OPLINQ: OPPORTUNISTIC LINK SCHEDULING FOR MASSIVE DEVICE-TO-DEVICE MMWAVE COMMUNICATION NETWORKS

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OPLINQ: OPPORTUNISTIC LINK SCHEDULING FOR MASSIVE DEVICE-TO-DEVICE MMWAVE COMMUNICATION NETWORKS

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To my family, for their endless support through all these years to take me to where I am today.

To my wife, for making me understand nothing is impossible and for every smile that gives me incredible strength and make me believe in myself.

ABSTRACT

mmWave communications networking is a promising physical layer technology for the requirement of the huge bandwidth in next generation 5G infrastructures. One of the emerging important applications for 5G mmWave architectures is device-to-device communications (D2D) among the mobile nodes with direct physical layer communication links. D2D communication systems are able to provide higher data rates as well as provide better QoS for end-users. However, mmWave communication channels have fundamental problems such as blockage due to objects, deafness due to incorrect alignment and costly beam searching due to directional property of beamforming. Furthermore, the problems become significant in dense and mobile D2D communication networks without any practical solution available currently. In this thesis work, a practical and opportunistic mmWave D2D link scheduling protocol is proposed which provides a cross-layer architecture combining physical and multiple access layers with a multi-hop relaying mechanism. In addition, it provides power and rate scheduling while considering real time channel conditions and mobility of the users. The proposed scheduling algorithm is numerically simulated for practical network topologies and compared with the case without any scheduling or interference control. The proposed solution provides significant advantages in dense and mobile mmWave D2D communication networks and is a promising solution for next generation 5G D2D communication architectures.

Keywords – Device-to-device communication, mmWave networks, directional communication, scheduling.

ÖZETÇE

Milimetre-dalga boyuna (mmWave) sahip haberleşme ağları, çok geniş bant aralıkları gerektiren yeni nesil haberleşme sistemleri için umut vaat eden bir teknolojidir. mmWave uyumlu 5G haberleşme sistemleri için öne çıkan önemli bir uygulama alanı olarak, cihazdan cihaza haberleşme yöntemleri gösterilmektedir. Cihazdan cihaza haberleşme, son kullanıcı için daha yüksek veri hızı sunmakla beraber daha yüksek kalitede bir deneyim sağlamaktadır. Ancak, mmWave haberleşme sistemlerinin objelerden kaynaklı blokaj, hatalı hizalanmadan kaynaklı sağırlık ve doğrusal karakterinden kaynaklı, operatörler için maliyetli olan ışın arama işlemi gibi temel problemleri bulunmaktadır. Ayrıca, bu henüz tam olarak çözülememiş problemler kalabalık ve hareketli D2D haberleşme ağları içerisinde daha da büyümektedir. Bu tez çalışmasında, fiziksel ve çoklu-erişim katmanlarını çok adımlı yönlendirme mekanizması ile bir araya getiren kullanışlı ve oportünist mmWave D2D link düzenleme protokolü önerilmektedir. Buna ek olarak, önerilen sistem ağ içerisindeki mobilite ve gerçek zamanlı kanal koşullarını değerlendirerek güç ve hız düzenlemesini de mümkün kılmaktadır. Önerilen link düzenleme algoritmaları gerçekçi topolojiler kullanılarak bilgisayar ortamında simüle edilmiştir ve hiç bir düzenleme ya da sinyal girişiminin olmadığı bir sistem ile karşılaştırılmıştır. Elde edilen sonuçlarda önerilen sistemin kalabalık ve hareketli mmWave D2D haberleşme ağlarında önemli gelişmeler sağladığı görülmüştür.

Anahtar kelimeler – Device-to-device haberleşme, mmWave haberleşme, doğrusal haberleşme, link düzenleme.

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Table 1: List of Abbreviations

mmWave	millimeter-wave
QoS	quality of service
D2D	device-to-device
M2M	machine-to-machine
V2V	vehicle-to-vehicle
V2I	vehicle-to-infrastructure
P2P	peer-to-peer
5G	fifth generation
SINR	signal-to-interference-plus-noise
SIR	signal-to-interference
5G	fifth generation
UE	user equipment
BS	base station
ER	exclusive region
LANs	local area networks
WLANs	wireless local area networks
WPANs	wireless personal area networks
LOS	line of sight
NLOS	non-line of sight

CHAPTER I

INTRODUCTION

Consistently evolving mobile network technologies from 1G, the very first generation of mobile networks established in early 1980s, to 2G, 3G and 4G has completely changed our daily living by changing redefining how mobile devices are being used. With the new introduction of mobile devices, many applications have arisen to be used in these devices such as social networking and video streaming. Today, mobile devices are not being used for only voice communication, but also for digital video broadcasting, HDTV, video chatting and other numerous applications. This remarkable increase in available applications have resulted in demand of higher data rates and larger bandwidth.

At this point, millimeter-wave (mmWave) communication systems are pointed out as an important candidate for next generation mobile network systems with their much more available bandwidth than current cellular systems. With this specific feature, it is expected that mmWave communication systems will provide desired data rates as well as quality of service (QoS) for end users. In order to increase data rates even more, device-to-device (D2D) communication mechanisms are proposed. D2D communication enables mobile devices to communicate with each other directly without any involvement of base stations or with just partially involvement of base station. Enabling direct communication between mobile devices makes improvements possible such as overall system throughput and energy efficiency.

1.1 Motivation

mmWave communication systems are getting higher interest as they pointed out as a strong candidate to meet increasing demand for multi-gigabit data rates, especially in short distances. These small wavelengths allow mmWave communications to integrate numerous antenna elements and hence a remarkable directivity gain is reached. The main features of mmWave are large bandwidth, directionality and high attenuation. Besides that, deafness is one of the other important issues which needs to be addressed in mmWave communication systems, since the signals in mmWave frequency bandwidth are not capable of penetrating obstacles or diffracting around. In mmWave communications, narrower beam-width introduces significant beam-searching overhead, since many directions have to be searched. However, it provides a higher transmission rate due to higher directivity gains and at the same time as beam-width gets larger, it speeds up the search process at the expense of loss in the transmission rate. Despite all of these capabilities, existing standards do not fully achieve the potential of mmWave communications.

Fifth generation (5G) networks request orders of magnitude larger communication channel capacities for crowded wireless communication networks. D2D communication is an emerging method to distribute the cellular spectrum usage between users in coordination with the base station to satisfy high demands. Furthermore, higher frequencies including mmWave spectrum are utilized to realize higher capacity channels. The mmWave communication networks have relatively low multi-user interference, due to directional channels with higher gain [12].

In the literature, many scheduling solutions have been studied for mmWave based D2D communication networks, such as a mechanism with received SINR based link establishment criterion and distance based relay selection scheme. Moreover, for omnidirectional D2D system, a synchronous node discovery and link scheduling system based on OFDM is presented in [34]. Besides that, many presented studies in the literature make use of beam-searching procedure which is time consuming and costly for the operators. However, in case of an ultra-dense network topology, the literature lacks of applicable mechanism for mmWave D2D networks and these studies do not fully exploit the potential of mmWave D2D communication systems.

This thesis work, presents a novel study on mmWave D2D communication systems by adapting an opportunistic link scheduling mechanism motivated by omni-directional FlashLinQ protocol and combined with multi-hop opportunistic relaying mechanism without time consuming beam-searching. OpLinQ takes advantage of the highly directional antenna gains for both at the transmitter and the receiver by providing priority ordered, signal-to-noise-interference (SNIR) threshold applied and opportunistically relayed high capacity links. It provides less interference by adapting capacity threshold to be satisfied for each link. In Chapter VI, the comparison between OpLinQ and a scenario with very high interference level where the system allows every mobile user to establish a link, is performed for varying beamwidths and capacity thresholds. In these results, it can be seen that OpLinQ provides higher data rates as the interference level in the system increases. However, the results show that even though OpLinQ provides better data rate and QoS, it results in a less number of active communication links but with higher data rates.

These features makes OpLinQ a promising link scheduling mechanism for next generation communication networks, especially in ultra-dense topologies. In such a topology, OpLinQ can be adapted to provide higher data rates and better QoS for end users, since the demand for higher data rates increases as the multimedia sharing becomes an essential part of our lives.

1.2 Contribution

In this thesis work, an opportunistic link scheduling mechanism without costly beam searching is proposed which takes advantage of the crowded network topology and channel aware link and rate scheduling mechanisms. The proposed method defines a novel link, rate and power scheduling mechanism adapting and improving link and rate scheduling intuitions of practical omnidirectional protocols, e.g., FlashLinq [3], to mmwave D2D communication networks. The channel access is scheduled based on the signal-to-interference plus noise ratio (SINR) outcomes of pilot training signals in predetermined or random beam directions in a time-slotted architecture. The proposed novel contributions are as the following:

- SINR based link, rate and power scheduling opportunistic mechanism for mmWave D2D networks combining PHY/MAC and multi-hop communication.
- A pilot signal based scheduling mechanism by utilizing OFDM for mmWave D2D communication systems.
- Adaptive algorithms for varying user population density and mobility immune to deafness and avoiding resource consuming beam searching.

1.3 Organisation

The organisation of this thesis is as follows. In Chapter II, related works from the literature are discussed in detail. Numerous novel scheduling algorithms are discussed briefly both for mmWave communication systems and D2D communication systems. Moreover, beamwidth optimization models and beamsearching methods are presented. Moreover, brief information about existing multi-hop scheduling methods and the problems for both mmWave and D2D communication systems are discussed.

In Chapter III, the fundamentals of D2D communications are discussed. The advantages and disadvantages of D2D mechanism are presented. In addition, main D2D communication types are presented as well as the arising technical challenges of D2D networks. Besides that, the promising application areas for D2D communications to be used in next generation communication networks are listed and discussed briefly.

In Chapter IV, millimeter-wave networks are discussed in detail. The fundamental characteristics of mmWave networks are presented. Main challenges to deploy mmWave communication systems such as rain attenuation and atmosphere absorption are discussed. Moreover, emerging mmWave applications are also listed in this section and discussed briefly.

In Chapter V, theoretical modelling of proposed OplinQ scheduling algorithm is presented in detail. Channel access and scheduling method are presented in detail by discussing beam selection phase, connection scheduling phase, relay scheduling phase, rate scheduling phase and data transmission phase.

Numerical simulations and results are presented in Chapter VI by making comparison between OpLinQ and full-interference scenario for varying beamwidths and capacity thresholds. The presented results are discussed in detail to clarify the advantages and disadvantages of OpLinQ. In addition, the future works are presented.

Finally, the conclusion is presented in Chapter VII and future application areas for OpLinQ are discussed.

CHAPTER II

RELATED WORK

A constant need to increase the network capacity in order to meet the ever growing demands due to the reasons mentioned in previous chapters has led many researchers to investigate new methods for exploring the potential of next generation communication networks. In the following, a literature review is provided while emphasizing the challenges and the advantages of our solution.

A beamwidth optimization model is described in [29] where the proposed system performs a beamwidth optimization according to the selected network model and an exhaustive beamsearch operation which causes a serious time-waste. Furthermore, the authors proposed beamwidth optimization with relay nodes for small cell networks in [30]. However, in proposed OpLinQ mechanism, this exhaustive and time consuming beamsearch protocol is replaced by an opportunistic discovery stage.

In [31], a link scheduling mechanism for mmWave WPANs based on the feedback beamforming information and SINR based link coexistence condition is proposed. SINR threshold is calculated by only at the receiver side. They make an presumption that the beamforming information, the transmit power, and SINR will be fed back to the PCP/AP after beamforming. Numerous beamforming methods are compared and analysed in the sense of the strict demands for indoor and outdoor mmWave communication scenarios in [32]. In [33], low-complexity beamforming approaches for initial user equipment (UE) discovery methods are investigated and beamforming tradeoffs are presented, where essential limits for the best beam broadening are explained. On the other hand, another SIR based system architecture, FlashLinQ, is introduced in [34] which takes advantage of parallel channel access offered by OFDM and integrate an analogue energy-level-based signalling mechanism. However, in OpLinQ mechanism, both transmitter and receiver effects on SINR level are combined for D2D enabled mmWave communication system.

