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# THESIS

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By:

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Theme:

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**Resource Allocation for Device-to-Device communications in future  
mobile networks (5G and beyond)**

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## **abstract**

The number of mobile users has increased at an unprecedented rate over the past ten years, overwhelming the cellular network core. Numerous technologies are being researched to advance to the next generation of cellular networks, dubbed "the fifth generation" (5G) and 5G beyond, in order to keep up with this expansion of cellular networks. One of those technologies claims to increase throughput overall, minimize latency, enhance spectral and energy efficiency, and offload the network core. The Device-to-Device (D2D) communication technology has claimed all of those claims. Direct connection between devices (D2D communication) excludes the Base Station (BS). D2D communication technology has numerous obstacles in achieving its goals. Throughput is maximized and interference is reduced when resources are allocated and power is controlled effectively. Within the context of 5G cellular networks, we study the joint power and resource allocation problem for D2D communication in this thesis. In this theses, we primarily utilize wireless channel data that exhibits slowly shifting large-scale fading to conduct spectrum sharing and power allocation. The overall ergodic capacity of all cellular user equipment (CUE) links is initially considered as the optimization target in order to maximize the overall throughput of CUE links while ensuring the reliability of each D2D link. Then, the expansion of the minimum ergodic capacity is measured to ensure a more consistent capacity performance across all CUE links. We utilized algorithms that are resilient to channel fluctuations and produce optimal resource allocation.

## **Keywords**

Cellular networks ,Device-to-device communication ,Ergodic capacity, Power allocation ,Resource allocation

## **Résumé**

Le nombre d'utilisateurs mobiles a augmenté à un rythme sans précédent au cours des dix dernières années, submergeant le cœur du réseau cellulaire. De nombreuses technologies sont étudiées pour passer à la prochaine génération de réseaux cellulaires, surnommée la cinquième génération (5G) et au-delà, la 5G, afin de suivre cette expansion des réseaux cellulaires. L'une de ces technologies prétend augmenter le débit global, minimiser la latence, améliorer l'efficacité spectrale et énergétique et décharger le cœur du réseau. La technologie de communication Device-to-Device (D2D) revendique toutes ces affirmations. La connexion directe entre les appareils (communication D2D) exclut la station de base (BS). La technologie de communication D2D se heurte à de nombreux obstacles pour atteindre ses objectifs. Le débit est maximisé et les interférences sont

réduites lorsque les ressources sont allouées et que la puissance est contrôlée efficacement. Dans le contexte des réseaux cellulaires 5G, nous étudions le problème conjoint de la puissance et de l'allocation des ressources pour la communication D2D dans cette thèse. Dans cette thèse, nous utilisons principalement des données de canaux sans fil qui présentent des évanouissements à grande échelle et à évolution lente pour effectuer le partage du spectre et l'allocation de puissance. La capacité ergodique globale de toutes les liaisons d'équipement utilisateur cellulaire (CUE) est initialement considérée comme la cible d'optimisation afin de maximiser le débit global des liaisons CUE tout en garantissant la fiabilité de chaque liaison D2D. Ensuite, l'expansion de la capacité ergodique minimale est mesurée pour garantir des performances de capacité plus cohérentes sur toutes les liaisons CUE. Nous avons utilisé des algorithmes résilients aux fluctuations des canaux et produisant une allocation optimale des ressources.

### **mots clés**

Réseaux cellulaires, communication d'appareil à appareil, capacité ergodique, allocation de puissance, allocation de ressources

### **ملخص**

ان زيادة عدد مستخدمي الهاتف المحمول بمعدل غير مسبوق على مدى السنوات العشر الماضية، أدى إلى زيادة العبء على الشبكة الخلوية الأساسية. حيث هذا الاخير حث الباحثين على البحث في العديد من التقنيات للتقدم إلى الجيل القادم من الشبكات الخلوية، والتي يطلق عليها اسم الجيل الخامس 5G وما بعده، وذلك لمواكبة هذا التوسع في الشبكات الخلوية. و من احد اهم هذه التقنيات هي الاتصال من جهاز الى جهاز ( D2D )، حيث انها تعمل على زيادة الإنتاجية بشكل عام و تقليل زمن الوصول، وتعزيز الكفاءة الطيفية والطاقة، وتخفيف عبء الشبكة.

تواجه تكنولوجيا الاتصالات D2D العديد من العقبات في تحقيق أهدافها. يتم تعظيم الإنتاجية وتقليل التداخل عندما يتم تخصيص الموارد والتحكم في الطاقة بشكل فعال. في سياق الشبكات الخلوية 5G، قمنا بدراسة مشكلة تخصيص الطاقة والموارد المشتركة للاتصالات D2D في هذه الأطروحة.

في هذه الأطروحة، نستخدم في المقام الأول بيانات القناة اللاسلكية التي تظهر تحولاً بطيئاً في الخبو واسع النطاق لإجراء تقاسم الطيف وتخصيص الطاقة. تعتبر السعة المريحة الإجمالية لجميع وصلات أجهزة المستخدم الخلوية (CUE) في البداية بمثابة هدف التحسين من أجل زيادة الإنتاجية الإجمالية لروابط CUE إلى أقصى حد مع ضمان موثوقية كل رابط D2D. بعد ذلك،

يتم قياس توسيع الحد الأدنى من السعة المرشحة لضمان أداء أكثر اتساقًا للسعة عبر جميع وصلات *CUE*. لقد استخدمنا خوارزميات تتسم بالمرونة في التعامل مع التقلبات وإنتاج التخصيص الأمثل للموارد.

### الكلمات المفتاحية

الشبكات الخلوية، الاتصالات من جهاز إلى جهاز، السعة الارجودية، تخصيص الطاقة، تخصيص الموارد

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<b>1G</b>	First generation.
<b>2G</b>	Second generation.
<b>3G</b>	Third generation.
<b>4G</b>	Fourth generation.
<b>5G</b>	Fifth generation.
<b>B5G</b>	beyond Fifth generation.
<b>6G</b>	Sixth generation.
<b>SINR</b>	signal-to-interference-plus-noise ratio.
<b>QOS</b>	quality-of-service.
<b>UUE</b>	uplink user equipment.
<b>3GPP</b>	third generation partnership project.
<b>MINLP</b>	mixed integer nonlinear programming.
<b>EE</b>	energy efficiency.
<b>PCRA</b>	power control and resource allocation.
<b>AMPS</b>	advanced mobile telephony system.
<b>LTE</b>	long-term evolution.
<b>IoT</b>	internet of things.
<b>eMBB</b>	enhanced mobile broadband.
<b>URLLC</b>	ultra-reliable low-latency communication.
<b>mMTC</b>	massive machine type communication.
<b>ITU</b>	international telecommunication union.
<b>NR</b>	new radio.
<b>TTN</b>	telegraph and telephone.
<b>SMS</b>	short message service.
<b>CDMA</b>	code division multiple access.
<b>GSM</b>	global system mobile.
<b>EDGE</b>	enhanced data rate for global evolution.
<b>UMTS</b>	universal mobile telecommunication system.
<b>HSPA</b>	high speed packet access.
<b>WiMAX</b>	wireless interoperability for microwave access.
<b>IP</b>	internet protocol.
<b>OFDM</b>	orthogonal frequency division multiplexing.

<b>OFDMA</b>	orthogonal frequency division multiple access.
<b>LAS-CDMA</b>	large area synchronied code division multiple access.
<b>IMT</b>	internatonal mobile telecommunication.
<b>UL</b>	uplink.
<b>DL</b>	downlink.
<b>FDD</b>	frequency division duplex.
<b>TDD</b>	time division duplex.
<b>CRS</b>	cell-specific reference signal.
<b>NSA</b>	non-standalone.
<b>SDN</b>	software defined networking.
<b>NFV</b>	network functional virtualiation.
<b>C-RAN</b>	cloud-based radio access network.
<b>RRU</b>	remote radio units.
<b>gNB</b>	5G nodeB.
<b>CPRI</b>	common public radio interface.
<b>SA</b>	services and systems aspects.
<b>CT</b>	core network and terinals.
<b>AOA</b>	angel of arrival.
<b>TOA</b>	time of arrival.
<b>TDOA</b>	time diffrence of arrival.
<b>GPS</b>	global positioning system.
<b>PRB</b>	physical resource block.
<b>SE</b>	spectral efficiency.

## General Introduction

New technology changed how individuals communicate with each other, particularly in wireless communication. Nevertheless, infrastructures continue to be a necessary component of cellular mobile networks. Cellular subscribers' communications are limited by base station (BS) coverage, which prevents direct contact between mobile devices. Despite being adjacent to one another, the traffic routing passes through the core network. Due to this limitation, there is limited potential data sharing between cellular mobile users, especially in light of the shift in personal computing from desktop personal computers (PCs) to portable PCs and finally to mobile devices. Mobile data traffic grew by over 30 Exabytes per month in 2020, which is eight times more than in 2015 due to the trend toward mobile equipment. By using appropriate network connectivity, innovative connection technologies can exchange data on-demand and scale the network's capacity.

A promising method that allows cellular mobile equipment to connect to one another directly without going via base stations or access points is device-to-device (D2D) communications. In a distributed setting, the D2D technique focuses on using the communication range of devices to enhance the signal for cellular mobile equipment. Cellular network services must function with D2D technology in order to complement one another. D2D planning requires careful consideration of a number of important factors, including mode selection, device detection, power and resource allocation, interference management, and security.

The fifth-generation (5G) and beyond 5G (B5G) cellular networks, which are the next generation, claim to support a large number of diverse users, high data rates, and low latency. D2D communication technology can assist in accomplishing those objectives because it is designed to increase cell radius, enhance network throughput, and offload network core. D2D communication is hampered, meanwhile, by the short battery life of devices and the constrained amount of usable spectrum. To address those problems, the researchers try to solve the power control and spectrum allocation problems in order to increase spectrum efficiency and decrease energy consumption. Traditional approaches have trouble solving the nonlinear spectrum allocation and power management problem

because it is constrained by many nonlinear constraints.

In this thesis, we suggest using By using graph theory, resources may be allocated effectively. Numerous optimization problems can be represented by graphs with nodes and arcs connecting the nodes. For example, by assigning the tasks to one group of nodes and the agents to another, it can be shown as a bipartite graph. The two sets of nodes will be connected by an arc if an agent is successful in finishing a task. Furthermore, in wireless radio resource allocation challenges, users that require spectrum resources and those that require communication resources might be represented by two different sets of nodes.

We examined the effectiveness of an enhanced power control strategy and channel allocation using a random D2D underlaid cellular network model. The study models the distance between D2D pairings at random in a variety of scenarios. In order to maximize its own D2D link rate, each D2D transmitter selects the transmission power level based on the channel circumstances, namely the distance-dependent path-loss between D2D pairs. also In order to maximize overall system data rate, We consider the possibility of resource sharing between the D2D links and a single cellular user.

## CHAPTER 1

# Introduction to 5G and Beyond

### 1.1 Introduction

Mobile communications services have increased rapidly during the past 40 years. Advanced Mobile Telephony System (AMPS), the country's first commercial cellular phone network, went into service in late 1983. Most people on the world utilize mobile communications services today, which are widely available. As of Q3 2019, there were 5.9 billion users and 8 billion subscriptions worldwide, according to the Ericsson Mobility Report [1]. More people have cellphone subscriptions overall than there are people on the world.

It's important to comprehend how mobile communications systems have evolved in order to comprehend how modern systems can now provide services at such an incredible scale. Since the introduction of the first generation (1G) of mobile communications standards in the 1980s, a new generation has arrived roughly every ten years. The main use case driving the development of mobile communications networks from the first generation (1G) to the third generation (3G) was mobile voice telephony. Mobile broadband data applications have since 3G taken center stage in the continued development of mobile communications systems. Mobile broadband data services are now being delivered via Long-Term Evolution (LTE), the fourth generation (4G) of mobile communications technologies. Although mobile voice telephony and mobile broadband data services continue to be the main applications of mobile communications systems, the Fourth Industrial Revolution and the Internet of Things (IoT) are beginning to drive additional development of mobile communications systems, including fifth-generation (5G) wireless access systems.

A greater variety of applications and use cases will be offered when 4G and 5G mi-

grate. Three types of usage and applications for the 5G era have been established by the International Telecommunication Union's Radio communication Sector (ITU-R): Massive machine type communications (mMTC), ultra-reliable low-latency communications (URLLC), and improved mobile broadband (eMBB). [2]. A new generation of mobile communications systems is required to achieve faster data speeds, decreased latency, more capacity, and more efficient spectrum use, even if the extension of LTE will be able to service a variety of usage scenarios and applications in the 5G era. A new generation of mobile communications systems is required [3]. To enable the wide variety of use cases and applications that are planned for the future of 5G, the fundamental enabling technology is the next generation wireless access technology known as New Radio (NR). This technology possesses these significant characteristics.

The intended scope of this chapter is further explained in the following parts. First, we give a summary of how mobile communications technologies have changed from 1G to 4G. then we detail about what 5G is by going over the primary technical requirements, the essential technological elements that make up the enhanced 5G capabilities. The 5G standardization process and important organizations that are necessary to define 5G are then discussed. An overview of 6G, the next-generation wireless access system, is given in the section that follows. We conclude the chapter by summarizing the information.

## **1.2 cellular networks generations (1G to 4G)**

In terms of subscribers and mobile technologies, the wireless sector has experienced astounding expansion in recent years [4]. There has been a significant transition from linear to mobile cellular telephony since the beginning of this century. Furthermore, data indicates that at the start of the previous decade, the number of mobile cellular users exceeded that of fixed line telephone systems by a factor of more than four. The necessity for efficient cellular network design and management was acknowledged by manufacturers and mobile network operators [5].

The rapid evolution of cellular technology from 2G to 4G and other technical breakthroughs increases the risk that services will have on the efficiency of networks [6]. There are now several planning scenarios due to the growth of 2G, 3G, and 4G networks in addition to 2.5G networks. In addition, consideration of network interoperability is still pending [7]. Figure 1.1 demonstrates the key variations between the first and fifth cellular

generations.

The analog cellular technologies of the first generation (1G), which initially appeared in the 1980s. In the Tokyo metropolitan area at first, Nippon Telegraph and Telephone (NTT) launched the country's first commercially viable cellular network (1G) in 1979. Second generation (2G) contains fundamental digital technologies with the addition of slower data and short messaging service (SMS) [8]. Global system for mobile communications (GSM) and code-division multiple access (CDMA2000) are the two main 2G technologies; while CDMA2000 is sometimes called a third generation (3G) technology due to its ability to meet the 144 kbps mobile throughput standard, GSM is the major 2G technology [9]. That being said, Enhanced Data Rates for Global Evolution (EDGE) and Enhanced Data Rates for GSM Evolution both satisfy this criteria. In the 1990s, there was access to 2G technology. The International Telecommunication Union (ITU) defined the 3G requirements, according to which digital networks have to provide throughputs of 144 Kbps for mobile speeds, 384 Kbps for pedestrian speeds, and 2 Mbps for indoor environments [10].

While wireless interoperability for microwave access (WiMAX) was also referred to as a 3G technology, the three primary 3G technologies are the Universal Mobile Telecommunications System (UMTS), High Speed Packet Access (HSPA), and CDMA2000 EV-DO (Evolution-Data Optimized). In the 2000s, the rollout of four-generation (4G) technology began [11].

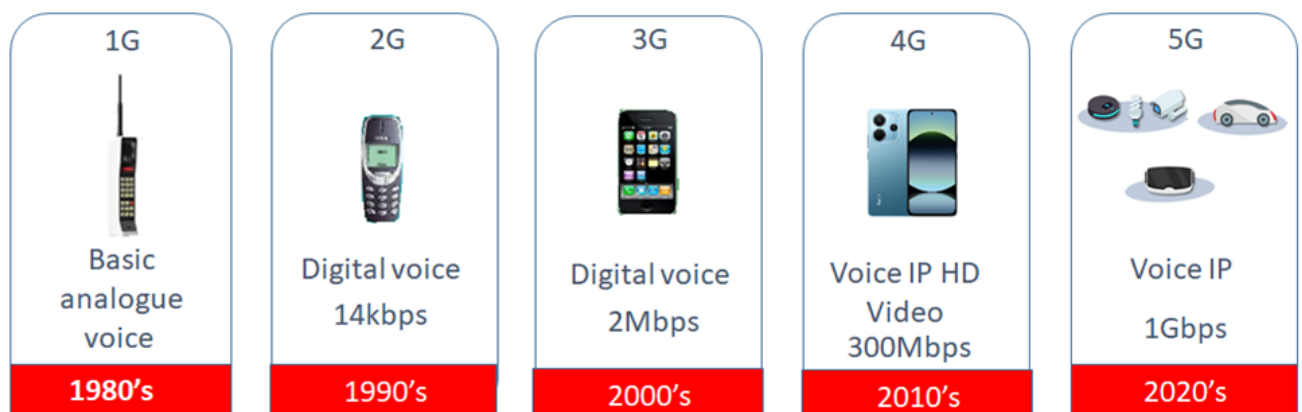


Figure 1.1: Evolution of the mobile networks.

Cellular networks' fourth generation (4G), which was based on an IP network tech-

nology, was declared back in the late 2000s. [12]. The primary objective of 4G is to provide high-speed, low-cost, high-capacity, high-quality, secure data and phone services as well as multimedia over IP and internet . The move to an IP system is being made to establish a single platform that unites all disparate technology. It can handle throughput speeds of up to 1Gbps [13]. The primary benefit of 4G is terminal mobility, which enables the provision of wireless services at all times and locations. The 4G technology integrates a variety of current and upcoming wireless technologies, including Orthogonal Frequency Division Multiplexing (OFDM), Local Multipoint Distribution Service (Network-LMDS) , Large Area Synchronized Code Division Multiple Access (LAS-CDMA), and Multi-Carrier Code Division Multiple Access (MC-CDMA) , to offer freedom of movement and constant roaming among heterogeneous technologies [14]. Long Term Evolution (LTE) and WiMAX are the next steps in the 4G evolution. The first potential 4G field trial was done in Japan towards the end of 2005 [15].

### 1.3 What is 5G?

The primary objectives of the 5G network are, as illustrated in Figure 1.2, to maintain a 1000-fold capacity gain and 10 Giga Bits per second delivered to a single user, as well as to ensure quality-of-service, higher spectral efficiency (SE), ultra-reliability, and improved battery life of devices. Only 5G and B5G networks are equipped to address these issues, and they will bring an improved mobile experience to everyone through low latency and ultra-reliable connectivity.

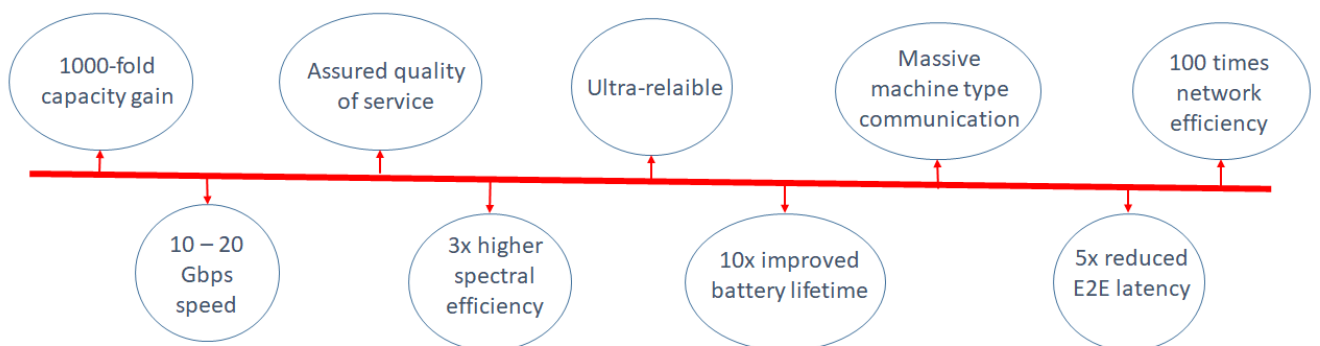


Figure 1.2: The prime objective of 5G

### 1.3.1 5G evaluation

In order to connect everyone and everything, everywhere, the 5G cellular network offers an extraordinarily adaptable and scalable network design. Many industries have poured money and energy into building 5G networks thus far, including DOCOMO, Huawei, ZTE, Qualcomm, Samsung, Vodafone, Ericsson, and Nokia Siemens Network. Three domains, which roughly correspond to 5G, are depicted in Figure 1.3. [16].

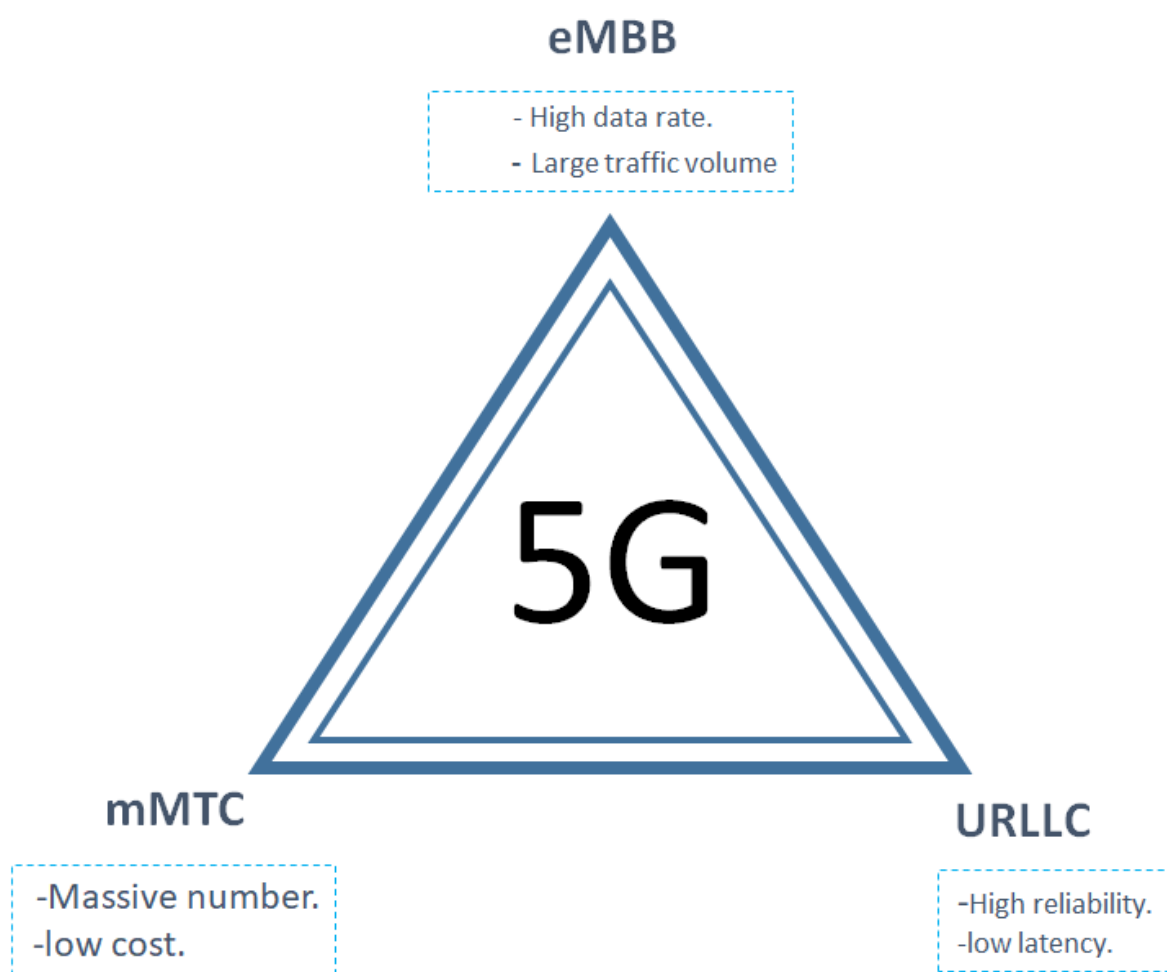


Figure 1.3: 5G usage scenarios.

