless communication are provided. Then, other avenues for research are given to motivate further work in these areas.

REFERENCES

[1] Feng Hu, Bing Chen, and Kun Zhu. Full spectrum sharing in cognitive radio networks toward 5g: A survey. *IEEE Access*, 6:15754–15776, 2018.

[2] Chungang Yang, Jiandong Li, Mohsen Guizani, Alagan Anpalagan, and Maged Elkashlan. Advanced spectrum sharing in 5g cognitive heterogeneous networks. *IEEE Wireless Communications*, 23(2):94–101, 2016.

[3] Lin Zhang, Ming Xiao, Gang Wu, Muhammad Alam, Ying-Chang Liang, and Shaoqian Li. A survey of advanced techniques for spectrum sharing in 5g networks. *IEEE Wireless Communications*, 24(5):44–51, 2017.

[4] Andra M Voicu, Ljiljana Simić, and Marina Petrova. Survey of spectrum sharing for inter-technology coexistence. *IEEE Communications Surveys & Tutorials*, 21(2):1112–1144, 2018.

[5] Mohamed Rihan, Mahmoud M Selim, Chen Xu, and Lei Huang. D2d communication underlaying uav on multiple bands in disaster area: Stochastic geometry analysis. *IEEE Access*, 7:156646–156658, 2019.

[6] J. G. Andrews, R. K. Ganti, M. Haenggi, N. Jindal, and S. Weber. A primer on spatial modeling and analysis in wireless networks. *IEEE Communications Magazine*, 48(11):156–163, 2010.

[7] Lili Wei, Rose Hu, Yi Qian, and Geng Wu. Enable device-to-device communications underlaying cellular networks: challenges and research aspects. *IEEE Communications Magazine.*, 52(6):90–96, 2014.

[8] Hao Chen, Lingjia Liu, Thomas Novlan, John D Matyjas, Boon Loong Ng, and Jianzhong Zhang. Spatial spectrum sensing-based device-to-device cellular networks. *IEEE Transactions on Wireless Communications*, 15(11):7299–7313, 2016.

[9] Arash Asadi, Qing Wang, and Vincenzo Mancuso. A survey on device-to-device communication in cellular networks. *IEEE Communications Surveys & Tutorials*, 16(4):1801–1819, 2014.

[10] Daquan Feng, Lu Lu, Yi Yuan-Wu, Geoffrey Ye Li, Gang Feng, and Shaoqian Li. Device-to-device communications underlaying cellular networks. *IEEE Transactions on Communication*, 61(8):3541–3551, 2013.

[11] Furqan Jameel, Zara Hamid, Farhana Jabeen, Sherali Zeadally, and Muhammad Awais Javed. A survey of device-to-device communications: Research issues and challenges. *IEEE Communications Surveys & Tutorials*, 20(3):2133–2168, 2018.

[12] Akram Al-Hourani, Sithamparanathan Kandeepan, and Ekram Hossain. Relay-assisted device-to-device communication: A stochastic analysis of energy saving. *IEEE Transactions on Mobile Computing*, 15(12):3129–3141, 2016.

[13] Pavel Mach, Zdenek Becvar, and Tomas Vanek. In-band device-to-device communication in ofdma cellular networks: A survey and challenges. *IEEE Commununications Surveys & Tutorials*, 17(4):1885–1922, 2015.

[14] Pimmy Gandotra, Rakesh Kumar Jha, and Sanjeev Jain. A survey on device-to-device (d2d) communication: Architecture and security issues. *Journal of Network and Computer Applications*, 78:9–29, January 2017.

[15] Hiroki Nishiyama, Masaya Ito, and Nei Kato. Relay-by-smartphone: realizing multihop device-to-device communications. *IEEE Communications Magazine*, 52(4):56–65, 2014.

[16] Akram Al-Hourani, Sithamparanathan Kandeepan, and Abbas Jamalipour. Stochastic geometry study on device-to-device communication as a disaster relief solution. *IEEE Transactions on Vehicular Technology*, 65(5):3005–3017, 2016.

[17] Ruofei Ma, Yao-Jen Chang, Hsiao-Hwa Chen, and Chun-Yuan Chiu. On relay selection schemes for relay-assisted d2d communications in lte-a systems. *IEEE Transactions on Vehicular Technology*, 66(9):8303–8314, 2017.

[18] Si Wen, Xiaoyue Zhu, Yanchao Lin, Zhesheng Lin, Xin Zhang, and Dacheng Yang. Achievable transmission capacity of relay-assisted device-to-device (d2d) communication underlay cellular networks. In *2013 IEEE 78th Vehicular Technology Conference (VTC Fall)*, pages 1–5. IEEE, 2013.

[19] Hao Feng, Haibo Wang, Xiaoli Chu, and Xiaohui Xu. On the tradeoff between optimal relay selection and protocol design in hybrid d2d networks. In *2015 IEEE International Conference on Communication Workshop (ICCW)*, pages 705–711. IEEE, 2015.

[20] Xi Luan, Jianjun Wu, Chengzhe Piao, Yuxin Cheng, and Haige Xiang. Cooperative transmission based on multi-relay device-to-device communications in cellular networks. In *11th International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM 2015)*, pages 1–5, Sep. 2015.

[21] Victor Wong and Cyril Leung. Transmission strategies in multihop mobile packet radio networks. In *1993 Canadian Conference on Electrical and Computer Engineering*, pages 1004–1008. IEEE, 1993.

[22] Z. Lin, Y. Li, S. Wen, Y. Gao, X. Zhang, and D. Yang. Stochastic geometry analysis of achievable transmission capacity for relay-assisted device-to-device networks. In *2014 IEEE International Conference on Communications (ICC)*, pages 2251–2256, June 2014.

[23] Hussain Elkotby and Mai Vu. Interference and throughput analysis of uplink user-assisted relaying in cellular networks. In *2014 IEEE 25th Annual International Symposium on Personal, Indoor, and Mobile Radio Communication (PIMRC)*, pages 1375–1380. IEEE, 2014.