In [35, 36, 37], multi-hop scheduling methods are investigated in order to boost spatial reuse for directional mmWave WPANs. In [38], an extension that points out spatial time slot scheduling for relay operation is proposed, where the throughput maximization with scheduling optimization is modelled and solved. Moreover, in [39] the authors investigated minimum time length scheduling for multi-hop mmWave networks where they formulate scheduling problem as a constrained binary integer programming problem, which aims to deliver data flow to all devices within a minimum number of time slots. Resource scheduling and relay selection to improve network capacity in mmWave based D2D networks are investigated and distributed receiver based relay selection scheme for intragroup transmission, while a distance based relay selection scheme for intergroup transmission is proposed to improve network capacity in [28] and a similar approach based on minimum distance in [49]. For future studies, these path discovery methods for enabling multi-hop in OpLinQ mechanism can be easily adapted to the proposed system.

The main problems of existing MAC protocols for mmWave communication networks such as deafness, high attenuation through obstructions and oxygen absorption are investigated and analysed several times in literature as well as the new challenges of mmWave networks [40, 41, 42, 43]. In order to handle these issues efficiently an adaptive STDMA scheduling scheme with related MAC protocol is proposed in [44]. In [45, 46], authors proposed a power control algorithm in order to overcome such issues mentioned above by improving the system capacity with an effective spatial reuse scheme that combines the existing exclusive region (ER) based scheduling algorithm with simple power control and establish a power control mechanism instead of constant transmit power. However, an angular-slot based scheduling algorithm is proposed in this work in order to increase the number of users that are able to communicate in the same time slot by managing interference levels.

The advantages and disadvantages of D2D communication networks are investigated in details as well as the challenges in 5G networks and MAC protocols in [6, 47, 48]. In [11], for the radio access and backhaul of small cells in the mmWave band, a joint transmission scheduling scheme is proposed, where a path selection condition is designed to enable D2D transmissions. The proposed OpLinQ mechanism are designed to exploit these advantages by deploying D2D enabled mmWave communication network.

In this thesis work, an opportunistic link scheduling mechanism without costly beam searching is proposed which takes advantage of the crowded network topology and channel aware link and rate scheduling mechanisms. The proposed method defines a novel link, rate and power scheduling mechanism adapting and improving link and rate scheduling intuitions of practical omnidirectional protocols, e.g., FlashLinq [34], to mmwave D2D communication networks. The channel access is scheduled based on the SINR, outcomes of pilot training signals in predetermined or random beam directions in a time-slotted architecture. The proposed novel contributions are as the following:

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- Adaptive algorithms for varying user population density and mobility immune to deafness and avoiding resource consuming beam searching

In the next chapter, system model for D2D mmWave communications networks is defined as well as channel access and scheduling mechanisms are presented and discussed. Finally, numerical simulations and results are represented.

CHAPTER III

FUNDAMENTALS OF MILLIMETER-WAVE COMMUNICATIONS

3.1 Introduction

Millimeter wave (mmWave) communication systems can be identified as the latest technological evolution in modern communication systems. As the technology of mobile communications has advanced especially in last two decades, wireless communication systems have become a vital part of our daily lives. The undeniable popularity of these technologies has forced mobile device makers, developers and manufacturers to seek greater spectrum in order to offer more products with more advanced technologies.

Increasing demand of mobile users for better QoS and higher data rates while lower delays and stable connectivity in order to be able to move and share multimedia files, turned researchers interest to millimeter wave frequencies which allow mobile wireless communication system operators to provide all the expectations listed above. In particular, the unlicensed band which mmWave systems operate at from 30 GHz to 300 GHz can provide 10-to-100 times more spectrum than is already available for conventional wireless local area networks or cellular networks. This capability of mmWave communication systems makes this technology a game-changing development in mobile wireless communication systems, since more available spectrum makes mmWave wireless communication systems to provide more resource to be shared by multiple users at the same time while allow to reach higher data rates than comparable modulation techniques. In Fig. 1, the comparison between the bandwidths of today's cellular networks and future's mmWave networks is presented. Since, mmWave has substantially wider bandwidth than today's cellular networks, dramatically higher data rates is reachable for next generation communication networks.

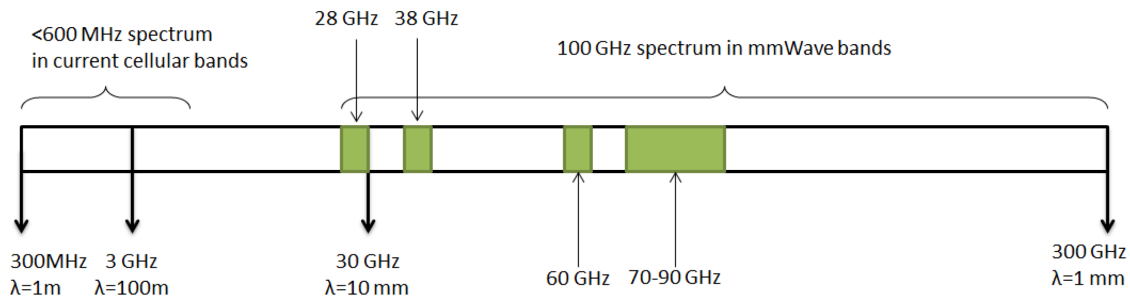

Figure 1: Bandwidth allocation comparison for current cellular networks and mmWave networks.

3.2 Millimeter-wave cellular networks

3.2.1 The path to millimeter-wave cellular networks

It is a known fact that the first mmWave communications are demonstrated back in 20th century by Bose [15]. In the past few decades, millimeter-wave bands have been used for satellite communication [16] and cellular backhaul. More recently, mmWave transmissions have been used in wireless local area networks (WLANs) and personal area networks (WPANs) [17] and in the newly unlicensed 60 GHz band; in order to reach very high system throughput levels. While these mentioned systems provides multi-gigabit data rates, the established links are typically for LOS settings or for short-range communications.

The development of mmWave bands for long range and NLOS communication is a relatively new research area and the possibility of such deployment has been a subject of many studies. While mmWave spectrum promises greater bandwidths than currently in use cellular systems, the propagation of mmWave signals remains as a serious issue to be addressed, since mmWave signals suffer from severe shadowing, intermittent connectivity, and will have higher Doppler spreads. Because of these characteristics, many researchers have doubts about mmWave band would be a sustainable approach for cellular systems that requires reliable communication across long distances and NLOS paths [18, 19]. However, with the recent advances in CMOS RF and digital processing have enabled mmWave chips suitable for commercial mobiles devices and significant progress has been made, in particular, in power amplifiers and free space adaptive array combining. It is expected that these technologies are most likely to advance even more with the growing interest in communication systems with 60 GHz feature. Other than these improvements, deployment of small cells is also in favor to mmWave communication systems. As mentioned in the previous section, small cell deployment with smaller radii, particularly micro-cells, picocells and femtocells will decrease the cell radius around a couple of hundred meters, which is possibly within the range of mmWave signals [20].

3.2.2 Challenges

Deployment of mmWave communication networks promise significant improvement in many aspects. However, there are a number of key issues that needs to be taken into consideration. In this part of this work, some of those issues are discussed briefly.

3.2.2.1 Range and directional communication

Friis' transmission in (1) says that the omnidirectional path loss in free space grows with the square of the frequency where the path loss exponent is taken as two. The derivation of the Friis' transmission equation can be found in Appendix-1.

$$P_r = \frac{P_t\, G_r\, G_t\, c^2}{(4\,\pi\, R\, f)^2} \tag{1}$$

At the same time, since mmWave signals have smaller wavelength, they provide proportionally greater antenna gain for the antennas with the similar physical characteristics. Hence, this feature results in free space propagation loss to remain suitable for directional transmission despite mmWave signals' higher frequencies. This statement is also confirmed by our simulation results shown in Chapter VI. However, certain design changes to current cellular systems still remains necessary in order to provide reliable communication network with mmWave feature.

3.2.2.2 Shadowing

Shadowing is a more significant issue to be addressed for mmWave networks, since mmWave signals are extremely vulnerable to shadowing. To be more precise, materials such as brick can attenuate mmWave signals by around 40-80dB [21] and the human body can attenuate 20 - 35dB [22]. In addition, many outdoor material with high reflective property can be considered as scatterers for mmWave signals.

3.2.2.3 Multiuser coordination

Currently used mmWave communication applications are mostly for point-to-point links wit a limited number of users allowed mechanisms that prohibit multiple simultaneous communication links to be established. However, in order to provide high spectral efficiency, next generation cellular systems need to allow simultaneous communication links to be established on multiple interfering links and manage them wisely at the same time to prevent decrease in QoS.

3.3 Emerging Applications of mmWave Communications

Even though mmWave communication mechanisms have been a growing research area especially for the last decade, it is still in its early stages. It is expected that mmWave communications provide a remarkable impact on other network technologies such as data centres and cloud services through unconventional wireless applications. Moreover, by enabling P2P communication and backhaul in communication networks, cellular systems will have significant improvements from mmWave mechanisms to provide higher bandwidths in order to solve spectrum efficiency issue. In this sense, many application areas have been studied for mmWave deployment such as broadband cellular communication, intra-vehicular communication, inter-vehicular communication and aerospace communication. In this part of this work, some of these areas are discussed briefly.

3.3.1 Mobile communications

The cellular networks of today use frequencies in Ultra High Frequency and low-microwave spectrum range, that is between 400 MHz and 4 GHz. These frequencies can be classified as relatively low against mmWave spectrum. This spectrum range have been in use for the last forty years of mobile communication journey.

For cellular communications with mmWave feature, the frequencies above 10 GHz can be considered as a frontier, since much greater bandwidth is available in these frequencies. The relatively smaller wavelengths of mmWave signals enables great capacity gains and with the additional capacity gains from spatial multiplexing and beamforming combined with large bandwidth provided by mmWave carrier frequencies, an evolution of Ultra-Wide Band (UWB) mobile communication systems that promise much greater data rates and system capacities is expected in near future.

As mentioned several times in previous sections of this work, demand for cellular data is growing more and more as time goes by. Many big companies have studied this growth and made projections for the future and the message is very clear. Much greater spectrum assignation will be required more than ever by the cellular networks. Even conservative projections estimates a growth in per-user data consumption of 50% to 70% per year, since operators already experience remarkable increase in especially video streaming through out the world [23]. This projections clearly indicates that this growth trend will only accelerate in time especially with Industry 4.0 revolution takes its place, as new social networking evolves and as the Internet of Things becomes a reality.

Recent studies in the last couple of years shows that the radio propagation at mmWave frequencies are not only viable, but may actually have significant advantages over the cellular networks that are currently in use. It is expected that the key technological elements will become mature to enable mmWave wireless networks using cellular networks with multi-Gpbs mobile data rates.

3.3.2 Data centres

Internet and cloud-based applications have been a subject to a sensational growth in the last decade. Thus, major Web portals such as Google, Microsoft, Amazon and Facebook and internet service providers have been building more and more data centres each year around the world. Data centres are being utilized to appropriate handling, memory stockpiling and storing through the worldwide Internet. As the size of multimedia contents gets larger and larger and these media are continuously being streamed over the internet, building data centres continues to increasing. [23]. A modern data center that consist of thousands of co-located computer servers can consume power up to 30 MW, which is almost an equivalent to a small city.

As the frequency increase for the next generation communication networks, the broadband wired connections that is currently being used in data centres will not be able to adapt bandwidth requirements of future networks due to the signal loss in metal wire. Hence, in order to meet the growing demands, data center owners will have to make appropriate transitions to other technologies. At this exact point, mmWave wireless communications using 60 GHz provides an remarkable alternative solution for data centres and offers greater flexibility, lower power consumption and lower cost.

3.3.3 The future of home and office

mmWave communication systems and the devices with mmWave feature are expected to evolve in next couple of decades. This revolution in communication systems would would effect the way in which our homes and offices are wired today. Moreover, the number of mobile devices that are now an essential part of our lives is expected to increase significantly as the bandwidth carried around our homes increases by orders of magnitude. It can be said that in the near future, we will witness the renaissance of wireless communications, where the devices will be connected by massive-bandwidth data links that able to carry data with the rate of multi-Gbps. With this revolutionary change in technology that we use in our daily lives, many low-power wireless memory devices are expected to replace the basic elements of our daily lives such as books. It is safe to say that, unlimited information access, in other words information will be available for everyone, any time, anywhere.

