

**ON THE OPTIMAL NOMA SCHEMES FOR FUTURE
WIRELESS NETWORKS**

BY

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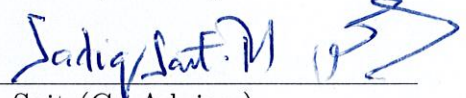
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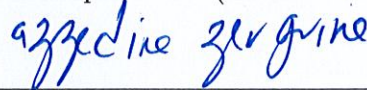
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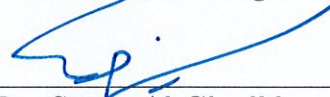
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To my parents (Ali and Raeda)
To my brothers (Mutasem and Baha)
To my wife (Islam)

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LIST OF ABBREVIATIONS

1G	first generation
2G	second generation
3G	third generation
3GPP	3rd Generation Partnership Project
4G	fourth generation
5G	fifth generation
6G	sixth generation
ABF	analog beamforming
AF	amplify-and-forward
AP	access point
B5G	beyond-fifth generation
BC	vector-broadcast channel
BF	beamforming
BS	base station
CDMA	code-division multiple-access
CF	compress-and-forward

C-LiAN	centralized light access network
CNOMA	cooperative NOMA
CoMP	coordinated multi-point
CPU	central process unit
CS	Cuckoo Search
CSI	channel state information
CSIT	channel state information at the transmitter
D2D	device-to-device
DCO-OFDM	direct-current biased optical-OFDM
DF	decode-and-forward
D-NLUPA	divide-and-next-largest-difference user-pairing algorithm
EAs	evolutionary algorithms
EE	energy efficiency
FD	full-duplex
FDD	frequency division duplex
FDMA	frequency-division multiple-access
FFR	fractional frequency reuse
FoV	field-of-view
FPA	fixed power allocation
GP	gradient projection
GRPA	gain ratio power allocation

H-CRAN	heterogeneous cloud radio access network
HD	half-duplex
HHO	Harris Hawks Optimizer
IoE	internet-of-everything
IoT	internet-of-things
IRS	intelligent reflecting surfaces
KKT	Karush–Kuhn–Tucker
LACO-OFDM	layered asymmetrically clipped optical OFDM
LED	light emitting diode
LoS	line-of-sight
LTE	long term evolution
LTE-A	long term evolution-advanced
MAC	multiple-access channel
MAR	mobile augmented reality
MEC	mobile edge computing
MIMO	multiple-input multiple-output
MISO	multiple-input single-output
ML	machine learning
MM	majorization-minimization
MMA	minorization maximization algorithm
mMIMO	massive-MIMO

MMSE	minimum mean square error
mMTC	massive machine-type communication
mmWave	millimeter-wave
MRC	maximum ratio combining
MU-MIMO	multi-user MIMO
MUST	multi-user superposition transmission
NAICS	network-assisted interference cancellation and suppression
NLIP	non-linear integer programming
NLoS	non-line-of-sight
NLUPA	next-largest-difference user-pairing algorithm
NOMA	non-orthogonal multiple access
NP	non-deterministic polynomial-time
NR	new radio
OFDM	orthogonal frequency-division multiplexing
OFDMA	orthogonal frequency-division multiple-access
OMA	orthogonal multiple access
PA	power amplifier
PAPR	peak-to-average-power-ratio
PD	photo-diode
PD-NOMA	power-domain NOMA
PHY	physical

PLC	power line communications
PS	phase shifter
QoS	quality-of-service
RF	radio frequency
RRHs	remote radio heads
RWP	Random Way-Point
SA	Simulated Annealing
SC	superposition coding
SDMA	space-division multiple access
SE	spectral efficiency
SI	self-interference
SIC	successive interference cancellation
SIMO	single-input multiple-output
SINR	signal-to-noise-interference ratio
SISO	single-input single-output
SNR	signal-to-noise ratio
SPS	single-phase shifter
TDMA	time-division multiple-access
THz	Terahertz
TS	Tabu-search
UAV	unmanned aerial vehicle

UE	user equipment
UL	uplink
ULA	uniform linear array
umMTC	ultra-massive machine-type communication
V2V	vehicle-to-vehicle
V2X	vehicle-to-everything
VLC	visible light communications
VR	virtual reality
WDMA	wavelength-division multiple-access
XR	extended reality
ZF	zero-forcing

DISSERTATION ABSTRACT

NAME: Omar Ali Adel Maraqa

TITLE OF STUDY: On the Optimal NOMA Schemes for Future Wireless Networks

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The ambitious high data-rate applications in the envisioned future beyond-fifth generation (B5G) and sixth generation (6G) wireless networks require new solutions, including the advent of more advanced architectures than the ones already used in fifth-generation (5G) networks, and the coalition of different communications schemes and technologies to enable these applications requirements. Among the candidate communications schemes for future wireless networks are non-orthogonal multiple access (NOMA) schemes that allow serving more than one user in the same resource block by multiplexing users in other domains than frequency or time. In this way, NOMA schemes tend to offer several advantages over orthogonal multiple access (OMA) schemes such as improved user fairness and spectral efficiency, better energy efficiency, massive connectivity support, and low transmission latency. With

these merits, NOMA-enabled transmission schemes are being increasingly looked at as promising multiple access schemes for future wireless networks. In this thesis, we provide a couple of works that embrace the integration of the NOMA scheme with some of the enabling technologies of future wireless networks. These works optimize future wireless networks in terms of fairness, energy efficiency, and energy consumption. Particularly, we propose and investigate three works, (i) a multi-user multi-carrier centralized NOMA visible light communications (VLC) system, (ii) a multi-user downlink cooperative Terahertz (THz) multiple-input single-output (MISO) NOMA system, and (iii) a multi-user uplink mobile edge computing (MEC)-assisted cooperative THz single-input multiple-output (SIMO) NOMA system. In the first work, we develop two NOMA variants, namely, NOMA-imposed schemes, where all the users are grouped into pairs, and NOMA-not-imposed schemes; and we illustrate that while varying different network parameters the performance of the NOMA-not-imposed scheme outperforms the performance of the NOMA-imposed scheme in terms of the max-min user rate. In the second work, we illustrate that the developed THz-NOMA cooperative scheme achieves around 9-20 times increase in average cell-center users rate compared to its millimeter-wave (mmWave)-NOMA counterpart. In the third work, we illustrate that the developed scheme can successfully handle relatively high offloading rate demands (several Gbits/user) with a reasonable total users' energy consumption within a predefined latency constraint.