[24] Mohsen Nader Tehrani, Murat Uysal, and Halim Yanikomeroglu. Device-to-device communication in 5g cellular networks: challenges, solutions, and future directions. *IEEE Communications Magazine*, 52(5):86–92, 2014.

[25] F. S. Shaikh and R. Wismüller. Routing in multi-hop cellular device-to-device (d2d) networks: A survey. *IEEE Communications Surveys & Tutorials*, 20(4):2622–2657, 2018.

[26] Eftychia Datsika, Angelos Antonopoulos, Nizar Zorba, and Christos Verikoukis. Cross-network performance analysis of network coding aided cooperative outband d2d communications. *IEEE Transactions on Wireless Communications*, 16(5):3176–3188, 2017.

[27] Syed Tariq Shah, Syed Faraz Hasan, Boon-Chong Seet, Peter Han Joo Chong, and Min Young Chung. Device-to-device communications: A contemporary survey. *Wireless Personal Communications*, 98(1):1247–1284, 2018.

[28] Sher Ali and Ayaz Ahmad. Resource allocation, interference management, and mode selection in device-to-device communication: a survey. *Transactions on Emerging Telecommunications Technologies*, 28(7):e3148, 2017.

[29] Leonard Kleinrock and John Silvester. Spatial reuse in multihop packet radio networks. *Proceedings of the IEEE*, 75(1):156–167, 1987.

[30] Electronic Communications Committee (ECC). Licensed shared access (lsa). (Report 205), Feb. 2014.

[31] Jemin Lee, Jeffrey G Andrews, and Daesik Hong. Spectrum-sharing transmission capacity. *IEEE Transactions on Wireless Communications*, 10(9):3053–3063, 2011.

[32] Mohammad Asif Hossain, Rafidah Md Noor, Kok-Lim Alvin Yau, Ismail Ahmedy, and Shaik Shabana Anjum. A survey on simultaneous wireless information and power transfer with cooperative relay and future challenges. *IEEE Access*, 7:19166–19198, 2019.

[33] Muhammad Amjad, Fayaz Akhtar, Mubashir Husain Rehmani, Martin Reisslein, and Tariq Umer. Full-duplex communication in cognitive radio networks: A survey. *IEEE Communications Surveys & Tutorials*, 19(4):2158–2191, 2017.

[34] Shree Krishna Sharma, Tadilo Endeshaw Bogale, Symeon Chatzinotas, Björn Ottersten, Long Bao Le, and Xianbin Wang. Cognitive radio techniques under practical imperfections: A survey. *IEEE Communications Surveys & Tutorials*, 17(4):1858–1884, 2015.

[35] Tevfik Yucek and Huseyin Arslan. A survey of spectrum sensing algorithms for cognitive radio applications. *IEEE communications surveys & tutorials*, 11(1):116–130, 2009.

[36] Ju Ren, Junying Hu, Deyu Zhang, Hui Guo, Yaoxue Zhang, and Xuemin Shen. Rf energy harvesting and transfer in cognitive radio sensor networks: Opportunities and challenges. *IEEE Communications Magazine*, 56(1):104–110, 2018.

[37] Xiaoming Chen, Hsiao-Hwa Chen, and Weixiao Meng. Cooperative communications for cognitive radio networks–from theory to applications. *IEEE Communications Surveys & Tutorials*, 16(3):1180–1192, 2014.

[38] Sudhir Srinivasa and Syed Ali Jafar. Cognitive radios for dynamic spectrum access-the throughput potential of cognitive radio: A theoretical perspective. *IEEE Communications Magazine*, 45(5):73–79, 2007.

[39] M. El Tanab and W. Hamouda. Resource allocation for underlay cognitive radio networks: A survey. *IEEE Communications Surveys & Tutorials*, 19(2):1249–1276, 2017.

[40] Federico Boccardi, Robert W Heath, Angel Lozano, Thomas L Marzetta, and Petar Popovski. Five disruptive technology directions for 5g. *IEEE Communications Magazine*, 52(2):74–80, 2014.

[41] S. Chen, R. Ma, H. H. Chen, H. Zhang, W. Meng, and J. Liu. Machine-to-machine communications in ultra-dense networks – a survey. *IEEE Communications Surveys & Tutorials*, 19(3):1478 – 1503, 2017.

[42] R. Lu, X. Li, X. Liang, X. Shen, and X. Lin. Grs: The green, reliability, and security of emerging machine to machine communications. *IEEE Communications Magazine*, 49(4):28–35, April 2011.

[43] Kwang-Cheng Chen and Shao-Yu Lien. Machine-to-machine communications: Technologies and challenges. *Ad Hoc Networks*, 18:3 – 23, 2014.

[44] M. T. Islam, A. e. M. Taha, and S. Akl. A survey of access management techniques in machine type communications. *IEEE Communications Magazine*, 52(4):74–81, April 2014.

[45] M. Dohler, J. Swetina, A. Alexiou, C. Wang, P. Martigne, and K. Zheng. Editorial: Ieee communications surveys & tutorials; machine-to-machine technologies & architectures. *IEEE Communications Surveys & Tutorials*, 16(1):1–3, 2014.

[46] P. Jain, P. Hedman, and H. Zisimopoulos. Machine type communications in 3gpp systems. *IEEE Communications Magazine*, 50(11):28–35, November 2012.

[47] S. Y. Lien, K. C. Chen, and Y. Lin. Toward ubiquitous massive accesses in 3gpp machine-to-machine communications. *IEEE Communications Magazine*, 49(4):66–74, April 2011.

[48] N. Xia, H. H. Chen, and C. S. Yang. Radio resource management in machine-to-machine communications - a survey. *IEEE Communications Surveys & Tutorials*, 20(1):791 – 828, 2017.

[49] M. I. Kamel, W. Hamouda, and A. M. Youssef. Downlink coverage and average cell load of m2m and h2h in ultra-dense networks. In *2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, pages 1–5, Oct 2017.