3.3.4 Vehicular applications

In vehicular context, there are many application areas, in which mmWave is suitable. Specifically, mmWave mechanisms can easily be adapted in intra-vehicle communication applications due to its inability to easily penetrate and interfere with other vehicular networks. One of the most important application is to remove wired connections within a car by establishing a broadband communication within the car. To be more specific, the wires used between the backseat displays and DVD player can be removed with such a deployment as well as the wires used for connectivity of portable devices such as MP3 players, cellphones, tablets, laptops. However, deployment of inter-vehicle communication with mmWave feature has many challenges due to the high Doppler effect [23]. On the other hand, there are many other applications for mmWave to be used in as listed below:

- Vehicle-to-Vehicle (V2V) communication
- Vehicle-to-Infrastructure (V2I) links

Especially, Vehicle-to-vehicle (V2V) communications can be used to avoid collisions by sending a pilot signal to a car that reaches within a range and activate coordinated systems in order to change the direction of the vehicles or to stop them before the collision happens. V2V communications also can be used for exchanging traffic information for specific area.
The vehicular applications of mmWave channel networking is shown in Fig. 2.

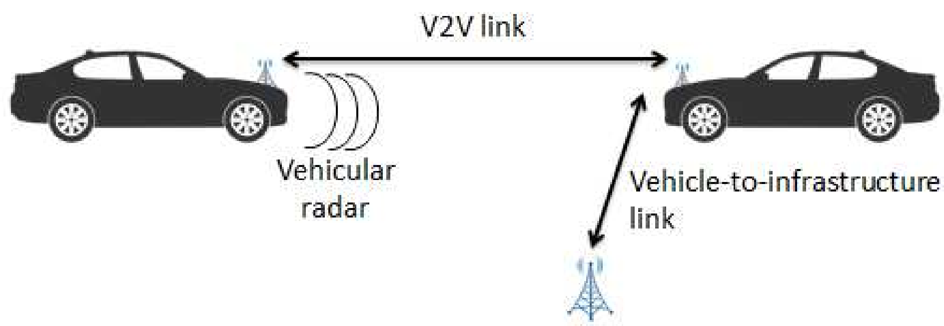

Figure 2: Different applications of mmWave in vehicular applications [23].

3.4 mmWave Propagation Characteristics

Some of the possible application areas for mmWave communication systems are discussed in the previous section of this work. However, for the outdoor scenarios such as vehicular applications, in principle, the additional attenuation due to gases in the atmosphere and rain should be taken into consideration.

In the frequency range of mmWave signals up to 100 GHz, there are two peaks in standard atmosphere. The largest of the two peaks is caused by oxygen absorption at 60 GHz and corresponds to 15 dB/km. Hence, gas attenuation isn't considered as a major concern for future mmWave indoor and small cell applications [18]. Fig. 3 shows atmospheric absorption characteristics of mmWave signals, presented in [18].

Table 2: Rain attenuation for mmWave signals in different frequencies [53].

Frequency	Rain attenuation for 200 m	
	5 mm/h (dB)	25 mm/h (dB)
28 GHz	0.18	0.9
38 GHz	0.26	1.4
60 GHz	0.44	2.0
73 GHz	0.60	2.4

Similarly, for rain effects of very heavy (100 mm/h) rainfall with a maximum attenuation of 30 dB/km shouldn't cause any big issue for indoor and small cell applications of mmWave.

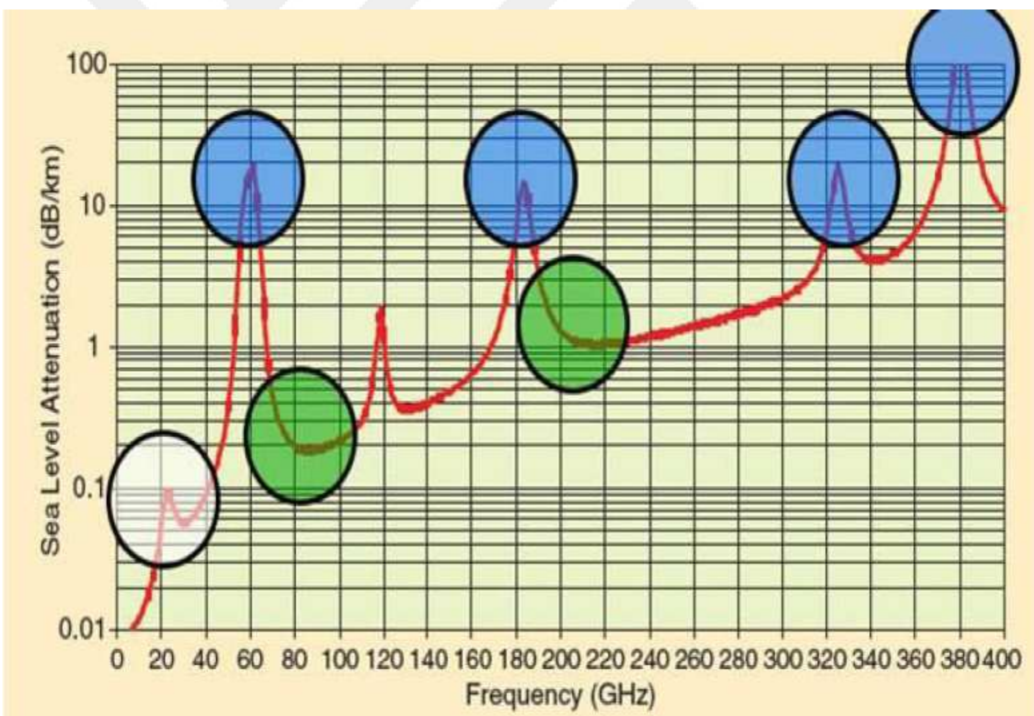

Figure 3: Atmospheric absorption characteristics of mmWave signals frequencies against dB/km [18].

Moreover, Table-2 presents the measurement results of how the most studied mmWave frequencies are effected by rain attenuation [52].

A more important issue for future mmWave deployments is caused by the high penetration loss due to building materials. Typical relative permittivity and conductivity for different building materials are studied in [25] and a study of comparison of 5.8 GHz and 62.4 GHz is presented in [26]. An expression for the conductivity σ which gives rise to the dB/m attenuation factor, as a function of frequency is provided in Recommendation 2040-1 as shown [27], where c and d represent material constants, for example, for a concrete wall $c = 0.0326$ and $d = 0.8095$.

$$\sigma = c\, f^{d}\, S/m \tag{2}$$

The studies in the literature on penetration losses at 60 GHz declares values on the order of some decibels for materials such as wood and thin plastic. Researches on 70 GHz also shows similar level of penetration losses to 60 GHz.

These discussed additional losses at mmWave signals' high frequency levels result in the requirement of compensation through more effective transmit powers and this issue may harm applications with NLOS situations.

Another important issue that requires attention of mmWave signals' propagation characteristic is rough-surface scattering. For materials such as bricks and concrete the standard deviation of surface-roughness σ_h is roughly 1-2 mm and doesn't satisfy Rayleigh criterion for lower frequencies [28]. This results in a lower specular reflectivity of the surface in favor of diffuse reflection.

3.5 mmWave Channel Modelling

In this section, the transmission model of mmWave channels is presented. The transmission and reception gains between i^{th} and j^{th} user is denoted by g^{t}_{ij} and g^{r}_{ij} is given by the following, respectively:

$$g^{t}_{i,j}(\alpha^{t}_{i,j}, \beta) \;=\; \frac{2\,\pi}{\beta} \quad \text{if} \quad |\alpha^{t}_{i,j}| \leq \frac{\beta}{2} \tag{3}$$

Table 3: The channel model parameters for the close-in free space reference distance and floating intercept models for both the 28 GHz and 73 GHz [56]

Omnidirectional Path Loss Models (d = 1 m)										
		TX Height (m)	RX Height (m)	LOS		NLOS		NLOS (Floating)		
				PLE	σ [dB]	PLE	σ [dB]	α [dB]	β	σ [dB]
28 GHz	Access	7; 17	1.5	2.1	3.6	3.4	9.7	79.2	2.6	9.6
73 GHz	Access	7; 17	2	2.0	5.2	3.3	7.6	81.9	2.7	7.5
	Backhaul		4.06	2.0	4.2	3.5	7.9	84.0	2.8	7.8
	Hybrid		2; 4.06	2.0	4.8	3.4	7.9	80.6	2.9	7.8

$$g^r_{i,j}(\alpha^r_{i,j}, \beta) \;\; = \frac{2\,\pi}{\beta} \quad \text{if} \quad |\alpha^r_{i,j}| \leq \frac{\beta}{2} \tag{4}$$

According to these antenna gains, the received power level at the receiver can be calculated by using Friis' equation as follows:

$$P_r = P_t\, g^t_{i,j}\, g^r_{i,j} \left(\frac{\lambda}{4\,\pi}\right)^2 \left(\frac{1}{d}\right)^n \tag{5}$$

$$P_r = P_t\, g^t_{i,j}\, g^r_{i,j} \left(\frac{c}{4\,\pi.f}\right)^2 \left(\frac{1}{d}\right)^n \tag{6}$$

Here, P_r represent the received power at the receiver, where P_t denotes the transmit power, λ is the wavelength, which is equal to c/f and d denotes the distance between the two mobile devices. n stands for the path loss exponent in (6), which can be selected as 2 to 6 for indoor scenarios [55]. For the rest of this thesis work, in order to simplify the simulations, path loss component is selected as 2, which also corresponds to free space transmission. It should be noted that more detailed examinations can be made by selecting n differently and taking other variables such as scattering and antenna height into consideration. Such a study is presented in [56] and the path loss exponent results of that study can be found in Table 3.

CHAPTER IV

FUNDAMENTALS OF DEVICE-TO-DEVICE COMMUNICATIONS

In the past decade, the high data rate and QoS demand of the mobile device users has highly increased. This increase has emerged a new problem for the networks operators as how can they manage to reach higher data rates and better QoS. As telecommunication operators searched for the correct and the best answer for this problem, the extensive improvements have been made in terms of potentiality of mobile communication networks. The innovation of new types of mobile devices have produced an outburst of new applications which will be used in cases for mobile connectivity. This growth in number of devices and applications result in exponential growth in network traffic.

In order to meet these requirements, one of the solutions is to improve the performance and QoS of the local area networks (LANs) significantly and one way to do this is reusing the spectrum resources. However, reuse of only the unlicensed spectrum does not provide a reliable communication. Therefore, exploiting the licensed spectrum in LANs had a lot of notice in recent years and D2D communication systems have been offered as a good solution for the challenges defined above.

4.1 Introduction

The basic definition of D2D communication refers to the methods or special techniques that are allow devices to communicate with each other and eliminate the elements of an infrastructure of a base station (BS) or access points. D2D communication systems amount to a technology component for the next generation mobile networks like LTE-A and 5G, where mobile devices are able to transmit data signals to each other using direct links between each device instead of getting communicated through a base station. Mobile D2D communication systems allow one to increase the spectral efficiency and hence reach higher data rates of multi-Gbps. As declared, D2D communication systems are considered as an add-on part of LTE-A communication systems are expected to be an important part of the next generations of mobile communication systems.

In a strict overview, D2D communications can be examined in three main categories as follows:

- Peer-to-Peer communications: This type of D2D communication systems are the most studied method since they are based on a simple point-to-point communication model.
- Cooperative communications: This method uses user equipments (UEs) as relay points in order to extend the coverage area of mobile network and obtain space diversity.
- Multiple-hop communications: This method includes data routing and complex data superposition like mobile ad-hoc network systems.

The different signalling mechanisms for P2P, cooperative and multihop communications are shown in Figs. 4(a), (b) and (c), respectively.

D2D communication systems brings an important improvement to mobile communication world by means of spectral efficiency and system capacity, but they also have challenges to be solved in order to be a big part of next generation communication systems. One of the important problems regarding omnidirectional D2D communication architectures is the performance degrading effects of interference from the neighbouring users. Mobile devices in D2D communication networks communicate with each other through direct links instead of a base station and this creates interference with

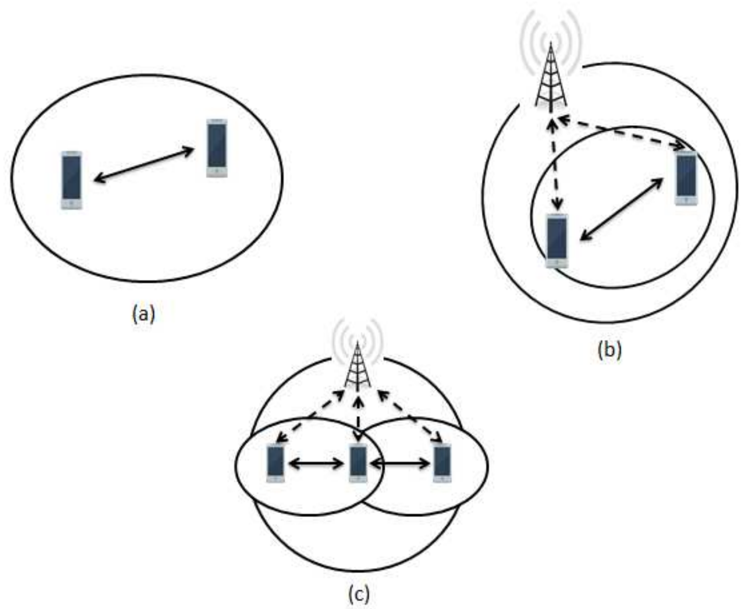

Figure 4: D2D communication topologies illustrating a) P2P communications, b) cooperative communications, and c) multi-hop communications [53].

other D2D users as well as with the cellular network users as a result of spectrum sharing. This issue is studied many times in the recent years and researches have come up with numbers of solutions. In [1], with the aim of guaranteeing the required performance for the D2D communications, MIMO transmission schemes to invalidate interference from the cellular downlink to D2D receivers are proposed. Interference management from both from D2D communication links to cellular network and the other way around is discussed in [2]. Moreover, in [3], the authors have studied a resource-allocation scheme which tracks the near-far interference and identifies cellular users and make sure that the uplink frequency bands are efficiently used in order to avoid harmful interference.