ملخص الرسالة

الاسم: عمر علي عادل مرقه

عنوان الدراسة: تصميم أنظمة الوصول المتعدد غير المتعامد المثلى للشبكات اللاسلكية المستقبلية

التخصص: الهندسة الكهربائية

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تتطلب التطبيقات الطموحة التي تحتاج معدل إرسال بيانات عالي في المستقبل المنظور مثل الشبكات التي سيتم تطبيقها بعد شبكات الجيل الخامس وشبكات الجيل السادس اللاسلكية حلولاً جديدة، بما في ذلك ظهور هندسة أكثر تقدماً من تلك المستخدمة بالفعل في شبكات الجيل الخامس، وائتلاف من أنظمة الوصول والتقنيات المختلفة لتمكين متطلبات هذه التطبيقات. ومن بين أنظمة الوصول المرشحة للشبكات اللاسلكية المستقبلية أنظمة الوصول المتعدد غير المتعامد التي تسمح بخدمة أكثر من مستخدم واحد في نفس كتلة الموارد. وبهذه الطريقة، تميل أنظمة الوصول المتعدد غير المتعامد إلى تقديم العديد من المزايا بالمقارنة مع أنظمة الوصول المتعدد المتعامد مثل إنصاف المستخدم، وتحسين الكفاءة الطيفية، وتحقيق كفاءة أفضل في استخدام الطاقة، ودعم الاتصال لعدد كبير من الأجهزة في آن واحد، وانخفاض زمن الوصول. مع هذه المزايا، ينظر على نحو متزايد إلى أنظمة الوصول المتعدد غير المتعامد على أنها أنظمة وصول واعدة للشبكات اللاسلكية في المستقبل. في هذه الأطروحة، نقدم عدد من الأبحاث التقنية التي تشمل دمج أنظمة الوصول المتعدد غير المتعامد مع بعض التقنيات التمكينية للشبكات اللاسلكية في المستقبل. مخرجات هذه الأبحاث التقنية تساعد في تحسين الشبكات اللاسلكية المستقبلية من حيث إنصاف المستخدم، وتحسين كفاءة استخدام الطاقة في النظام، وتقليل استهلاك الطاقة لأجهزة المستخدمين. على وجه الخصوص، تم العمل على ثلاثة أبحاث تقنية وهي كالتالي، أولاً: تم اقتراح نظام مركزي متعدد المستخدمين متعدد النواقل من خلال الدمج بين نظام الوصول المتعدد غير المتعامد مع أنظمة الاتصالات الضوئية المرئية بهدف إلى إنصاف المستخدمين في النظام. ثانياً: تم اقتراح نظام تعاوني متعدد المستخدمين متعدد الهوائيات في المحطة الأساسية من خلال الدمج بين نظام الوصول المتعدد غير

المتعامد مع أنظمة الاتصالات التي تستعمل ترددات عالية (تيراهيرتز) في نقل الاشارات يهدف إلى تحسين كفاءة استخدام الطاقة في النظام. ثالثاً: تم اقتراح نظام تعاوني متعدد المستخدمين متعدد الهوائيات في المحطة الأساسية من خلال الدمج بين نظام الوصول المتعدد غير المتعامد مع أنظمة الاتصالات التي تستعمل ترددات عالية (تيراهيرتز) في نقل الاشارات وأنظمة الحوسبة المساندة في المحطة الأساسية لخدمة أجهزة المستخدمين التي تحتاج إلى معالجة بيانات ضخمة وتقليل استهلاك الطاقة في هذه الأجهزة. في العمل الأول، تم تطوير نوعين مختلفين من أنظمة الوصول المتعدد غير المتعامد، وهما 1-وجود نظام الوصول المتعدد غير المتعامد لوحده، حيث يتم تجميع جميع المستخدمين في أزواج، 2-وجود نظام الوصول المتعدد غير المتعامد مع نظام الوصول المتعدد المتعامد. من خلال تحليل هذين النظامين بتغيير معاملات متعددة، تبين أن النظام الثاني يتفوق على النظام الأول من حيث قدرته على تحقيق معدل بيانات أعلى للمستخدمين مع الحفاظ على إنصاف المستخدمين في النظام. في العمل الثاني، من خلال تحليل النظام تم التوضيح أن النظام المقترح الذي يستعمل الترددات العاليه (تيراهيرتز) يتفوق على مثيله الذي يستعمل ترددات متوسطة (الموجات المليمترية) بنحو 9-20 ضعف من حيث قدرته على تحقيق معدل بيانات أعلى للمستخدمين القريبين من المحطة الاساسية. في العمل الثالث، من خلال تحليل النظام تم التوضيح أن النظام المقترح يمكنه بنجاح التعامل مع متطلبات معدل التفريغ المرتفعة نسبياً (عدة جيغابت/مستخدم) مع إجمالي إستهلاك معقول للطاقة للمستخدمين ضمن المهلة المحددة مسبقاً.

CHAPTER 1

INTRODUCTION

1.1 Motivation

Future wireless networks such as beyond-fifth generation (B5G) or sixth generation (6G) networks are expected to support extremely high peak data rates (up to 1 Tbps) and a very large number of users or nodes (up to 10^7 nodes per km^2) with a variety of applications and services [1]. However, multiple access schemes used in the past generations of cellular networks will not scale to meet these unprecedented demands for user density and network traffic. The multiple access schemes used to date in cellular networks include frequency-division multiple-access (FDMA) in first generation (1G) systems, time-division multiple-access (TDMA) in second generation (2G), code-division multiple-access (CDMA) in third generation (3G), and orthogonal frequency-division multiple-access (OFDMA) in fourth generation (4G) networks. The common theme in all these multiple access schemes is “orthogonality” where, theoretically, the different users are allocated distinct frequency channels or time slots or signature codes or resource blocks so that they do not interfere with one another when

they access the network resources. However, this insistence on orthogonality poses a limit on the number of users that can access the network resources and thereby reduces the overall spectral efficiency (SE). non-orthogonal multiple access (NOMA) schemes, on the other hand, allow multiple users to share the same resource (e.g., a time/frequency resource block) and separate the users in other domains with some additional receiver complexity. When the power domain is used to separate the users, it is referred to as the power-domain NOMA (PD-NOMA) [2] scheme.

To support the large explosion of connected users forecast in the massive machine-type communication (mMTC) paradigm of fifth generation (5G) and beyond networks, interest has been growing in academia, industry and even standardization bodies like the 3rd Generation Partnership Project (3GPP) to adopt NOMA schemes [3]. NOMA and/or hybrid NOMA-orthogonal multiple access (OMA) schemes tend to have the following attractive merits for 5G [4] and B5G networks:

- Improved spectral efficiency; as multiple users of the networks that adopt NOMA schemes can occupy the same bandwidth which is not applicable in multi-user networks that utilize OMA schemes. Moreover, in OMA schemes, the resource block might be allocated to a user with a poorly received signal strength leading to reduced spectral efficiency.
- Improved user fairness; as NOMA schemes can accommodate multiple users in the same resource block with guaranteed minimum rate requirements. On the contrary, OMA users with poor channel conditions might not be served for a long time by a scheduler trying to optimize the overall spectral efficiency.