[50] Ajinkya Rajandekar and Biplab Sikdar. A survey of mac layer issues and protocols for machine-to-machine communications. *IEEE Internet of Things Journal*, 2(2):175–186, 2015.

[51] Asma Afzal, Syed Ali Raza Zaidi, Des McLernon, Mounir Ghogho, and Afef Feki. M2m meets d2d: Harnessing d2d interfaces for the aggregation of m2m data. In *2017 IEEE International Conference on Communications (ICC)*, pages 1–6. IEEE, May 2017.

[52] Mehaseb Ahmed Mehaseb, Yasser Gadallah, Ahmed Elhamy, and Hadya Elhennawy. Classification of lte uplink scheduling techniques: An m2m perspective. *IEEE Communications Surveys & Tutorials*, 18(2):1310–1335, 2016.

[53] A. Laya, L. Alonso, and J. Alonso-Zarate. Is the random access channel of lte and lte-a suitable for m2m communications? a survey of alternatives. *IEEE Communications Surveys & Tutorials*, 16(1):4–16, 2014.

[54] Amira Barki, Abdelmadjid Bouabdallah, Saïd Gharout, and Jacques Traoré. M2m security: Challenges and solutions. *IEEE Communications Surveys & Tutorials*, 18(2):1241–1254, 2016.

[55] Pawan Kumar Verma, Rajesh Verma, Arun Prakash, Ashish Agrawal, Kshirasagar Naik, Rajeev Tripathi, Maazen Alsabaan, Tarek Khalifa, Tamer Abdelkader, and Abdulhakim Abogharaf. Machine-to-machine (m2m) communications: A survey. *Journal of Network and Computer Applications*, 66:83 – 105, 2016.

[56] Pouya Kamalinejad, Chinmaya Mahapatra, Zhengguo Sheng, Shahriar Mirabbasi, Victor CM Leung, and Yong Liang Guan. Wireless energy harvesting for the internet of things. *IEEE Communications Magazine*, 53(6):102–108, 2015.

[57] Nan Zhao, Shun Zhang, F Richard Yu, Yunfei Chen, Arumugam Nallanathan, and Victor CM Leung. Exploiting interference for energy harvesting: A survey, research issues, and challenges. *IEEE Access*, 5:10403–10421, 2017.

[58] Xiao Lu, Ping Wang, Dusit Niyato, Dong In Kim, and Zhu Han. Wireless networks with rf energy harvesting: A contemporary survey. *IEEE Communications Surveys & Tutorials*, 17(2):757–789, 2014.

[59] Xiao Lu, Ping Wang, Dusit Niyato, Dong In Kim, and Zhu Han. Wireless charging technologies: Fundamentals, standards, and network applications. *IEEE Communications Surveys & Tutorials*, 18(2):1413–1452, 2015.

[60] Tharindu D Ponnimbaduge Perera, Dushantha Nalin K Jayakody, Shree Krishna Sharma, Symeon Chatzinotas, and Jun Li. Simultaneous wireless information and power transfer (swipt): Recent advances and future challenges. *IEEE Communications Surveys & Tutorials*, 20(1):264–302, 2017.

[61] Lina Mohjazi, Mehrdad Dianati, George K Karagiannidis, Sami Muhaidat, and Mahmoud Al-Qutayri. Rf-powered cognitive radio networks: technical challenges and limitations. *IEEE Communications Magazine*, 53(4):94–100, 2015.

[62] Xueqing Huang, Tao Han, and Nirwan Ansari. On green-energy-powered cognitive radio networks. *IEEE Communications Surveys & Tutorials*, 17(2):827–842, 2015.

[63] Meng-Lin Ku, Wei Li, Yan Chen, and KJ Ray Liu. Advances in energy harvesting communications: Past, present, and future challenges. *IEEE Communications Surveys & Tutorials*, 18(2):1384–1412, 2015.

[64] Jinhyun Park, Chulhee Jang, and Jae Hong Lee. Outage analysis of underlay cognitive radio networks with multihop primary transmission. *IEEE Communications Letters*, 20(4):800–803, 2016.

[65] Jeffrey G Andrews. Interference cancellation for cellular systems: a contemporary overview. *IEEE Wireless Communications*, 12(2):19–29, 2005.

[66] Yuanjie Wang, Qimei Cui, Martin Haenggi, and Zhenhui Tan. On the sir meta distribution for poisson networks with interference cancellation. *IEEE Wireless Communications Letters*, 7(1):26–29, 2018.

[67] Young-Chai Ko, M-S Alouini, and Marvin K Simon. Outage probability of diversity systems over generalized fading channels. *IEEE Transactions on Communications*, 48(11):1783–1787, 2000.

[68] Hesham ElSawy, Ekram Hossain, and Martin Haenggi. Stochastic geometry for modeling, analysis, and design of multi-tier and cognitive cellular wireless networks: A survey. *IEEE Communications Surveys & Tutorials*, 15(3):996–1019, 2013.

[69] Hesham ElSawy, Ahmed Sultan-Salem, Mohamed-Slim Alouini, and Moe Z Win. Modeling and analysis of cellular networks using stochastic geometry: A tutorial. *IEEE Communications Surveys & Tutorials*, 19(1):167–203, 2017.

[70] Xiao Lu, Ping Wang, Dusit Niyato, and Ekram Hossain. Dynamic spectrum access in cognitive radio networks with rf energy harvesting. *IEEE Wireless Communications*, 21(3):102–110, 2014.

[71] Sanket S Kalamkar and Adrish Banerjee. Interference-aided energy harvesting: Cognitive relaying with multiple primary transceivers. *IEEE Transactions on Cognitive Communications and Networking*, 3(3):313–327, 2017.

[72] Bruno Clerckx, Alessandra Costanzo, Apostolos Georgiadis, and Nuno Borges Carvalho. Toward 1g mobile power networks: Rf, signal, and system designs to make smart objects autonomous. *IEEE Microwave Magazine*, 19(6):69–82, 2018.