All of the above works and the other existing works in the literature show that, D2D communication models can improve the system performance effectively with minimized interference level both between cellular networks and D2D communication links and between D2D communication.

4.2 Device-to-Device Communication Systems

A device-to-device communication system can be examined under two levels of network: i) macro-cell level and ii) device level. The macro-cell level of the system consists of the base station for device communications as in an conventional cellular communication system, while the device level contains D2D communications. In other words, if a device connects to the cellular network through the base station, it will be in the macro-cell. Similarly, if a device connects directly to another device, then it will be in the device level.

In the insight of device level communications, the base station may have either full or partial control over the resource allocation amid transmitter, receiver and relaying devices or not it may have any control at all. Hence, main types of device level communications can be listed as in following sub-sections. The general ideas of these four classifications by the degree of independence of D2D system can be found below as well as the figures to visualize them.

4.2.1 Relay with BS control mechanism

This type of link establishment can be useful for devices with low signal reception, i.e. devices at the edge of a cell or in coverage areas which have low signal strength. In this scheme, the relays nodes are used to make a communication possible between a mobile device and BS. It should be noted that, in this method the BS communicates with the relay devices in order to create the control mechanism over the link establishment. Such a communication mechanism is advantageous to have higher QoS and respectively increased battery life.

4.2.2 BS Controlled direct D2D communication mechanism

In this model of D2D formation, the BS doesn't communicate with the devices. The transmitter and the receiver communicate with each other directly. However, they are supported by the base station for link establishment.

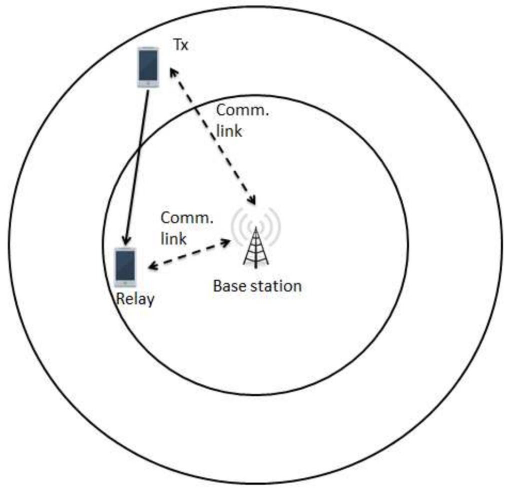

Figure 5: Device relaying with base station controlled link establishment for D2D communication [51].

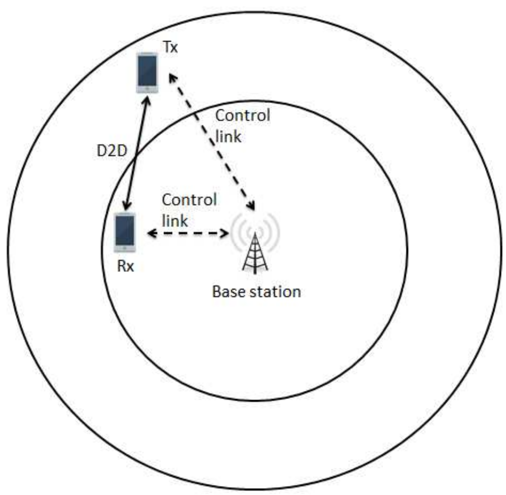

Figure 6: Base station controlled link formation for D2D communication [51].

4.2.3 Device controlled relay mechanism

This type of D2D mechanism doesn't involve BS to link establishment. Hence, the transmitter and the receiver are completely in charge for synchronizing communication utilizing relay nodes among each other.

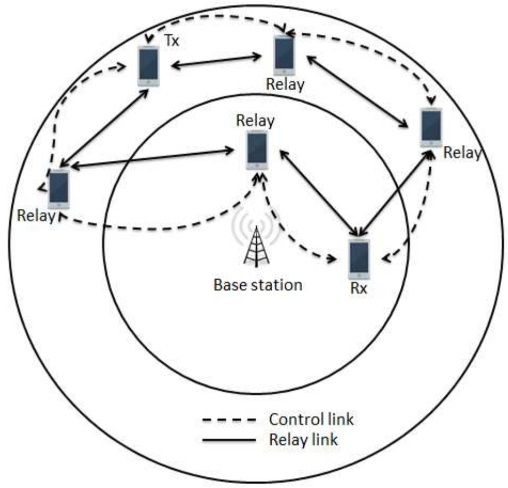

Figure 7: Device relaying with device controlled link formation for D2D communication [51].

4.2.4 Device controlled direct D2D communication mechanism

In this type of communication, the transmitter and the receiver have a direct communication link between each other and the link formation is controlled by the devices without taking any help from the base station. Hence, the resource need to be optimized by the transmitter and the receiver in such a way to satisfy limited interference conditions.

Other than these four types, device-to-device communication systems can be classified by the spectrum that they use as follows:

4.2.5 In-band D2D communication systems

In this type of D2D communication systems, both the cellular users and D2D users operate on the same cellular spectrum. Since the base-stations have definite control over the cellular spectrum, the interference issue caused by D2D communications can be managed easily.

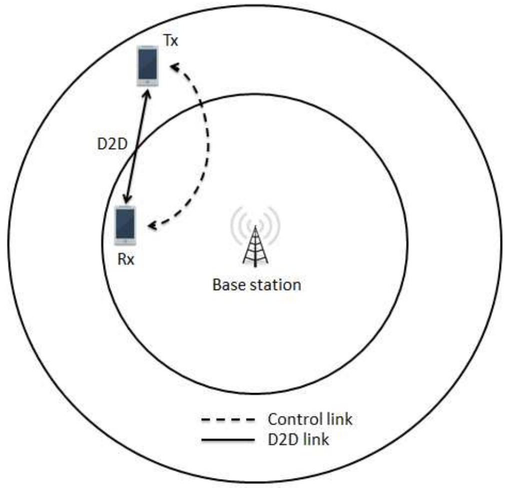

Figure 8: Direct device-to-device communication with device controlled link formation for D2D communication [51].

4.2.6 Out-band D2D communication systems

In out-band D2D communication systems, in order to realize D2D communications, the unlicensed spectrum is utilized. To use the unlicensed spectrum efficiently, another interface such as Wi-Fi Direct, ZigBee or FlashLinQ is required.

The main focus of this thesis work is an out-band device-to-device communication system with the use of FlashLinQ protocol.

4.3 Technical Challenges of D2D communication networks

Even though D2D communication systems are being studied since 3GPP [4], D2D is still in its early stages and there are many technical challenges still need to be addressed such as device discovery, security and interference management. In this sub-section, these open research areas are discussed briefly.

Other than these important challenges, following items can be listed in the general challenges in D2D communication systems:

- Scaling law and capacity analysis.
- Channel measurement and modelling, and interference analysis.

- Proximity-based applications, such as context-aware networks, and offload in concert and stadium networks.
- Mobility measurement, modelling, and management.
- Reduction of signalling overhead.
- Limited-backhaul issues for cross-cell D2D transmission.
- Multi-hop relaying algorithm

In addition, in order to minimize the impact power control, cooperative transmission, and multiple-access methods need to be carefully researched.

4.3.1 Device discovery

Two device need to find each other when they are close by in order to start the protocols to communicate with each other. In the conventional approach, during this discovery stage, both device search for their peer in the range of D2D communication. [5] However, in this work a novel scheduling algorithm is studied which doesn't require beam or device searching. Instead, opportunistic peer discovery method is proposed as one of the main contribution.

In the conventional device discovery method, the discovery of other devices is made possible by sending a pilot signal in order to recognize devices within range. After this, the identity of devices can be exchanged between transmitter and receiver pairs. When two device pair find each other successfully at the end of this stage, they can be considered as only D2D candidates. The conditions that pairs need to satisfy in order to establish a successful communication link together are explained in Chapter V in details.

4.3.2 Security

One of the biggest challenges in D2D communication systems can be addressed as security and privacy. Security issues of D2D communication systems involve potential cyber-attacks, threats and vulnerability of the established system. Especially in a model which doesn't use secure macro-cell provided by GSM operators, the data is transmitted / received through other mobile devices instead of a main base-station; the privacy of the shared information has to be maintained in a secure way. This case is named as open access and each device can act as relay point for other mobile devices without any boundaries. Since this method doesn't contain any supervision, security and privacy of the shared information is a challenging open issue.

4.3.3 Interference management

Other than the security and device discovery, interference management issue remains as an important challenge for D2D communication systems to be established widely. Since the devices that communicate with each other directly and the ones that communicate through macro-cell operate in the same licensed band, these devices will have an impact on each other, inevitably. To make this impact as minimum as possible on the performance of the existing macro-cell system, a two-tier network needs to be established with the condition of smart interference management strategy and resource allocation scheme. [6] The first tier in this smart interference management strategy is called the first tier which is the conventional macro-cell layer where the communication happens between the base station and the mobile device. The second tier is called the device tier, where the communication happens between two mobile devices as D2D. If designed properly, this second tier provides significant enhancement in terms of quality of service, coverage and channel throughput. However, beside these strong positive aspects, this second tier comes with an important challenge, namely interference, since the devices in both tiers would cause interference for each one another. If this generated interference is not taken well under control, it would worsen the advantages of D2D communication by decreasing the overall system capacity and efficiency.

4.3.3.1 Interference types for two-tiered network architecture

The interference types in two-tiered network architecture can be named as co-tier interference and cross-tier interference.

In co-tier interference, as can be understand from the title, the interference on a device is caused by another device which is in the same tier of the network. In other words, in a cellular network where D2D is enabled, co-tier interference can only occur between two D2D users that are in the same tier.

The co-tier interference occurs in OFDMA systems, during the identical resource blocks are assigned to more than one D2D users.

The proposed scheduling method in this work requires the SINR of a link to be high enough to satisfy a pre-defined capacity threshold in order the link to be established successfully. Otherwise, if the SINR falls below a certain level that would not satisfy the capacity threshold, the communication link cannot be established. Other than this threshold condition, the proposed method uses angular beams for all users with a pre-defined beamwidth in order to manage interference even more precisely.

Moreover, the cross-tier interference is the interference caused from a device that belongs to different tier of the network. This type of interference occurs if the resource block assigned to a cellular user is reused by one or more D2D users.

4.3.3.2 Interference management techniques for D2D enabled networks

The two type of interference caused by the addition of a new device tier is explained in previous section. This section is about the discussion of several interference management techniques for D2D enabled networks. It needs to be stated that the research of interference management is still ongoing and the methods that are discussed in this part of this work would be reviewed.

- *Spectrum Splitting*

The spectrum splitting is one of the most used methods in order to manage cross-tier interference between cellular tier and device tier. In [7], spectrum splitting is used, where the division of the spectrum band into two part is suggested as one for cellular users and one for D2D users. At this point, it should be noted that the spectrum splitting method only focus on managing cross-layer interference. Therefore, in order to manage interference properly, an extra mechanism is needed in spectrum splitting technique.