- Low transmission latency; as the users in the networks that adopt OMA schemes need to wait for an available orthogonal resource block to grant access for transmission. In contrast, NOMA schemes offer more flexible user scheduling opportunities as well as grant-free transmission.
- Higher cell-edge throughput; as NOMA schemes allow a base station (BS) to flexibly change the fraction of power allocated to a cell-edge user to support a certain quality-of-service (QoS), which accordingly enhances its transmission rate.

With its promising performance, PD-NOMA scheme is considered as a candidate multiple access scheme in various standardization activities. For long term evolution-advanced (LTE-A) systems (3GPP release 13), NOMA was considered under the name of multi-user superposition transmission (MUST) [5]. Furthermore, in LTE-A Pro (3GPP release 14), the standardization body recognized that at least uplink NOMA schemes should be considered especially for mMTC [6]. In 5G new radio (NR) phases (1 & 2) (3GPP release 15 and release 16) [7], [8], multiple studies on the advancements needed in the transmitter and receiver sides for adopting NOMA schemes have been proposed. Also, some link-level and system-level performance evaluations that show the potential of adopting NOMA schemes have been conducted in these studies.

Further, apart from NOMA schemes, several other physical (PHY)-layer schemes, technologies, and network architecture paradigms are brewing in the literature to meet the aforementioned high data-rate demands of future wireless networks. These include multiple-input single-output (MISO), multiple-input multiple-output (MIMO),

massive-MIMO (mMIMO), millimeter-wave (mmWave) and Terahertz (THz) communications, cooperative communications, visible light communications (VLC) systems, mobile edge computing (MEC) systems, and other enabling schemes and technologies for B5G networks. The realization of the target rates in these networks will require the integration of two or more of these enabling schemes and technologies. Hence, these schemes and technologies can be potentially integrated with PD-NOMA scheme in one form or the other and is not simply the addition of two existing technologies as discussed in detail in [9].

In this thesis, we provide a couple of works that embrace the integration of PD-NOMA scheme with the aforementioned enabling technologies of future B5G networks. These works optimize B5G networks in terms of fairness, energy efficiency, and energy consumption. Particularly, (i) a multi-user multi-carrier centralized NOMA-VLC system is discussed in Chapter 3, (ii) a multi-user downlink cooperative THz-MISO NOMA system is discussed in Chapter 4, and (iii) a multi-user uplink MEC-assisted cooperative THz-single-input multiple-output (SIMO) NOMA system is discussed in Chapter 5.

1.2 General Background

In this section, we highlight the different multiple access schemes in cellular wireless networks. Particularly, we focus our discussion on the NOMA communication scheme that is an important research topic in both the industry and academia these years, because of its benefits in accommodating more users in the same resource blocks

at the expense of an increase in the receiver complexity. In addition, this section introduces some fundamentals and theoretical background about the enabling schemes and technologies used in the thesis to facilitate the understanding of the subsequent chapters. Moreover, as all the formulated problems in this thesis are non-convex, we list the main techniques for solving the non-convex optimization problems.

1.2.1 Multiple Access Schemes in Wireless Networks

In 2G cellular systems, conventional schemes such as TDMA and FDMA were used to support multiple users. The 3G cellular systems adopted CDMA where the set of users employ spreading or signature sequences to allow orthogonal multiple access while sharing the same time and frequency. In CDMA systems, the detection can be either based on single-user detection where the other users' interference is treated as additional noise or multi-user detection where all the users' data are jointly detected using optimal maximum likelihood detection or linear zero-forcing (ZF) or minimum mean square error (MMSE) detection schemes. In 4G networks, OFDMA was used where the sub-carriers are assigned to the users in an interleaved or random manner.

B5G networks need to guarantee services for a large number of high data-rate users that share the same resources. NOMA is a multiple access candidate scheme for B5G networks [10], which can be applied in both multiple-access channel (MAC) and vector-broadcast channel (BC) channels. In contrast to orthogonal multiple access schemes, NOMA scheme allows multiple users to allocate the same resources in the same frequency, time, and space dimensions. There are three major versions of NOMA, namely, the power-domain NOMA, the code-domain NOMA, and NOMA

multiplexing in multiple domains (i.e., the power domain, the code domain, and the spatial domain) [10]. However, the widely adopted one is the power-domain NOMA scheme where the channel gain difference is exploited at the receiver to separate the multiplexed users' signals. A graphical representation of the main PHY-layer enabling schemes and technologies of future wireless networks is depicted in Figure 1.1.