[73] Yang Yang, Yuan Zhang, Linglong Dai, Jianjun Li, Shahid Mumtaz, and Jonathan Rodriguez. Transmission capacity analysis of relay-assisted device-to-device overlay/underlay communication. *IEEE Transactions on Industrial Informatics*, 13(1):380–389, 2017.

[74] Z. Yan, S. Chen, X. Zhang, and H. Liu. Outage performance analysis of wireless energy harvesting relay-assisted random underlay cognitive networks. *IEEE Internet of Things Journal*, 5(4):2691–2699, Aug 2018.

[75] Jemin Lee, Jeffrey G Andrews, and Daesik Hong. Spectrum-sharing transmission capacity with interference cancellation. *IEEE Transactions on Communications*, 61(1):76–86, 2013.

[76] Steven Weber, Jeffrey G Andrews, and Nihar Jindal. An overview of the transmission capacity of wireless networks. *IEEE Transactions on Communications*, 58(12):3593–3604, 2010.

[77] Steven P Weber, Jeffrey G Andrews, Xiangying Yang, and Gustavo De Veciana. Transmission capacity of wireless ad hoc networks with successive interference cancellation. *IEEE Transactions on Information Theory*, 53(8):2799–2814, 2007.

[78] Joseph Blomer and Nihar Jindal. Transmission capacity of wireless ad hoc networks: Successive interference cancellation vs. joint detection. In *IEEE International Conference on Communications, 2009, ICC'09*, pages 1–5. IEEE, August 2009.

[79] Steven Weber, Jeffrey G Andrews, and Nihar Jindal. The effect of fading, channel inversion, and threshold scheduling on ad hoc networks. *IEEE Transactions on Information Theory*, 53(11):4127–4149, October 2007.

[80] Nihar Jindal, Steven Weber, and Jeffrey G Andrews. Fractional power control for decentralized wireless networks. *IEEE Transactions on Wireless Communications*, 7(12):5482–5492, December 2008.

[81] Nihar Jindal, Jeffrey G Andrews, and Steven Weber. Bandwidth partitioning in decentralized wireless networks. *IEEE Transactions on Wireless Communications*, 7(12), December 2008.

[82] Vikram Chandrasekhar and Jeffrey G Andrews. Spectrum allocation in tiered cellular networks. *IEEE Transactions on Communications*, 57(10):3059–3068, October 2009.

[83] Kaibin Huang, Vincent KN Lau, and Yan Chen. Spectrum sharing between cellular and mobile ad hoc networks: transmission-capacity trade-off. *IEEE Journal of Selected Areas in Communications*, 27(7):1256–1267, September 2009.

[84] Kostas Stamatiou, John G Proakis, and James R Zeidler. Information efficiency of ad hoc networks with fh-mimo transceivers. In *2007 IEEE International Conference on ommunications, ICC'07.*, pages 3793–3798. IEEE, June 2007.

[85] Jeffrey G Andrews, Steven Weber, and Martin Haenggi. Ad hoc networks: to spread or not to spread? [ad hoc and sensor networks]. *IEEE Communications Magazine*, 45(12):84–91, December 2007.

[86] Rahul Vaze. Transmission capacity of spectrum sharing ad hoc networks with multiple antennas. *IEEE Transactions on Wireless Communications*, 10(7):2334–2340, 2011.

[87] R. Vaze and R. W. Heath. Transmission capacity of ad-hoc networks with multiple antennas using transmit stream adaptation and interference cancellation. *IEEE Transactions on Information Theory*, 58(2):780–792, Feb 2012.

[88] J. Ji and W. Chen. Transmission capacity of two co-existing wireless ad hoc networks with multiple antennas. In *2011 IEEE International Conference on Communications (ICC)*, pages 1–6, June 2011.

[89] Yi Zhao, Raviraj Adve, and Teng Joon Lim. Outage probability at arbitrary snr with cooperative diversity. *IEEE communications letters*, 9(8):700–702, 2005.

[90] Mazen Omar Hasna and M-S Alouini. Outage probability of multihop transmission over nakagami fading channels. *IEEE Communications Letters*, 7(5):216–218, 2003.

[91] L. Luo, P. Zhang, G. Zhang, and J. Qin. Outage performance for cognitive relay networks with underlay spectrum sharing. *IEEE Communications Letters*, 15(7):710–712, July 2011.

[92] Jemin Lee, Hano Wang, Jeffrey G Andrews, and Daesik Hong. Outage probability of cognitive relay networks with interference constraints. *IEEE Transactions on Wireless Communications*, 10(2):390–395, 2010.

[93] M. Haenggi, J. G. Andrews, F. Baccelli, O. Dousse, and M. Franceschetti. Stochastic geometry and random graphs for the analysis and design of wireless networks. *IEEE Journal of Selected Areas in Communications*, 27(7):1029–1046, September 2009.

[94] Alaa Kachouh, Youssef Nasser, and Hassan A Artail. On the capacity optimization of d2d underlying cellular communications. In *2016 23rd International Conference on Telecommunications (ICT)*, pages 1–5. IEEE, 2016.

[95] Ziyang Liu, Tao Peng, Hao Chen, and Wenbo Wang. Transmission capacity of d2d communication under heterogeneous networks with multi-bands. In *2013 IEEE 77th Vehicular Technology Conference (VTC Spring)*, pages 1–6. IEEE, 2013.

[96] Ziyang Liu, Tao Peng, Qianxi Lu, and Wenbo Wang. Transmission capacity of d2d communication under heterogeneous networks with dual bands. In *2012 7th International ICST Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM)*, pages 169–174. IEEE, 2012.

[97] Xingqin Lin, Jeffrey G Andrews, and Amitava Ghosh. Spectrum sharing for device-to-device communication in cellular networks. *IEEE Transactions on Wireless Communications*, 13(12):6727–6740, 2014.

[98] Tsingsong Zhou, Lin Liu, Yuan Zhang, and Yang Yang. Transmission capacity analysis of relay-assisted device-to-device communication in cellular networks. In *2016 IEEE/CIC International Conference on Communications in China (ICCC)*, pages 1–6. IEEE, 2016.