**eMBB** : is the logical progression of broadband mobile data services, which are still The main uses of mobile communication technologies. It is characterized by a lot of traffic and high data rates . eMBB services include things like virtual and augmented reality, 4K streaming, and 3D HD media.5G will improve the user experience by offering eMBB applications high-speed mobile access. Enterprise communication services apps could also be included in eMBB.

**URLLC:** URLLC is compatible with services that demand extremely high reliability and fast response times. One such use is the wireless industrial control production operations and manufacturing . In intelligent transportation systems, high reliability and low latency will additionally be essential to safety and traffic control.

**mMTC :** IoT services with a high number of connected devices are referred to as mMTC. Smart homes, smart cities, smart utilities, and remote monitoring are some of the uses for IoT. One of the most important requirements for these kinds of services is that they support a large number of devices; other requirements consist of a long battery life, little gadget complexity, and a large coverage expansion. These services usually have low latency requirements, and every device usually meets them.

In the age of 5G, there are more scenarios and uses that might not strictly fit into the three classes of URLLC, eMBB, and mMTC. As an illustration, some operators are utilizing 5G as a home last-mile access solution. The expensive deployment of fiber connections to houses may be replaced with 5G fixed wireless access. Similar to the previous example, mobile voice telephony is still a crucial component of 5G mobile communications systems, although it does not necessitate high data rates, ultra-high dependability, or low latency[16].Table 1.1compares B5G to 5G in a quick discussion of the performance goals [17].

Table 1.1: Comparison of 5G and Beyond.

Attribute	5G	Beyond 5G
Types of application	-URLLC - Reliable eMBB - enhanced Mobile Broadband - massive Machine Type communication	-Hybrid emBB and URLLC -mMTC - URLLC
Types of Device	- Tablets and Smartphones - Drones - Wearable appliances - Sensor	-Tablets and Smartphones. - Drones - Sensors
Energy and SE	- $10\times$ (bps/Hz/m <sup>2</sup> /Joule)	- $100\times$ (bps/Hz/m <sup>2</sup> /Joule)
Data Rate	- 1 Giga bits	- 100 Giga bits
End-to-end Delay	- 5(ms)	1(ms)
Processing Delay	- 100(ns)	- 10(ns)
Spectrum	-MmWave - MmWave	-Sub-6GHz - Sub-6 GHz

### 1.3.2 5G Technical Requirements

MT-2020 is a project that ITU-R launched in early 2012 to create international mobile telecommunications for 2020 and beyond [18]. Table 1.1 provides a summary of the technical performance requirements for 5G as defined by IMT-2020.

Data rates will increase ten times over 4G with 5G. In particular, 5G is expected to deliver 10 Gbps peak data speeds in the uplink (UL) and 20 Gbps peak data rates in the downlink (DL). In a densely populated area, 5G can support user-experienced data rates of 50 Mbps in the UL and 100 Mbps in the DL (at the five percentile). 5G will provide a significantly improved mobile broadband experience because to the drastically increased data rates.

5G spectral efficiency is expected to be significantly greater, with peak spectral efficiency reaching 30 bps/Hz in the DL and 15 bps/Hz in the UL. For eMBB, different contexts can support different user spectral efficiency. For instance, 5G can enable user spectral efficiencies of 0.12 and 0.045 bps/Hz in the DL and UL, respectively, in rural areas, whereas 0.3 and 0.21 bps/Hz can be achieved in the DL and UL, respectively, in indoor hotspots. Consequently, an indoor hotspot's DL area traffic capacity can approach 10 Mbps/m<sup>2</sup>. In comparison to 4G, 5G spectral efficiency has increased by three times overall.

The user plane latency of 5G is anticipated to be 1 ms, a ten-fold reduction over 4G user plane latency. The significantly enhanced latency performance can satisfy the demanding latency needs of autonomous transportation and industrial IoT. Furthermore, 5G promises significantly better performance and reliability. It is anticipated that in an urban macro environment, there is a 99.999 chance of successfully transmitting a 32-byte layer 2 protocol data unit in 1 ms with good channel quality at the coverage edge.

Peak spectral efficiency for 5G is predicted to be substantially higher, hitting 15 bps/Hz in the UL and 30 bps/Hz in the DL. For eMBB, various contexts can support various user spectral efficiency. For instance, 5G can support user spectral efficiencies of 0.045 and 0.12 bps/Hz in the UL and DL, respectively, whereas indoor hotspots can achieve user spectral efficiencies of 0.21 and 0.3 bps/Hz in the UL and DL, respectively. As a result, an indoor hotspot's Traffic capacity in the DL area can exceed 10 Mbps/m<sup>2</sup>. Overall, 5G's spectral efficiency outperforms 4G by a factor of 3.

The user plane latency of 5G is predicted to be 1 ms, which is a 10x improvement

over that of 4G. The significantly increased latency measurement can satisfy the strict latency specifications of autonomous transportation and industrial IoT. Additionally, 5G promises significantly higher dependability and performance. The success probability of transmitting a 32-byte layer 2 protocol data unit in coverage edge channel quality within 1 ms is expected to reach 99.999 in an urban macro setting.

Mobility performance is anticipated to be greatly improved with 5G. The mobility interruption time will be 0 ms. A quality of service that is acceptable for a mobility speed of up to 500 km/h can be supported by 5G.

One million devices per square kilometer of connection density is anticipated for 5G. The requirements of mMTC scenarios can be met with ease because to 5G's higher capacity. Another important factor is energy use. We expect 5G to have a high network energy consumption since it supports a high sleep ratio and a long sleep time.

### **1.3.3 Technology Components**

5G will completely restructure the mobile communications system in order to create networks that are far more efficient and to make new services, ecosystems, and sources of income possible. From 1G to 4G, the majority of mobile communications technologies were radio-focused.

### **1.3.4 Radio Access Network**

NR is a brand-new wireless access technology that was created by 3GPP, a multinational organization for the development of mobile communications standards. The basis for 5G radio access networks is NR [19]. The following list summarizes important NR features:

- **Spectrum flexibility:** millimeter wave to sub-1 GHz are among the bands in which NR may operate. 5G NR is the first mobile communications technology to enable the utilization of millimeter wave bands. Both the sub-6 GHz spectrum shortage and 5G's multiple gigabit-per-second traffic speeds may be supported by large quantities of millimeter wave spectrum. Sub-6 GHz frequency bands are where 5G, like previous generations of mobile communications technologies, must function in order to offer wide field coverage. 5G NR may leverage both low (sub-6 GHz) and high (millimeter wave) frequency bands to complement one other. This allows for more

Table 1.2: Summary of 5G key technical requirements

Metric	5G target	Usage scenario
Peak data	rate DL: 20 Gbps; UL: 10 Gbps	eMBB
Five percentile user experienced data rate	DL: 100 Mbps; UL: 50 Mbps	eMBB: dense urban
Peak spectral efficiency	DL: 30 bps/Hz; UL: 15 bps/Hz	eMBB
Five percentile user spectral efficiency	DL: 0.3 bps/Hz; UL: 0.21 bps/Hz	eMBB: indoor hotspot
	DL: 0.225 bps/Hz; UL: 0.15 bps/Hz	eMBB: dense urban
	DL: 0.12 bps/Hz; UL: 0.045 bps/Hz	eMBB: rural
Average spectral efficiency per transmission reception point	DL: 9 bps/Hz; UL: 6.75 bps/Hz	eMBB: indoor hotspot
	DL: 7.8 bps/Hz; UL: 5.4 bps/Hz	eMBB: dense urban
	DL: 3.3 bps/Hz; UL: 1.6 bps/Hz	eMBB: rural
Area traffic capacity	DL: 10 Mbps/m <sup>2</sup>	eMBB: indoor hotspot
User plane latency	4 ms	eMBB
	1 ms	URLLC
Control plane latency	20 ms	eMBB/URLLC
Connection density	1,000,000 devices per km <sup>2</sup>	mMTC
Success probability	99.999%	URLLC: urban macro
Normalized channel link data rate	UL: 1.5 bps/Hz for mobility speed up to 10 km/h	eMBB: indoor hotspot
	UL: 1.12 bps/Hz for mobility speed up to 30 km/h	eMBB: dense urban
	UL: 0.8 bps/Hz for mobility speed up to 120 km/h	eMBB: rural
	UL: 0.45 bps/Hz for mobility speed up to 500 km/h	eMBB: rural
Mobility interruption	time 0 ms	eMBB/URLLC

focus on low band coverage while still taking advantage of the speed and capacity advantages associated with employing high bands.

- Duplex possibilities that are flexible: NR offers dynamic TDD, semi-statically configurable UL/DL, frequency division duplex (FDD), and time division duplex (TDD) with flexible duplex options. While spectra allocations are usually coupled in low-frequency bands, TDD is more commonly employed in higher-frequency bands where spectra allocations are unpaired. Large over-the-rooftop cells can effectively handle inter-cell interference issues with semi-static TDD. 5G NR additionally provides dynamic TDD capability, whereas 4G LTE only supports FDD and semistatic TDD. Dynamic TDD offers the ability to dynamically distribute radio resources to small/isolated cells utilizing TDD spectrum in order to adapt to variations in UL/DL traffic.
- Ultra-lean architecture: With its ultra-lean architecture, NR lowers the amount of always-on transmissions. As an example, think about the generation of NR reference signals. The NR reference signals are available on-demand whenever possible, and their frequency and temporal distributions can be altered to best suit requirements while minimizing overhead. There are several uses for the cell-specific reference signals (CRS), which are always present in LTE. Transmission of NR reference signals can be extremely sparse when demand is low. 5G NR's ultra-lean architecture leads to lower interference and higher network energy efficiency.
- Forward compatibility: New technologies and applications can be introduced more easily thanks to NR's high degree of forward compatibility in design. First, NR can specify reserved radio resources that aren't allowed to be used for transmission. Resources are left empty through reservation, making them usable for prospective extensions. Second, radio resources that can be configured or scheduled are limited in terms of physical signals and channels. Backward compatibility and flexibility are both produced by this. Thirdly, always-on transmissions are reduced by NR. These forward compatibility designs are evidently in line with the ultra-lean design tenet. A high level of forward compatibility is produced by the design's high degree of flexibility and the on-demand approach.
- Support for low latency: In NR, latency optimization has been a key factor. Many

tools have been implemented in NR to reduce latency. For example, "mini-slot" transmission is supported by NR; it starts at any OFDM symbol and continues only as long as the number of symbols needed to establish the connection. Furthermore, NR supports control signaling and frontloaded reference signals that are inserted at the beginning of the transmission. Consequently, a device does not have to wait for a buffer to fill before processing the received data. In addition to the physical layer, certain enhancements have been made to higher layer protocols to provide lower latency.

- **Advanced antenna technologies:** NR greatly improves the ability to enable the use of several antenna elements for both transmission and reception, enabling the deployment of huge MIMO systems in sub-6 GHz frequency ranges and beamforming in millimeter wave bands. Up to eight MIMO layers in the downlink and four MIMO levels in the uplink can be spatially multiplexed using an NR device. The addition of twelve orthogonal demodulation reference signals (DMRS) greatly expands the multi-user MIMO capacity. Analog beamforming, digital beamforming, or a combination of the two is provided by NR through careful channel, signal, and procedure preparation. In order to support beamforming operations in the millimeter wave ranges, NR incorporates beam management techniques such as beam selection and beam-failure recovery. NR allows the transmission of phase tracking reference signals (PTRS) to help equipment handle the higher phase noise power in millimeter wave bands.
- **Effective coexistence with LTE:** NR offers capabilities to do so. The non-standalone (NSA) option enables NR to concentrate on user plane capabilities while utilizing the current LTE network for control plane operations during initial NR deployment. The dynamic spectrum sharing between NR and LTE is made possible by NR, which facilitates the potential of NR and LTE carriers having frequency overlap. This makes the transition from LTE to NR easier. Solutions like the ability of NR physical downlink shared channels to map around LTE CRS and the potential for flexible downlink control channel, initial access related reference signal, and data channel placements to minimize collisions with LTE reference signals are suggested in order to facilitate this type of operation. When using high frequency bands,

NR enables the employment of a so-called supplementary uplink (SUL), which is a low-band addition to the cell's uplink. Another feature that NR provides is a supplementary downlink (SDL). For instance, this can be used to downlink-only spectrum.

### 1.3.5 Core Network

In order to adapt to a range of services with different performance requirements in the 5G era, 3GPP has also built a new 5G core network (5GC) in addition to a new radio access network. 5GC is responsible for the development of end-to-end connections, mobility management, authentication, and charging. 5GC's service-based architecture prioritizes services over nodes [20]. By separating the essential network hardware from the software functionalities, 5GC offers end-to-end freedom. Software-defined networking (SDN), network slicing, cloud-based radio access networks (C-RAN), and network functional virtualization (NFV) are used to do this.

- SDN distinguishes between network forwarding and control functions. Through this separation, actual networking resources like routers, switches, and gateways are abstracted and network control is made directly programmable. The physical networking resources' configuration and management can be shifted to central data centers. One distinctive aspect of 5GC is the division of user plane functions from control plane functions. It makes SDN adoption easier by enabling separate scalability, user plane , and Flexible control plane deployments and evolution .
- NFV virtualizes every aspect of networking, including network forwarding, independent of the hardware it uses. Instead of requiring bespoke hardware, a virtualized network function can run on commercially available hardware. NFV can enable the balance of loads, scalability, and upgrades and help to lower the cost of network improvements by enabling the instantiation of network functions on-demand. NFV deployments are made possible by 5GC's architecture to include virtualized, software-based network services.
- Network slicing enables the division of a single common physical network into several virtual networks. A network slice is a specific type of virtual network that has segregated capabilities to support a certain type of service or client. Network slicing,

a crucial component of 5G, makes it possible to accommodate a variety of services with different performance needs. The resources allotted to a network slice depend on the needs of the service. For instance, an eMBB network slice must have high bandwidth, whereas a network slice for URLLC must have low latency and good reliability. The modularized function design of 5GC may make flexible and efficient network slicing feasible.

- The C-RAN architecture uses virtualization and centralized processing units and is based on cloud computing. Cloudification can make it easier to manage network slices, which will improve support for the diverse range of 5G services. By supporting SDN and NFV in 5G deployments, 5GC naturally promotes cloudification and permits the instantiation of a network function that has been virtualized on cloud infrastructure.

### **1.3.6 Backhaul and Fronthaul**

Backhaul connects the radio access network to the core network. More capacity, reduced latency, and significantly greater data rates are required of 5G compared to previous generations of mobile communications systems. Because of this, 5G backhaul must be able to satisfy the technological requirements of 5G and should not constitute a bottleneck for 5G systems. There are two types of backhaul: wireless and wired. Fiber is the most popular kind of wired backhaul. Fiber optics can provide 5G backhaul with excellent reliability and large capacity. For instance, although fiber backhaul is often considered a default option by many operators, the cost of building it in suburban and rural areas may be a problem.

For 5G networks, wireless backhaul is an appealing realistic alternative, particularly in cases where installing wired backhaul is prohibitively expensive. From around 6 to 86 GHz (and even higher frequencies that are being researched) may be used for microwave backhaul. The microwave backhaul can be employed in a variety of settings, including sparsely populated cities and remote places, thanks to the wide frequency range. Beyond terrestrial, wireless backhaul may be used. Satellite technology and high-altitude platform systems (HAPS) might also be used for 5G backhaul. By providing backhauling to locations that are challenging for terrestrial backhaul to reach, they can supplement it.

Fronthaul links the base station's remote radio units (RRU) to the centralized radio

controllers. The 5G NodeB (gNB) logical architecture is divided into two sections called CU (central unit) and DU (distributed unit). A new interface known as F1 links the CU and DU. A fronthaul network must be able to satisfy the demanding requirements of 5G, which include high data speeds, low latency, and enormous capacity needs. The demands for fronthaul latency and bandwidth increase with the degree of centralization of operations. The traditional fronthaul based on the common public radio interface (CPRI) is unable to meet the 5G technical standards. The 5G fronthaul capabilities will be improved by the enhanced CPRI (eCPRI), which has reduced latency and increased bandwidth efficiency and capacity. Because eCPRI allows beamforming computation to be moved from the baseband to the radio, it can facilitate the implementation of massive MIMO in 5G.

### 1.3.7 5G Spectrum

A broad spectrum of frequencies can be used by 5G NR to function. Each band of the spectrum has distinct properties. Both the newly designated 5G frequency bands and the frequency bands that were repurposed from the spectrum that was utilized by earlier generations of mobile communications systems are compatible with NR. To maximize performance and maximize the value of spectrum assets, a service provider should mix and balance the use of low-band, midband, and high-band spectrum.

- Low-band spectrum is that which is below 1 GHz. Low-band spectrum is effective at providing broad and deep indoor coverage because of the favorable propagation characteristics. Low-band spectrum has relatively narrow channel bandwidths (e.g., 20 MHz).
- Mid-band spectrum ranges between 1 and 7 GHz. In the mid-band spectrum, channel bandwidths of 50 to 100 MHz are feasible. Networks with large capacity, low latency, and high data rates can be supported by wide bandwidths. Compared to high-band spectrum, mid-band spectrum offers better indoor and wide-area coverage. Thus, the mid-band spectrum provides a reasonable balance between latency, capacity, coverage, and data flow.
- High-band spectrum is found above 24 GHz in the millimeter wave range. Channel bandwidths of up to 400 MHz are conceivable in high-band frequency. Wide-

bandwidth spectrums can offer extremely high data rates and extremely huge capacity. High bands are useful for enabling high-throughput and low-latency services in localized dense deployments. However, due to millimeter wave propagation characteristics, it is challenging to offer widespread coverage utilizing only high-band bandwidth.

To achieve the strict technological requirements, 5G networks need a lot more spectrum resources. IMT frequency bands are located and coordinated by ITU-R for spectrum harmonization. The newly identified frequency ranges include the 3.5 GHz band in the mid-band spectrum and the 600 MHz and 700 MHz bands in the low-band spectrum. In order to facilitate equipment scale-up and device global roaming, ITU-R seeks to define a basic set of bands.

New operating bands for NR, such as paired bands for FDD and unpaired bands for TDD, are still being defined by the 3GPP. Additionally, unpaired SDL and SUL bands exist, which are meant to be used in conjunction with other bands. In Release 15, the NR frequency bands are separated into two frequency ranges (FR):

- FR2: millimeter wave, or the range between 410 MHz to 7.125 GHz [21].
- FR1: 24.25 and 52.6 GHz [22]. The "n" prefix is used to define NR operating bands, which have numbers ranging from n1 to n512. In FR1, the NR bands fall between n1 and n256, while in FR2, they fall between n257 and n512. Band N261 is an unpaired band in the 28 GHz frequency range for TDD with uplink and downlink frequency ranges of 27.50-28.35 GHz; band N71 is a paired band in the 600 MHz frequency range for FDD with uplink frequency range of 663-698 MHz and downlink frequency range of 617-652 MHz.

#### **1.4 5G Standardization**

The standardization of mobile communications is based on agreement among all pertinent parties. Global standards are essential to the success of mobile technology, as demonstrated by the history of mobile communications networks. Global roaming is made possible by globally standardized mobile technology, which also provides compatibility, global interoperability, and quality. As a result of economies of scale, the technology is

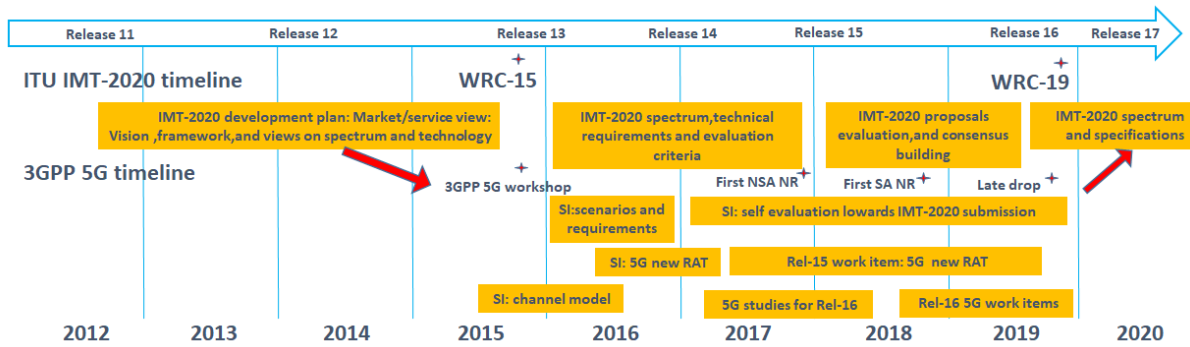


Figure 1.4: 5G standardization timeline

also more reasonably priced. However, the standardization processes are very complicated, involving groups that establish standards, international and regional regulatory organizations, national governments, and business forums.

ITU and 3GPP are the two key organizations that define 5G in terms of standardization. ITU is one of the United Nations’ specialized agencies for information and communication technologies. ITU’s primary responsibilities for 5G include worldwide spectrum regulation and establishing 5G standards. A global standard-development body for mobile communications is called 3GPP. Its core members are seven regional telecommunications organizations from Asia, Europe, and North America.

The primary 5G standardization initiatives in ITU and 3GPP are described in the next two sections, respectively. A high-level timeline for 5G standardization can be found in Figure 1.4.

### 1.4.1 ITU 5G Activities

ITU is divided into three sectors: ITU-R for radio communication, ITU-T for telecommunication standards, and ITU-D for telecommunication development. The ITU-R oversees satellite orbits and radio spectrum. ITU-R’s goal is to ensure that all radio communication services use the radio spectrum in a way that is reasonable, equitable, efficient, and cost-effective. The global radiocommunication conferences (WRC), which are held every three to four years, are one of ITU-R’s primary activities. ITU-R research groups’ recommendations are approved by ITU-R. ITU-R currently has six study groups:

- Study group 1: Spectrum management.
- Study group 3: Radiowave propagation.