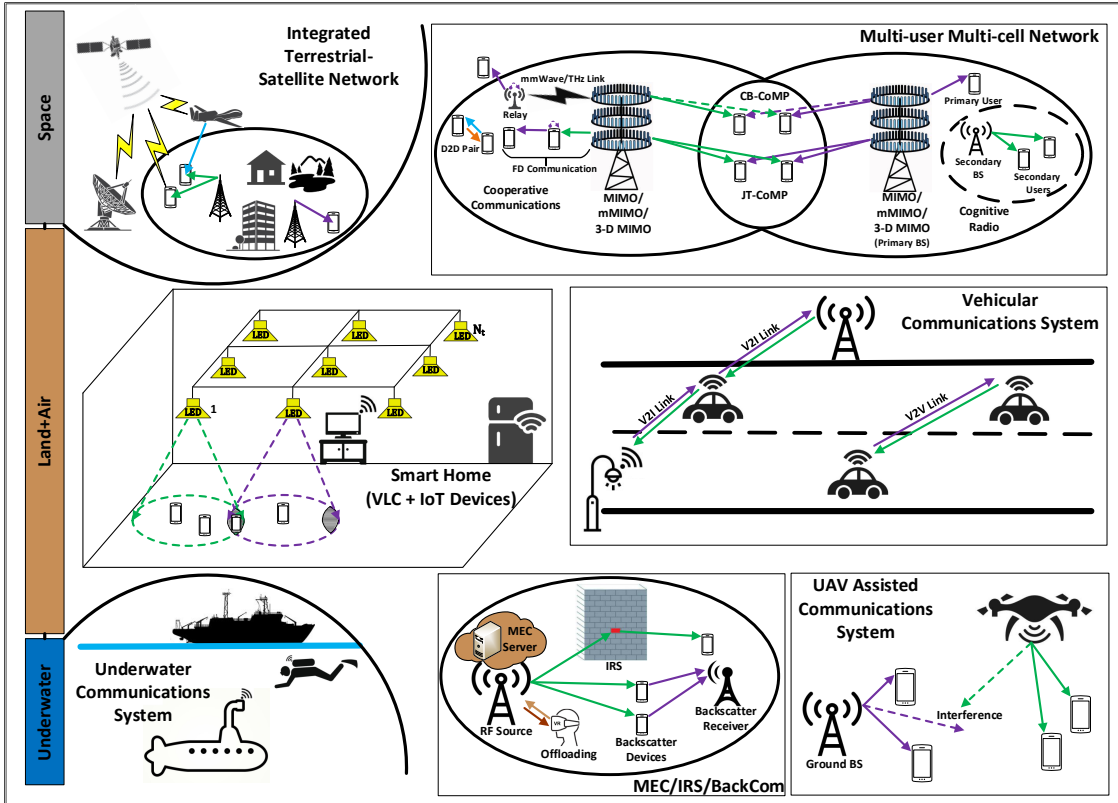


Figure 1.1: The enabling schemes and technologies of future wireless networks, including MISO, MIMO, mMIMO, mmWave and THz, cooperative communications, VLC, MEC, and others [10].

1.2.2 Power-Domain NOMA Scheme

The power-domain NOMA concept was first introduced in [11] to improve the spectral efficiency of wireless networks by allowing multiple users to simultaneously share both

the time and frequency resources. The theoretical roots of the PD-NOMA scheme lie in multi-user information theory. These include scalar and vector multiple access and broadcast channels along with the superposition coding, successive interference cancellation (SIC), joint decoding, iterative water-filling, dirty paper coding, and other related transmission and reception schemes [12]. However, NOMA schemes add additional "comm-theoretic" constraints on the users' target rates, in addition to the typical transmit power constraint in the info-theoretic models, to guarantee fairness among the served users.

A basic two-user downlink NOMA scheme is shown in Figure 1.2. User 1 (strong user) is close to the BS with strong channel gain and User 2 (weak user) is farther away from the BS with weaker channel gain. At the transmitter, both signals for the weak and the strong users are superimposed upon each other with different power allocation. To achieve user fairness, the transmitter tends to allocate more power to the weak user

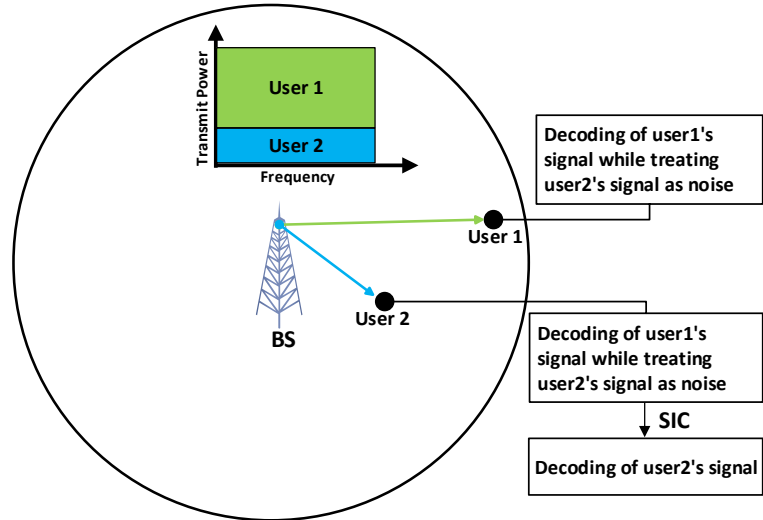


Figure 1.2: An illustration of a two-user downlink power-domain NOMA scheme [10].

as it has a larger path loss, as compared to the strong user (note that the size of the rectangles for User 1 and User 2 are different indicating the different powers allocated for each user). At the strong user receiver, the signal of the weak user has a high signal-to-noise ratio (SNR) which implies that the strong user can successfully decode and subtract the weak user signal before decoding its own signal (i.e., performing SIC). On the other hand, at the weak user receiver, the strong user signal is considered as noise as its transmission power is lower than the weak user signal. Subsequently, the weak user can decode its signal directly without SIC [13]. In a basic two-user uplink (UL) NOMA scheme, both users transmit their signals to the BS simultaneously (i.e., in the same time slot and frequency channel). For practical reasons [14], both users need to have some sort of cooperation to transmit both signals under a total transmit power constraint. The power share of both users is distributed based on their channel conditions with respect to the BS. After the transmission process, the BS receives a superimposed signal that contains both users' signals. Subsequently, the BS performs SIC with a decoding order from the strongest user to the weakest user to decode both individual users' signals. Noting that user equipments (UEs) interference cancellation capability is already incorporated in an earlier wireless standard, namely, network-assisted interference cancellation and suppression (NAICS) in long term evolution (LTE) (3GPP release 12) [15].

1.2.3 MISO, MIMO, and mMIMO Communications

The use of multiple antennas at the transmitter, receiver, or both has helped significantly drive up data rates and been an integral part of cellular systems right from

4G [16]. When multiple antennas are available at the BS, but only a single antenna at the user, it is referred to as a MISO system; while if multiple antennas are also available at the receiver, it is referred to as a MIMO system. These multiple antennas at the transmitter and receiver are used to realize beamforming or spatial multiplexing gains in single-user scenarios. In a multi-user environment, the multiple antennas can be used to separate the users in the space domain, creating the so-called spatial division multiple access [16]. The use of large-scale antenna arrays at the BS, where the number of transmit antennas far exceeds the number of users in the system, is referred to as a mMIMO system. In theory, mMIMO systems can have infinite number of antennas but practically 64 to 128 have been used [17]. In such mMIMO systems, when the number of transmit antennas approach infinity, it creates favorable propagation conditions whereby a unique beam can be formed for each user and perfect separation in the space domain is possible [18]. When a very large number of antennas are used for MIMO, it is sometimes referred to as ultra mMIMO.

1.2.4 mmWave and THz Communications

In contrast to the sub-6 GHz frequency range, a large amount of bandwidth is available in the mmWave frequency bands and beyond. Hence, they are seen as a key enabler of high data rates in 5G and beyond cellular networks. However, unlike in the sub-6 GHz spectrum, the propagation of electromagnetic waves in the mmWave bands exhibits high path loss and is highly directional in nature [19]. As a result, the beam gain offered by large-scale antenna arrays, i.e., mMIMO systems, is typically seen as a requirement to enable successful deployment of networks in these mmWave-frequency

bands [20]. Additionally, the short wavelengths of the electromagnetic waves in the mmWave frequency band make it practical to deploy large antenna arrays in a compact area, as required by a mMIMO system [21].