[99] Indrasen Singh and Niraj Pratap Singh. Coverage and capacity analysis of relay-based device-to-device communications underlaid cellular networks. *Engineering Science and Technology, an International Journal*, 21(5):834–842, 2018.

[100] Oscar Delgado and Fabrice Labeau. D2d relay selection and fairness on 5g wireless networks. In *2016 IEEE Globecom Workshops (GC Wkshps)*, pages 1–6. IEEE, 2016.

[101] Zhijian Lin, Lianfen Huang, Yujie Li, Han-Chieh Chao, and Pingping Chen. Analysis of transmission capacity for multi-mode d2d communication in mobile networks. *Pervasive and Mobile Computing*, 41:179–191, 2017.

[102] Lilin Fan, Zhengnan Dong, and Peiyan Yuan. The capacity of device-to-device communication underlaying cellular networks with relay links. *IEEE Access*, 5:16840–16846, 2017.

[103] Y. J. Chun, G. B. Colombo, S. L. Cotton, W. G. Scanlon, R. M. Whitaker, and S. M. Allen. Device-to-device communications: A performance analysis in the context of social comparison-based relaying. *IEEE Transactions on Wireless Communications*, 16(12):7733–7745, Dec 2017.

[104] Yang Yang, Ziyang Liu, Zuohui Fu, Tao Peng, and Wenbo Wang. Transmission capacity of device-to-device communication under heterogeneous networks with cellular users assisted. In *2013 IEEE Globecom Workshops (GC Wkshps)*, pages 635–341. IEEE, 2013.

[105] Chang Liu and Balasubramaniam Natarajan. Power-aware maximization of ergodic capacity in d2d underlay networks. *IEEE Transactions on Vehicular Technology*, 66(3):2727–2739, 2017.

[106] Min Wang, Xianxian Wang, Xiaomeng Chai, and Wei Huangfu. The impact of device-to-device communication on the capacity of cellular systems. In *2016 International Conference on Computer, Information and Telecommunication Systems (CITS)*, pages 1–5. IEEE, 2016.

[107] Pekka Janis, YU Chia-Hao, Klaus Doppler, Cassio Ribeiro, Carl Wijting, HUGL Klaus, Olav Tirkkonen, and Visa Koivunen. Device-to-device communication underlaying cellular communications systems. *International Journal of Communications, Network and System Sciences*, 2(03):169, 2009.

[108] K. Doppler, M. Rinne, C. Wijting, C. B. Ribeiro, and K. Hugl. Device-to-device communication as an underlay to lte-advanced networks. *IEEE Communications Magazine*, 47(12):42–49, Dec 2009.

[109] Yuan Zhang, Yang Yang, and Linglong Dai. Energy efficiency maximization for device-to-device communication underlaying cellular networks on multiple bands. *IEEE Access*, 4:7682–7691, 2016.

[110] W. Lu and M. Di Renzo. Stochastic geometry modeling and system-level analysis & optimization of relay-aided downlink cellular networks. *IEEE Transactions on Communications*, 63(11):4063–4085, Nov 2015.

[111] Konstantinos Ntontin, Marco Di Renzo, and Christos Verikoukis. On the feasibility of full-duplex relaying in multiple-antenna cellular networks. *IEEE Transactions on Communications*, 65(5):2234–2249, 2017.

[112] Abraham P Buunk and Frederick X Gibbons. Social comparison: The end of a theory and the emergence of a field. *Organizational Behavior and Human Decision Processes*, 102(1):3–21, 2007.

[113] Zhiguo Ding and H Vincent Poor. Cooperative energy harvesting networks with spatially random users. *IEEE Signal Processing Letters*, 20:1211–1214, 2013.

[114] Binod Prasad, Adduru UG Sankararao, Sumit Kundu, and Sanjay Dhar Roy. Throughput and outage probability of wireless energy harvesting based cognitive df relaying network. *Materials Today: Proceedings*, 4(9):10304–10308, 2017.

[115] Anupam Shome, Saswat Chakrabarti, and Priyadip Ray. Successful one way data communication probability of energy harvesting cognitive relay network with spatially random primary users. In *2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, pages 1–5. IEEE, 2017.

[116] Yuanwei Liu, S Ali Mousavifar, Yansha Deng, Cyril Leung, and Maged Elkashlan. Wireless energy harvesting in a cognitive relay network. *IEEE Transactions on Wireless Communications*, 15(4):2498–2508, 2015.

[117] Zheng Yang, Zhiguo Ding, Pingzhi Fan, and George K Karagiannidis. Outage performance of cognitive relay networks with wireless information and power transfer. *IEEE Transactions on Vehicular Technology*, 65(5):3828–3833, 2015.

[118] Yamuna Dhungana and Chintha Tellambura. Outage probability of underlay cognitive relay networks with spatially random nodes. In *2014 IEEE Global Communications Conference*, pages 3597–3602. IEEE, 2014.

[119] Jonghyun Bang, Jemin Lee, Seokjung Kim, and Daesik Hong. An efficient relay selection strategy for random cognitive relay networks. *IEEE Transactions on Wireless Communications*, 14(3):1555–1566, 2014.

[120] Chao Zhai, He Chen, Zhiyuan Yu, and Ju Liu. Cognitive relaying with wireless powered primary user. *IEEE Transactions on Communications*, 67(3):1872–1884, 2018.

[121] Tianxin Feng, Ganggang Ma, and Jie Xu. Cognitive wireless power transfer in the presence of reactive primary communication user. *IEEE Transactions on Cognitive Communications and Networking*, 5(2):370–381, 2019.

[122] Howard H Yang, Jemin Lee, and Tony QS Quek. Heterogeneous cellular network with energy harvesting-based d2d communication. *IEEE Transactions on Wireless communications*, 15(2):1406–1419, 2015.

[123] Van-Dinh Nguyen, Hieu V Nguyen, and Oh-Soon Shin. Wireless energy harvesting for cognitive multihop wireless sensor networks. *International Journal of Distributed Sensor Networks*, 11(8):613165, 2015.