- Study group 4: Satellite services.
- Study group 5: Terrestrial services.
- Study group 6: Broadcasting services.
- Study group 7: Science services.

Within each research group, task groups (TGs) and working parties (WPs) are established to carry out certain studies. The overall radio system components of IMT systems are under the jurisdiction of ITU-R study group 5's working party 5D (WP 5D). Currently, the umbrella name IMT includes 3G, 4G, and 5G mobile communications technologies, respectively, which are referred to as IMT-2000, IMT-Advanced, and IMT-2020. WP 5D monitors the radio interface standards, or RSPC, but does not provide technical requirements. There are a number of radio interface technologies (RITs) with each iteration of IMT. The RSPC includes summaries of each RIT as well as references to the in-depth specifications created and updated by the relevant standards developing bodies.

IMT for 2020 and beyond is an initiative that was launched by ITU-R WP 5D in the beginning of 2012. This paved the way for global 5G research initiatives. The framework and overarching goals of IMT's future development for 2020 and beyond are described in Recommendation ITU-R M.2083 [18]. Report ITU-R M.2370 [23] examines IMT traffic growth, while Report ITU-R M.2320 [24] examines technology trends, Report ITU-R M.2376 [25] examines the technical viability of IMT between 6 and 100 GHz, and the advice considers user and application trends as well as spectrum implications. The recommendation emphasizes how crucial it is for IMT to keep advancing the market for information and communications technology, global connection, closing the digital divide, new educational opportunities, energy efficiency, social change, and new forms of art and culture. The recommendation lists numerous IMT usage scenarios, such as eMBB, URLLC, and mMTC, that are projected for 2020 and beyond. To support the anticipated use cases, the guideline expects a broad range of IMT-2020 capabilities.

At WRC 2015 (WRC-15), the spectrum for IMT was considered. WRC-15 has declared the 700 MHz band (694–790 MHz) to be a globally harmonised frequency for the delivery of more mobile broadband capacity. Furthermore, frequency bands in the L-band (1427-1518 MHz) and lower C-band (3.4-3.6 GHz) were discovered. More spectrum

needs to be discovered for IMT in the bands above 6 GHz because there is a shortage in the sub-6 GHz frequency range. Consequently, WRC15 agreed to include an agenda item (1.13) to identify the frequency bands that fall between 24.25 and 86 GHz in the 2019 WRC calendar.

Following WRC-15, WP 5D continued to work on IMT-2020's spectrum arrangements, technical performance specifications, and evaluation criteria. In 2017, WP 5D released three reports:

- The Minimum Technical Performance Requirements of IMT-2020 Candidate Radio Interface Technologies are described in Report ITU-R M.2410 [26].
- The Report ITU-R M.2411 [27] offers a thorough explanation of the service, spectrum, and technical performance requirements for the IMT-2020 candidate radio interface technologies in addition to the assessment standards and submission guidelines for creating recommendations and reports on IMT-2020.
- In the Report ITU-R M.2412 [28], the standards, procedure, and methodology for assessing the IMT-2020 candidate radio interface technologies are detailed. WP 5D hosted a workshop on "IMT-2020 Terrestrial Radio Interfaces" in October 2017. The event included information on the IMT-2020 standardization process and potential proponents of IMT-2020 technology. Independent evaluation groups also gave presentations outlining their proposed activities.

Proponents of IMT-2020 technology submitted their ideas between 2018 and 2020, and they were evaluated by impartial external review groups.

High frequency millimeter wave spectrum in the frequency ranges of 24.25-27.5 GHz, 37-43.5 GHz, 45.5-47 GHz, 47.2-48.2, and 66-71 GHz was made accessible for 5G in a significant way at WRC 2019 (WRC-19). Following the WRC-19, a total of 17.25 GHz of spectrum was designated for IMT.

The full IMT-2020 process is anticipated to be completed in 2020. The primary outcome will be the release of a new ITU-R Recommendation with comprehensive specifications for the IMT-2020 radio interfaces.

### 1.4.2 3GPP 5G Standardization

Technical specifications for mobile technologies are written by 3GPP. The standardization process is consensus-based and driven by contributions. The whole 3GPP effort is coordinated by the project coordination group (PCG). Three technical specification groups (TSGs)—TSG RAN (Radio Access Networks), TSG SA (Services and Systems Aspects), and TSG CT (Core Network and Terminals)—are responsible for carrying out the specification work. Four overlapping, iterative steps typically make up the standardization process:

- The service needs are specified in stage 1.
- In stage 2, the architecture is defined to support the service requirements, including reference points and interfaces.
- In stage 3, the particular protocol specifications for the established architecture are created.

Test specifications are defined in stage four. Each edition of the 3GPP specifications has its own section. Each release includes a number of features that are specified in approved work items.

While ITU started defining IMT-2020, 3GPP began work on 5G. The official launch of 3GPP's 5G NR development took place during the TSG RAN 5G workshop in September 2015. During this session, it became increasingly clear that 5G would include a new, non-backward-compatible radio access technology. In order to ensure that the new radio access technology could handle any new use cases into two phases, it was emphasized during the workshop that it should have forward compatibility:

- Phase 1 would be completed by the second half of 2018 by the time 3GPP Release 15 was released. It was underlined that in order to facilitate early 5G deployments, eMBB should take center stage at this point.
- By the end of 2019 (i.e., 3GPP Release 16), Phase 2 would be finished to satisfy all specifications and use cases. The IMT-2020 standard might then be submitted to the ITU by the 3GPP.

Additionally, a study item on channel modeling for frequencies up to 100 GHz was approved by the 3GPP TSG RAN 5G workshop. In order to evaluate potential solutions for new radio access technologies that would utilize new spectrum—specifically millimeter wave—this study built channel models. 3GPP TR 38.900 [29], which details the channel models for frequencies ranging from 6 GHz to 100 GHz, contains the investigation’s findings. A new 3GPP TR 38.901 [30] was later developed to capture the channel models for frequencies between 0.5 GHz and 6 GHz as well as those between 6 GHz and 100 GHz.

In December 2015, TSG RAN70 approved a new study item that concentrated on creating NR requirements and scenarios as a result of the 3GPP TSG RAN 5G workshop. 3GPP TR 38.913 [31], which describes the needs, scenarios, and critical performance indicators for the next-generation access technologies, contains the study’s findings.

In March 2016, TSG RAN71 authorized the new radio access technology study item. Examining the technological factors that must be considered for NR was the aim of this study. The results of the study are documented in 3GPP TR 38.912 [32], which covers all the RAN aspects of the technology components. In March 2017, the 3GPP authorized a work item for NR standards as part of Release 15 at TSG RAN75 after the investigations. NSA NR was introduced at this RAN plenary conference, and 3GPP agreed to speed up the 5G NR schedule so that it could be finished by December 2017, but SA NR would still be finished by June 2018 as previously planned. To enable early, widespread 5G testing and deployments, the 5G NR timeline was expedited. An interim objective was achieved in December 2017 with the acceptance of the NSA NR standards. The SA version was finished in June 2018. The last action for Release 15 was a late drop, which was completed in March 2019.

A significant accomplishment was the completion of the Release 15 NR standards. While URLLC was addressed to some extent, eMBB was the primary focus of NR in Release 15. A portion of the ITU 5G standards can be satisfied by the set of Release 15 specifications. It also serves as the foundation for additional 5G NR development. Release 16 of the 3GPP continues NR evolution in the direction of more comprehensive standards that can fully satisfy all ITU 5G requirements. The 3GPP utilizes Release 16 for submissions for IMT-2020. Enhancements to vehicle-to-everything (V2X), industrial IoT, dual connectivity and carrier aggregation, URLLC enhancements, MIMO enhancements, integrated access, backhaul and positioning and unlicensed operation, UE power

conservation, cross-link interference handling, and remote interference management are some of the major work items for Release 16. Additionally, the 3GPP started a number of research to expand the scope of 5G NR's applicability, such as utilizing frequencies outside of 52.6 GHz and nonterrestrial radio access (mainly satellites).

In order to prepare for the IMT-2020 submission, the 3GPP conducted a study on self-evaluation in addition to preparing the 5G NR specification. The study looks at the evaluations of two 5G submissions: one is a single RIT for NR only, while the other is a group of RITs that include both NR and LTE. The study's results were described in full in 3GPP TR 37.910 [33], which also contained evaluations with respect to the ITU-R's technical performance, spectrum, and service needs. According to the analysis, the NR RIT and the RIT collection can both satisfy the IMT2020 requirements.

## **1.5 What Will 6G Look Like?**

Research communities have lately begun to consider the next generation of mobile communication systems, often known as 6G systems, as the 5G NR specification matures. Even though 6G is still in its infancy, this section seeks to give an outline of its goals, difficulties, and major enabling technologies. While this overview offers some unique perspectives for 6G, it also shares certain concepts with [34] [35] .

### **1.5.1 The 6G Vision**

What will 6G entail? It might be argued that consumers will be able to access intelligent and tailored (or task-dependent) services at any time and wherever thanks to 6G technologies. In homes, cars, buildings, factories, cities, and other surroundings, there will be billions of wireless devices, including sensors and mobiles. When necessary, these devices routinely connect to the network. Through interaction with (distributed) data centers, each with strong processing capabilities, meaning information is created for each activity that is required. Thus, the impending 6G will usher in a paradigm shift by not only linking all wireless devices but also promptly delivering optimum information in response to any unique requirements from consumers in a particular setting. One possible idea for 6G is to offer brand-new intelligent connectivity services.

### 1.5.2 Technical Requirements and Applications

Massive connectivity solutions, ultra-high dependability, low latency, and very high data rates have already been successfully achieved under the 5G NR specification. However, 6G systems could have to meet more difficult requirements than 5G in order to deliver task-dependent intelligent services. Ultra-high data rates (a few terabits per second), super-low latency (less than hundreds of microseconds), and ultra-massive connectivity (more than  $10^7$  connections per square kilometer) are three capabilities that the current 5G standard cannot offer. Numerous cutting-edge applications, like 3D holographic displays, ubiquitous networking, and replicated digital twins, could hasten the development of such 6G.

- Making a flawless digital duplicate of a difficult physical system or thing is the idea behind the replicated digital twin [36], [37]. In order to learn how the real system can evolve over time and predict the appropriate course of action to optimize the system, this replica mimics the behaviors of the original object by feeding it a collection of data collected from the original. The development of this advanced control system is already complete. Digital twins of jet engine components, for instance, were developed by General Electric and are crucial for controlling the engine's lifespan. This concept will be investigated in various complicated systems, such as quantum computers, industrial IoT networks, and 6G wireless networks, to enhance their efficiency while delivering the most recent data for a specific job request. The key technical requirements for this application may be very high data rates of a few Tbps and very low latency of less than a few hundred microseconds, in addition to the availability of cloud computing and machine learning capabilities.
- Widespread connectivity for automation: The Cisco Annual Internet Report, published in February 2020, projects that by 2023, there will be more than 14.7 billion IoT (or M2M) connections globally. In a particular urban area, a connectivity solution that offers over  $10^7$  IoT device connections per square kilometer would be necessary. 6G networks are consequently necessary to seamlessly connect this enormous number of sensors in homes, cars, factories, and cities. These days, connectivity is ubiquitous, or "connectivity everywhere." The confluence of communications and cognitive computing capabilities enabled by machine learning technologies will

enable 6G to offer intelligent automation services for a wide range of wireless devices in addition to ubiquitous connectivity. The primary need for a wireless connection in order to support these situational awareness automation services is an extremely low latency of less than a few hundred microseconds. A major part of overcoming scaling challenges for huge networking will be energy efficiency.

Future wireless devices like smartphones, tablets, and laptops may have improved display technologies, including 3D holographic displays [38] [39]. The most promising technology that can be included in upcoming wireless gadgets is 3D holographic display. The peak data rates for 6G networks will be primarily increased by this next-generation display system. For instance, a raw hologram would need to be transmitted at a data rate of 4.32 Tbps without the use of any sophisticated compression techniques [40]. When creating a 3D image in real time, hundreds of separate 2D images must be synthesized and synchronized, which requires extremely low latency of less than a few hundred microseconds.

### 1.5.3 Key Enabling Technologies

**Terahertz communications:** Using a wider signal bandwidth can effectively boost the transmission rate by an order of magnitude more than 5G. This tactic was already used when millimeter wave frequency bands were adopted during the transition from 4G to 5G. The next-generation wireless systems, 6G, will follow this pattern and have higher data rates than 5G. A new category of experimental spectrum licenses for frequencies between 95 GHz and 3 THz was announced by the FCC in March 2019. This has motivated scientists to focus their attention on subterahertz bands, particularly between 140 GHz and 300 GHz [40]. For 6G to deliver incredibly high data rates, the usage of THz frequency bands for wireless transmissions will be a crucial enabler.

THz frequency ranges present significant communication challenges. Ultra-wide signal bandwidth and extremely directed signal transmission are both present. Additionally, the consequences of compound channels, such as blocking and molecule absorption, are still not fully understood. Pencil beams will also offer two perspectives on how interference can be managed, which will have an impact on medium access control and handover. Physical layer designs will face a new problem as a result of terahertz communications. The development of modulation, coding, and beamforming algorithms within the constraints of lowpower AD/DA conversion circuits and antenna mutual coupling effects will

be among the challenges.

Obtaining spatial multiplexing gains in sub-terahertz line-of-sight (LOS) MIMO-communications is likewise not simple. Fixed-link LOS MIMO channels in sub-terahertz bands are entirely defined by physical parameters such as link distances, antenna array shapes, and wavelengths, in contrast to traditional MIMO channels operating inside the 6 GHz frequency range, where rich scattering is prominent. Utilizing sub-terahertz bands, orbital angular momentum (OAM) multiplexing technology may be appropriate for short-range MIMO communications [41]. Reconfigurable uniform linear arrays are another interesting approach for sub-terahertz LOS MIMO communications, which has recently been shown to be the best from an information-theoretic perspective. In LOS MIMO channels, this approach can attain the highest spectral efficiency in all conceivable antenna configurations [42].

**Pilot-free communications:** To enable extremely low-latency communications, brief packet transmissions are required. By reducing the packet size, it may be possible to reduce both the air-interface time and the calculation time for decoding, thus allowing for the achievement of the demanding 6G delay requirement of less than 100 microseconds. Longer pilots provide bigger transmission delays in pilot-based short packet communications, which presents a difficulty. To accommodate the vast connectivity, the pilot length can also grow linearly as the number of wireless devices connected. Additionally, pilot-based communication is not particularly successful when a channel coherence time is relatively short, like in scenarios like V2X, because the pilots must be constantly broadcast anytime the channel realizations change. Finally, the pilot contamination effects in TDD huge MIMO systems can be removed thanks to the pilot-free uplink communications. Theoretically, if there are an endless number of base station antennas, this might lead to an infinite cellular capacity. In order to handle enormous IoT/V2X communications that are time-sensitive and massive MIMO systems for 6G, pilot-free communication technologies will be a critical enabler.

Due to the lack of channel information, reliable message decoding will be fundamentally difficult with pilot free communications. Differential modulation and a geometric

strategy based on the Grassmann manifold are two examples of noncoherent communication techniques that have been developed [43]. These methods might not be able to satisfy the demanding standards of ultrahigh dependability and low latency. Pilot-free communications for 6G are anticipated to be made possible by joint modulation and coding approaches employing compressive sensing and machine learning-aided blind detection technologies.

**Technology convergence in computing, sensing, and communications:** The convergence of computer, sensing, and communications technologies will be crucial to 6G. The multi-functional capabilities provided by communication transceivers, radar, and several sensors are anticipated to be present in future wireless devices like self-driving automobiles and next-generation smartphones. In order to find things, radar systems examine the reflections of probing signals. Vision sensors can also capture the sights and environments that are all around people or vehicles. As a result, they offer users information on complex surroundings from many angles. This environmental information can be analyzed to produce user-specific contextual data by utilizing mobile edge computing technologies and the strength of machine learning. This contextual data will include the user's multidimensional information, such as their pattern of activity (for example, their mobile content usage) and a space-time map of their geographic location. This comprehensive data can be used to forecast user behavior in the future, enhancing service quality and enabling context-aware communication systems.

**Quantum computation for communications:** The development of new communication methods may be aided by the availability of quantum computation. Different from quantum communications, which use the quantum physical phenomenon known as quantum entanglement to transmit information from one location to another, is quantum computation. Instead, it accelerates computing when addressing a class of NP-hard optimization problems by using quantum entanglement. The quantum community has recently demonstrated that for a particular class of NP-hard optimization tasks, exponential speedups in computation are feasible. The primary research issue in this field is the creation of low-cost quantum processors as well as cutting-edge algorithms that utilize quantum processors. As an illustration, the quantum processor D-Wave pro-

vides quantum annealing, a metaheuristic method for locating a global optimal solution based on quantum fluctuations [44]. The quantum approximate optimization algorithm (QAOA), which employs gate-based noisy quantum devices (such as IBM quantum computers) to address combinatorial optimization problems, is another intriguing example of a quantum-classical hybrid approach [45]. These quantum optimization techniques may be used to solve the long-standing computationally challenging optimization problems in communications, including capacity-maximizing resource allocation algorithms, maximum likelihood (ML) detection in massive MIMO, and ML decoding of channel codes. 6G's data throughput and latency performance could be significantly improved by this additional processing power.

Flexible 4D cellular networks are possible because of mobile base stations mounted on moving objects like unmanned aerial vehicles (UAVs), drones, and autonomous vehicles (AVs) [45]. With this unprecedented level of freedom, infrastructure configurations can be changed adaptively over time and space to improve network performance. A crucial component of 6G cellular networks will be this. By offloading effects, one can optimize network performance by flying UAV base stations in a heavily populated area. By removing the coverage restrictions of the current cellular networks, the movable base stations can also give cellular operators adaptable and expandable space-time coverage maps. They are able to cost-effectively create wireless connectivity when the cellular infrastructures fail as a result of catastrophic occurrences. For instance, in emergency situations, people may use UAV base stations as mobile relays or routers to connect to satellite networks for communications. While ensuring high service quality standards, the mobile base stations will present new chances to deliver user-specific contents.

To enable the adaptable cellular networks in space-time, a number of important issues still need to be solved. Ultra-high throughput wireless backhaul systems would be necessary. To attain data rates of a few Tbps, the flying base stations, for instance, might use millimeter wave or sub-terahertz LOS MIMO transmission technology. For UAVs and drones to fly base station missions for an extended period of time, innovative battery solutions are required. The implementation of mobile cellular base stations will also require low-power mobile edge computing technologies that support cutting-edge

machine learning techniques.

## **1.6 Conclusion**

The development of mobile communications technologies from 1G through 4G, what 5G is, and a quick glance at 6G are all summarized in Chapter 1. The fundamental technological ingredients that support the advanced 5G capabilities are summarized in this chapter. The standardization of 5G and the major groups that are crucial to its definition are also covered in this chapter.

## CHAPTER 2

# An Overview on D2D Communications Towards 5G

### 2.1 Introduction

Over the last ten years, the widespread use of smartphones has improved living quality and productivity. Nowadays, high-speed, high-quality data transmission via ubiquitous wireless access is essential to modern living. However, the extensive usage of cellular devices results in an exponential increase in the volume of wireless traffic, placing a great deal of strain on the constrained cellular bandwidth and capacity. The third generation partnership project (3GPP) long-term evolution (LTE) is working to standardize technologies with reduced latency, greater data rates, and lower power consumption in order to address these and related difficulties. For LTE to provide a greater variety of communication service requirements, LTE-Advanced (LTE-A) now enables new technological components [46] [47]. As a component of LTE-A technology, device-to-device (D2D) communication enables direct wireless links between mobile users without rerouting data via a base station (BS) or the core network. In comparison with traditional infrastructure-based communication, D2D communications can have certain advantages due to the rapidly increasing volume of data traffic, the scarcity of radio spectrum, and the urgent requirement for battery energy usage. Enhanced system throughput, higher energy and spectrum efficiency, decreased transmission latency, and so on are some of the immediate advantages.

This chapter presented D2D communication for cellular networks, including its classification, difficulties, and potential advantages for cellular networks of the future. First, we presented D2D communication and its use in traditional cellular networks. Next, we talk about D2D technology in 5G, the next generation of cellular networks. We finish the chapter with a summary of the information provided.

## 2.2 D2D Communications Towards 5G

Systems from the second generation (2G) to the fourth generation (4G) are often created with the network in mind. But 5G networks, which are anticipated to become standardized by 2020, do not have to be network-centric; instead, they can adopt device-centric architectures. Since operators have a strong incentive to offload traffic off the core network, it is only natural that 5G networks will leverage the intelligence at the user equipment (UE) side to enable D2D connectivity. A significant advancement in lowering transmission latency and increasing energy efficiency is the implementation of D2D connectivity, especially for networks (like social networking) that offer proximity-based services. Various technological issues and design aspects for D2D communications towards 5G will be covered in the major body of this chapter [48].

### 2.2.1 History of D2D Standardization Activities

The standardization of D2D technologies is being driven by the growing acceptance among mobile stakeholders, including device manufacturers and network operators, that D2D communications will form the basis of future 5G networks. Qualcomm submitted the idea of D2D discovery and communication no later than the 3GPP summit in June 2011 [49]. Meanwhile, at the August 2011 3GPP conference, a study item description on LTE Direct (LTE-D) was submitted [50], proposing to examine the service need for direct over-the-air LTE D2D discovery and communications. The November 2011 meeting also looked at important discoveries about D2D use cases and potential requirements for a network operator overseeing communication and device discovery between neighboring devices. [51]. The agenda for LTE Release-12 was started by 3GPP during a workshop in June 2012, with the goal of finalizing LTE Release-11. It was decided at the session that new traffic kinds may be accommodated by embracing machine type and short-range communication scenarios [52]. In December 2012, the 58th plenary meeting of the radio access network (RAN) resolved to start studying LTE D2D proximity service (ProSe). [53]. There are two sections to the ProSe study: D2D communication and D2D discovery. The majority of the research on LTE D2D ProSe is devoted to technical aspects, including channel models, resource allocation and scheduling, synchronization mechanism, and discovery signal design [54].