- *Power Control*

It is a known fact that higher transmit power means wider coverage and better signal quality for D2D communication systems, but at the same time high transmit power cause a significant increase in the interference. An accurate power control is an important aspect to deal with cross-tier interference as well as co-tier interference. Such a mechanism coordinates the interference created by managing the transmit power level of D2D users. Hence, increased cell coverage and improved system throughput are provided. Moreover, this method has advantages to decrease total power consumption. In order to meet these demands, power control mechanisms focus on maximizing the transmit power and limiting the interference level. Moreover, several power control mechanisms are proposed for different objectives, such as minimizing total power [8], maximizing the rate [9], or "maximizing a utility function characterized by the trade-off between spectrum and spectral efficiency" as proposed in [5]. The most important advantage of power control mechanisms is that D2D users and cellular users can exploit the whole available bandwidth with interference coordination.

In order to make sure the reliability of cellular users, the authors in [10] proposed a mechanism that doesn't cause an outage for cellular users. It is stated that, with the assumption of D2D users have knowledge of the location and channel state of cellular users is not practicable in a real system. Hence, a power control scheme that doesn't involve the BS is designed. In such a system, the D2D power management can only be done if the interference limit and estimating channel gain between the BS and the D2D user are known. Then, dynamic source routing protocol is being utilized between the transmitter D2D user and the receiver to discover the adequate route.

4.4 Integrant features of D2D

The D2D communication concept initially designed for networks without any controlling mechanism such as sensor networks and mesh networks, where devices communicated in industrial, scientific, medical (ISM) band. However, lately D2D has gained a great interest to be used in the licensed band for LTE-A and the next generation networks, since generating direct links useful for the overall system throughput improvement.

In this part, several features of 5G networks can be integrated with D2D communication are listed and discussed briefly.

4.4.1 mmWave D2D communication

An important technology candidate for the 5G networks is mmWave communication, which makes multi-Gbps data rates reachable to the end user and also the main topic of interest of this work. mmWave communication performs on a wide frequency band rage of 30 GHz to 300 GHz. A number of direct communication links can be supported by making use of D2D communication in mmWave cellular networks, providing a significant improvement in overall network capacity. Moreover, due to the highly directional antennas, simultaneous communication links can be supported by the use of D2D communications in mmWave networks. As a scheduling mechanism for mmWave small cells by exploiting D2D transmissions is proposed in [11].The results of their work show an overall enhancement in transmission efficiency.

The literature shows two type of available D2D communication for mmWave 5G networks, namely local D2D communication and global D2D communication. In local D2D communications, a possible path is established between two devices connected with the same base station, if the LOS path is blocked or not available. On the other hand, in global D2D communication type, devices tied in different base stations are connected through back-bone networks via hopping. However, D2D communications may suffer a significant interference in mmWave networks in the case of there are multiple local D2D communications, which makes interference management a very important issue to be solved. [12]

Co-presence of global D2D communications and local D2D communications in the same communication system results in high interference between local D2D communications and between BS-to-BS or device-to-BS communications. A successful communication between two base stations with relatively high data rate can be supported by mmWave networks due to their highly directional nature. Even though there are many advantages of highly directional antennas in terms of improved network throughput and efficient spectrum utilization, there are certain challenges that come along with it. Generally, problems come up with the case of neighbour discovery, like deafness problem, which is another topic of interest of this work. One of the other major problems for mmWave communications is discussed in the literature as unavailability of a standard channel model.

4.4.2 Cooperative D2D communication

Cooperative communication mechanism is a focused technology in cellular networks which is expected to have remarkable impact on D2D communication systems. In the case of a long distance communication between two D2D pair, the direct link is not good enough to establish a successful communication. Cooperation aims improving the quality of D2D communication between users for data offloading and it provides increased network coverage as well as interference reduction.

In case of cooperative D2D communication, relay path selection is very critical. Since many relay paths can be available, the selection needs to be efficient and optimum. For such a scenario, relay selection methods are presented in [13], in which the algorithm helps the base station to find the best possible relay path among all.

Beside the positive effects, cooperative D2D communication mechanisms have a problem that needs to be optimized since it consumes a large amount of power.

4.4.3 D2D communication in ultra-dense networks

As the number of smart phones and tablet increase day by day in the last decade, offloading cellular data has become an important problem for the network operators. Due to substantial increase in the utilization of smart devices, have a tendency to overload and in order to free up the loaded path, traffic offloading is necessary.

As an efficient solution to offload traffic, small cell technique is studied in the literature widely. As the size of a cell gets smaller over the generations, the users have less competition for resource, which provides a substantial improvement in spectrum efficiency. Types of small cells including picocells, microcells and femtocells, changes according to cell sizes and transmission power. Establishing a low power small cell base station in large number creates ultra-dense networks and it is acknowledged as an important emerging technology for improving the overall network throughput.

Combining D2D communications with small cells plays a key role in offloading traffic, since hot-spot traffic is being offloaded by the mall cells and proximity services are being focused by D2D. Consolidation of these two mechanisms results in ultra-dense 5G deployments as shown in Fig. 9.

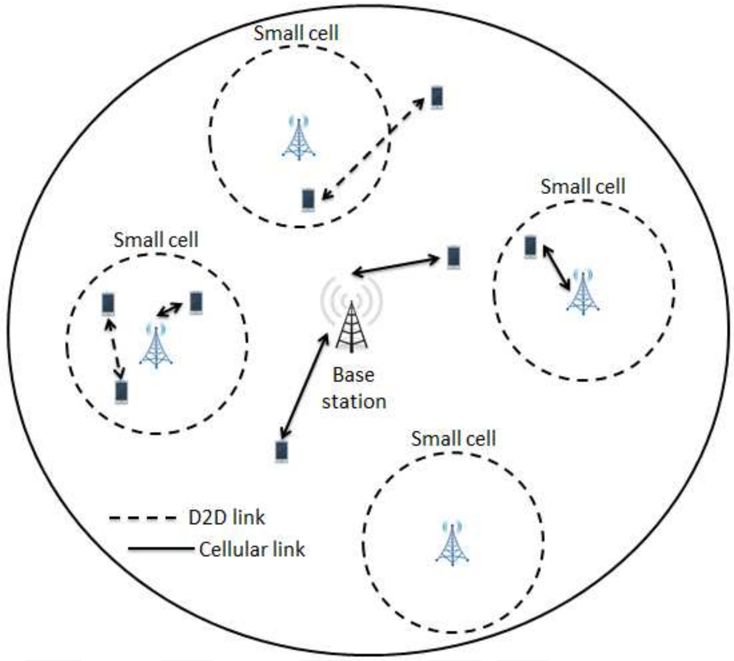

Figure 9: D2D deployment with small cell mechanism. [54]

Even though the deployment of small cells is a great challenge itself, with the establishment of small cells in next generation communication systems, greater data rates and fewer delays in the network is expected. In small cell enabled networks, there is a high chance of interference between the D2D links, macro-cell links and small cell links. It needs to be noted that this interference level can get worse if the D2D links are from different cells.

4.5 Applications and business opportunities enabled by D2D communications

With the introduction of D2D communication systems in mobile wireless communication world, many new applications have been emerged which D2D communication can be beneficial. Below, some of these applications are listed, but this is not a complete list of applications which can benefit from D2D technology.

- Social networking.

- Machine-to-Machine communications.
- Public safety.

4.5.1 Social networking

Social networks take an important and a big part of lives since last decade. Mobile users log in to social networks all the time and share great number of multimedia with each other. This is, on its own, one of the most important reasons of ever growing demand which also causes communication systems need to change in a better way. As mentioned before, D2D communications may provide high speed direct link between mobile users in a certain range, over which the users may share multimedia content with each other. It is obvious that day by day, the size of a single multimedia content gets bigger with the used technology in mobile devices gets improved and this generates a great amount of load on the communication networks. At this point, D2D communications systems are able to lower the load on the communication networks, by establishing direct links between the mobile users, while providing better QoS and higher data rates.

Other than this scenario, D2D communication system can be beneficial for social networks which enable teachers could exchange information with students in a lecture hall. The number of these examples of course can be increased with new emerging social media applications.

4.5.2 Machine-to-Machine (M2M) communications

Machine-to-Machine systems are taking serious attention recently with new technologies which allows machines to communicate with each other without the need of a human interaction being developed. Furthermore, many researchers and scientists indicated that these technological developments now allow industrial systems to go for a new revolutionary change called Industry 4.0. This industrial movement is based on machines that are located in a factory doing related works to communicate with each other and more over make decisions on their own in order to increase the production efficiency. Therefore, D2D communication systems play a critical part in order to provide stable and efficient communication between devices.

4.5.3 Public safety

D2D communications are expected to play an important role in case of emergency communication. With the base station independent feature, D2D communications are capable to guarantee public protection and disaster relief and national security and public safety services [14]. In case of a natural disaster like flood or earthquake, conventional cellular networks can get damaged as seen many times in the past. In such a scenario, D2D communications can be used to setup wireless network between terminals.

CHAPTER V

THEORETICAL MODELLING OF OPLINQ SCHEDULING ALGORITHM

This chapter includes detailed information about the system model for the system that is proposed in this thesis work and is based on the paper prepared to be published by Özen and Gülbahar. Table-2 belongs to the symbols used in this thesis work and what they refer to.

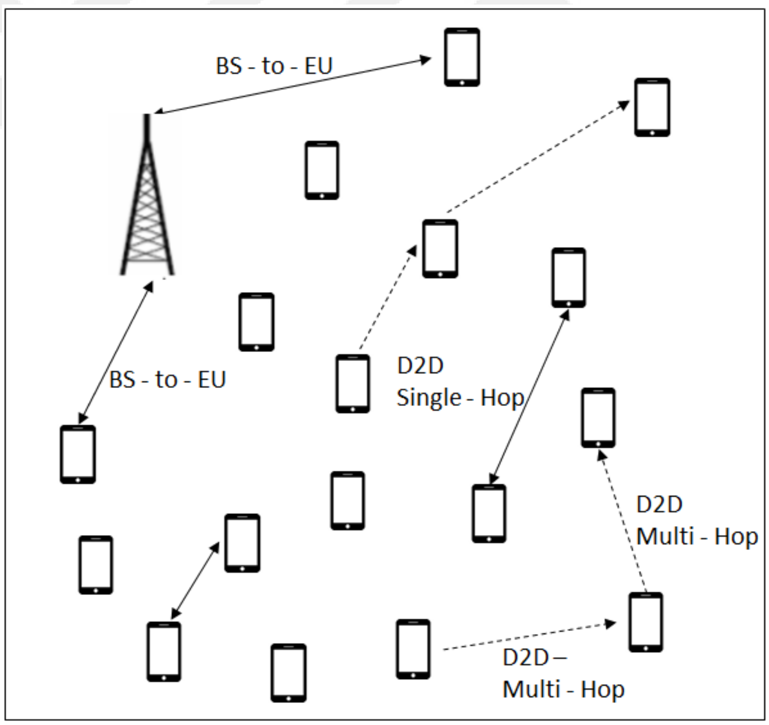

Figure 10: System topology of D2D mmWave communication network.

In this work, a crowded mmWave D2D communication network is considered as shown in Fig. 10. It is assumed that there are N receivers and N transmitters in two dimensional network topology since D2D communications occurs among the people with similar antenna height. In the remaining of this work, i^{th} transmitter and the

Table 4: Simulation Parameters

Symbol	Parameter	Value
A	cell area	30m x 30m
N	total number of Tx and Rx	100
K	the number of set of beam orientation angles	4
P	transmit power	0.1 mW - 1 mW
N_0	background noise	-136 dBm/MHz
B	bandwidth	2 GHz
f	frequency	60 GHz
β	the beam-level beamwidth	30°, 60°
t_{Tot}	the total number of time-slots	4000
t_{Loc}	the number of time-slots for the duration to take local averages	100
γ	SINR threshold	8 dB, 15 dB, 24 dB, 224 dB

j^{th} receiver are denoted by T_i and R_j, relatively. Furthermore, it is assumed that there are L link requests for peer-to-peer communication between users. Each user is assumed to have predetermined set of K beam orientation angles decided at the beginning of each time slot as shown in Fig. 11.

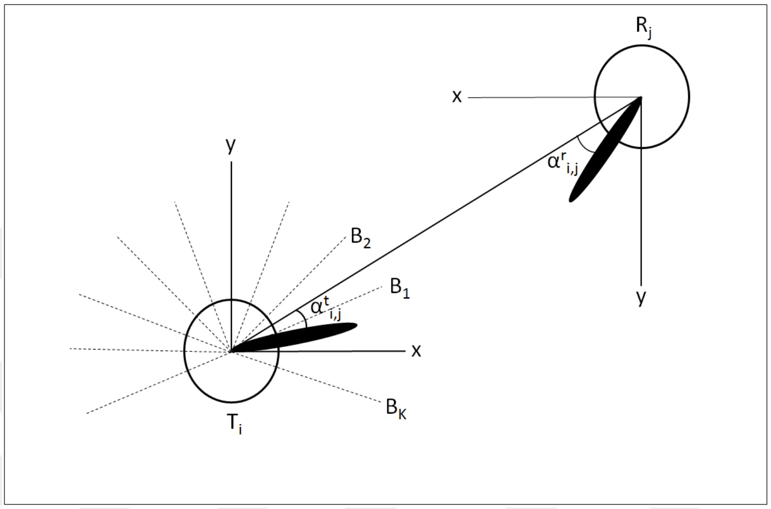

Figure 11: Beam selection mechanism.