[124] Soumen Mondal, Sanjay Dhar Roy, and Sumit Kundu. Energy harvesting based multihop relaying in cognitive radio network. *Wireless Personal Communications*, 97(4):6325–6342, 2017.

[125] Miao Pan, Chi Zhang, Pan Li, and Yuguang Fang. Spectrum harvesting and sharing in multi-hop crns under uncertain spectrum supply. *IEEE Journal on Selected Areas in Communications*, 30(2):369–378, 2012.

[126] Chi Xu, Meng Zheng, Wei Liang, Haibin Yu, and Ying-Chang Liang. End-to-end throughput maximization for underlay multi-hop cognitive radio networks with rf energy harvesting. *IEEE Transactions on Wireless Communications*, 16(6):3561–3572, 2017.

[127] Thanh-Dat Le and Oh-Soon Shin. Buffer-aided relaying scheme with energy harvesting in a cognitive wireless sensor network. *International Journal of Distributed Sensor Networks*, 13(5):1550147717709962, 2017.

[128] N. T. Van, T. N. Do, V. N. Q. Bao, and B. An. Performance analysis of wireless energy harvesting multihop cluster-based networks over nakagami- m fading channels. *IEEE Access*, 6:3068–3084, 2018.

[129] Ming Li, Pan Li, Xiaoxia Huang, Yuguang Fang, and Savo Glisic. Energy consumption optimization for multihop cognitive cellular networks. *IEEE Transactions on Mobile Computing*, 14(2):358–372, 2014.

[130] Pham Minh Nam, Tran Trung Duy, and Phan Van Ca. Performance of cluster-based cognitive multihop networks under joint impact of hardware noises and non-identical primary co-channel interference. *TELKOMNIKA*, 17(1):49–59, 2019.

[131] Soumen Mondal, Sanjay Dhar Roy, and Sumit Kundu. Outage analysis of a multihop cognitive network with energy harvesting from a primary cluster. In *2017 2nd IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT)*, pages 81–85. IEEE, 2017.

[132] V. N. Q. Bao, T. T. Duy, and N. T. Van. Exact outage analysis of energy-harvesting multihop cluster-based networks with multiple power beacons over nakagami-m fading channels. In *2018 2nd International Conference on Recent Advances in Signal Processing, Telecommunications Computing (SigTelCom)*, pages 1–6, Jan 2018.

[133] Xiaoli He, Hong Jiang, Yu Song, Chunlin He, and He Xiao. Routing selection with reinforcement learning for energy harvesting multi-hop crn. *IEEE Access*, 7:54435–54448, 2019.

[134] Tran Dinh Hieu, Tran Trung Duy, and Seong Gon Choi. Performance enhancement for harvest-to-transmit cognitive multi-hop networks with best path selection method under presence of eavesdropper. In *2018 20th International Conference on Advanced Communication Technology (ICACT)*, pages 323–328. IEEE, 2018.

[135] Chi Xu, Changqing Xia, Chunhe Song, Peng Zeng, and Haibin Yu. Multi-hop cognitive wireless powered networks: Outage analysis and optimization. *IEEE Access*, 7:4338–4347, 2018.

[136] Soumen Mondal, Sanjay Dhar Roy, and Sumit Kundu. Closed-form outage probability expressions for multihop cognitive radio network with best path selection schemes in rf energy harvesting environment. *Wireless Personal Communications*, 103(3):2197–2212, 2018.

[137] Soumen Mondal, Sanjay Dhar Roy, and Sumit Kundu. Primary behaviour-based energy harvesting multihop cognitive radio network. *IET Communications*, 11(16):2466–2475, 2017.

[138] T. Nguyen, S. Nam, and B. An. Performance analysis of multihop multirelay multiuser crns with energy harvesting. In *2019 International Conference on Electronics, Information, and Communication (ICEIC)*, pages 1–2, Jan 2019.

[139] Shashibhushan Sharma, Binod Prasad, Sanjay Dhar Roy, and Sumit Kundu. Outage performance of secondary user in cognitive relay network with multiple pus. In *2016 3rd International Conference on Recent Advances in Information Technology (RAIT)*, pages 19–24. IEEE, 2016.

[140] L. Ge, G. Chen, Y. Zhang, J. Tang, J. Wang, and J. A. Chambers. Performance analysis for multi-hop cognitive radio networks with energy harvesting by using stochastic geometry. *IEEE Internet of Things Journal*, 7(2):1154 – 1163, 2019.

[141] Nurul H Mahmood, Luis G Uzeda Garcia, Petar Popovski, and Preben E Mogensen. On the performance of successive interference cancellation in 5g small cell networks. In *2014 IEEE Wireless Communications and Networking Conference (WCNC)*, pages 1154–1159. IEEE, 2014.

[142] Chuan Ma, Weijie Wu, Ying Cui, and Xinbing Wang. On the performance of interference cancelation in d2d-enabled cellular networks. *Wireless Communications and Mobile Computing*, 16(16):2619–2635, 2016.

[143] Matthias Wildemeersch, Tony QS Quek, Marios Kountouris, Alberto Rabbachin, and Cornelis H Slump. Successive interference cancellation in heterogeneous networks. *IEEE Transactions on Communications*, 62(12):4440–4453, 2014.

[144] Hesham ElSawy, Ekram Hossain, and Mohamed-Slim Alouini. Analytical modeling of mode selection and power control for underlay d2d communication in cellular networks. *IEEE Transactions on Communication*, 62(11):4147–4161, 2014.

[145] N. Lee, X. Lin, J. G. Andrews, and R. W. Heath. Power control for d2d underlaid cellular networks: Modeling, algorithms, and analysis. *IEEE Journal of Selected Areas in Communications*, 33(1):1–13, Jan 2015.

[146] P. Sun, K. G. Shin, H. Zhang, and L. He. Transmit power control for d2d-underlaid cellular networks based on statistical features. *IEEE Transactions on Vehicular Technology*, 66(5):4110–4119, May 2017.