While mmWave communications in the 30 GHz spectrum is already part of the 5G standard, the academic literature is growing in even higher frequency bands such as mmWave for 100-300 GHz and THz bands [22]. The sheer amount of bandwidth available in this region of the frequency spectrum makes it very appealing to meet the large data requirements of 100 Gbps and more for B5G networks, but it comes at the cost of very high propagation loss. The study by Rappaport *et al.* in [23] highlights several promising applications for communications above 100 GHz in 6G networks, including wireless fiber for back-haul and information showers where a blast of data is sent to the user in a short amount of time as the user passes through an area of coverage at these high frequencies. The same study in [23] also highlights the additional challenges for wave propagation at these frequencies, particularly that the free-space path loss and penetration loss increase significantly as we go to higher frequencies, leading to shorter coverage areas. However, at these frequency bands, the wavelength and consequently the size of the antennas are very small, allowing for the use of highly directional antennas for ultra-precise beamforming, multi-reflector antennas, lens-integrated antenna arrays, and other such innovative solutions [22]. Hence, B5G networks will likely employ ultra mMIMO systems to solve the propagation challenges at these bands.

1.2.5 Cooperative Communications

Cooperative communications systems allow some communication terminals in the network to interact with each other for the sake of improving reliability, enhancing spectrum efficiency as well as power efficiency, and improving network connectivity by taking advantage of the broadcast nature of the wireless links [24]. B5G networks are expected to comprise billions of heterogeneous nodes, each with different processing capabilities, transmit power, etc. As a result, a network where the nodes co-operate with each other for common goals offers the potential for great enhancements in overall spectral efficiency. In what follows, we discuss different realizations for cooperative communications schemes.

There are three possible ways to realize the cooperation among the nodes in the network; (i) by allowing the communication terminals to hear-and-forward messages to other terminals, (ii) by using a dedicated relaying node to help in information and/or energy transfer between the source(s) and their corresponding destination(s), and (iii) by allowing some user pair(s)/group(s) to interchange signals without traversing the BS or the core network. The first type of cooperation is often referred to as user-assisted communications, the second one is often referred to as relay-assisted communications, and the third type is often referred to as device-to-device (D2D) communications [25].

In addition to the above, there are two types of relaying strategies, namely, half-duplex and full-duplex. In the half-duplex strategy, the communication between the source and the destination takes place in two phases, where in the first phase, the BSs

or access points (APs) broadcast the signals to the nearby receivers (i.e., users/relays). Consequently, in the second stage, the nearby receivers forward the messages of far receivers. On the other hand, in the full-duplex relaying strategy, the relays/users simultaneously receive and forward the signals to their intended destinations. Although the full-duplex strategy introduces some self-interference (SI) caused by the signal leakage from the transceiver output to the input [26], which degrades the performance of the full-duplex system, still full-duplex technology has the capability of utilizing the total bandwidth of the system as it hears-and-forwards the signals on the same frequency. Recent advancements in SI cancellation techniques and the move towards short-range networks such as small-cell cellular networks, which have lower path loss than the traditional cellular networks, have reduced the severity of SI and paved the way for the full-duplex strategy to be an enabling scheme for future wireless networks [27].

Moreover, there are three main relaying protocols: (i) decode-and-forward (DF) relaying, (ii) amplify-and-forward (AF) relaying, and (iii) compress-and-forward (CF) relaying. In DF relaying protocol, the received signal is completely decoded and then re-encoded and sent to the intended receiver(s). In AF relaying protocol, the received signal with its embedded noise is amplified and forwarded to the designated receiver. While in CF relaying protocol, the relay quantizes/compresses the overheard signal and then sends the resultant signal to the designated receiver [28].

1.2.6 Visible Light Communications (VLC)

VLC has recently emerged as a potential technology for complementing and/or off-loading radio frequency (RF) communications systems for various indoor user-dense scenarios such as homes, office rooms, conference and exhibition halls, airplanes and train cabins as well as some outdoor and vehicle-to-everything (V2X) applications in 5G and 6G networks. VLC is based on the principle of modulating light emitted by diodes, without any adverse effects on the human eye and the required illumination levels, which allows exploiting the existing illumination infrastructure for wireless communication purposes. VLC technology is expected to play an important role in enabling very high data-rate short-range communications as well as vehicle-to-vehicle (V2V) and in general V2X applications in B5G networks.

A generic model for a multi-user VLC system is shown in Figure 1.1 where a set of transmitting N_t light emitting diodes (LEDs) communicate with a set of users. This is a typical indoor downlink scenario where the LEDs on the ceiling transmit the downlink data to the VLC receivers that are typically equipped with photo-detectors [29]. The field-of-view (FoV) of the LEDs and the photo-diodes are designed to satisfy both the illumination and communication requirements. Each shaded area represents the interference or overlap region imposed by the signals carrying different information and arriving from the neighboring LEDs. While there is negligible signal fading experienced in VLC channels, the signal-to-noise-interference ratio (SINR) significantly drops at the boundary of the interference region and by obstruction of the line-of-sight (LoS) path due to user mobility, especially for outdoor applications.

1.2.7 Mobile Edge Computing (MEC)

Mobile edge computing technology offers remote computation for low computing-capability internet-of-things (IoT) devices that may need intensive computing-capability in some latency-sensitive applications like interactive networked gaming, real-time control, and virtual reality. In the MEC network, the BS usually equipped with a MEC server. The MEC server can receive and execute some offloaded tasks from the IoT devices. Later, the results are sent to the IoT devices after execution. There are two offloading scenarios in the MEC network, namely, partial and binary offloading. In the former scenario, a task can be divided into two parts: a local computing part and an offloading part. While in the latter scenario, a task can be either locally computed by the IoT device or remotely accomplished by the MEC server, i.e., cannot be divided [30].

1.2.8 Optimization Tools for NOMA-enabled Optimization Problems

Generally, when it comes to NOMA-enabled optimization problems, researchers focus on optimizing the power allocation, the user pairing, the antennas beamforming, and the resource-block assignment, or a combination of them. Such optimization problems can be convex or non-convex. For the convex ones, researchers resort to analytical methods or numerical methods. In general, both of these methods can provide a globally optimal solution with polynomial-time complexity [31]. For the analytical methods, the Lagrangian duality method can be used when the strong duality holds

between the original problem and the dual problem. For the numerical methods, one might use the Newton's method, the Interior-point method, and the convex solvers (such as CVX and YALMIP). On the other hand, the non-convex optimization problems are more involved and some of them may require an exhaustive search which is not feasible for practical systems and networks with a large number of users [32]. For this reason, researchers resort to low complexity solutions to solve these non-convex problems, such as [12]:

- The monotonic optimization approach as in [33]; the monotonic nature of the objective function and constraints allows researchers to limit the exhaustive search to a much smaller region of the feasible set; this accordingly simplifies the problem and can lead to the optimal solution but still with relatively high complexity.
- The combinatorial relaxation approach; in NOMA user clustering problems, the selection and association of a particular user to a particular cluster is realized by a binary variable; by relaxing this variable to a continuous one, the original non-convex problem can be transformed to a convex one and solved optimally through classic Lagrangian dual method [34], but this relaxation results in a performance gap between the original problem and the relaxed one.
- The matching theory approaches; which are often utilized to deal with problems that have beneficial relationship parties, such as the many-to-one bipartite matching problem [35], the many-to-one two-sided matching problem [19], and the many-to-many two-sided matching problem [36].