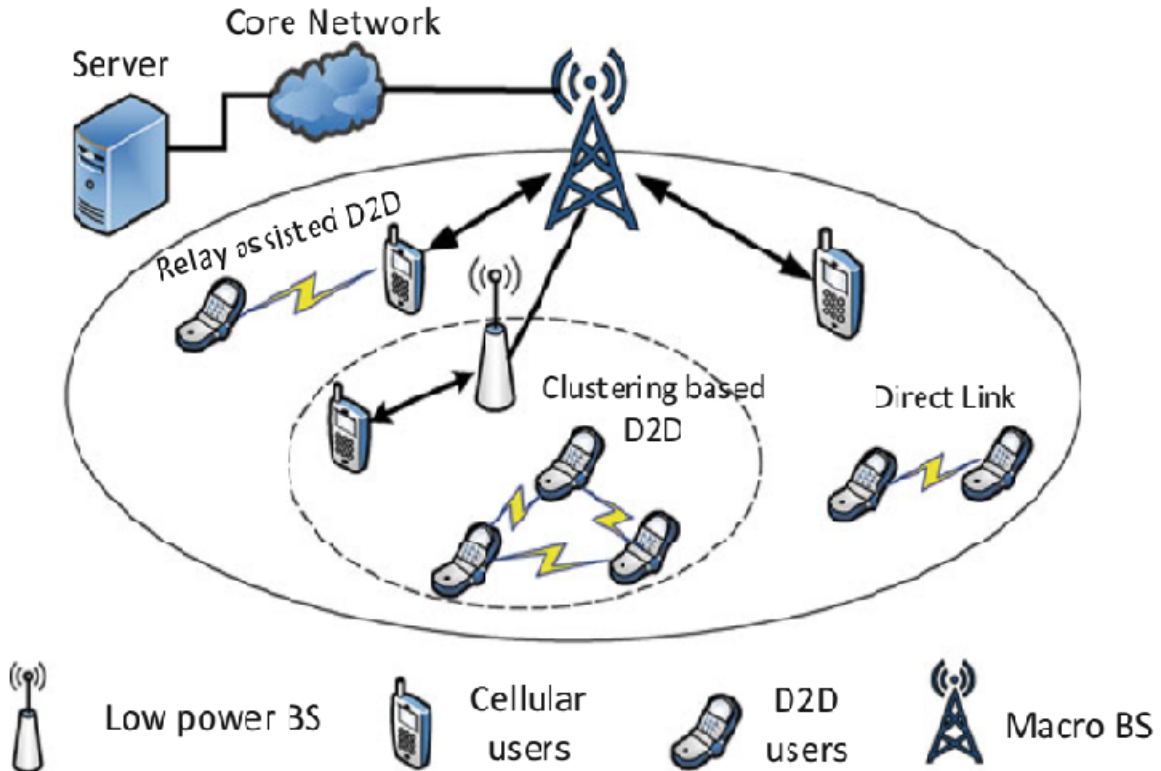


Figure 2.1: Different use cases of D2D communications

The general plan for the ProSe function’s implementation is currently taking shape, and steps have been taken to enable infrastructure like billing [55]. In the TS 23.303 document [56], the majority of the architectural advancements related to ProSe and D2D communications have been compiled. Some of the relevant concepts about LTE-based short-range radio within licensed bands [57] and prospective license-assisted communication (RP-140770) have already been reported today.

### 2.2.2 Classifications of D2D Communications

As seen in Figure 2.1, D2D users can generally interact with each other using one of three methods: clustering-based communications, D2D direct link, or D2D communications with relay assistance.

- D2D Direct Link: The simplest form of D2D communication involves direct data transfer between transmitters and receivers without the use of intermediary nodes.

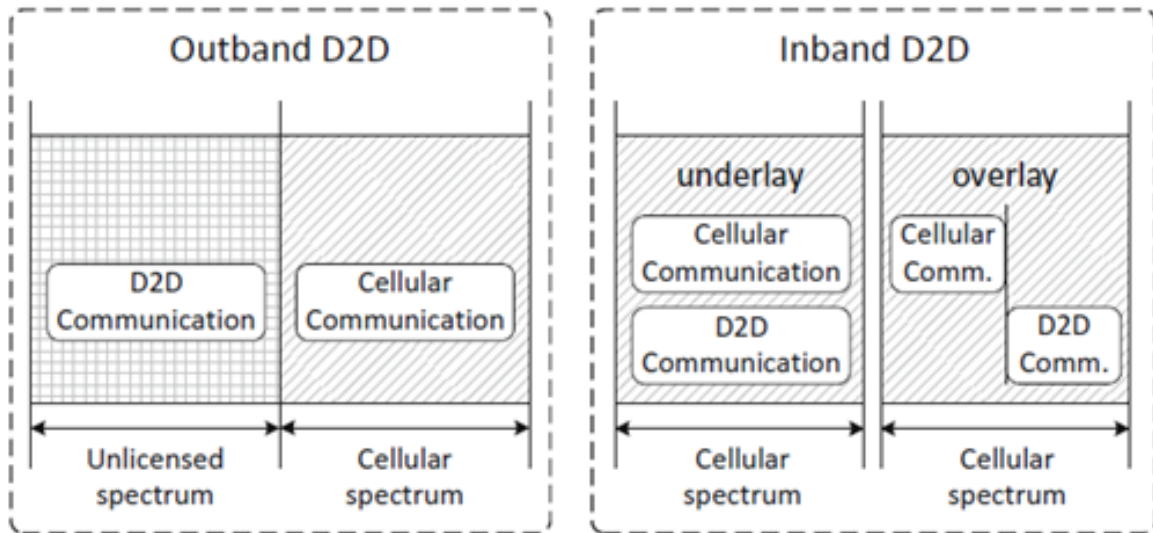


Figure 2.2: inband D2D communication vs.outband D2D communication

- Relay Assisted D2D Communications: Cellular users can serve as relays to enhance data transmission between transmitters and receivers when a mobile device has to connect to a node that is outside of its communication coverage or in a weak channel. state [58].
- Clustering-Based Communications: When users within a short range request the same file, they may form a cluster that enables the required file to be multicasted within the cluster, saving time and bandwidth. This is applicable to content sharing and information diffusion scenarios. Additionally, people who share similar interests or have close social relationships—as seen by their propensity to “follow” one another—can group together and share content via D2D communications [59].

However, D2D users may utilize both licensed and unlicensed spectrum resources for communication, which allows us to further categorize D2D communications into inband and outband D2D communications [54]:

- Outband D2D: As seen on the left side of Figure 2.2, D2D communications falling under this category make use of unlicensed spectrum [47]. Since D2D communications take place on license-exempt bands, one of the main benefits of outband D2D communications is the lack of interference between cellular links and D2D links. It should be noted that in order to utilize unlicensed spectrum, an additional

radio interface is required. This raises the possibility of combining other wireless technologies, like Bluetooth, Ultra Wideband, Wi-Fi and Wi-Fi Direct [60]. Moreover, outband D2D can be broadly classified into two categories: autonomous and controlled communications. Cellular networks manage the coordination of radio interfaces in regulated outband D2D communications. While D2D conversations are left up to the users, the cellular network manages all other communications in autonomous outband D2D communications. To put it another way, the second (additional) interface/technology functions similarly to the current Wi-Fi link but is not dependent on cellular networks. Since D2D communications typically occur on a second radio interface, outband D2D communications have less difficulties in coordinating the communication resources over two different bands. Outband D2D, however, can only be used by cellular devices that have two radio interfaces (such as LTE and Wi-Fi) and can maintain both cellular and D2D connections at the same time.

- Inband D2D: D2D communications fall under this category and take place over licensed spectrum, also referred to as cellular spectrum, which is allotted to cellular links [61]. Strong control over licensed (cellular) spectrum suggests that better user experiences are more practical in a planned setting. Underlay D2D and overlay D2D are the two additional categories into which inband D2D communications can be separated. As seen in the right hand of Figure 2.2, DUEs and certain other cellular user equipments (CUEs) share the same spectrum resources in underlay D2D communications. Through spectrum sharing, D2D communications can improve two critical performance metrics: network throughput and spectrum efficiency. DUEs in underlay D2D mode in cellular networks have the ability to reuse CUE downlink or uplink resources (channels), or both. Mutual interference between DUEs and CUEs could, however, have a detrimental effect on system performance. On the other hand, D2D lines that are in overlay communication mode are given particular cellular resources. Under dedicated resources, overlay D2D communications can usually provide better system performance without co-channel interference, but at the expense of worse spectral efficiency. Overlay D2D communications are less efficient than underlay in terms of spectrum efficiency.

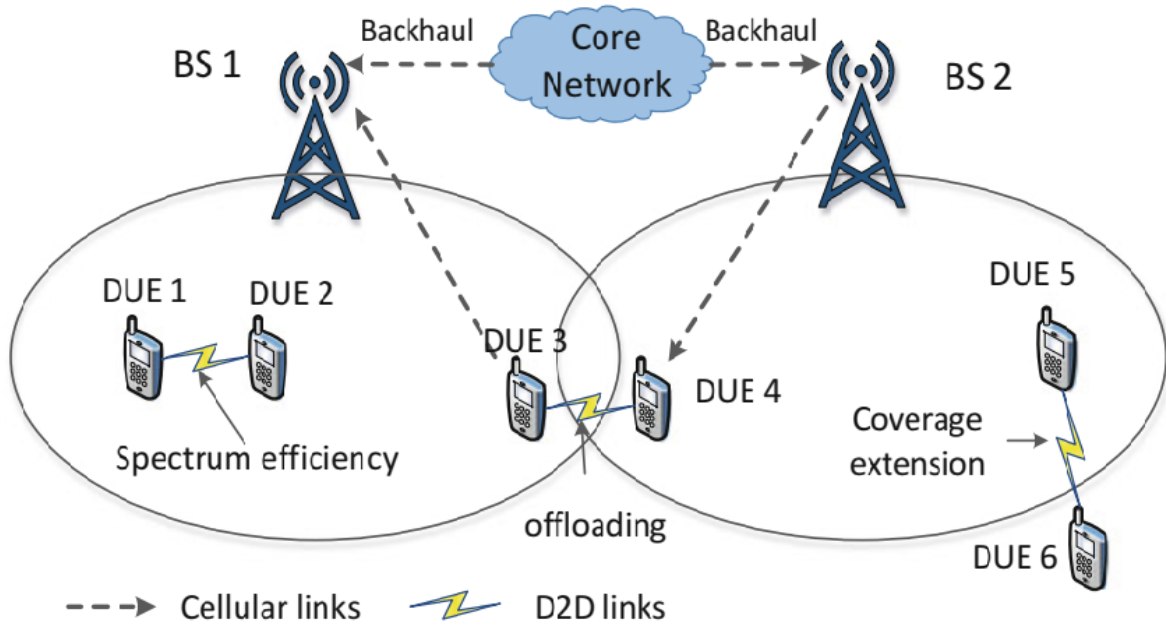


Figure 2.3: Potential benefits of D2D communications

### 2.2.3 D2D-Assisted Cellular Communication

Keep in mind that D2D communications use cellular spectrum under the guidance of cellular infrastructure to enable direct device-to-device communication without the need for intermediary nodes. Due to their capacity to share data more rapidly through local links, D2D communications on cellular networks are also gaining popularity as mobile apps that take use of the proximity of mobile devices continue to grow in popularity. Numerous performance advantages are anticipated with the introduction of D2D communications in cellular networks [62]. D2D can generally support communications with reduced latency, higher bit rates, and lower energy consumption. For instance, instead of relying on BS 1 as a relay, two nearby devices, DUE 1 and DUE 2 in Figure 2.3, can typically perform better when interacting directly through the establishment of a D2D link. Specifically, direct communication between neighboring DUEs is more resource-efficient than data routing through a BS or even the core network. Put another way, D2D communications are more energy-efficient and enhance spectrum efficiency than standard cellular communications, which use both uplink and downlink resources. Moreover, moving from an infrastructure path to a direct connection can help other CUEs in the network by relieving network congestion and offloading cellular and backhaul traffic; an example of this is the D2D communication link between DUE 3 and DUE 4 depicted in Figure 2.3. An additional

benefit is the extending of coverage. For instance, even when DUE 6 is outside of BS coverage, it can still transmit data by interacting with DUE 5 using D2D lines.

### 2.3 Research Challenges in D2D-Assisted Networks

D2D communications offer a viable solution for future wireless networks to enhance network capacity and user experience by facilitating local area services. It is evident from 3GPP Release 12 that D2D technology is very desirable for further research and development. As previously mentioned, mobile network operators stand to gain a great deal from utilizing coordinated and network-assisted D2D technologies. Notwithstanding, the integration of D2D technology with the present-day network infrastructure presents several obstacles and necessitates functional modifications to the established cellular architecture, including but not limited to synchronization, device discovery, mode selection, interference management, power control, and channel measurements. We outline several research issues in D2D communications in the section that follows.

#### 2.3.1 Synchronization

Two user equipments (UEs) of a D2D pair are synchronized with the base station (BS) in a D2D scenario aided by an LTE network. This implies that slot and frame timing, as well as frequency synchronization, are learned and matched. Summataz (2014) Direct. Since BSs are able to supply synchronization beacons, synchronized D2D transmissions are attractive. For example, asynchronous discovery techniques involve constant searching for discovery signals. However, UEs can only be active for receiving discovery-related signals during designated time periods in the time-synchronized device discovery process, which consumes significantly less energy [18]. However, there are at least two reasons why synchronization between two UEs is challenging [63]:

- Even when UEs are located in the same cell, there may be differences in the distance between each UE and the BS, necessitating the application of separate timing advance adjustments.
- Two UEs that constitute a D2D link pair may be associated with distinct BSs that are not synchronized.

Consequently, more research is needed to determine how temporal misalignment affects system performance, and if the impact is shown to be non-negligible, more synchronization techniques will be necessary.

### 2.3.2 Device Discovery

UEs must first look for possible D2D communication devices nearby and identify the identified peers before initiating a conversation. Device discovery is therefore a fundamental component of D2D networks. The concept of proximity device discovery refers to a user's capacity to actively look for relevant peers in its immediate physical vicinity. In order to initiate a proximity discovery process, only D2D links that have successfully completed a proximity discovery procedure are taken into account for further D2D communication processes.

How to find appropriate peers to quickly and effectively build D2D linkages in order to balance the trade-offs between system throughput, interference control (elimination), and resource utilization efficiency is a key question in device discovery.

- **Discovery Signal (Pilot) Design:** During the device discovery process, other UEs may be able to identify the discovery signals that a UE transmits. It goes without saying that the data carried by the discovery signals needs to be carefully arranged. For instance, the volume of data transmitted by user equipment (UEs) during the discovery process might affect many design elements, such as the quantity of radio resources needed and the discovery signal's or channel structure's design. Therefore, in order to facilitate the design, a preliminary estimate of the amount of discovery information is needed [63].
- **Synchronous vs. Asynchronous Discovery:** Due to its ability to produce reduced energy consumption and higher spectrum efficiency, synchronous discovery is generally more desirable than asynchronous systems. Furthermore, synchronous discovery strategies typically lead to faster and more dependable discovery. For those UEs that are not inside the scope of cellular networks, it is dubious to presume synchronization a priori prior to device detection [63].

### 2.3.3 Modes Selection

UEs interact with one another through the BS in conventional cellular networks by occupying both uplink and downlink channels. UEs can choose from a variety of communication modes when D2D communications are enabled; this process is known as mode selection. By taking into account the network load, channel state, and interference situation while selecting a mode, the optimal mode can be chosen to maximize system performance. Mode selection is difficult since the schemes' design must take several factors into account [54]:

- How frequently mode selection and related channel quality estimates should be used. The mode selection timescale cannot be too coarse given the quickly changing radio circumstances both within and between the D2D pairs. However, in order to minimize overhead, the measurements and control signaling needed for mode selection should be reduced to a minimum [60].
- Which metrics, reporting systems, and (hybrid, event-triggered, and/or periodic) algorithms should be used by the devices and BSs to choose between various communication modes [60].

### 2.3.4 Interference Management

In cellular mode or specialized D2D mode, users are provided with orthogonal spectrum, which may result in an inefficient use of available spectrum resources. To increase spectrum efficiency, D2D links can communicate by sharing the same spectral resources, called physical resource blocks (PRBs), with cellular lines. Co-channel interference resulting from spectrum sharing must be properly managed to ensure the necessary quality of service (QoS) for the participating UEs. When D2D communications can reuse cellular downlink or uplink channel resources, interference possibilities change in a co-channel sharing mode [64].

When D2D lines reuse downlink resources, the same spectrum resources used by CUEs and D2D receivers may cause interference. DUEs that reuse the downlink bandwidth are interfered with by the BS and other co-channel DUEs. Because a D2D pair is usually formed between UEs in close proximity, D2D communications need a lot less

power than normal cellular communications. DUEs must therefore stay away from high-power BS in this situation to protect themselves from being the objects of excessive interference power. All other co-channel DUEs are the source of interference for CUEs that supply downlink resources. Therefore, in order to prevent damaging interference to the regularly connected CUE downlinks, DUEs must maintain a distance from the CUEs.

In contrast, when DUEs share the uplink cellular resources, BS and D2D receivers are similarly susceptible to interference. In this instance, DUEs must avoid interfering with co-channel CUEs in order to prevent crippling interference. The stationary base station (BS) is the receiving node for CUEs on the uplink. Coordinating the DUEs and controlling interference from all co-channel DUEs are among its responsibilities.

In cellular networks enabling D2D communications, intercell interference coordination has emerged as a key design concern in addition to intra-cell interference. Since interference must be coordinated between several cells as well as between cellular and D2D layers, interference management in this situation is rather difficult.

### **2.3.5 Power Control**

Power control is helpful in D2D-assisted networks for minimizing interference, conserving energy, and maximizing throughput, among other things [65]. Generally speaking, coordinating the many BSs and devices as well as the duration of the network's engagement with DUEs is a crucial issue for power control design in network-assisted D2D communications [54]. A different concept lets the BS handle long-term power regulation and lets D2D pairs schedule their transmit powers independently. One way is to let the BS schedule dynamically on a very short timescale. Reduced signaling overhead and latency may result from giving DUEs autonomy over their own transmit power and control capabilities.

For instance, the BS might only be in charge of establishing an approximate transmit power level and allowable power range, as well as open loop power control; in contrast, DUEs can manage more precise closed loop power control in response to quick changes in the mobile channel [63].

### 2.3.6 channel Measurements

Channel measurement is necessary to notify networks about the channel conditions of participating users so that power control and interference mitigation can be implemented. Even though initial channel measurement can be achieved by using discovery signals during the device discovery phase, more study is needed to enable the production of reference signals utilized for D2D communications. In general, the interference caused by D2D communications can be assessed using the received strength of reference signals provided by the BS on the downlink. When allocating resources for D2D links, the BS could find these measurement reports useful. The two reference signal types commonly used in the uplink are sounding and demodulation reference signals. [48].

In order to assist the estimation of channel information, the sounding reference signals (SRS) are typically provided over a larger bandwidth than the actual data transfer. In D2D-assisted networks, where resource allocation is strictly regulated, this could also be helpful. The demodulation reference symbols (DMRS), on the other hand, are carried alongside the payload's PRBs and can be utilized for demodulation, channel equalization, and channel estimation. They may also be utilized for the same function in D2D communications [48]. Whether other reference signals would be more appropriate for D2D communications is still up in the air.

## 2.4 Technology Requirements for D2D Communications

As mentioned in Sect. 2.3, D2D communications is a relatively new study topic, and the technologies that are pertinent to it are still being developed. Utilizing D2D communications in cellular networks encourages innovative, promising approaches to highly efficient network operation. We list several essential requirements for D2D communications below, grouping them into three categories: mode selection, resource management, and proximity discovery.

### 2.4.1 Discovering The proximity

Remember that finding proximity devices is a requirement before starting D2D communication. UEs search for possible candidates and get ready to build direct communication

channels during the discovery phase.

## **D2D Proximity Discovery Classification**

For D2D communications, the proximity discovery techniques now in use can be broadly divided into two categories:

**Dispersed Techniques** Under this category, UEs broadcast their identities on a regular basis so that other UEs can be informed of their presence and choose whether or not to initiate D2D talks. This dispersed strategy eliminates the need for the BS to be involved. Using beacon signals and advanced scanning, distributed proximity discovery techniques are adaptable yet time- and energy-consuming.

**Network-Aided Techniques** Pairable D2D UEs use the network to help them find and identify one another during network-assisted proximity discovery. One UE sends out its own beacon signal and notifies the BS that it intends to interact with a different partner UE. Subsequently, the BS conducts message exchanges in order to obtain the identification and details of the possible link [46]. The degree of BS engagement in the proximity detection process determines whether this strategy is centralized or semi-centralized [66].

## **The Proximity Discovery Process**

Although UEs are capable of autonomously, flexibly, and scalably detecting nearby devices, network-assisted discovery ensures more consistent performance since the operator will handle resource management and interference coordination. Network-assisted proximity finding algorithms have numerous significant advantages over scattered approaches. As previously indicated, peer finding utilizing beacon signals and advanced scanning, particularly in a high load system, is usually time- and energy-consuming without network support. Additionally, if the network coordinates the discovery process, unanticipated interference can be minimized. In light of these, this section considers discovery processes with network support.

In centralized network-assisted proximity discovery, the base station (BS) coordinates all communications in each phase, and Unified Edge Units (UEs) only transmit or

listen in response to base station requests [67]. As shown in Figure 2.4, the centralized network-assisted proximity discovery process can be summed up as follows:

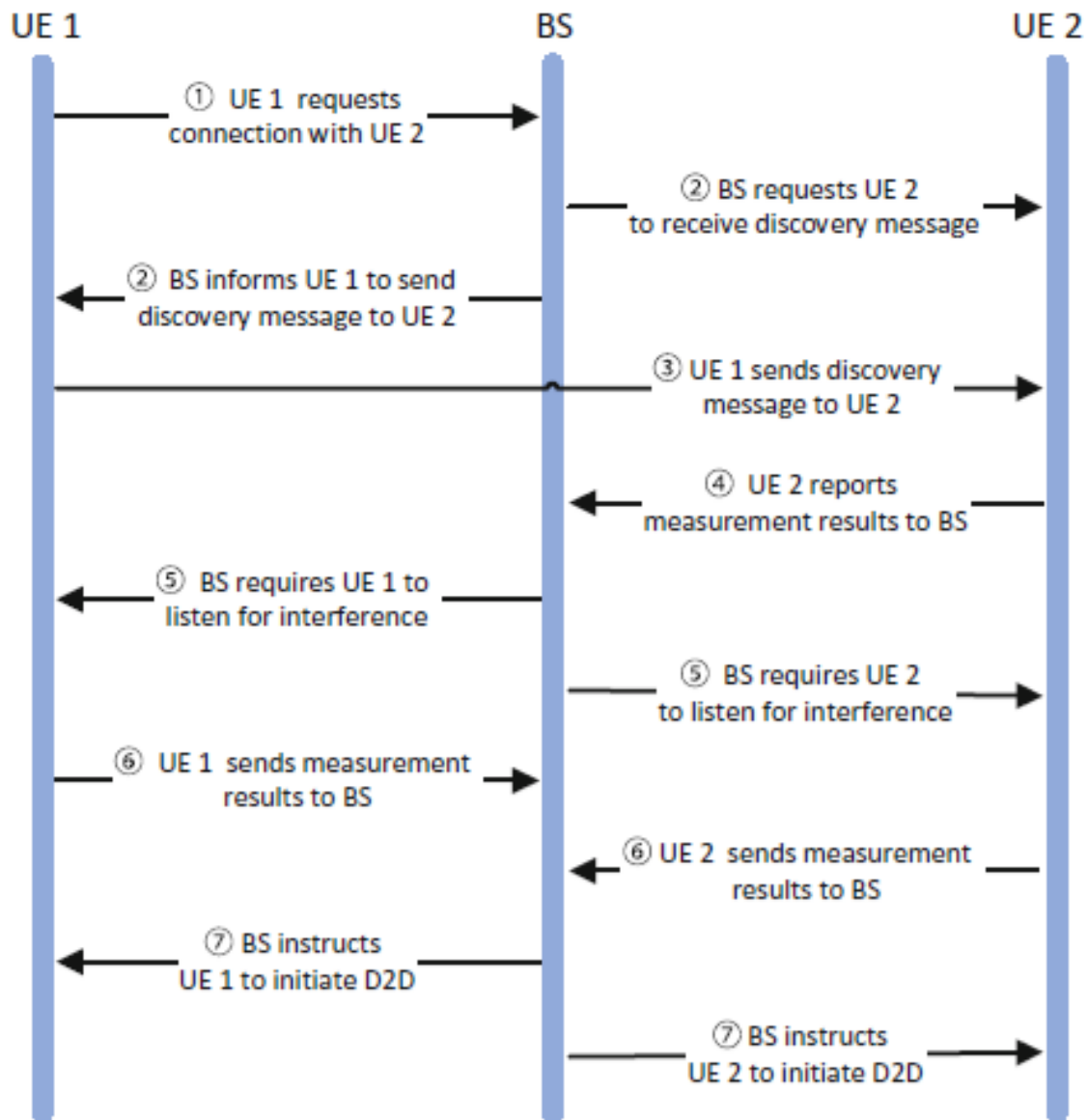


Figure 2.4: Centralized proximity discovery procedure.