[147] Fatima Hussain, Alagan Anpalagan, and Rath Vannithamby. Medium access control techniques in m2m communication: survey and critical review. *Transactions on Emerging Telecommunications Technologies*, 28(1), September 2014.

[148] K. Zheng, S. Ou, J. Alonso-Zarate, M. Dohler, F. Liu, and H. Zhu. Challenges of massive access in highly dense lte-advanced networks with machine-to-machine communications. *IEEE Wireless Communications*, 21(3):12–18, June 2014.

[149] Jithin Jagannath, Nicholas Polosky, Anu Jagannath, Francesco Restuccia, and Tommaso Melodia. Machine learning for wireless communications in the internet of things: a comprehensive survey. *Ad Hoc Networks*, page 101913, 2019.

[150] Mingzhe Chen, Ursula Challita, Walid Saad, Changchuan Yin, and Mérouane Debbah. Artificial neural networks-based machine learning for wireless networks: A tutorial. *IEEE Communications Surveys & Tutorials*, 21(4):3039–3071, 2019.

[151] Chaoyun Zhang, Paul Patras, and Hamed Haddadi. Deep learning in mobile and wireless networking: A survey. *IEEE Communications Surveys & Tutorials*, 21(3):2224–2287, 2019.

[152] Shree Krishna Sharma and Xianbin Wang. Towards massive machine type communications in ultra-dense cellular iot networks: Current issues and machine learning-assisted solutions. *IEEE Communications Surveys & Tutorials*, 22(1):426 – 471, 2019.

[153] S. Dang, G. Chen, and J. P. Coon. Multicarrier relay selection for full-duplex relay-assisted ofdm d2d systems. *IEEE Transactions on Vehicular Technology*, 67(8):7204 – 7218, 2018.

[154] Cisco visual networking index: Global mobile data traffic forecast update, 2016–2021 white paper, 2017.

[155] Y. Chen and W. Wang. Machine-to-machine communication in lte-a. In *2010 IEEE 72nd Vehicular Technology Conference - Fall*, pages 1–4, Sept 2010.

[156] Dietrich Stoyan, Wilfrid S Kendall, and Joseph Mecke. *Stochastic geometry and its applications*. John Wiley & Sons, 2nd edition, 1996.

[157] Jeffrey G Andrews, François Baccelli, and Radha Krishna Ganti. A tractable approach to coverage and rate in cellular networks. *IEEE Transactions on communications*, 59(11):3122–3134, 2011.

[158] Wolfram alpha, 2018.

[159] Martin Haenggi. *Stochastic geometry for wireless networks*. Cambridge University Press, 2012.

[160] Monowar Hasan, Ekram Hossain, and Dong In Kim. Resource allocation under channel uncertainties for relay-aided device-to-device communication underlaying lte-a cellular networks. *IEEE Transactions on Wireless Communications*, 13(4):2322–2338, 2014.

[161] R. Ma, N. Xia, H. H. Chen, C. Y. Chiu, and C. S. Yang. Mode selection, radio resource allocation, and power coordination in d2d communications. *IEEE Wireless Communications*, 24(3):112–121, June 2017.

[162] Yasir Mehmood, Carmelita Görg, Maciej Muehleisen, and Andreas Timm-Giel. Mobile m2m communication architectures, upcoming challenges, applications, and future directions. *EURASIP Journal on Wireless Communications and Networking*, 2015(1):250, 2015.

[163] F. Ghavimi and H. H. Chen. M2m communications in 3gpp lte/lte-a networks: Architectures, service requirements, challenges, and applications. *IEEE Communications Surveys & Tutorials*, 17(2):525–549, Secondquarter 2015.

[164] S. Hamdoun, A. Rachedi, and Y. Ghamri-Doudane. Radio resource sharing for mtc in lte-a: An interference-aware bipartite graph approach. In *2015 IEEE Global Communications Conference (GLOBECOM)*, pages 1–7, Dec 2015.

[165] Ahmed Hamdi Sakr and Ekram Hossain. Cognitive and energy harvesting-based d2d communication in cellular networks: Stochastic geometry modeling and analysis. *IEEE Transactions on Communications*, 63(5):1867–1880, 2015.

[166] Lorenza Giupponi and Christian Ibars. Distributed cooperation in cognitive radio networks: overlay versus underlay paradigm. In *VTC Spring 2009-IEEE 69th Vehicular Technology Conference*, pages 1–6. IEEE, 2009.

[167] Ian F Akyildiz, Won-Yeol Lee, Mehmet C Vuran, and Shantidev Mohanty. A survey on spectrum management in cognitive radio networks. *IEEE Communications Magazine*, page 41, 2008.

[168] Bhoopendra Kumar, Sanjay Kumar Dhurandher, and Isaac Woungang. A survey of overlay and underlay paradigms in cognitive radio networks. *International Journal of Communication Systems*, 31(2):e3443, 2018.

[169] Martin Haenggi. On distances in uniformly random networks. *IEEE Transactions on Information Theory*, 51(10):3584–3586, 2005.

[170] Zouhair Al-Qudah and Khalid A Darabkh. Achievable rates of gaussian cognitive interference channel with common interference. *IET Communications*, 14(16):2802–2812, 2020.

[171] Suren Dadallage, Changyan Yi, and Jun Cai. Joint beamforming, power, and channel allocation in multiuser and multichannel underlay miso cognitive radio networks. *IEEE Transactions on Vehicular Technology*, 65(5):3349–3359, 2015.

[172] Jemin Lee, Jeffrey G Andrews, and Daesik Hong. The effect of interference cancellation on spectrum-sharing transmission capacity. In *2011 IEEE International Conference on Communications (ICC)*, pages 1–5. IEEE, 2011.

[173] Seunghyun Lee, Rui Zhang, and Kaibin Huang. Opportunistic wireless energy harvesting in cognitive radio networks. *IEEE Transactions on Wireless Communications*, 12(9):4788–4799, 2013.