Here, B^t and B^r are the related beam-angle slot number of transmitter and receiver, respectively, as shown in Fig. 11. The angles between transmitter i (T_i) and receiver j (R_j) are denoted by $\alpha^t_{i,j}$ and $\alpha^r_{i,j}$. The transmission and reception antenna gains between i^{th} and j^{th} user is denoted by g^t_{ij} and g^r_{ij} is given by the following, respectively:

$$g^t_{i,j}(\alpha^t_{i,j}\,\beta) \;\; = \frac{2\,\pi}{\beta} \quad \text{if} \quad |\alpha^t_{i,j}| \leq \frac{\beta}{2} \tag{7}$$

$$g^r_{i,j}(\alpha^r_{i,j},\beta) \;\; = \frac{2\,\pi}{\beta} \quad \text{if} \quad |\alpha^r_{i,j}| \leq \frac{\beta}{2} \tag{8}$$

Here, β is the beam-level transmitter and receiver beamwidth of the related link, respectively. For the rest of this thesis work, the beamwidth is selected equal for all transmitters and receivers. The cross-link gains, which shows the interference level from a transmitter to a non-desired receiver $g^t_{k,j}$ can be calculated in the same manner as equations above, where $k \neq i$.

The fundamental aim of this work is to satisfy the link requests with an opportunistic mechanism in a way leading to low latency and high throughput without any detrimental effects of beam searching, deafness, varying dynamic channel conditions, and collision avoidance based channel access mechanisms especially in dense and wireless D2D mobile networks. Next, the channel access and scheduling mechanisms are described.

5.1 Channel Access and Scheduling

In this section, the scheduling algorithm is defined, which schedules a feasible set of links with a SINR based rate optimization in a given time slot. A synchronous time-slotted architecture for mmWave D2D channel access mechanism is provided. The mechanisms of OFDM based pilot signalling developed for omni-directional antennas is adapted to directional beamforming based network topology [34]. Hence, in the proposed mechanism, the link capacity threshold comparisons for transmitters and receivers are also in directional topology. In order to avoid any interference between communication links, the orthogonality feature of OFDM signalling is used. The proposed system checks SINR levels of the links in each time slot while taking crowdedness of the system into consideration, which makes it a channel aware communication network. Furthermore, new phases in a single time slot are defined, i.e., beam scheduling, position estimation and relay scheduling.

A single time slot consists of six main phases as shown in Fig. 12 namely, beam selection and position estimation, connection scheduling, relay scheduling, rate scheduling, data transmission and acknowledgement, relatively. Next, the details of these phases are explained.

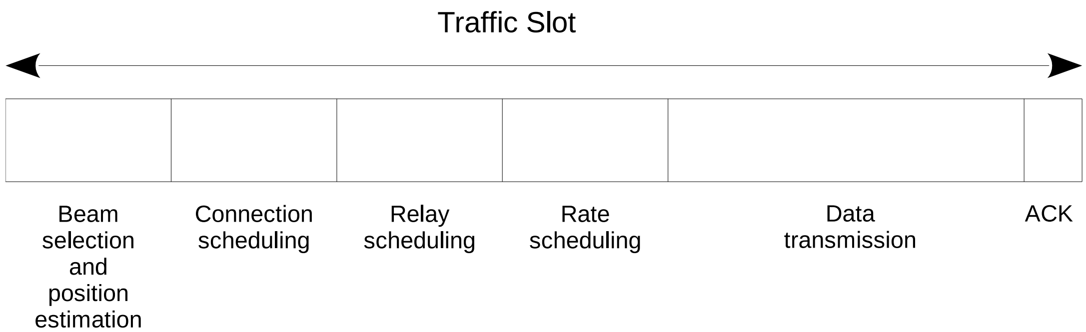

Figure 12: Structure of one time slot

5.1.1 Beam selection & Position estimation

In this phase, optimum beam searching procedure is replaced with a beam selection procedure from a predetermined set of K beam directions. This feature gives the proposed system consistency with the mobility of the users and continuously changing topology of the system due to mobility. This way, instead of performing exhaustive beamsearching phase, link pairs are being established opportunistically. Beam selection procedure is effected by the preference of single hop or multi hop scheduling options. For the single-hop option, the system changes the beams in order to increase the possibility of intersecting with other beams. In multi-hop case, the system analyses the mobility and defines a connectivity/rate network topology graph which is being kept in a central coordinator for each time slot.

The proposed system checks the mobility and position estimation according to the SINR values in central coordinator. If the mobility is on a small scale, that means the connectivity/rate graph doesn't need to be changed in current time slot and beams can be kept as the same. However, in a high mobility scheme, the connectivity/rate graph has to be renewed and the system changes the beam positions accordingly in order to maximize the feasible link number.

5.1.2 Connection scheduling

Scheduling is realized by utilizing orthogonal channels in a OFDM framework using distinct time-frequency slots in an efficient manner as defined and discussed in [34] for omni-directional network topologies. In connection scheduling phase, the system assigns the users a random priority, checks the transmitter and receiver yielding requirements and makes a list of successful links.

The transmitter and receiver pair exchange an analogue signal between each other in order to measure interference and power levels of the link to be established. This stage is named as direct power transmission and echo broadcast. In this article, beam directions are also included in connection scheduling compared with FlashLinQ protocol utilizng omni-directional channel gains. In the direct power transmission stage, the transmitter should provide information regarding its angular value in which it is communicating with the desired receiver. In response to this, the receiver should send its own angular value, in which it is accepting data from the transmitter, to the transmitter in echo broadcast stage. In this thesis work, it is proposed to have K angular segments for each user. Each transmitter and receiver are to share the segment number that they are operating on to each other during an attempt to establish a successful communication link. During this stage, direct transmission and echo matrices are formed which provide connectivity information between different beam angles of neighbour users and the channel gain among them. Transmission matrix informs the receivers about the possible interferers and provides receiver yielding mechanism while the echo matrix informs the transmitters about their interfering effects and provides the transmitter yielding mechanism. These two matrices are referred as the "*connectivity and channel gain matrices*" of the system.

After this stage is completed, the receivers send the echo signal from all K beam directions and at the end of this stage another matrix with the size NxN is formed similar to the connectivity matrix described for direct power transmission from the

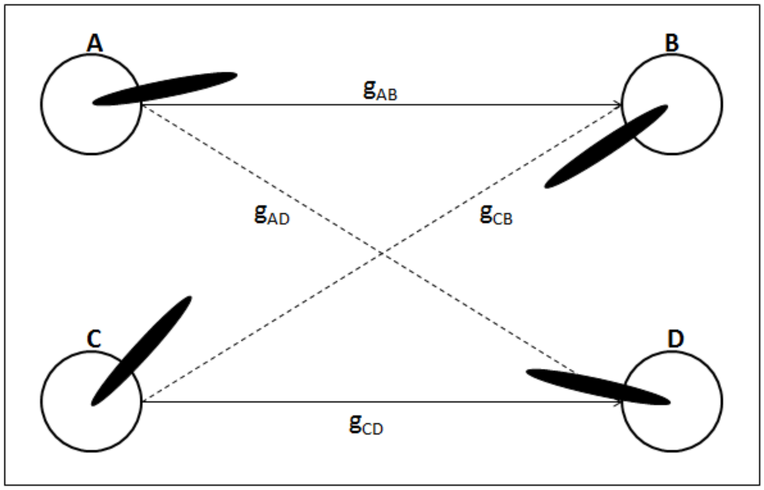

Figure 13: Bidirectional two link system.

transmitters.

In this phase, a link is established if the power and interference levels acquired in previous steps are greater than the given threshold values. Consider the system in the Fig. 13 which consists of four mobile devices. The main design ideas for a system with two links to be scheduled is explained in [34] with making the assumption as link $A \rightarrow B$ has higher priority than link $C \rightarrow D$

- Link $C \rightarrow D$ can be scheduled simultaneously only if it does not interfere with the high prior link.
- Likewise, if the cross link gains are higher then the given threshold, then only the link with high priority can be scheduled.

Let $g^t_{i,j}$ and $g^r_{i,j}$ represent the transmission and reception gains at transmitter i and receiver j respectively. Since link $A \rightarrow B$ has higher priority as mentioned earlier, link $C \rightarrow D$ can be scheduled only if it does not interfere with high prior link. This rule can only be satisfied when the SINR of the link $A \rightarrow B$ to be at least γ_{Tx} dB and the protection condition can be written as follows:

$$\frac{P_A \, |g^t_{ab}|^2}{P_C \, |g^r_{cb}|^2} > \gamma_{Tx} \tag{9}$$

where P_A denotes transmit power used by node A and P_C denotes transmit power used by node C. One additional condition for link $C \rightarrow D$ to be scheduled is D should expect adequate SINR due to A's transmission if scheduled.

$$\frac{P_C \, |g^r_{cd}|^2}{P_A \, |g^t_{ad}|^2} > \gamma_{Rx} \tag{10}$$

With all these informations are gathered, the signal-to-interference plus noise ratio (SINR) at the receiver of link between Tx_i and Rx_j can be expressed as follows:

$$SINR_{i,j} = \frac{P_i \, g^t_{i,j} \, h^c_{i,j} \, g^r_{i,j}}{\sum\limits_{\substack{k=1 \\ k \neq i}}^{N} P_k \, g^t_{k,j} \, h^c_{k,j} \, g^r_{k,j} + N_0 \, B} \tag{11}$$

Here, $h^c_{i,j}$ denotes the channel gain between related T_x and R_x and expressed as follows:

$$h^c_{i,j} = P_i \, g^t_{i,j} \, g^r_{i,j} \left(\frac{\lambda}{4 \, \pi \, D} \right)^n \tag{12}$$

In (12), λ is the wavelength, which is equal to c/f and d denotes the distance between the two mobile devices. As declared in Chapter III, in order to simplify the simulations, path loss component n is selected as 2, which corresponds to free space transmission.

Finally, with the SINR value calculated, the link capacity can be expressed as follows, where B denotes the bandwidth:

$$C_{i,j} = B \, log_2(1 + SINR_{i,j}) \tag{13}$$

Since the threshold inequalities defined above directly effects the link capacity, these threshold conditions can be applied to link capacity as well. The final condition for a link to be established can be expressed as shown in (14) below, where γ describes link capacity threshold.

$$C_{i,j} = B\, log_2(1 + SINR_{i,j}) > \gamma \tag{14}$$

5.1.3 Relay scheduling

Relay nodes are also an important point, since mmWave transmission model is pointed out as one of the most important models to achieve higher data rates in order to increase capacity in next generate mobile communication systems such as 5G, for outdoor applications 38 GHz and 28 GHz channels are being used for designing such systems. Furthermore, 60 GHz band is suggested for outdoor and indoor systems.

In spite of the advantages of the use of mmWave band in mobile communication systems, it has important and critical challenges in the real world applications because of their quite different propagation characteristics from the bands that are being used in older generation of mobile communication systems. In mmWave band, electromagnetic signals have very little ability to penetrate through solid materials, since the higher frequency results in smaller wavelength. Such small wavelengths cause blockage of links in non-line-of-sight situations and even by human body in more than 40dB of attenuation to the path loss [4]. Additionally, D2D communication systems suffers from high attenuation due to free-space loss caused by oxygen absorption in this band reaching 15dB. A simple solution for this problem is using relay methods via D2D communication. Relay methods for mmWave is studied widely in recent years and many solutions are proposed in the literature. In a scenario in which a user trying to communicate to a destination through mmWave transmission, if the mmWave signal does not have a sufficient SINR value at the destination due to the numerous blockages, the communication would fail.