- ❑ Step 1: UE 1 notifies the BS that it wants to talk to UE 2;
- ❑ Step 2: UE 1 is notified to send the discovery message, and BS asks UE 2 to anticipate receiving one from UE 1;
- ❑ Step 3: UE 1 notifies UE 2 of its discovery;

- ❑ Step 4: The signal-to-interference-plus-noise ratio (SINR) value of the message sent by UE 1 is reported to the BS by UE 2;
- ❑ Step 5: In order to prevent interference from other users in the cell, BS requires UEs 1 and 2 to listen for it;
- ❑ Step 6: UEs 1 and 2 send their measured interference findings to the BS;
- ❑ Step 7: If the direct link between UE 1 and UE 2 is advantageous, BS advises UE 1 and UE 2 to speak with each other via D2D link.

Since message transfers with the BS are not part of the first steps of the operation, the role of the BS is less prominent in semi-centralized proximity discovery. The process of semi-centralized proximity discovery can be explained as seen in Figure 2.5.

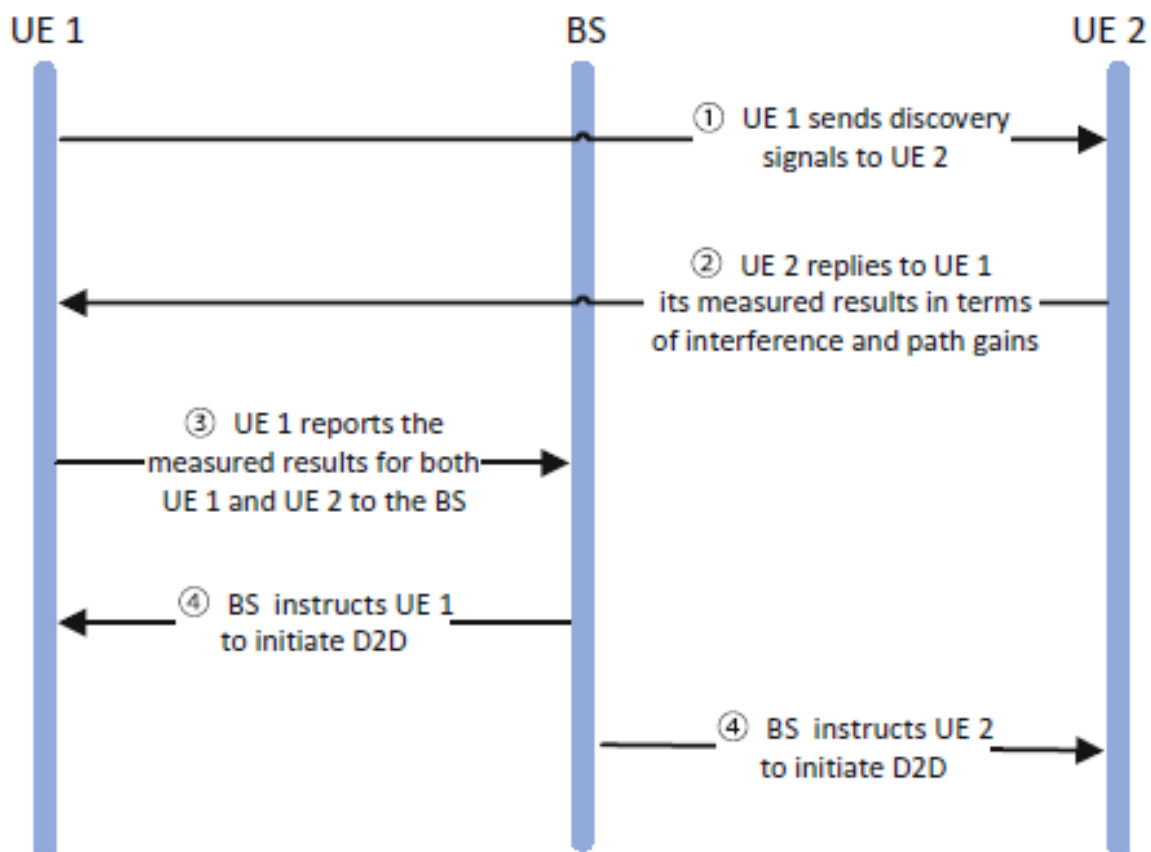


Figure 2.5: Semi-centralized proximity discovery procedure.

- ❑ Step 1: Without asking the BS for permission, UE 1 sends a discovery message to UE 2. As soon as UE 1 and UE 2 receive the message provided by UE 1, they both

start listening for interference from other users in the cell and estimate their route gains to the BS;

- ❑ Step 2: UE 2 notifies UE 1 with its measured results, including the interference it experienced and the route gains it made to the base station (BS);
- ❑ Step 3: UE 1 provides the BS with information regarding the SINR and interference measurements for both UE 1 and UE 2;
- ❑ Step 4: BS asks each UE to start a D2D conversation.

## Related Works and Motivations

High energy efficiency, extended discovery range, low channel resource cost, and little interference from discovery beacon transmissions are the four criteria that should be taken into account while designing proximity discovery algorithms. Typically, D2D discovery techniques that are beacon-based and location-based are both available. In order to track the location of each UE, location-based proximity discovery makes use of wireless localization techniques [68], such as angle-of-arrival (AOA), time-of-arrival (TOA), time-difference-of-arrival (TDOA), and global positioning system (GPS) [69]. Nevertheless, neither UEs without GPS devices nor UEs in areas where the GPS signal is unreachable may use GPS-based localization; the precision of detection cannot be guaranteed by the AOA, TOA, or TDOA. On the other hand, UEs can send beacons to adjacent devices through beacon-based D2D proximity discovery. A DUE can regularly emit a beacon message to be discovered by other devices in a wireless local area network (WLAN), as explored in [70]. For FlashLinQ, the authors of [60] have suggested a D2D discovery protocol in which every device sends out a discovery signal. Nevertheless, the previously indicated peer discovery is carried out without network assistance, resulting in significant time and energy expenditures.

Networks are able to identify whether two devices are able to form a D2D link and facilitate the discovery process in network-assisted D2D discovery. Networks can also arrange for devices to emit beacons at the right time, frequency, and coding scheme [60]. Based on the time link between the discovery phase and the communication phase, the authors of [28] have divided network-assisted discovery into two categories: a priori discovery and a posteriori discovery. Making such peer discovery and pairing processes quicker,

more energy-efficient, and easier to use is a design objective for network-assisted discovery [71]. To execute D2D neighbor discovery, as described in [60] [72], more resources are needed. Consequently, in order to enable proximity finding, new techniques that operate on channels that already exist must be proposed.

### 2.4.2 Mode Selection

Keep in mind that D2D communications could outperform conventional cellular communications in terms of power, bandwidth, and latency. However, this does not imply that, in terms of performance, using D2D mode is always the best option for UEs. Two UEs can communicate with each other directly in D2D mode or through the BS in standard cellular mode in D2D-assisted cellular networks. Moreover, when operating in D2D mode, data transmission can be accomplished by employing a dedicated cellular frequency or by sharing the spectrum among CUEs. By taking into account the QoS requirements, those UEs can transition between two modes. Generally, depending on the needs of the situation, two UEs requesting communication can operate in one mode or in hybrid modes.

### Classification of Basic Communication Modes

UEs can essentially operate in any of the four modes, as shown in Figure 2.6. **D2D Silent Mode** When there are insufficient resources available for dedicated D2D connections, and severe interference prevents spectrum reuse, D2D users are forced to remain silent and are unable to transmit data.

**D2D Reuse Mode :** Through the collection of CUEs' uplink or downlink spectrum resources in cellular D2D underlay, UEs can communicate directly with one another over D2D links.

**Dedicated Mode D2D :** UEs can communicate directly through D2D networks thanks to the allocation of dedicated cellular frequency resources.

**Cellular Mode :** In this mode, two UEs can talk to one another via the BS without using the conventional co-channel spectrum sharing method.

In practice, many communication modalities can be used based on service requirements and variations in channel conditions. Although D2D reuse mode has a higher spec-

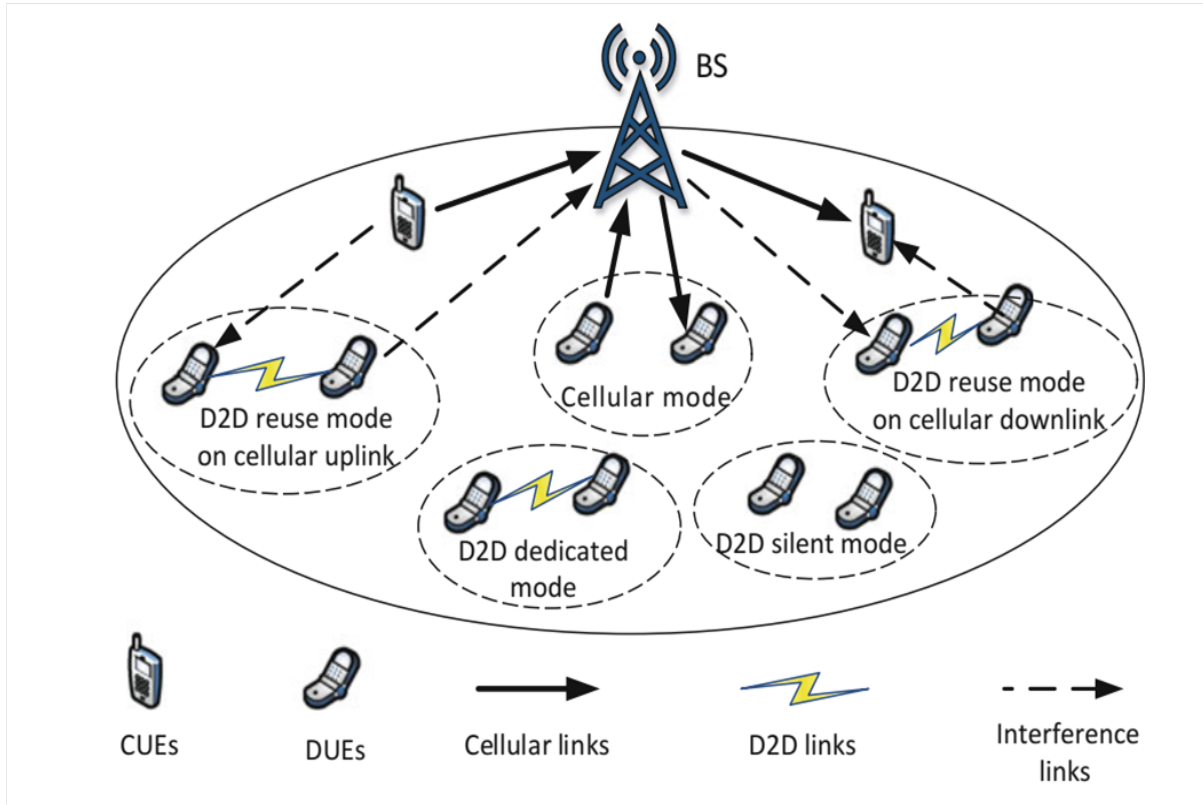


Figure 2.6: D2D communication modes.

trum efficiency, co-channel interference caused by spectrum sharing is an issue. At the expense of less ideal spectrum efficiency, cellular mode and D2D dedicated mode can be chosen to streamline interference control and improve user experience. The overall network performance can be improved while ensuring that engaged users' QoS expectations are met by choosing the best transmission modes for potential D2D lines.

### Related Works and Motivations

Numerous mode selection systems have already been developed, such as those in [73] [74] [75] [76] [77] [64], which take into account the system's QoS needs, power limitations, and channel circumstances. Specifically, [73] [74] has studied a basic situation where every single cell has a single D2D link and a single cellular link. While [74] only addressed mode selection and power control in tandem to maximize the sum rate of both cellular and D2D communications in a single cell, the authors of [73] examined a mode selection scheme for both single-cell and multiple-cell scenarios, including one D2D link and one cellular link in each cell.

Investigations into scenarios involving D2D and several cellular links have been conducted in [75] [76]. The authors of [75] concentrated on the issue of minimizing transmission power while adhering to predetermined link rate restrictions by combined mode selection and power allocation. Additionally, in [76], mode selection, channel allocation, and power regulation were all taken into account in tandem to improve system throughput while maintaining the SINR of D2D and cellular networks.

From a distinct perspective, many literary works have examined different alternative means of communication. The authors of [77] suggested a mode selection method that considers only the D2D dedicated mode and reuse mode in a single cell. In [64], network condition data, such as noise levels and user-required SINR, were taken into consideration while deciding between cellular mode and D2D reuse mode. Furthermore, by taking into account the QoS requirements of both DUEs and CUEs, mode selection between cellular mode, D2D dedicated mode, and D2D reuse mode has been proposed to lessen the interference caused by D2D connections [73] [76].

The majority of previous work, however, has concentrated on binary mode selection, in which a binary mode indicator is used to signify the selected mode for each D2D connection, allowing it to operate in just one mode. It is useful to design mixed-mode operation such that each D2D link can make use of several modes by means of resource multiplexing. In practical terms, mixed-mode operation can be preferred when both D2D and cellular links need to achieve specific QoS requirements since it can take advantage of the advantages of multiple modes. Consequently, studies on mixed-mode selection techniques might be beneficial in meeting the requirements of differentiated cellular and D2D links.

### **2.4.3 Resources Management**

Resource management is typically applied concurrently with mode selection in order to assess achievable performance when operating in various modes. One of the most important problems in wireless networks is resource management, which may be done to help with energy conservation, throughput maximization, and interference reduction, among other things.

## Resource Management Technologies

Spectrum allocation and power control are the two primary components of resource management in network-assisted D2D communications, and they are further explained as follows:

**Spectrum Allocation:** Physical resource blocks, or PRBs, are described as the number of subcarriers that are assigned to user equipment (UEs) for a predefined period of time in 3GPP LTE specifications. Every PRB takes up one slot in the frequency domain and 180 kHz in the time domain, or 12 subcarriers spaced 15 kHz apart. The smallest spectral resource unit that the BS is able to assign is a PRB. Allotting cellular resources for D2D communications is essential since, in order to ensure QoS requirements, interference with other CUEs and DUEs must be kept to a minimum. Resource allocation and mode selection are typically taken into account when deciding which PRBs should be used for D2D communications: shared or dedicated PRBs. Which CUE resources should be shared when DUEs communicate in overlay mode? Conversely, if DUEs operate in overlay mode, then the number of PRBs allowed for D2D communications should be taken into account [78].

**Control Power:** One important tool for reducing user interference in D2D-assisted networks is power control. To ensure that various users in the network meet QoS criteria (such as SINR requirements), concerned users' transmit power needs essentially be managed. Power control can be used to maximize the throughput of the network as a whole. This means that in some circumstances, we might need to reduce the transmit power of cellular links in order to increase the DUEs' achievable data rate and raise the network's total sum rate. Furthermore, it should be ensured that CUE performance is guaranteed. Furthermore, power saving is essential for D2D communications because mobile devices run on a limited amount of battery energy [78]. Consequently, while implementing power control, the trade-off between energy savings and possible throughput is typically taken into account.

Power regulation and spectrum allocation are typically linked and interdependent. Mutual interference occurs between co-channel 2CUEs and DUEs sharing the same resource in cellular D2D underlay when shared spectrum resources are assigned. In this scenario, DUE transmit power should be decreased in accordance with the transmit power's backoff value as established by cellular power control [79]. Furthermore, BS has the

ability to adjust the maximum D2D transmit power to a predefined number based on long-term observations of how various D2D power levels affect link quality. Dedicated spectrum resources, on the other hand, do not need a backoff value, therefore DUEs' maximum transmit power is typically larger than in cases of spectrum sharing.

In D2D-assisted cellular networks, resource management can essentially be applied in two ways: centrally or dispersion-wise. Under centralized resource management, business services (BS) take complete responsibility for managing D2D communications resources. Conversely, DUEs sense their network environment and consume resources in an adaptable manner in a distributed manner, all the while avoiding undue interference to other users. Generally speaking, centralized resource management can produce better, more predictable results, but at the expense of increased complexity. On the other hand, distributed methods with greater flexibility, reduced complexity, and enhanced scalability may yield less ideal solutions.

## **Related Works and Motivations**

In particular, Wang (2017) created a spectrum sharing protocol aimed at a cellular D2D overlay network to boost the system total rate, and Fodor (2012) offered BS-assisted scheduling and D2D power control algorithms to improve energy efficiency.

In contrast to overlay situations, the underpinning D2D case's resource management is more concerned with mutual interference brought on by spectrum sharing. The impact of resource management has been assessed in the literature using a range of criteria, including power efficiency, spectrum efficiency, maximizing permitted D2D links, fairness enhancement, etc. There have been studies on improving spectrum efficiency in [80] and [81]. In particular, Xu et al. [80] suggested a novel interference cancellation mechanism based on user location, and D2D users have been assigned a distinct control channel to prevent using resource blocks that interfere with CUEs. The work in [81] created an interference-limited space where no CUEs could use the same resources as D2D pairings in order to investigate interference management. Furthermore, research on improving power efficiency through appropriate resource management has been done by [82] [75].

[75] presents a heuristic technique that focuses on power allocation and mode selection in cellular networks based on orthogonal frequency division multiple access (OFDMA).

In [82], the authors formulated a problem involving the simultaneous allocation of power, spectrum, and mode selection using linear programming to lower the overall transmission power in a multicell orthogonal frequency division multiplexing (OFDM) cellular network. Furthermore, in a single-cell network, the maximizing of the number of permitted D2D linkages has been taken into consideration in [83]. Another parameter taken into account in resource management for D2D communications is the fairness index [84]. Likewise, resource management for D2D underpinning communications with an emphasis on other metrics—like traffic unloading, increased dependability, and cellular coverage extension—has also been studied.

Nonetheless, the majority of resource management studies now in existence make the ideal assumption that D2D linkages are consistently steady. However, because users move around a lot, D2D links could actually encounter sporadic outages. Stable D2D link development can be aided by taking use of social relationships and engagement amongst mobile users [85] [86]. Therefore, in order to increase system robustness and dependability, resource management techniques that take into account both user social behavior and physical channel conditions should be researched.

In reality, D2D-assisted cellular networks frequently employ integer programming to solve resource management issues like channel allocation and partner selection. When selecting a partner to create a D2D link, for example, a DUE may take into account a variety of factors, such as whether the partner has the target content required, whether the physical link is dependable enough to support data transfer, and whether the partner is reputable or has a strong connection. To achieve specific goals, such as satisfying QoS requirements for both D2D links and CUEs, optimizing the total sum data rate or secrecy rate for all D2D links and CUEs in the system, and maximizing the number of D2D links that could be practical in cellular D2D underlay networks, spectrum resources can also be assigned for each D2D link. By choosing suitable partners, all of these requirements can be met; this can be expressed as a bipartite graph problem [87]. The well-researched bipartite graph matching in graph theory offers effective solutions to resource allocation issues based on the needs of each entity.

The idea of using graph theory to allocate resources in a network is not new. This method is, nevertheless, dispersed throughout the literature in areas like cognitive networks and cooperative networks with relay assistance [88] [89]. A very early relationship

between bipartite graphs and resource management in networks was documented in [90], wherein bipartite graph edge coloring algorithms are linked to network control algorithms. In reality, bipartite graph matching has been extensively investigated and used for a long time in social economics for discrete resource allocation [91] [92]. Its diverse applications include college admission/selection, house assignment, and hospital bed matching, among others. In wireless mesh networks, a bipartite graphical technique has been devised to dynamically allocate resources while taking hunger and bandwidth consumption into account at the same time [93]. Resource management in D2D-assisted networks can benefit from the concept of using bipartite graphs. One of these studies employed graph theory to match D2D links and CUEs in order to maximize system throughput [74] [94]. Therefore, it is worthwhile to investigate extra resource management issues in D2D-assisted cellular networks that use bipartite graphs.

## **2.5 Summary Chapter**

In the cellular spectrum, network-assisted D2D communications can benefit from the close proximity of communication equipment, facilitate resource sharing between D2D pairs and cellular users, and achieve additional benefits like multi-hop network gain. Careful interconnected mechanism design is required to realize these potential improvements.

## CHAPTER 3

# Joint power and resource Allocation for Device-to-Device Communication Underlying Cellular Networks

### 3.1 Introduction

Many efforts have been undertaken to increase spectrum efficiency in order to meet the demands of the fifth generation (5G) wireless networks in the future (1000 times more data traffic) [95]. Device-to-device (D2D) communication is gaining increasing attention from the academic and industrial communities. It is a viable method for 5G systems to increase spectrum utilization by enabling direct interaction between two nearby end users instead of relying on the base station (BS) [96]– [97].

The reuse of cellular user equipment (CUE) subcarriers by D2D user equipment (DUE) in D2D communications utilizing cellular networks results in increased interference [98]. For such networks, system performance could decrease in the absence of effective interference management. Therefore, to investigate the efficiency advantages given by D2D communications, effective resource management strategies must be developed.