- The game theory approaches; which transform the clustering problem to a game, such as the coalition game proposed in [37], improved coalition game proposed in [38], and the Stackelberg game proposed in [39].
- The evolutionary algorithms; such as Simulated Annealing (SA) and Tabu-search (TS) [40], which can provide sub-optimal solutions to the non-convex problems but require much engineering efforts to solve such problem efficiently.

1.3 Thesis Objectives

The main objectives of the thesis are to investigate novel optimal power-domain NOMA scheme in the upper frequency-spectrum of mmWave and THz bands, in multi-antenna setups (i.e., MISO setups), in user-assisted cooperative networks, in VLC networks, and in MEC-assisted networks. Thus, the objectives can be listed as follows:

- Conduct a comprehensive survey on multi-user VLC systems that discusses the recent advances on multi-user precoding, multiple access, resource allocation, and mobility management [41].
- Conduct a comprehensive survey on the adoption of power domain NOMA scheme to maximize the achievable rates in wireless networks with emphasis on the system models, optimization methods [10].
- Develop a communication scheme that maximizes the minimum user rate of a multi-cell indoor centralized VLC network through optimizing user pairing,

subcarrier allocation, and power allocation [40].

- Develop an energy-efficient cooperative NOMA (CNOMA) scheme that guarantees the minimum required rate for the cell-edge users in an indoor THz-MISO communications network [42].
- Develop an energy-efficient MEC-assisted cooperative THz-SIMO NOMA scheme to allow the uplink transmission of offloaded data from the far cell-edge users to the computing resources in the base station [Under review in IEEE Transactions on Communications].

1.4 Thesis Publications

- **Direct Outcomes**

1. **Omar Maraqa**, Aditya S. Rajasekaran, Hamza U. Sokun, Saad Al-Ahmadi, Halim Yanikomeroglu, and Sadiq M. Sait, “Energy Minimization in MEC-assisted Cooperative THz-SIMO NOMA Systems”, under review in IEEE Transactions on Communications.
2. **Omar Maraqa**, Aditya S. Rajasekaran, Hamza U. Sokun, Saad Al-Ahmadi, Halim Yanikomeroglu, and Sadiq M. Sait, “Energy-efficient Coverage Enhancement of Indoor THz-MISO Systems: An FD-NOMA Approach”, IEEE PIMRC 2021, 13–16 September 2021 || Virtual Conference.
3. **Omar Maraqa**, Umair F. Siddiqi, Saad Al-Ahmadi, and Sadiq M. Sait. “On the Achievable Max-Min User Rates in Multi-Carrier Centralized NOMA-VLC

Networks.” *Sensors* 21, no. 11 (2021): 3705.

4. **Omar Maraqa**, Aditya S. Rajasekaran, Saad Al-Ahmadi, Halim Yanikomeroglu, and Sadiq M. Sait, “A Survey of Rate-Optimal Power Domain NOMA with Enabling Technologies of Future Wireless Networks,” in *IEEE Communications Surveys & Tutorials*, vol. 22, no. 4, pp. 2192-2235, 4th Quarter 2020.
5. Saad Al-Ahmadi, **Omar Maraqa**, Murat Uysal, and Sadiq M. Sait, “Multi-User Visible Light Communications: State-of-the-Art and Future Directions,” in *IEEE Access*, vol. 6, pp. 70555-70571, 2018.

- **In-direct Outcomes (Not included in the thesis)**

1. Aditya S. Rajasekaran, Hamza U. Sokun, **Omar Maraqa**, Halim Yanikomeroglu, and Saad Al-Ahmadi, “Vision-Assisted User Clustering for Robust mmWave-NOMA Systems”, under review.
2. Aditya S. Rajasekaran, Halim Yanikomeroglu, Hamza U. Sokun, **Omar Maraqa**, and Saad Al-Ahmadi, “Vision Assisted User Clustering in mmWave/THz-NOMA Systems,” International patent application No: PCT/IB2021/057455, application date: 12 Aug 2021 USA provisional application no: 63/231597, application date: 10 Aug 2021.
3. Hamza U. Sokun, Aditya S. Rajasekaran, **O. Maraqa**, Halim Yanikomeroglu, and Saad Al-Ahmadi, “Deep Learning-based User Clustering in Millimeter Wave

Non-orthogonal Multiple Access Communications,” International patent application no: PCT/IB2020/062488, application date: 28 Dec. 2020.

4. Aditya S. Rajasekaran, **Omar Maraqa**, Hamza U. Sokun, Halim Yanikomeroglu, and Saad Al-Ahmadi, “User Clustering in mmWave-NOMA Systems with User Decoding Capability Constraints for B5G Networks,” in *IEEE Access*, vol. 8, pp. 209949-209963, 2020.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The ambitious high data-rate applications in the envisioned future B5G wireless networks require new solutions, including the advent of more advanced architectures than the ones already used in 5G networks, and the coalition of different communications schemes and technologies to enable these applications requirements. Among the candidate communications schemes for future wireless networks are NOMA schemes that allow serving more than one user in the same resource block by multiplexing users in other domains than frequency or time. In this way, NOMA schemes tend to offer several advantages over OMA schemes such as improved user fairness and spectral efficiency, higher cell-edge throughput, massive connectivity support, and low transmission latency. With these merits, NOMA-enabled transmission schemes are being increasingly looked at as promising multiple access schemes for future wireless networks. In this chapter, we survey the integration of PD-NOMA scheme with some of the enabling communications schemes and technologies that are expected to meet

the various requirements of B5G networks. In particular, this chapter surveys the different rate optimization scenarios studied in the literature when PD-NOMA scheme is combined with MISO, MIMO, mMIMO, higher frequency mmWave and THz communications, cooperative communications, VLC, and MEC. The considered system models, the optimization methods utilized to maximize the achievable rates, and the main lessons learnt on the optimization of these NOMA-enabled schemes and technologies are discussed in detail throughout the chapter. An illustration of the commonly utilized system models in NOMA-enabled schemes and technologies of future wireless networks is depicted in Figure 2.1.