The proposed system decides whether there are pairs that need multi-hop case or not by checking the connectivity and rate backbone matrices. If a device pair does not satisfy the required conditions described earlier, the system checks if there is a possible relay node for the failed pair to be able to communicate by looking at the neighbour and SINR rates. If there is a possible relay path, the node gets activated. Where Multi-hop scheduling is available, the links which dropped due to not satisfying the conditions may be established even though they do not have line-of-sight path. After all the calculations described earlier are completed, a new matrix is created but this time only with dropped transmitters and receivers. Then the system checks whether there is logical path for a dropped transmitter to reach its intended receiver through a middle device, which is needed to relay the data traffic for transmitter to its intended receiver.

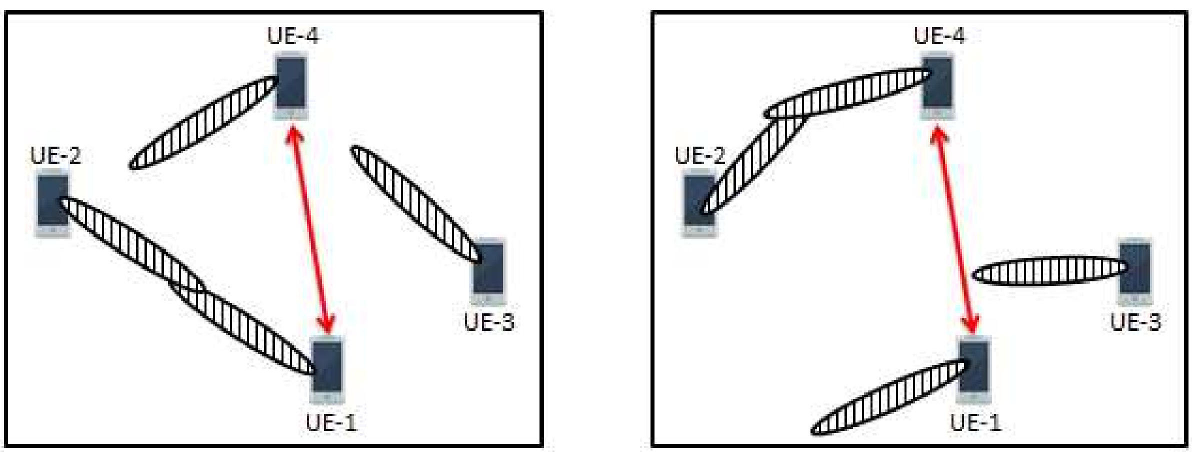

Figure 14: Multi-hop system.

Consider the system shown in Fig. 14, where the i^{th} and j^{th} timeslots are represented, respectively. Let us assume that UE-1 wants to connect to UE-4. In the i^{th} timeslot these two devices don't see each other and don't satisfy the conditions to establish a link. However, in the same timeslot, UE-1 and UE-2 are able to see each other and satisfy all the conditions for a successful communication link. In such a scenario, multi-hop algorithm allows UE-1 to send the data to UE-2 to be delivered to UE-4 in next timeslots. Then, after several timeslots, in j^{th} timeslot UE-2 and

UE-4 can see each other and satisfy the conditions as well. At this point, data can be transferred to desired destination. In a case that UE-1 don't see the desired destination device, but able to see each other with multiple other devices, the path selection algorithm is introduced in [5]. It should be noted that in multi-hop scenario, all UEs act as transceivers.

The proposed system provides one other important advantage called *hidden-beam problem*. In previously proposed systems, a Tx - Rx pair may fail in establishing a link due to high interference level at Rx side caused by another transmitter. This issue gets critical in dense areas especially. The proposed system provides better solution to this problem by making available angle-slots, multi-hop scheme and OFDM orthogonality.

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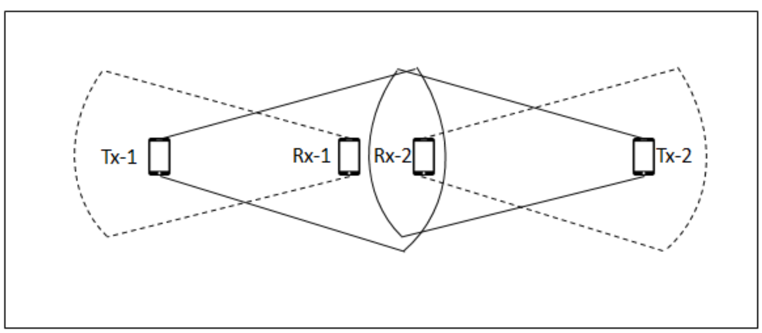

Figure 15: Hidden node problem.

5.1.4 Rate scheduling

In rate scheduling phase, according to the connection and relay decisions made in previous phases, by the use of wideband OFDM signals, the data rate for each communication link is decided.

5.1.5 Data transmission & acknowledgement

This phase of the time slot is where the data is being sent from transmitter to receiver. Please note that at this phase, the entire channel is being used and the proposed system mechanism ensures that as maximum as possible number of links can be scheduled simultaneously without interfering with each other.

CHAPTER VI

SIMULATION RESULTS

In this chapter of this thesis work, the results of the simulations performed on MATLAB are presented. The model that is described in the previous chapter is applied to a dense network with randomly positioned and pre-oriented N number of transmitters and N number of receivers in a 30 m x 30 m square area. During these simulations, N is chosen as 100 for the scenarios where the number of user is constant. The number of beam directions is taken as $K = 4$ to cover orthogonal directions and the beamwidth β is set to 30° or 60° for the cases where β is constant.

Consider a system where the algorithm doesn't allow any relay mechanism, but only Single-Hop where the beam angles change in each time slot. In this mechanism, all transmitters are paired with one receiver. The algorithm computes the corresponding SINR value for each geometrically possible link where the transmitter and the receiver are both able to see each other in one of their angular-slots. The system then computes link capacity and compares this value with pre-defined capacity threshold and allows data transmission for all those links that satisfies the threshold condition. At this point, the algorithm lists successful and dropped (failed) links as well. In other words, if there are nodes realizing interference from other users that would cause link capacity to drop less than pre-defined threshold, one of the nodes are dropped similar to CSMA mechanism. The algorithm for the Single-hop stage can be summarized as shown in Algorithm-1.

The first results are provided for only OpLinQ algorithm. Fig. 16 shows the link capacity against increasing beamwidth from 10° to 90° for five different links with different Tx - Rx distances. The results show that as beamwidth gets larger the

Algorithm 1 Single-Hop OpLinQ

initially assign random positions and priorities.
the transmitters send pilot signal to the receivers.
the receivers send echo information to the transmitters.
for i = 1:N, j = 1:i **do**
    calculate interference from j^{th} to i^{th} link
    compare i^{th} link capacity level with threshold.
    if $SINR_{i,j} > \gamma$ **then**
        list the i^{th} link as successful.
    else
        list the i^{th} link as failed.
    endif
    create the list of all successful and failed links.
endfor

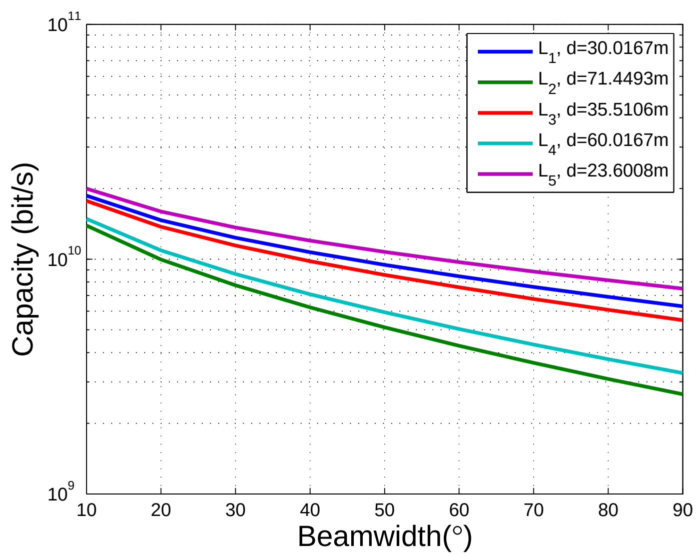

Figure 16: Capacity level of each link on a given transmit power and increasing beamwidth and distance.

channel capacity decrease for OpLinQ, since the antenna gains decrease. Also, it can be seen that as the distance gets longer between the Tx - Rx pair, the channel capacity also decreases for OpLinQ, since the received power drops significantly.

The results that are shown in Fig. 17 belong to the channel capacity for 5 links against increasing transmit power from 0.1 mW to 1 mW and beamwidth from 5° to 60°. As expected, an increase in transmit power provides higher channel capacity and as the beamwidth gets larger the channel capacity drops due to the decrease in gain.

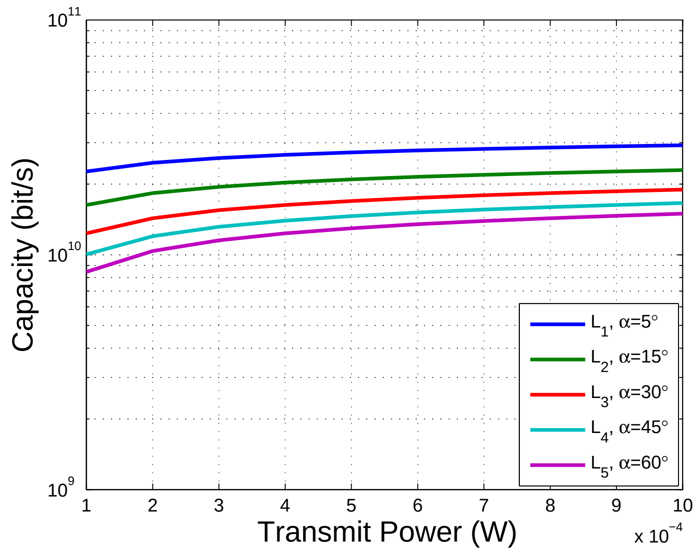

Figure 17: Capacity level of each link with increasing transmit power and beamwidth level.

In order to make compassion, a scenario where the system has all the same geometrical properties but only allows every desired link to communicate as long as the transmitter and the receiver see each other is created. In other words, this scenario doesn't require capacity threshold conditions to be satisfied. In the rest of this thesis work, this scenario is referred as "Full-interference".

Two different network performance metrics are defined. In the simulation studies, $C_i(t)$ denotes the channel throughput of the link L_i between Tx_i and Rx_i in timeslot t. The first performance metric $C_{min}(t_A)$ denotes the minimum successful link capacity for the overall network defined as follows:

$$C_{min}(t_A) = \min_{t \in [(t_A - 1)t_{Loc}, t_A t_{Loc}], i \in [1, N]} C_i(t) \tag{15}$$

The second performance parameter $C_{av}(t_A)$ denotes the average of the successful link capacities for all the links in the network defined as follows:

$$C_{av}(t_A) = \frac{1}{S(t_A)} \sum_{t=(t_A-1)t_{Loc}}^{t_A t_{Loc}} \sum_{i=1}^{N} C_i(t) \tag{16}$$

where $S(t_A)$ denotes the number of successful links in the network in the duration with the index t_A.

Fig. 18 represents the average minimum level of each 100 timeslots for full-interference scenario and OpLinQ with four different capacity threshold values. The simulation is performed with the parameters of N = 100, $\alpha = 60°$ and transmit power of 0.1 mW . In order to successfully simulate ultra-dense network, all users are randomly located in 30m x 30m area. With the careful examination of the results, it can be seen that the proposed system provides higher average minimum throughput level than full-interference scenario, since the strict threshold conditions of OpLinQ eliminates great portion of links with interference, which results in increase of overall system throughput dramatically.

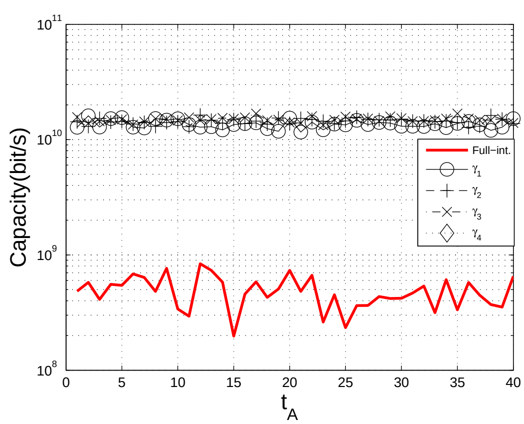

Figure 18: Comparison between average minimum of OpLinQ and full-interference scenario for each 100 timeslot for $\alpha = 60°$ and N = 100 in 30m x 30m area.