Resource allocation in D2D communications has recently been the subject of significant study [94]– [99], mainly falling into two areas. One is the distribution of uplink resources for D2D communication (e.g., DUEs only reuse CUEs' uplink subcarriers) [94]– [100]. in [94] - [101] more specifically increased the overall system data rate while securing the quality-of-service (QoS) requirements for both DUEs and CUEs. The weighted system data rate maximization problem was further investigated by the authors in [102] while ensuring the minimum data rate for each individual CUE and proportionate fairness among DUEs. in [103] sought to maintain the fundamental rate requirements of all users while reducing the system's overall power consumption across CUEs and DUEs.

in [100] was written with the goal of reducing user interference. The allocation of downlink resources for D2D communication falls under a separate category (e.g., DUEs only reuse CUEs' downlink subcarriers) [104]– [99]. The effectiveness of D2D communication when DUEs use the downlink subcarrier resources of CUEs has been investigated by authors in [104]. in [105] - [106] used a range of mathematical techniques to maximize the system's sum data rate. The energy efficiency (EE) maximization problem was studied in [107]– [99] in order to realize green communication. in [108] maximized the system's overall EE, in [99] further balanced the system's EE and spectral efficiency (SE), and in [107] solely considered the EE maximization problem for all DUEs.

As previously mentioned, in [94] through [100] only took the result of uplink subcarriers into consideration, while in [104] through [99] only permitted the DUEs to share the downlink subcarriers. They haven't investigated techniques to simultaneously reuse the downlink and uplink subcarriers. Due to DUEs' limited ability to reuse the system's uplink or downlink subcarriers, the entire crowded wireless radio spectrum has not been completely utilized. In light of this, in [109] through [110] jointly investigate the reuse of uplink and downlink subcarriers in cellular networks. To maximize the sum rate of all DUEs, the interference management algorithm with admission control was investigated in [109], [111], which also created a unique GainAware Uplink-Downlink (GAUD) resource allocation scheme.

To increase the total data rate of all users in the system while ensuring the quality of service for both CUEs and DUEs, we examine power control and resource allocation. In specifically, we create a two-step PCRA method for power control and resource allocation. To increase the overall data rate, an ideal power control strategy is first created for each potential DUE-CUE pair. The optimal subcarrier for every DUE is then selected in the second stage using a maximum weight bipartite matching algorithm. Simulations suggest that the suggested PCRA method could greatly enhance the system's performance in terms of both the overall system data rate and the D2D access rate.

The remainder of the chapter is structured as follows. The system data rate maximization problem is formulated in Section II along with our system model. Section III presents the suggested power control and subcarrier allocation method. In Section IV, the results of the simulation are reported, and Section V brings the study to a conclusion.

## 3.2 System Data Rate Maximization Problem

### 3.2.1 Model Assumption

As can be seen in 3.1 we consider a single cell network with  $C$  cellular users (CUs) which connect to the base station (BS) and  $D$  D2D pairs that communicate directly without the help of the BS. Let  $\mathcal{C}$  be the set of CUs  $\mathcal{C} = \{1, \dots, m\}$  and  $\mathcal{D}$  be the set of D2D

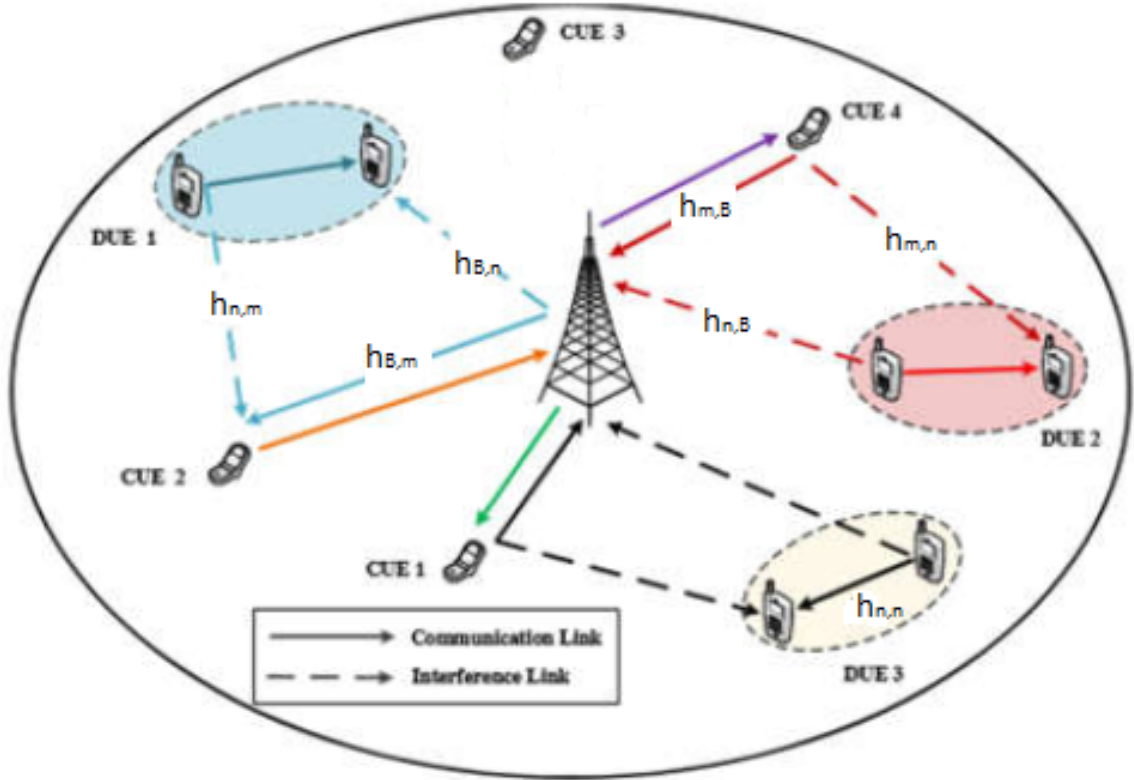


Figure 3.1: System scenario of the device-to-device underlying communication.

pairs  $D = \{1, \dots, n\}$ . We assume each CUE has been pre-allocated one orthogonal uplink subcarrier [109]. We assume that each DUE can reuse a maximum of one subcarrier and that each subcarrier can be reused by a maximum of one DUE in order to control interference. We assume that all links undergo quick fading brought on by multi-path propagation in addition to sluggish shadowing and path loss, as in [112]. In other words, the channel gain between CUE and the BS is modeled as instantaneous.

$$h_{m,B} = H\beta_{m,B}\mu_{m,B}d_{m,B}^{-\alpha} \quad (3.1)$$

where the path loss constant, fast fading gain with exponential distribution, slow

fading gain with lognormal distribution, distance between CU and BS, and path loss exponent are denoted by  $H, \beta_{m,B}, \mu_{m,B}, d_{m,B}$ , and  $\alpha$ , respectively. Likewise, we define  $h_{B,m}, h_{n,B}, h_{B,n}, h_{n,B}, h_{n,m}, h_{n,m}, h_{m,n}$ , and  $h_{n,n}$  as the channel gain between the DUE and the BS, between the BS and DUE, between the DUE and DUE, between the DUE and DUE, between the DUE and DUE, between the DUE and CUE, between the DUE and CUE, between the DUE and CUE, and between the D2D transmitter and the D2D receiver, respectively.

The received signal to interference-plus-noise-ratio (SINR) for CUE and DUE is expressed as:

$$\gamma_m^c = \frac{p_m^c h_{m,B}}{\sigma^2 + \sum_{n \in N} x_{n,m} p_n^d h_{n,B}} \quad (3.2)$$

$$\gamma_n^d = \frac{p_n^d h_{n,n}}{\sigma^2 + \sum_{m \in M} x_{n,m} p_m^c h_{m,n}} \quad (3.3)$$

Therefore, the achievable data rate for CUE and DUE can be respectively expressed as

$$R_n^d = \log_2(1 + \gamma_n^d) \quad (3.4)$$

$$R_m^c = \log_2(1 + \gamma_m^c) \quad (3.5)$$

and the sum data rate of the overall system is

$$R_{sum} = \sum_{m=1}^M R_m^c + \sum_{n=1}^N R_n^d \quad (3.6)$$

### 3.2.2 Mathematical Optimization Problems

It is evident that the presence of D2D communications undoubtedly impairs cellular and D2D users' performance. Therefore, in order to reduce the performance degradation that D2D communication causes for both cellular and D2D users, we examine resource

allocation and power control in this research. More specifically, our goal is to maximize data rate of the overall system. Denote  $x$  as the channel assignment matrix, where  $x = \{x_1, x_2, \dots, x_i\} \forall i \in C \cup D$  is channel assignment matrix in the reusing mode. The transmit power matrix of the CUs and D2D pairs is denoted by  $p$ . The following is how we formulate the mathematical optimization problems based on this assumption:

$$\max_{x,p} R_{sum} \quad (3.7)$$

$$\gamma_m^c \geq \gamma_m^{c,req} \quad \forall m \in C \quad (3.7a)$$

$$\gamma_n^d \geq \gamma_n^{d,req} \quad \forall n \in D \quad (3.7b)$$

$$0 \leq p_n^d \leq p_n^{d,max} \quad \forall n \in D \quad (3.7c)$$

$$0 \leq p_m^c \leq p_m^{c,max} \quad \forall m \in C \quad (3.7d)$$

$$\sum_{n \in D} x_{n,m} \leq 1 \quad (3.7e)$$

In 3.7,  $x$  is the set of binary variables that indicate the subcarrier assignment of DUEs, and  $p$  is the set of transmit power that includes the transmit power of CUEs, DUEs, and the BS. The data rate needs of CUEs are guaranteed by constraint 3.7a, where  $\gamma_m^{c,req}$  represents the CUE's minimum SINR requirements.  $\gamma_n^{d,req}$  indicates the minimum SINR needs of DUEs, whereas 3.7b ensures the data rate requirements of DUEs. The constraints 3.7c, 3.7d are the power constraints where  $p_n^{d,max}, p_m^{c,max}$  are maximal transmit power of DUEs, CUEs, respectively. Each D2D pair can only select one communication mode, according to Constraints 3.7e, which prevents any more than two CUs from sharing

the same channel.

### 3.3 Matching-Based PCRA Scheme

Both continuous and discrete variables are present in the mixed integer nonlinear programming (MINLP) problem 3.7, which is typically mathematically unsolvable. Thus, we propose a RAPC scheme to solve the MINLP problem 3.7. In order to reduce computing complexity, the RAPC algorithm divides the difficult problem into two subproblems: the

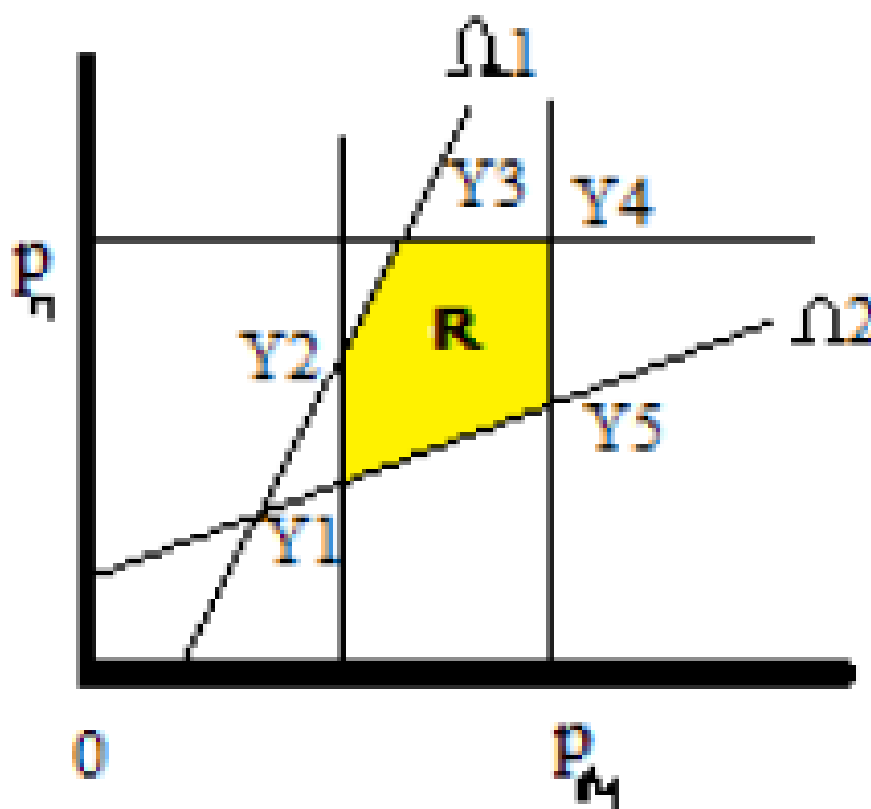


Figure 3.2: Feasible power allocation region.

subcarrier assignment and power allocation subproblems. In particular, we first construct the power allocation problem as a non-linear programming problem for each DUE  $n$  and each CUE  $m$ , after which we provide the optimal power solution. DUE  $n$  is permitted to reuse the subcarrier of CUE  $m$  if the power control problem is practical; if not, they are eliminated from the list of viable partners for the second problem. Then, in order to enhance the overall system data rate, we must use maximum weight bipartite matching to choose the optimal subcarrier for each DUE from all viable options. [113].

### 3.3.1 Power Allocation

The optimisation power allocation problem 3.7 for cellular and D2D users is a non-linear programming problem. In order to solve the problem, we first analyse the feasible region  $R$ . We divide the constraints into two parts: power constraints  $\Omega_1 = \{p_n, p_m\} : p_{min} \leq p_n \leq p_{max}, 0 \leq p_m \leq p_{max}$ , and rate constraints  $\Omega_2 = \{(p_n, p_m) : \gamma_m^c \geq \gamma_m^{c,min}, \gamma_n^d \geq \gamma_n^{d,min}\}$ , then  $R = \Omega_1 \cap \Omega_2$ . Since  $\Omega_1$  is a finite closed region,  $R$  is a finite closed region or empty set. Note that we can properly set parameters  $p_n, p_m, \gamma_m^{c,min}, \gamma_n^{d,min}$  to guarantee  $R$  is not empty. Therefore the following discussions are based on the assumption that  $R$  is a non-empty finite closed region as see in 3.2. Since  $R$  is a closed and bounded set and  $f(p_n, p_m)$  is continuous, the optimisation problem has a solution [111].

To find the optimal power solution  $(p_n, p_m)$  of 3.7, we have the following lemmas [114].

Lemma 1: The optimal solution  $(p_n^*, p_m^*)$  has  $p_n$  or  $p_m$  equal to the maximum power.

Proof: Substitute  $(\alpha p_n, \alpha p_m)$  for  $(p_n, p_m)$  in 3.7, for  $(p_n, p_m) \in R \quad \forall \alpha \geq 1, \alpha \in \mathcal{R}^+$  and  $(p_n, p_m) \in R$ , we have

$$f(\alpha p_n, \alpha p_m) = \log_2 \left( \left( 1 + \frac{p_n^d h_{n,m}}{\left(\frac{\sigma^2}{\alpha}\right) + p_m^c h_{m,n}} \right) \left( 1 + \frac{p_m^c h_{m,B}}{\left(\frac{\sigma^2}{\alpha}\right) + p_n^d h_{n,B}} \right) \right) \geq f(p_n, p_m) \quad (3.8)$$

Lemma 2: The optimal transmitting power allocation  $(p_n^*, p_m^*)$  for 3.7 only exists on the corner points of  $R$ .

The optimal power solution is assigned at a single point in a finite collection  $\{Y1, Y2, Y3, Y4, Y5\}$  based on the lemmas and formulas mentioned above. To get the largest  $R_{sum}$ , we can search every element in the set. Therefore, it is possible to determine the ideal power solution when DUE  $n$  reuses CUE  $m$ 's uplink subcarrier resource.

### 3.3.2 Subcarrier Assignment

We have created the best power allocation plan for every DUE-CUE combination in the above. The maximum data rate that CUE  $m$  can achieve on the uplink when there is no

DUE recycling its subcarrier is

$$R_m^{max} = \log_2\left(1 + \frac{p_m^c h_{m,B}}{\sigma^2}\right) \quad (3.9)$$

The possible sum data rate of CUE  $m$  and DUE  $n$  is  $R_{n,m}$  when they share an uplink subcarrier resource. Consequently, we can characterize the uplink capacity gain as

$$\nabla R_{n,m} = R_{n,m} - R_m^{max} \quad (3.10)$$

The optimal CUE-DUE pairing problem therefore becomes a bipartite matching problem with greatest weight. It can be expressed as

$$\max_{x_{n,m}} \sum_{n \in D} x_{n,m} \nabla R_{n,m} \quad (3.11)$$

$$0 \leq \sum_{n \in D} x_{n,m} \leq 1, \forall m \in C \quad (3.11a)$$

$$x_{n,m} \in [0, 1], \forall n \in D, \forall m \in C \quad (3.11b)$$

where the DUEs and  $\nabla R_{n,m}$  corresponds to the set of vertices in the bipartite graph, the edge connecting DUE  $n$  and

the uplink subcarrier of CUE  $m$  has a weight  $\nabla R_{n,m}$  and the edge connecting DUE  $n$ . The bipartite matching problem can be resolved in polynomial time using the traditional Kuhn-Munkres algorithm [115], [116].

### 3.4 Simulation Results

To confirm the suggested PCAR algorithm, we give numerical results in this section. Consider a 500 (m) radius circular cell with uniformly and randomly distributed CUEs and DUEs. Utilizing MATLAB software, we put our PCAR algorithm into practice. Each piece of data is averaged over 1000 simulations to level out simulation randomness.

Table 3.1: summary of the simulation parameters values

Parameter	Value
Cellradius(R)	0.5 km
CUEs and DUEs location	Uniformdistributedin $[0, R]$
Multiple-path fading	Exponential distribution unit mean
Pathloss exponent ( $\alpha$ )	3
Pathloss constant (G)	2 -10
Shadowing	Log-normal distribution with standard deviation of 8 dB
Noise spectral density ( $N_0$ )	-174 dBm/Hz
Maximal transmit power of CUEs ( $P_{max}^n$ )	24dBm
Maximal transmit power of DUEs ( $P_{max}^m$ )	24dBm
Maximal transmit power of BS ( $P_{max}^{B,m}$ )	46dBm
Number of CUEs (M)	20
Number of DUEs (N)	50 -10
the value of D2D distance (d)	5 -45
$\gamma_m^{c,req}, \gamma_n^{d,req}, \gamma^{req}$	7dB

In Table I, the default parameters are presented.

The two metrics used to evaluate the system's performance are the system data rate, which is the overall system data rate, and the D2D access rate, which is determined by dividing the number of accessed DUEs by the total number of DUEs. Additionally, we compare methods 1 and 2 with the suggested PCAR technique.

Figure 3.3 illustrates the system data rate performance of the three Systems in relation to various DUE counts. It is evident that the system data rate risesmonotonically as DUE sincrease. The cause is that DUEs with better capacity gains may be able to connect to the cellular network. Additionally, because all subcarriers can be chosen to be reused by DUEs, our suggested PCAR system performs better than the previous benchmark approaches.Contrary to other algorithms.

### 3.5 Summary Chapter

In order to maximize the system's total data rate while ensuring the QoS requirements of both CUEs and DUEs, this study set out to evaluate the power control and resource allocation problem for D2D communications that underpin cellular networks. Effectively solving the optimization problem can be challenging because it is a MINLP problem. To solve the problem, we have separated it into two smaller issues: the subcarrier assignment

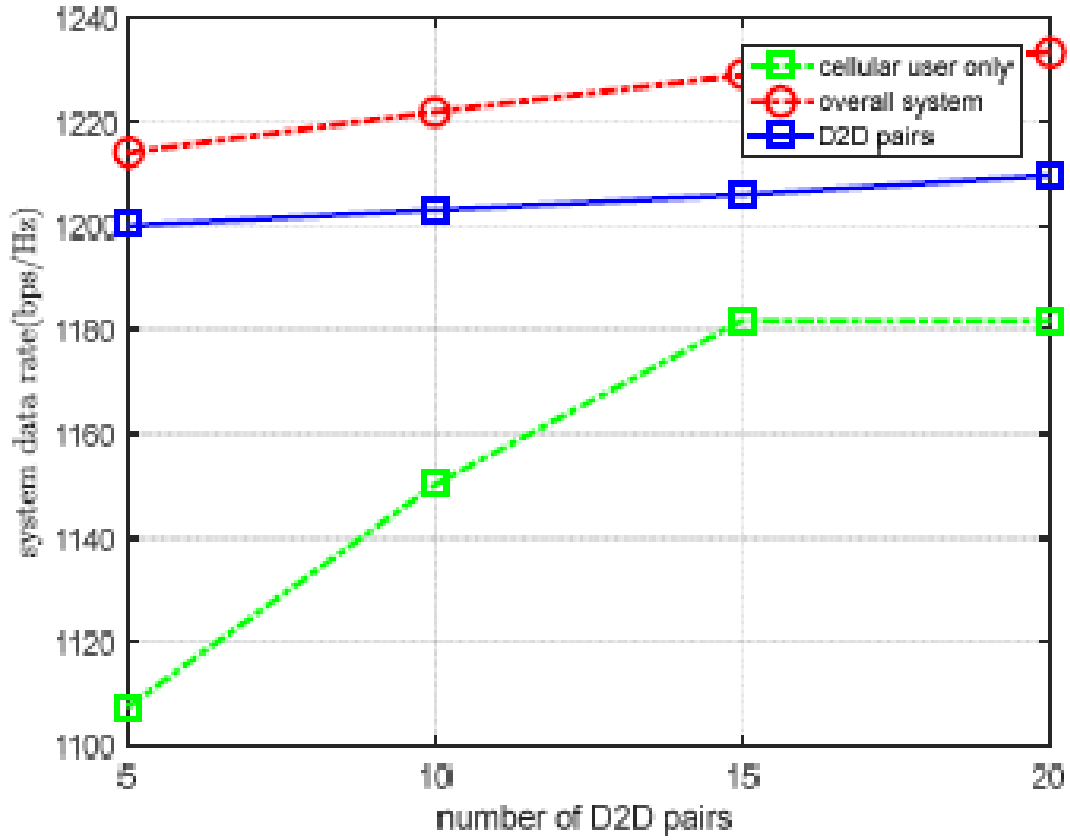


Figure 3.3: the system data rate performance

and power allocation subproblems. Comparing our proposed PCAR scheme to various benchmark systems, simulation results demonstrate that it consistently outperforms them in terms of system data rate and D2D access rate.