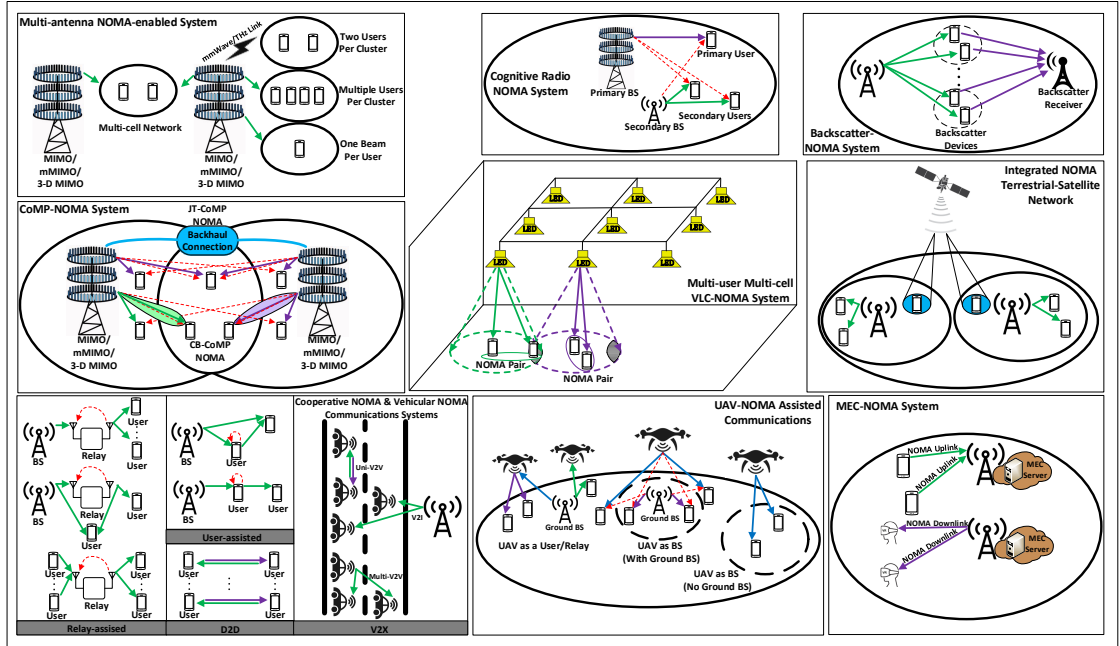


Figure 2.1: NOMA-enabled schemes and technologies for future wireless networks as outlined before in the caption of Figure 1.1 [10].

2.2 Rate-optimal NOMA with MISO, MIMO, and mMIMO Communications

In this section, we first present the representative work for conventional multi-antenna NOMA systems, sometimes referred to as MISO/MIMO NOMA systems as it forms the base for rate optimization works for all other multi-antenna NOMA-enabled technologies. The representative work on MISO integrated NOMA systems is presented in Table 2.1 for both the single-cell and multi-cell scenarios. Also, the representative work on MIMO and mMIMO integrated NOMA systems are presented in Table III and Table IV, respectively, in [10]. Compared to the basic single-input single-output (SISO)-NOMA system described in Section 1.2.2, the use of multiple antennas at either the transmitter, receiver, or both means that the channel is now described by a vector or a matrix. Hence, unlike in a SISO-NOMA system, the ordering of users according to their channel conditions is no longer trivial. Hence, the MIMO-NOMA system is usually broken down into a SISO-NOMA form that is easier to work with [43]. This is typically achieved by using the multiple antennas at the transmitter for beamforming, such that users can be grouped into beams, often referred to as clusters. Within each cluster, the problem breaks down into a typical SISO-NOMA setting and the traditional PD-NOMA scheme as described in Section 1.2.2 can be used. This approach is classified as NOMA-beamforming (BF) in [44] and cluster-based MIMO-NOMA in [12]. Alternatively, the multiple antennas at the base station can also be used to form one beam per user like in multi-user MIMO (MU-MIMO), and then the beamforming weights are designed to create enough difference between

Table 2.1: MISO-NOMA Communications Systems: Current Status of Rate Optimization Schemes [10].

[#]	Classification	System Model	Design Objective	Optimization Method
[46]	Two users only	One BS + two users	Max. ergodic sum-rate	Gradient projection algorithm (GPA) and Bisection algorithm (BA)
[47]	Multiple users with clustering	One BS + K users (Two users per cluster)	Max. sum rate	Iterative clustering and power allocation algorithm
[48]		One BS + K users (Two users per cluster)	Max. sum rate	Geometric programming (GP), then successive optimization to find Karush-Kuhn-Tucker (KKT) point
[49]		One BS + K users (Two users per cluster)	Maxmin user-rate	Pareto-boundary computed using reformulation and convex-concave procedure
[50]		One BS + K users (Two users per cluster)	Max. sum rate	Branch-and-bound (BnB) method
[51]		One BS + K users uniformly distributed around the BS	Max. ergodic sum rate	One dimensional search
[52]		One BS + K users Imperfect CSI modelled through worst-case model	Max. worst-case sum rate	Alternating optimization (AO) method
[45]	One beam per user (user ordering assumed)	One BS + K users	Max. sum rate	Minorization maximization algorithm (MMA)
[53]		One BS + K users	Max. weighted sum rate (WSR)	KKT optimality conditions (hidden convexity for homogeneous channels)
[54]	Other	Multiple groups each getting multi-cast data	Max. sum rate	Bisection with Majorization-Minimization algorithm
[55]		An UL system with one BS + K users, SIC is applied at the codeword-level	Maxmin weighted average SINR	Geometric programming (GP)
[56]		K users in G groups (Groups based on channel gain)	Max. sum rate	Singular value decomposition-based multi-user scheme that exploits CSI

the users' channel conditions such that the NOMA principles can be applied [45].

With the clustering-based approach, the two users should have sufficient difference in the magnitude of the channel gain coefficients for the PD-NOMA scheme to work well [2]. Thus, user selection is a key parameter in such schemes. The objective here is to pair users who have sufficiently different channel conditions and also fit within a cluster, i.e., a beam. This design variable (or parameter) is often optimized in such schemes along with the power allocation coefficients assigned to each user in

the cluster, e.g., [47], [57]. However, with randomly located users, good user pairing algorithms are not guaranteed to find the ideal user clustering even with an exhaustive search of all possible solutions [58] because acceptable solutions may not exist. Hence, user-specific beamforming weights are also considered as a parameter in these sum-rate optimization problems [49], [52], [59], [60], [58]. The addition of the optimization of the per-user BF weights to the clustering-based MIMO-NOMA rate optimization problem allows the schemes to either create more channel gain difference among the users in a cluster, or to better separate the different clusters from each other.