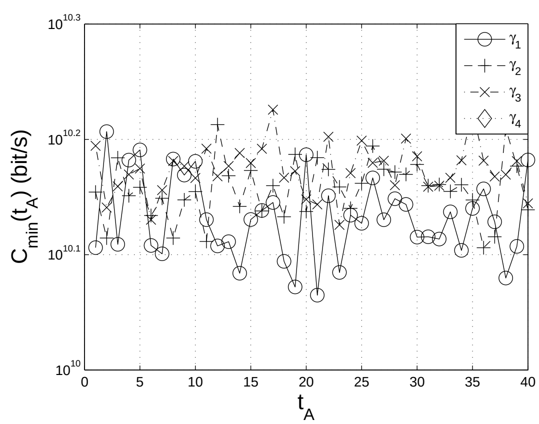

Figure 19: Average minimum of OpLinQ with 4 different threshold for each 100 timeslot for $\alpha = 60°$ and N = 100 in 30m x 30m area.

Fig. 20 represents the results that belong to the average channel throughput of successful users for each hundred timeslots for full-interference scenario and that of OpLinQ with 4 different threshold. Moreover, Fig. 21 presents the same results for only OpLinQ with four different thresholds. Again, the simulation is performed with the parameters of N = 100, $\alpha = 60°$ and transmit power of 0.1 mW. These results shows, as expected, as the threshold conditions gets higher, OpLinQ provides higher data rates than full-interference scenario. Also, the results proves that as the threshold level gets higher, the average data rate provided by OpLinQ also increases, since more interference gets blocked by the mechanism.

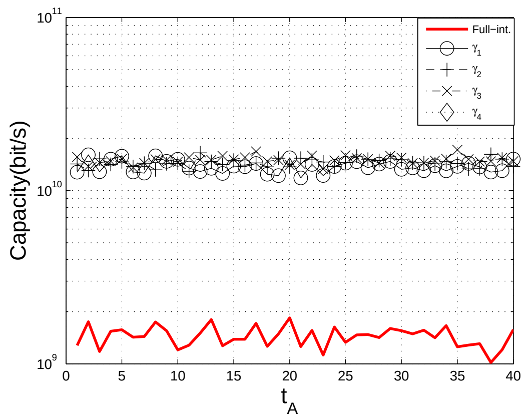

Figure 20: Comparison between average channel throughput of successful links of OpLinQ and full-interference scenario for each 100 timeslot for $\alpha =$ 60° and N=100 in 30m x 30m area.

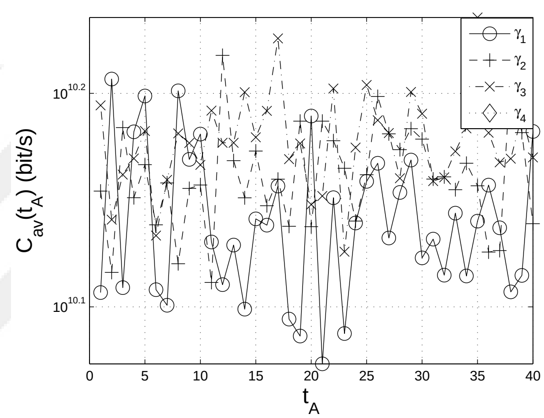

Figure 21: Average channel throughput of successful links of OpLinQ with 4 different threshold for each 100 timeslot for $\alpha = 60°$ and N=100 in 30m x 30m area.

In order to show the effect of beamwidth on the overall system performance, same simulations are repeated with narrower beamwidth as $\alpha = 30°$. Fig. 22 shows the results of the average minimum level of each hundred timeslots for full-interference scenario and OpLinQ with four different capacity threshold values, where the system parameters, again, set to N = 100 and transmit power of 0.1 mW. From this result and a comparison between Fig. 18, it can be said that as the beamwidth gets narrower and the gains gets higher, the gap between the minimum levels of OpLinQ and full-interference scenario gets smaller, since the interference level gets lower as it is harder for the users to see each other with narrower beamwidths.

In Fig. 24, the results that belong to the average channel throughput of successful

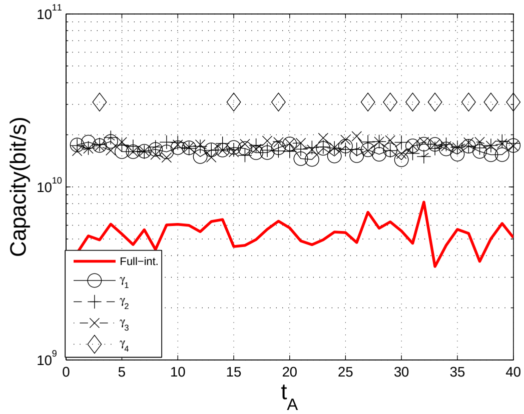

Figure 22: Comparison between average minimum of OpLinQ and full-interference scenario for each 100 timeslot for $\alpha = 30°$ and N = 100 in 30m x 30m area.

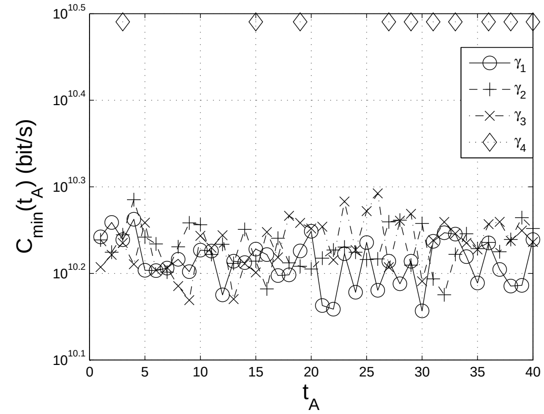

Figure 23: Average minimum of OpLinQ with 4 different threshold for each 100 timeslot for $\alpha = 30°$ and N=100 in 30m x 30m area.

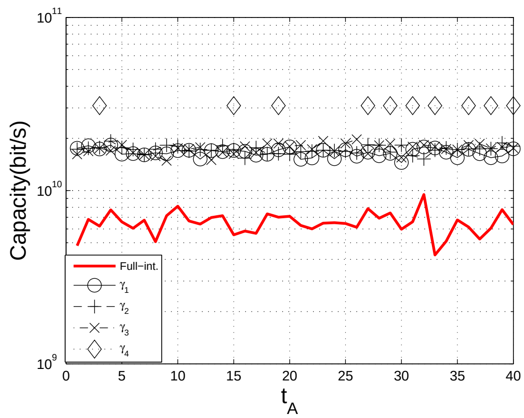

Figure 24: Comparison between average channel throughput of successful links of OpLinQ and full-interference scenario for each 100 timeslot for $\alpha = 30°$ and N = 100 in 30m x 30m area.

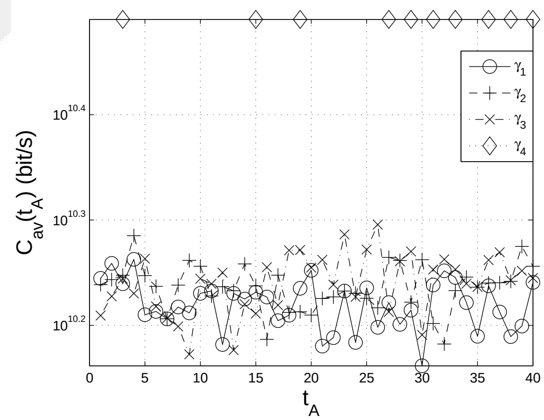

Figure 25: Average channel throughput of successful links of OpLinQ with 4 different threshold for each 100 timeslot for $\alpha = 30°$ and N=100 in 30m x 30m area.

users for each hundred timeslots for full-interference scenario that of OpLinQ with four different threshold is shown. This result also supports the fact that as the beamwidth gets decreased, the gap between the proposed system and full-interference scenario gets smaller. On the other hand, this figure confirms an important result. It can be seen that, as the threshold values gets larger and the conditions to establish a successful link gets harder, OpLinQ provides much higher data rates. With the narrower beamwidth and increased gains, only few links were able to pass the largest threshold and in that case, since other links are eliminated and interference level dropped dramatically, the proposed system provides much higher data rates and QoS for end users. Moreover, Fig. 25 presents the same results for only OpLinQ with 4 different thresholds.

CHAPTER VII

FUTURE WORK

In previous section, it is proven that the proposed system provides higher channel capacity rates against existing- methods in literature. In order to exploit the potential of mmWave communication systems potential even more, a Multi-Hop option can be easily adapted to the proposed method. Such system can be established by finding possible relay paths for the links that is listed as dropped in Single-Hop scenario by opportunistically making use of every UE available for Multi-Hop. An abstract algorithm for such system is summarized in Algorithm-2. With the multi-hop option, it is safe to believe that the efficiency of the proposed system would increase even more compared to those of in the literature especially in ultra-dense networks.

Algorithm 2 Multi-Hop OpLinQ

```
perform Single-Hop OpLinQ without checking the target receivers.
for all the transmitters with the indices i = 1 : N do
    if data is received then
      wait until the next time slot to relay the data to a random relay node.
      endif
endfor
for all the receivers with the indices i = 1 : N do
    if data is received then
        if the received data is not intended for the ith receiver then
        wait until the next time slot to relay the data to a random relay node.
        endif
      endif
endfor
```

Moreover, as the Industry 4.0 evolution has started to take its place, the communication between devices is much more important than ever. The proposed D2D mmWave communication system, can be applied in order to establish efficient and reliable communication between devices. Since majority of industrial devices would be placed relatively close to each other, mmWave protocols can be taken as a strong candidate to provide communication systems with desired data rates. The proposed method suggests a scheduling mechanism which includes prioritization of link and this feature could increase the efficiency of such a system, by taking the role of each device into consideration. Moreover, in a factory setting, the mobility of the devices would be very limited, even none for most of the cases and with the knowledge of other devices' exact location, a D2D or M2M communication system with mmWave feature could provide even higher data rates with a proper deployment.

CHAPTER VIII

CONCLUSION & DISCUSSION

Millimeterwave (mmWave) communication systems are highly considered for the next generation mobile communication systems since they promise a significant performance improvement in efficiency, once the major problems such as deafness and hidden-node problem are successfully addressed. In this thesis work, it is demonstrated that with the knowledge of existing protocols in the literature, there is an optimal way to exploit this huge potential of mmWave spectrum. In order to achieve this, an algorithm depends on an beam selection mechanism is proposed, which provides very low interference level then existing protocols in literature. With this angular mechanism, a novel connection scheduling mechanism is demonstrated. The link capacity results are presented for various scenarios where the proposed system is analysed in terms of transmit power, beamwidth and threshold. It has to be noted that, the results indicates that OpLinQ promises better channel quality and improved end user experience by providing higher data rates, but it also lets less number of links to communicate at the same time due to its threshold conditions.

In this work, it is proven that the proposed mechanism results higher capacity rates then already existing mechanism in literature. These results promise that Multi-Hop option would provide even better results for next generation communication systems, where the users are expecting much higher data rates as well as much better QoS. The results and theoretical analyses open a new research area for D2D mmWave communication systems, where both beam selection mechanism and relay mechanism can be combined together. In addition, potential research areas for future studies are given as multi-hop scenario and multi-disciplinary Industry 4.0 related works.

APPENDIX A

FRIIS' TRANSMISSION EQUATION

In this appendix, the derivation of Friis' transmission equation is presented. Consider two antennas placed with a distance of R and are in free space. Such a topology is represented in Fig. 26.

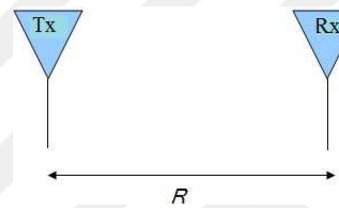

Figure 26: Topology

Assume that, an omnidirectional and lossless transmit antenna has a transmit power of P_T. The power density p on the receive antenna can be expressed as follows:

$$p = \frac{P_t}{4\,\pi\,R^2} \tag{17}$$

If the transmit antenna has an antenna gain in the direction of the receive antenna given by G_T, then the power density equation above becomes:

$$p = \frac{P_t}{4\,\pi\,R^2}\,G_T \tag{18}$$

Then, if the receive antenna has an effective aperture given by A_{ER}, the received power can be calculated with the following equation.

$$P_R = \frac{P_t}{4\,\pi\,R^2}\,G_T\,A_{ER} \tag{19}$$

Since the effective aperture for any antenna can be expressed as follows:

$$A_e = \frac{\lambda^2}{4\,\pi}\,G \tag{20}$$

The resulting received power can be written as below and this equation is known as Friis' transmission equation.

$$P_r = \frac{P_t\,G_r\,G_t\,c^2}{(4\,\pi\,R\,f)^2} \tag{21}$$

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