## CHAPTER 4

# Cellular D2D Underlay Resource Management

### 4.1 Introduction

D2D communications can be supported by cellular networks in both overlay and underlay modes. However, cellular D2D overlay seems to have received more attention than cellular D2D underlay, which may be responsible for the exceptional spectrum efficiency that comes with spectrum reuse. Mutual interference, however, is an unavoidable issue brought on by cellular users and D2D networks sharing spectrum. Therefore, it is crucial to manage mutual interference and create a thorough plan for power control and spectrum distribution. In this chapter, we examine cellular D2D underlay networks, where D2D links can "share" or reuse cellular customers' spectrum resources for data transmission, resource management, by using wireless channel data that presents slowly varying large-scale fading to perform spectrum sharing and power allocation. We propose to use two characteristics: the sum ergodic capacity of all CUE links and minimum ergodic capacity maximization. We also used an optimization algorithm that produces optimal resource allocation and is impervious to channel variations.

### 4.2 Important Resource Management Issues

Effective resource management, encompassing channel allocation and power control, is crucial for reducing interference and enhancing network performance in wireless networks. The variables that reflect channel resource assignment in resource management problems involving channel allocation are typically limited to being integral. An example of a general definition for this type of variable is

$$x_{i,j} = \begin{cases} 1 & : \text{resource } j \text{ is assigned to user } i. \\ 0 & : \text{otherwise.} \end{cases} \quad (4.1)$$

The optimization issue turns into a combinatorial challenge in this scenario. In wireless resource allocation, combinatorial optimization challenges come in a variety of forms.

#### 4.2.1 Basic Problems

Numerous possible applications exist for resource allocation in wireless networks, and combinatorial optimization issues can be formulated into various types of challenges, including [117]:

**Assignment Issues** It is possible to express many optimization issues as assignment problems. One common example of an assignment problem is this: a group of agents is given a number of jobs to complete, and each task must be allocated to an agent in a way that minimizes the assignment's overall cost. It is possible to formulate the assignment problem in a flexible way using several assumptions. One can assume that there are exactly the same number of tasks as agents in order to minimize the overall cost, or that there are more tasks than agents in order to allow some agents to "keep silent doing nothing," or that one agent can perform multiple tasks because there are more tasks than agents. Furthermore, the assignment problem's purpose can be modified to maximize profits as opposed to minimize costs. The spectrum matching between cellular resources and D2D links is referred to as the assignment problem in cellular D2D underlay. One can characterize the spectrum resources of CUEs as agents and D2D links as tasks.

**Scheduling Issue** Problems with scheduling are frequently created when certain requirements must be met at various times. One of the representative scheduling difficulties is the channel assignment problem, which calls for assigning a particular useful user to the channel in order to maximize system performance or quality of service based on the channel's current conditions or transmission history.

**Issue with the Knapsack** Assume that there is a list of  $n$  potential objects, each with a value of  $v_i$  and a weight of  $w_i$ . One wants to fill the knapsack with a certain combination

of goods from the list of  $n$  possible items in order to maximize the value of the items packed within, allowing the knapsack to hold a total weight of  $c$ . The two limitations of this problem, which is referred to as the "Knapsack problem," are that the weight of the items in the knapsack cannot be greater than  $c$  and that each item can only be in the knapsack or not—that is, only a complete quantity of the item can be present. The problem with cellular D2D underlay networks can be explained as follows. Assume that many D2D lines can share the spectrum resource of each CUE. To ensure that it meets its unique QoS requirements, each CUE has a maximum permitted interference level. The CUE that provides the spectrum may be hampered by each D2D connection's ability to reuse spectrum in order to increase system throughput. Therefore, optimizing the system's overall throughput while ensuring that the interference from D2D links sharing resources doesn't surpass the permitted amount of interference is the optimization goal.

### 4.3 Graph-Based Bipartite Resource Management

In this work, we concentrate on the assignment problem outlined in Sect. 4.4, which is to maximize the matching between spectrum resources of CUEs and D2D links in cellular D2D underlay networks. Graph theory, especially in the context of bipartite graphs, is applied to achieve effective resource allocation.

#### 4.3.1 Problems Graph Matching

Graphs with nodes defined and arcs connecting the nodes can be used to depict a wide range of optimization challenges. The assignment problem discussed earlier, for instance, can be represented as a bipartite graph by designating the tasks as one set of nodes and the agents as another. If an agent is able to complete a task, an arc will connect the two sets of nodes. Additionally, two distinct sets of nodes can be utilized to represent users in wireless radio resource allocation problems who need spectrum resources and those who need communication resources.

Since bipartite graphs are generalizable and can be created adaptively to meet unique demands, they are utilized in this section to solve resource allocation problems. Generally speaking, there are two ways to form a bipartite graph: weighted and unweighted. The weight of the arcs linking two nodes from different sets in a weighted bipartite network can be uniquely specified based on practical requirements [93]. For

example, the spectrum allocation for DUEs in cellular D2D underlay networks can be represented as a bipartite graph, as Figure 4.1 illustrates. Several clustered DUEs can share a single CUE's spectrum resource for data transfer. Observe that the resource allocation problem reduces to a straightforward scenario in which each CUE's spectrum is allocated to a single D2D connection when the number of members in cluster  $M$  falls to 1, or  $KM = 1$ . Stated differently, the resource matching problem based on clustering is reverted to a resource pairing problem. To be clear, the primary distinction between the pairing and clustering problems is in whether or not the D2D links inside a cluster require consideration of either spatial reuse or interference management. As illustrated in the picture, a spectrum resource and a D2D link/cluster are connected by an edge only when specific requirements are met when assigning that spectrum resource to the appropriate D2D link/cluster. Constraints can be specified to, for example, transmit power restrictions, transmission success probability, and SINR requirements. It is also possible to determine the weights of the edges that link DUEs and spectrum resources according to certain goals, such as transmission latency, feasible network capacity, outage likelihood, and energy efficiency.

### 4.3.2 Typical Matching Objectives and Goals

Following the creation of bipartite graphs, various matching algorithms based on various matching objectives can be used to maximize the matching between nodes from two distinct sets. Three types of common pairing challenges are given below, along with matching solutions, for wireless resource matching between cellular users and D2D links in D2D underlays, for instance.

#### Maximum Cardinality Pairing Problem

Issue It may be desirable in some circumstances to match as many node pairs as you can. For instance, if the traffic loads are moderate, it could be desirable to match as many pairs of D2D links/clusters and CUEs (spectrum resources) as feasible. Stated differently, the optimum quantity of D2D links that reuse cellular user resources is achieved while maintaining fundamental quality of service standards. This leads to an overall improvement in spectrum efficiency. More D2D links are allowed to communicate in cellular D2D

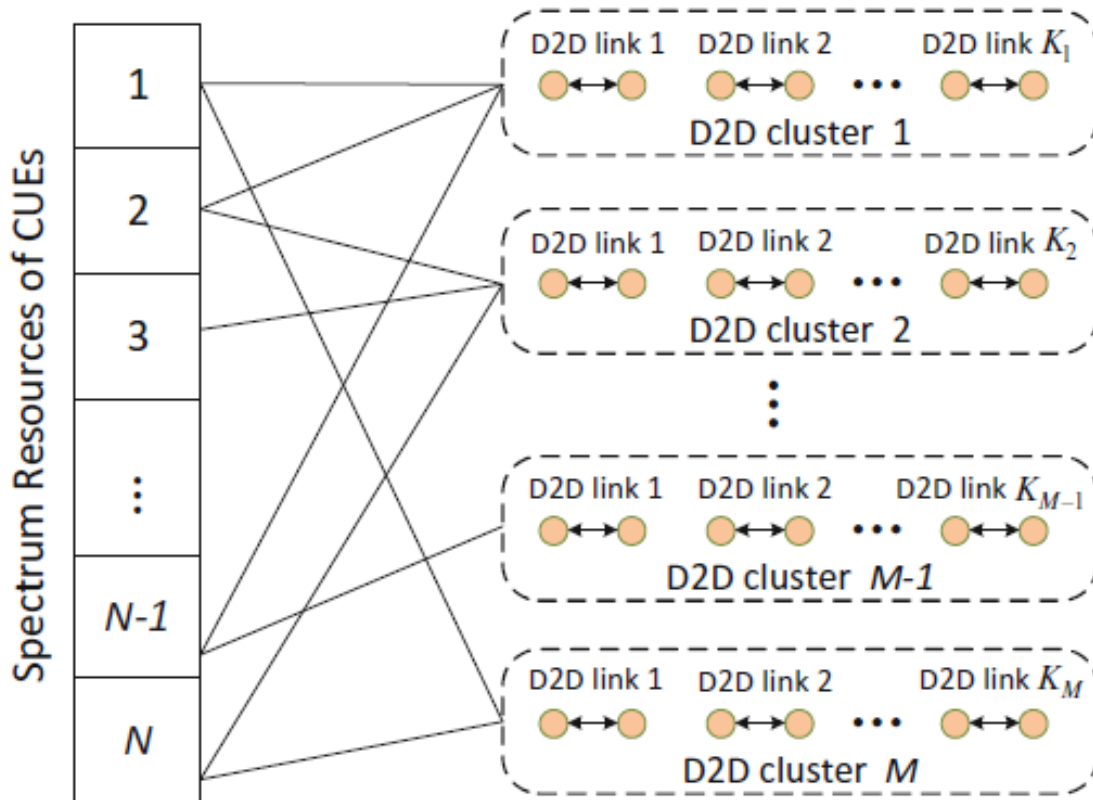


Figure 4.1: Bipartite graph based resource matching in D2D underlay

underlay networks as a result.

Resolution One of the most effective algorithms for resolving the aforementioned issue is the Hopcroft-Karp (HK) algorithm, which aims to find a maximum cardinality matching in a bipartite graph. In particular, by identifying augmenting pathways, the HK algorithm continuously expands the amount of a partial match. Nevertheless, the technique finds a maximal collection of shortest augmenting paths every iteration rather than simply one. When there are no more augmenting paths in the bipartite graph, the method comes to an end. You'll notice that in maximum cardinality pairing issues, bipartite graphs are typically unweighted.  $O(n^{5/2})$ , where  $n$  is the bipartite graph's number of vertices, is the computational complexity of HK [118].

### Stable Marriage for Maximum Pairing Satisfaction

Problem This is the explanation for the well-known steady marital conundrum. Finding a good way to marry off every member of the society is desired in order to ensure stable marriages. Assume a community of  $n$  men and  $n$  women exists, and each member has ranked every person of the other sex based on their preferences for a spouse. A marriage

is deemed unstable when two persons of the opposite sex are not wedded to each other but instead cherish each other more than their actual partners. When such pairs of people do not exist, the set of marriages is regarded as stable. The stable marriage difficulty is highly pertinent to our D2D and CUE pairing. Resource sharing between CUEs and D2D pairings may be sustained over time if CUEs are matched with D2D linkages. Each D2D connection or CUE should not be encouraged to look for better pairings while assessing good performance because the stable marriage problem aims to distribute resources in a fair and equitable way.

Resolution One of the most often used algorithms for solving the stable marriage problem is the Gale-Shapley (GS) algorithm, which was first introduced by David Gale and Lloyd Shapley in [119]. The goal of the GS algorithm is to locate a stable match using a directed, weighted bipartite graph. The weight of the edge from node  $a$  in set  $A$  to node  $b$  in set  $B$ , given two sets of nodes, set  $A$  and set  $B$ , with equal numbers of nodes, reflects the preference of  $a$  to  $b$ . Based on the preference list, the nodes in one set (set  $A$ ) in the GS algorithm make proposals to the nodes in another set (set  $B$ ). The best proposal that each node in set  $B$  has received can then be held onto. The nodes in set  $A$  may make a proposal to the node after it in the preference list if it is denied. When no more suggestions are created by nodes in set  $A$ , the algorithm comes to an end. Since no nodes in distinct sets would prefer to be matched with one another than stick with their partners who were assigned to them throughout the matching process, the matching in this instance is stable. The GS algorithm has an  $O(n^2)$  computational complexity, where  $n$  is the number of nodes in each collection.

### **The Optimal Assignment Problem**

Issue Assuming that each agent will receive a numerical reward based on how well they do on each task, the optimal assignment issue can be defined as the problem of selecting the best possible assignment of  $n$  agents to  $n$  tasks. The goal of this challenge is to maximize the agents' total rewards for completing their assigned tasks by optimizing the match. In a similar vein, the problem can be written to minimize the overall cost—that is, the total time spent on the tasks—of the agents doing them. The problem of maximizing/minimizing the sum of the weights of surviving edges on the bipartite graph, which is generated based on various constraints and objective functions as stated in Sect. 4.4.2,

can be turned into the optimal assignment problem. The problem can be defined as the maximizing of the total system throughput for all CUEs and D2D connections inside the same cell by taking appropriate pairing selections into consideration when applied to cellular D2D underlays.

The goal of the Solution Kuhn-Munkres (KM) approach is to maximize the overall system reward by locating the ideal matching in a weighted bipartite graph. It was first put forth by H. W. Kuhn in 1955 [120] and improved by J. Munkres in 1957 [116]. Let  $A_i$  and  $B_j$  represent nodes from sets A and B, respectively, that have been divided. Each node  $A_i$  receives variable  $\alpha_i$ , and each node  $B_j$  receives variable  $\beta_j$ , according to the algorithm. It takes advantage of the fact that when  $\alpha_i + \beta_j \leq C_{i,j}$ , where  $C_{i,j}$  is the weight of the edge linking  $A_i$  and  $B_j$ , the assignment issue can be optimized. When  $\alpha_i + \beta_j = C_{i,j}$ , an edge in the bipartite graph is considered acceptable. An equality subgraph is a subgraph that contains only the edges that are currently acceptable. The KM algorithm's fundamental tactic is to continuously look for augmenting paths in the equality subgraph, starting with an empty matching. The current set of matches is enhanced by inverting the matched and unmatched edges along any detected augmenting paths. This flipping completes one stage of the algorithm by increasing the cardinality of the matching by one because there are one more unmatched edges than matched edges. In the event that an augmenting path cannot be discovered, the variables  $\alpha_i$  and  $\beta_j$  are made acceptable in order to add more edges to the equality subgraph, and the search is resumed. Since the KM algorithm has  $n$  stages and each step requires  $O(n^2)$  arithmetic operations, the total computing complexity of the process is  $O(n^3)$ , where  $n$  is the number of nodes in either set.

#### 4.4 Resource allocation for device-to-device communications underlying up-link cellular networks

Device-to-device (D2D) communication is one of the technology elements of the third generation partnership projects (3GPPs) long term evolution advanced (LTE-A) [121]. Instead of sending and receiving signals through a cellular base station (BS), D2D communication allows nearby cellular users (CUs) to speak with one another directly over a direct link. When D2D users communicate directly, they are still subject to BS control. In contrast to routing through a BS, CUs in close proximity can save energy and resources

when engaging directly with one another. Additionally, D2D users can take advantage of rapid data rates and low transmission delays due to the short distances involved in direct interaction [121]. Bypassing the BS and other network elements and enabling direct user-to-user transmission of cellular traffic, D2D communication further lessens the strain on the network. This contributes to the effective capacity of the network. Other benefits and uses are discussed in [72].

In this paper, we investigate the performance of an enhanced power control technique and channel allocation using a random D2D underlaid cellular network model. The study models the distance between D2D pairings at random in a variety of scenarios. In order to maximize its own D2D link rate, each D2D transmitter selects the transmission power level based on the channel circumstances, namely the distance-dependent path-loss between D2D pairs. We also consider the possibility of resource sharing between the D2D links and a single cellular user.

#### 4.4.1 Related work

Power control strategies for D2D underlaid cellular networks have garnered significant attention. For a deterministic network model and a single-cell scenario, [122] introduced a simple power control method that restricts D2D transmit power to protect the existing cellular links. [123] introduced a dynamic power control system for a single D2D link communication with the aim of enhancing cellular system performance by reducing interference caused by D2D communication. [73] presented a D2D transmit power allocation strategy for the stochastic network model in order to maximize the network's sum rate. The primary idea was to use BS to change the D2D transmit power in order to protect CUs. In order to get the quality-of-service (QoS) that D2D and CUs need, a power reduction approach was put out in [74]. Mode selection, adaptive modulation, and joint subcarrier allocation are all included in this system. Yu et al. [73] examined power control and resource allocation between D2D and CUs and suggested an optimization approach to increase system capacity. Bidirectional data transmission and network complexity were taken into account when examining the network's capacity [124]. Furthermore, in [125], an ideal D2D transmission capacity was suggested. In [94]–[101], more research was done on cooperative communication in D2D, where CUs inside the networks can help with D2D transmission. This improvement increased the overall system data rate and

met QoS requirements for both uplink and downlink user equipments (DUEs and UUEs). Li et al. [102] focused on maximizing the data rate of the weighted system while preserving D2D user equipment (DUE) fairness and minimizing the data rate for each distinct cellular user equipment (CUE). According to research by Kai et al. [103], their objective was to meet each user's basic rate requirements while minimizing the system's overall power consumption of the CUEs and DUEs.

aimed at reducing user disruption [100]. The alternative kind of resource allocations is D2D downlink [104]– [99]. DUEs only employ CUEs' downlink subcarriers, for instance. In their study, Hu et al. [107] investigated how DUE downlink subcarrier resource reuse affected D2D. In [105], [106], several mathematical strategies are used to increase the system's overall data rate. Scholars [107]– [99] studied the problem of maximizing energy efficiency (EE) in order to achieve green communication; [107] only studied the problem of maximizing EE for all DUEs; [108] concentrated on maximizing the EE of the entire system; and [99] sought to balance the system's EE and spectral efficiency (SE). [109]– [110] conducted concurrent studies on the reuse of uplink and downlink subcarriers in cellular networks. Maximizing the overall rate of all DUEs was the aim of [46], [126] in particular. [109] introduced the novel resource allocation method known as gain aware uplink-downlink (GAUD). Conversely, [111] examined interference management techniques based on access control, power allocation, and channel assignment.

In order to minimize interference with cellular receivers, a D2D transmitter lowers its broadcast power when reusing cellular resources [46]. recommends the use of an area management system for interference limitation in order to prevent D2D receivers from being affected by cellular interference. D2D users are not allowed to share spectrum with CU under this technique. if the interference-to-noise ratio of the D2D receiver exceeds a specific threshold. Interference nulling is used to reduce interference from the cellular link to the D2D communications base station (BS) when numerous antennas are placed there (Yu et al., 2012). With a single D2D pair and a single cellular user, [73] optimized the network's total D2D and Cus rates while maintaining a minimal rate for the cellular user. Numerous D2D and cellular users in more realistic settings have spurred studies on spectrum and power distribution design in [127] and [94]. The BS in [127] controls the transmit power of D2D devices to optimize the signal-to-interference-plus-noise ratio (SINR) of D2D connections while maintaining a manageable degree of cellular link

interference. Additionally, [94] suggests a three-step procedure for developing spectrum allocation and power regulation in order to boost system throughput and maintain a minimum SINR for D2D links.

#### 4.4.2 Model Assumption

Figure 4.2 illustrates the presentation of the system model and the network metrics that will be utilized in this section of the article. This section outlines the network metrics that will be utilized in the study and presents the system model. Our consideration is a D2D underlay cellular network.

In this model, the coverage region of a BS centered at the origin is represented by the circular disk  $C$  with a radius of  $R$ . The number of cellular uplink users evenly distributed throughout this area is denoted by  $M = \{1, \dots, m\}$ . Furthermore, we assume that  $K = \{1, \dots, k\}$ , the number of D2D users, is distributed according to a homogeneous Poisson point process (PPP)  $\Phi$  with a density of  $\lambda$  throughout the entire  $R^2$  plane. A D2D transmitter's corresponding receiver is located in an isotropic direction at a configurable distance. Every node is assumed to have a single antenna.

The number of D2D transmitters in  $C$  is a Poisson random variable with a mean of  $E[K] = \lambda\pi R^2$  based on the assumptions made. It is anticipated that the channel power gain between CUE  $m$  and the BS will follow a specific realization of the PPP.

$$h_{m,B} = g_{m,B} \beta_{m,B} A d_{m,B}^{-\alpha} \quad (4.2)$$

Where  $\xi$  is the standard deviation of  $\beta_{m,B}$  is a log-normal shadow fading random variable,  $d_{m,B}^{-\alpha}$  is the distance between the  $m$ -th CUE and the BS,  $\alpha$  is the decay exponent, and  $A$  is the pathloss constant. Additionally, there is the small-scale fast fading power component, which is assumed to be exponentially distributed with a mean of one unit. Similar definitions apply to the interfering channels  $h_{k,B}$  from the  $k$ -th DUE to the BS,  $h_{m,k}$  from the  $m$ -th CUE to the  $k$ -th DUE, and the channel  $h_k$  between the  $k$ -th D2D pair. The received SINRs for the  $m$ -th CUE and the  $k$ -th DUE at BS can be written as 4.3:

$$\gamma_m^c = \frac{p_m^c h_{m,B}}{\sigma^2 + \sum_{k \in K} x_{m,k} p_k^d h_{k,B}} \quad (4.3)$$

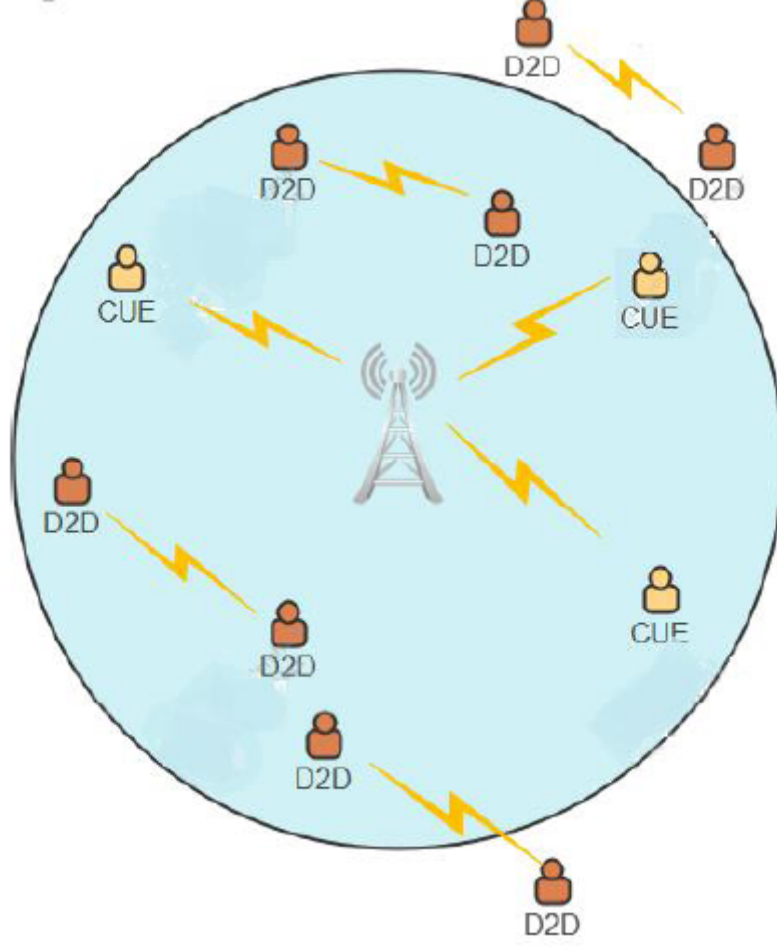


Figure 4.2: A single-cell D2D underlaid cellular system

$$\gamma_k^d = \frac{p_k^d h_{k,k}}{\sigma^2 + \sum_{m \in M} x_{m,k} p_m^c h_{m,n}} \quad (4.4)$$

Where the transmit powers of the  $m$ -th CUE and the  $k$ -th DUE are denoted, respectively, by  $p_m^c$  and  $p_k^d$ . The noise power is represented by  $\sigma^2$ , and the spectrum allocation is indicated by  $x_{m,k}$ , where  $x_{m,k} = 1$  indicates that the  $k$ -th DUE reuses the  $m$ -th CUE's spectrum and  $x_{m,k} = 0$  otherwise. Next, assuming Gaussian inputs, the ergodic capacity of the  $m$ -th CUE is given by:

$$C_m = E[\log_2(1 + \gamma_m^c)] \quad (4.5)$$

where the fast fading distribution is taken up by the expectation  $E[\cdot]$ .