[174] Ting-Chao Hou and Victor Li. Transmission range control in multihop packet radio networks. *IEEE Transactions on Communications*, 34(1):38–44, 1986.

[175] Pedro HJ Nardelli, Paulo Cardieri, and Matti Latva-aho. Efficiency of wireless networks under different hopping strategies. *IEEE Transactions on Wireless Communications*, 11(1):15–20, 2012.

[176] Muhammad Junaid Farooq, Hesham ElSawy, Quanyan Zhu, and Mohamed-Slim Alouini. Optimizing mission critical data dissemination in massive iot networks. In *2017 15th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt)*, pages 1–6. IEEE, 2017.

[177] Victor Wong and Cyril Leung. Effect of rayleigh fading in a multihop mobile packet radio network with capture. *IEEE Transactions on Vehicular Technology*, 44(3):630–637, 1995.

[178] R. Atat, L. Liu, J. Ashdown, M. Medley, and J. Matyjas. On the performance of relay-assisted d2d networks under spatially correlated interference. In *2016 IEEE Global Communications Conference (GLOBECOM)*, pages 1–6, Dec 2016.

[179] Muhammad Junaid Farooq, Hesham ElSawy, and Mohamed-Slim Alouini. A stochastic geometry model for multi-hop highway vehicular communication. *IEEE Transactions on Wireless Communications*, 15(3):2276–2291, 2016.

BIODATA OF STUDENT

Amodu Oluwatosin Ahmed received his Bachelor of Technology degree in electrical electronics engineering from The Federal University of Technology, Akure, Nigeria in 2012. He received his master's degree in computer science with a specialization in distributed computing from Universiti Putra Malaysia, in 2016, where he pursued the Ph.D. degree in wireless communication and network engineering. His research interests include sensor networks, machine-type communications, device-to-device communication, spectrum sharing networks, and stochastic geometry.

LIST OF PUBLICATIONS

International Refereed Journals

Amodu, O. A., and Othman, M. (2018). A survey of hybrid MAC protocols for machine-to-machine communications. Telecommunication Systems, 69(1), 141-165. **(Published, IF = 1.707, Q3, ISI, JCR)**

Amodu, O. A., and Othman, M. (2018). Machine-to-machine communication: An overview of opportunities. *Computer Networks*, 145, 255-276. **(Published 2018, IF = 3.030, Q2, ISI, JCR)**

Amodu, O. A., Othman, M., Noordin, N. K., and Ahmad, I. (2019). A primer on design aspects, recent advances, and challenges in cellular device-to-device communication. *Ad Hoc Networks*, 94, 101938. **(Published, IF = 3.490, Q1, ISI, JCR)**

Amodu, O. A., Othman, M., Noordin, N. K., and Ahmad, I. (2019). Relay-assisted D2D underlay cellular network analysis using stochastic geometry: Overview and future directions. *IEEE Access*, 7, 115023-115051. **(Published 2019, IF = 4.098, Q1, ISI, JCR)**

Amodu, O. A., Othman, M., Noordin, N. K., and Ahmad, I. (2019). Transmission capacity analysis of relay-assisted D2D cellular networks with M2M coexistence. *Computer Networks*, 164, 106887. **(Published 2018, IF = 3.030, Q2, ISI, JCR)**

Amodu, O. A., Othman, M., Noordin, N. K., and Ahmad, I. (2020). Outage analysis of energy harvesting-based relay-assisted random underlay cognitive radio networks with multi-hop primary transmissions. *IEEE Systems Journal*, doi:10.1109/JSYST.2020.3011040. **(Published, IF = 3.987, Q1, ISI, JCR)**

Amodu, O. A., Othman, M., Noordin, N. K., and Ahmad, I. (2020). Outage minimization of energy harvesting relay-assisted random underlay cognitive radio networks with interference cancellation. *IEEE Transactions on Mobile Communications* **(Under review, IF = 5.112, Q1, ISI, JCR)**

Amodu, O. A., Othman, M., Noordin, N. K., and Ahmad, I. (2021). Transmission Capacity Analysis of Relay-Assisted D2D Cellular Networks With Interference Cancellation. *Ad Hoc Networks*, doi:10.1016/j.adhoc.2020.102400 **(Published, IF = 3.643, Q1, ISI, JCR)**

Amodu, O. A., Othman, M., Yunus, N.A.M, Hanapi, Z. M. (2021). A primer on design aspects and recent advances in shuffle exchange multistage interconnection networks. *Symmetry*, 13 (3), 378. **(Published, IF = 2.645, Q2, ISI, JCR)**

UNIVERSITI PUTRA MALAYSIA

STATUS CONFIRMATION FOR THESIS / PROJECT REPORT AND COPYRIGHT

ACADEMIC SESSION : _________________

TITLE OF THESIS / PROJECT REPORT :

____

____

____

NAME OF STUDENT : ____

I acknowledge that the copyright and other intellectual property in the thesis/project report belonged to Universiti Putra Malaysia and I agree to allow this thesis/project report to be placed at the library under the following terms:

1. This thesis/project report is the property of Universiti Putra Malaysia.
2. The library of Universiti Putra Malaysia has the right to make copies for educational purposes only.
3. The library of Universiti Putra Malaysia is allowed to make copies of this thesis for academic exchange.

I declare that this thesis is classified as :

*Please tick (√)

☐	**CONFIDENTIAL**	(Contain confidential information under Official Secret Act 1972).
☐	**RESTRICTED**	(Contains restricted information as specified by the organization/institution where research was done).
√	**OPEN ACCESS**	I agree that my thesis/project report to be published as hard copy or online open access.

This thesis is submitted for :

☐	**PATENT**	Embargo from_____________ until _____________ (date) (date)

Approved by:

_____________________ (Signature of Student) New IC No/ Passport No.:	_____________________ (Signature of Chairman of Supervisory Committee) Name:
Date :	Date :

[Note : If the thesis is CONFIDENTIAL or RESTRICTED, please attach with the letter from the organization/institution with period and reasons for confidentially or restricted.]