### 4.4.3 Resource And Power Allocation Desin

#### Resource allocation

The design of resource distribution under prior constraints is examined in this paper. Our resource allocation strategy is to maximize the combined ergodic capacity of M CUEs while offering the highest degree of reliability for every DUE. We have set a minimum capacity requirement for each CUE to guarantee a certain degree of service quality. The device's dependability is guaranteed by controlling the probability of outages occurring when its received SINR drops below a predetermined level. It is expected that the ergodic capacity of CUEs covers several coherence periods over the slow fading time scale since the codeword length is calculated using the long-term average of the rapid fading [128]. It should be noted that the system's ability to approximate the ergodic capacity is ultimately determined by the permitted latency and the temporal variation of the user channels. Faster variation introduces more channel states in a given time period, which helps to reduce the effect of fading and enhance the system's performance in reaching the anticipated ergodic capacity. By doing this, the code word is guaranteed to go across the majority of the channel states, if not all of them [129]. The radio resource allocation problem can be expressed as (4.5a)-(4.5f).

$$\max_{x_{m,k}, p_m^c, p_k^d} \sum_{m \in M} E[\log_2(1 + \gamma_m^c)] \quad (4.6)$$

$$E[\log_2(1 + \gamma_m^c)] \geq r_0^c \quad \forall m \in M \quad (4.5a)$$

$$Pr\{\gamma_k^d \leq \gamma_0^d\} \leq p_0 \quad (4.5b)$$

$$0 \leq p_m^c \leq p_{max}^c, \quad \forall m \in M \quad (4.5c)$$

$$0 \leq p_k^d \leq p_{max}^d, \quad \forall k \in K \quad (4.5d)$$

$$\sum_{m \in M} x_{m,k} \leq 1, \quad x_{m,k} \in \{0, 1\} \forall k \in K \quad (4.5e)$$

$$\sum_{k \in K} x_{m,k} \leq 1, \quad x_{m,k} \in \{0, 1\} \forall m \in M \quad (4.5f)$$

Where  $\gamma_0^d$  is the minimum SINR required by the DUEs to create a reliable link, and  $r_0^d$  is the minimum capacity required by the data rate-intensive CUEs. The permissible outage probability at the physical layer of the D2D connections is indicated by  $p_0$ , whereas  $P_r\{\cdot\}$  assesses the input probability. The maximum transmit powers of the CUE and DUE are  $p_{max}^c$  and  $p_{max}^d$ , respectively. For each CUE and DUE, the related minimum capacity and reliability needs are represented by constraints (4.5a) and (4.5b).

The minimum capacity and reliability requirements for each CUE and DUE are outlined in constraints (4.5a) and (4.5b), respectively. The transmit powers of CUEs and DUEs are prevented from exceeding their maximum limitations by (4.5c) and (4.5c), respectively. We mathematically represent our assumptions that only one DUE can access a single CUE's spectrum and that only one CUE can share a spectrum with another in (4.5e) and (4.5f). This premise simplifies the intricacy that intricate interference scenarios in networks-assisted D2D bring, and it offers a strong basis for examining the difficult issue of resource allocation in D2D networks.

From the perspective of the network operator, the previously stated resource allocation system may ensure a high overall throughput. However, it frequently seems unjust from each CUE's point of view, particularly for users who are having channel issues. In this case, the CUEs with bad channel conditions will suffer in order to accomplish the overall performance improvement. In this section, we will optimize the minimum capacity among all CUEs in order to resolve this problem and guarantee consistent performance across all CUEs. The optimization problem that has been proposed is:

$$\max_{x_{m,k}, p_m^c, p_k^d} \min_{m \in M} E[\log_2(1 + \gamma_m^c)] \quad (4.7)$$

With the same equations: (4.5a)-(4.5f) as conditions.

### Power allocation

The best way to divide power among all potential DUE and CUE reuse combinations will be covered in this section. For a single CUE-DUE pair, the power allocation problem boils down to determining an arbitrary spectrum reuse pattern in which the  $k$ -th DUE and the  $m$ -th CUE share the band.

$$\max_{p_m^c, p_k^d} E[\log_2(1 + \gamma_m^c)] \quad (4.8)$$

$$Pr\{\gamma_k^d \leq \gamma_0^d\} \leq p_0 \quad (4.7a)$$

$$0 \leq p_m^c \leq p_{max}^c, \quad \forall m \in M \quad (4.7b)$$

$$0 \leq p_k^d \leq p_{max}^d, \quad \forall k \in K \quad (4.7c)$$

In the subsequent lemma, we evaluate the reliability requirement of the  $k$ -th DUE (4.7a) and demonstrate the areas of the reduced D2D power optimization problem that are feasible.

**Lemma 1:** The D2D transmitter selects its broadcast power based on the channel conditions, i.e., the distance-based path-loss  $d_{k,k}^{-\alpha}$ , in order to maximize its own D2D link rate. The  $k$ -th D2D TX's utilization of transmit power  $p_k^d$  with transmit probability  $\mathcal{P}_{tx}$  is dependent on the  $k$ -th D2D link's good channel quality. The probability of transmission can be ascertained by:

$$\mathcal{P}_{tx} = P[|h_{k,k}|^2 d_{k,k}^{-\alpha} \geq \gamma_0^d] \approx \exp(-\gamma_0^d E[d_{k,k}^\alpha]) \quad (4.9)$$

Additionally, an error margin  $\epsilon$  is provided to account for estimation mistakes in

the D2D pair distances. Consequently, the D2D link's power distribution is guided by the channel inversion technique outlined in [130].

$$P_k^d = \begin{cases} p_{rx} d_{k,k}^\alpha (1 + \epsilon) & : \text{with } \mathcal{P}_{tx} \\ 0 & : \text{with } 1 - \mathcal{P}_{tx} \end{cases} \quad (4.10)$$

where  $d_{k,k}$  is the distance between the k-th D2D pairings,  $\epsilon$  is the estimate error margin of  $d_{k,k}^\alpha$ , and  $\alpha$  is the path-loss exponent, with  $0 \leq \epsilon \leq 1$ .

Theorem 1: for optimization problem (4.8), the optimal power allocation solution is provided by (4.11).

$$\begin{cases} p_m^c = \min(p_{max}^c, p_{d,max}^c) \\ \\ p_k^d = \min(P_{max}^d, p_{c,max}^d) \end{cases} \quad \text{and} \quad (4.11)$$

By maximizing the ergodic capacity of the CUE in question and ensuring the reliability of the reused DUE, Theorem 1 provides the optimal power distribution for a single CUE-DUE pair. There is only interference within each reuse pair as the initial resource allocation problem in (4.6) to maximize the sum ergodic capacity of all CUEs has been divided into two major pieces. The first section discusses Theorem 1's ideal power distribution for each individual pair. To increase the cumulative ergodic capacity of CUEs while meeting all QoS requirements, optimal spectrum reuse pair matching should be employed.

each CUE-DUE combination's proper power allocation. Excluding any CUE-DUE pairs that don't satisfy the CUE's lowest QoS condition, as stated in (4.5a) [125], is the next step. This is accomplished by referring to the optimal allocation strategy found in step (4.11). The closed form of the m-th CUE's ergodic capacity when sharing spectrum with the k-th DUE is:

$$C_{m,k}(p_m^c, p_k^d) = E[\log_2(1 + \gamma_m^c)] \quad (4.12)$$

#### 4.4.4 Results And Discussin

To configure the system, we used the settings given in Table 4.1. In order to evaluate the effectiveness of our proposed algorithm, we also changed those parameters for the outcomes. We consider a single cell with a radius of 500 meters in our simulation. Only a maximum of 15 meters could separate the D2D transmitter and receiver since any further distance would negate the benefits of D2D communication. The network operator can modify the ergodic capacity, although 10 was used in the calculation. The number of D2D users increased by 5 points, from 15 to 50. The average of several repetitions for every scenario is the result. The maximum number of users per cellular device was fifty. However, when the number of mobile users grew, we found that our algorithm consistently provided results.

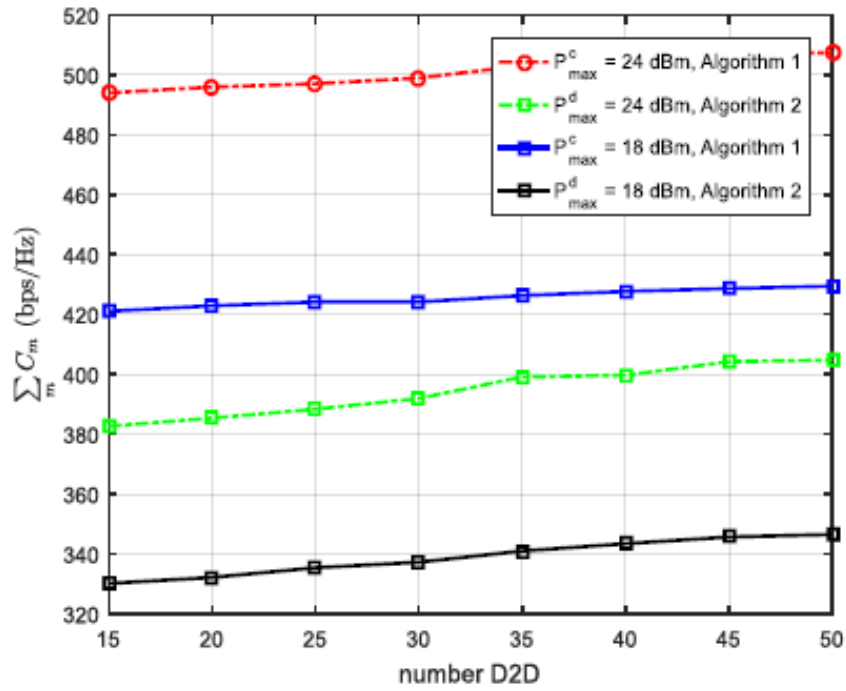
Figures 4.3a and 4.3b show the minimum and total ergodic capacities of all D2Ds as the number of D2D pairs rises. The results show that the more D2D pairings there are, the higher the minimum and total capacities of D2D. This is due to the fact that effective CU resource reuse would boost capacities and produce long-lasting D2D links with ideal received power. Because of the maximum transmit power limitations, DUEs could be able to withstand less interference from CUEs. As a result, CUEs would get less power, which would increase their minimum and total ergodic capacities. Additionally, each picture shows the outcomes of using Algorithms 1 and 2. The best resource allocation for (4.6) and (4.7) is represented by algorithms 1 and 2, respectively. In terms of cumulative ergodic capacity, Algorithm 2 outperforms Algorithm 1 while taking into account the lowest ergodic capacity. This makes sense since the goal of Algorithm 1 is to raise the sum ergodic capacity, whereas the goal of Algorithm 2 is to decrease ergodic capacity.

Interestingly, when the maximum transmit power is raised as the number of D2D pairs increases, the cumulative D2D capacity performance of both Algorithms 1 and 2 remains constant (Figure 4.3a). This is not the case when looking at the minimum D2D capacity, as seen in Figure 4.3b. couples who have a strong D2D.

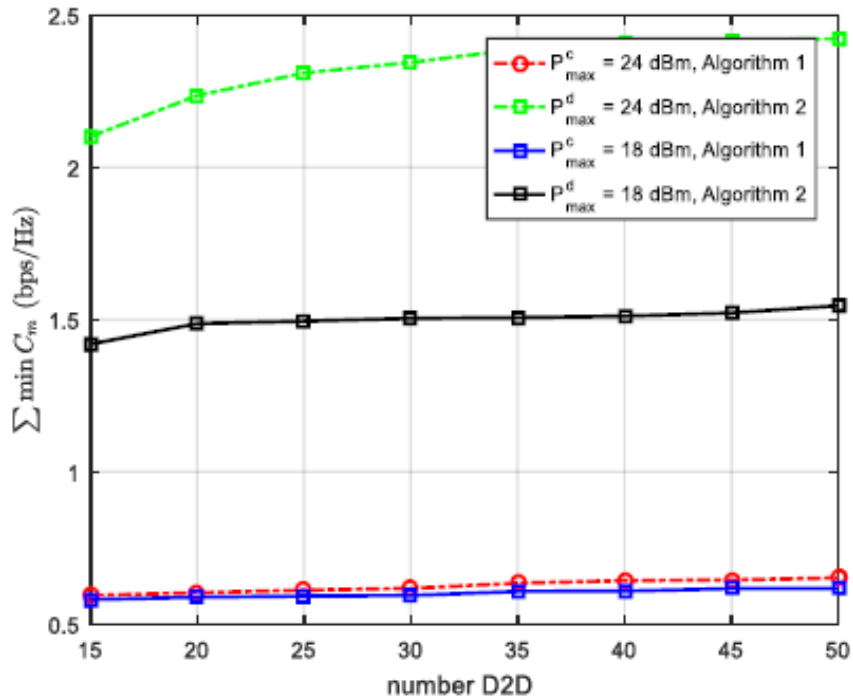
Parameter	Value
Carrier frequency	2 GHz
Bandwidth	10 MHz
Cell radius	500 m
BS antenna height	25 m
BS antenna gain	8 dBi
BS receiver noise figure	5 dB
Distance between BS and users	35 m
Number of sup channel	6
Minimum capacity of DUE $r_0^c$	0.5 bps/Hz
SINR threshold for DUE $\gamma_0^d$	5 dB
Reliability for DUE $p_0$	0.001
Number of DUEs K	50
Number of CUEs M	50

Table 4.1: Simulation parameters

Figure 4.4 shows the minimum and total ergodic capacity of D2D communications at increased SINR thresholds for DUEs. It is evident from Figures 4.4a and 4.4b that when the minimal QoS requirement for DUEs rises, the evaluated ergodic capacity falls in both scenarios. Figure 4.4a shows the cumulative ergodic capacity of D2Ds, whereas Figure 4.4b shows the minimal ergodic capacity of D2Ds. The paired CUEs' allowed transmit power is further constrained by the DUEs' decreased ability to withstand interference as a result of raising their necessary SINR threshold. smaller transmit power is associated with smaller sums and minimum ergodic capacities that D2Ds can attain while still satisfying all QoS requirements.



(a)

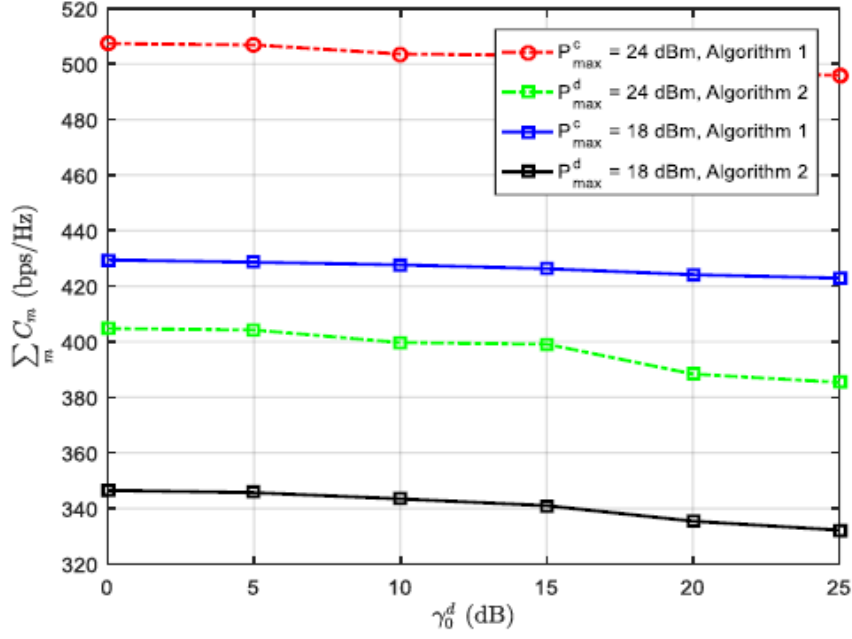


(b)

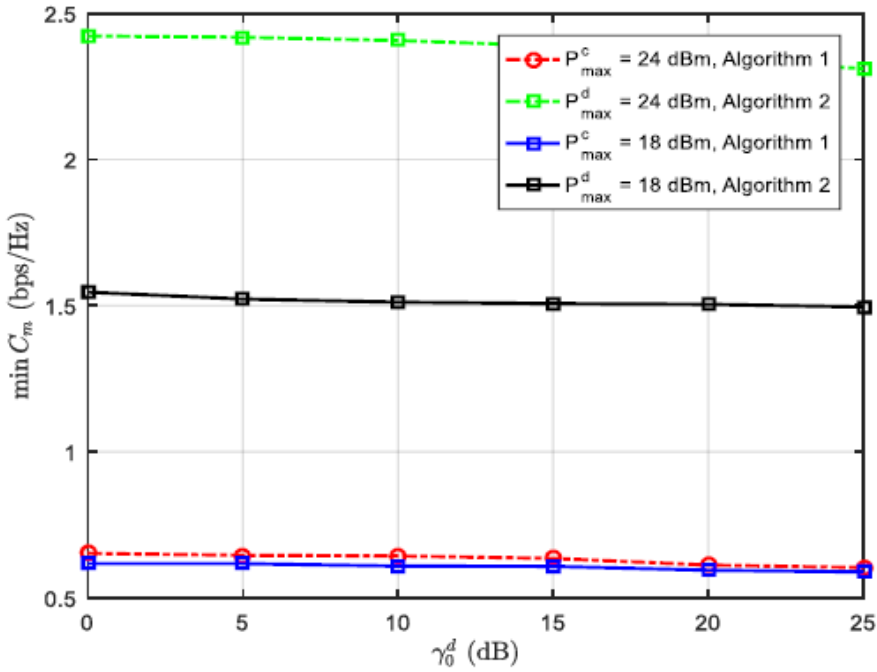
Figure 4.3: Capacity performance of D2Ds with varying number D2D pairs; (a) sum ergodic capacity of D2Ds and (b) minimum ergodic capacity of D2Ds

#### 4.4.5 Summary Chapter

In this post, we looked at D2D network resource allocation strategies, like spectrum sharing.



(a)



(b)

Figure 4.4: Capacity performance of D2Ds with varying DUE SINR threshold; (a) sum ergodic capacity of D2Ds and (b) minimum ergodic capacity of D2Ds

The goal of our optimization tasks is to create a resource allocation plan based only on large-scale fading data that changes slowly. We accomplished this by taking into account the various QoS requirements of device communications. Sturdy methods have improved the total and minimum ergodic capacity of CUE lines while guaranteeing reli-

able D2D links. This is accomplished by making use of the possibility of energy allocation separation and by remembering that the overlap is restricted to each CUE-DUE reuse pair when creating the spectrum reuse pattern. focusing on each pair of cues and due dates. By comparing the viability of each CUE-DUE pair with the minimum capacity needs for CUE, we were able to identify the optimal spectrum sharing arrangement between the CUE and DUE groups. We then created a bipartite histogram using the Hungarian algorithm. Unworkable pairs were then eliminated. The results of the simulation show that the proposed method can determine the best possible configuration for CUEs and DUEs to share spectrum out of all the possible options. Furthermore, it may produce the best power control strategy for every pair reuse, leading to the most effective use of available resources. The current study limits spectrum sharing to a single CUE-DUE pair and does not include wider spectrum reuse. In the future, these limitations may be removed, enabling CUE and D2D links to share a sizable number of resource blocks.

## conclusion

A crucial technology for 5G and future cellular networks is D2D communication (B5G). It claims to increase cell radius, increase network throughput, and offload network core. Allocating power and resources is one of the biggest issues affecting D2D communication. We tackled this joint problem for D2D communication in 5G cellular networks in our dissertation. First, we give the reader the background information they need to understand this topic, beginning with a brief summary of cellular networks from the first generation to the fifth generation now in use and beyond.

Subsequently, we gave a thorough overview of D2D communication, including use cases, features, and difficulties. During this presentation, we also discussed the shared issue of resource allocation and power control. After that, we outlined the problem formulation and provided the resource allocation and power control concerns together with a multitude of associated studies. As a result, we concluded that the problem of allocating power and resources is nonlinear and constrained by several nonlinear constraints, making it difficult to solve using conventional techniques. Subsequently, we introduced our initial proposal, wherein we employ the Hungarian method to address the joint challenge of D2D communication within 5G networks. The Hungarian method is a combinatorial optimization algorithm that foreshadowed subsequent primal-dual methods and solves the assignment issue in polynomial time. We looked into how well our proposal worked.

In this post, we looked at D2D network resource allocation strategies, like spectrum sharing. The goal of our optimization tasks is to create a resource allocation plan based only on large-scale fading data that changes slowly. We accomplished this by taking into account the various QoS requirements of device communications. Sturdy methods have improved the total and minimum ergodic capacity of CUE lines while guaranteeing reliable D2D links. This is accomplished by making use of the possibility of energy allocation separation and by remembering that the overlap is restricted to each CUE-DUE reuse pair when creating the spectrum reuse pattern. focusing on each pair of cues and due dates. By comparing the viability of each CUE-DUE pair with the minimum capacity needs for CUE, we were able to identify the optimal spectrum sharing arrangement between the CUE and DUE groups. We then created a bipartite histogram using the Hungarian algorithm. Unworkable pairs were then eliminated. The results of the simulation show that the proposed method can determine the best possible configuration for CUEs and

DUEs to share spectrum out of all the possible options. Furthermore, it may produce the best power control strategy for every pair reuse, leading to the most effective use of available resources.

The current study limits spectrum sharing to a single CUE-DUE pair and does not include wider spectrum reuse. In the future, these limitations may be removed, enabling CUE and D2D links to share a sizable number of resource blocks.

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