With the one-beam-per-user model, the user ordering is predefined and the optimization schemes design a set of precoder weights to meet the given user ordering [45], [53]. The sum rate of the users is maximized through a minorization maximization algorithm (MMA) for the non-convex problem proposed by Hanif *et al.* [45]; while in the technique suggested by Zhu *et al.* [53], it is shown that forming a weighted sum-rate maximization problem instead has hidden convexity that can be solved using the Karush–Kuhn–Tucker (KKT) optimality conditions. While this one-beam-per-user approach generally requires full channel state information at the transmitter (CSIT) for the required beamforming design, the study in [61] framed an optimization problem to maximize the worst-case achievable rate in order to offer robustness to channel uncertainties.

The availability of CSIT also affects the formulation of the MIMO-NOMA rate optimization problems considered in the literature. If the full CSIT is available, the design objective is to maximize one of the overall sum-rate [47], [60], [45], weighted sum-rate [62], [63], or, the worst user-rate [49], [64]. On the other hand, if only

statistical CSIT is available, then the design objective is to maximize the ergodic sum-rate [46], [65] rather than the actual sum rate. While obtaining full CSIT helps maximize the system throughput, it comes with additional cost and overhead, especially in frequency division duplex (FDD) systems where reciprocity cannot be used. This motivates the need for system design assuming only limited feedback or partial CSIT [66]. In [51], the number of feedback bits for CSIT is optimized and it is demonstrated that the system throughput (i.e., sum rate) can be increased as the number of feedback bits for CSIT is increased.

Further, for the representative works on mMIMO integrated NOMA systems, presented in Table IV in [10], while the favorable propagation conditions in mMIMO systems say that an individual beam can be formed per user when the number of antennas at the BS is infinite, users with highly correlated user channels are hard to separate through space-division multiple access (SDMA) with a finite number of antennas. However, as with the cluster-based MIMO-NOMA systems, such users are ideal to be grouped in a cluster if there is sufficient difference in their large-scale fading coefficients [67]. This leads to similar user selection and power allocation optimization algorithms as the cluster-based MIMO-NOMA systems. As such, sum-rate optimization problems in such a mMIMO-NOMA setting have been studied in single-cell [68], [69] and multi-cell [70] frameworks using this clustering-based approach.

■ Lessons Learnt

- The literature of NOMA integrated with conventional MIMO forms the base for integrating NOMA with almost every other technology surveyed

in this chapter, as multiple antennas are typically involved at either end of the communication system. The typical approach in most of the literature is to form effective clusters of users after considering the effective channel gains that account for the beamforming weight multiplication. Typically, once the clusters are formed and user ordering is established, optimal power allocation coefficients are derived to maximize the sum rate of the users in the cluster.

- In mMIMO systems that serve multiple users, cluster formation for NOMA and SDMA can be seen as complementary approaches to jointly serve multiple users and improve the overall spectral efficiency. Users with channels that are highly correlated are easy to separate through the NOMA scheme but hard to separate through the SDMA scheme and vice-versa. This property of SDMA and NOMA to favor opposing characteristics in the channel conditions make them well suited to be used in conjunction with each other.

2.3 Rate-optimal NOMA with mmWave and THz Communications

The representative works on higher frequency mmWave and THz communications integrated NOMA systems are presented, respectively, in Table IV [10] and in Table 2.2. When operating in these higher frequency bands, the system model needs to consider the low-rank channels and spatial correlation characteristics that are typical for the

Table 2.2: THz-NOMA Systems: Current Status of Optimization Schemes [10].

[#]	Classification	System Model	Design Objective	Optimization Method
[76]	THz Communications	A downlink THz-NOMA scheme with hybrid BF, K multiple-antenna users	Max. sum rate	Dual-decomposition method with iterative sub-gradient algorithm
[77]		A downlink heterogeneous THz-NOMA cache-enabled system, K single-antenna users	Max. energy efficiency	Enhanced K-means algorithm and distributed alternating direction method of multipliers (ADMM) algorithm
[78]		A machine-type communication (MTC) downlink subTHz-NOMA system, K multiple-antenna users	Max. energy efficiency	ϵ -constraint method

mmWave communications [19], [35], [71]. While the high spatial correlation of users is typically a constraint for user separation in MU-MIMO systems, MIMO-NOMA systems operating in the mmWave band can use the clustering approach to exploit this correlation to form a cluster and separate the users in the power domain [19], [72]. Another practical limitation of systems operating in the mmWave bands with mMIMO large scale antenna arrays is that scaling the number of transceivers with the number of antennas is often unfeasible. Hence, unlike with regular MIMO-NOMA systems, the system models studied in the literature often use either analog BF with a single RF chain [21] or a hybrid BF design with a reduced number of RF chains [73], [19], [74]. With these additional constraints in the system model, sum-rate optimization schemes in the mmWave bands have similar user selection and power allocation design objectives as those with other MIMO-NOMA schemes, e.g., [35]. In multi-cell mmWave-NOMA settings, the authors in [75] propose an angle-domain NOMA scheme that schedules one cell-center and one cell-edge user in a NOMA pair, for each beam in each cell. The sum rate is then maximized by optimizing the precoder and decoder BF design along with the selection of paired users, in settings where the cells co-operate as well as when they do not.

The appeal of integrating NOMA scheme in even higher parts of the spectrum, e.g., THz communications, that offer orders of magnitude more bandwidth than even the mmWave spectrum is obvious for B5G networks, as it offers opportunities to cluster more users in a very wide band. Through the joint optimization of beam, bandwidth, and power allocation, a THz-NOMA system allows opportunities for meeting both massive connectivity and extremely high data rates in B5G systems [22]. In [76], the authors design a THz-NOMA system that accounts for the distance and frequency selective properties of the THz band. In traditional THz bands, the Long-User-Central-Window principle is usually used to assign the central sub-band to long users, while the side sub-bands are allocated to the short users [22]. Through the integration of NOMA scheme, the authors in [76] enhance this principle to NOMA clusters of four users each, rather than individual users. Through a hybrid BF design in an ultra mMIMO system that forms 4-user clusters, followed by power allocation and sub-band assignment, a rate optimization that outperforms THz-OMA is demonstrated in [76].

■ Lessons Learnt

- In mmWave systems, due to the high correlation amongst user channels, particularly when users are geographically clustered, it offers great opportunities for integrating NOMA scheme. Users that are hard to separate with individual beams using MU-MIMO techniques can now easily be grouped in a NOMA cluster. Through the use of mMIMO, beams are formed to serve clusters of users and separated from other beams (clusters) using BF techniques. Since the mmWave channels are usually dominated

by the most dominant path, usually the LoS path, the user selection problem breaks down to finding users with highly correlated channels in the angle domain, often captured through the cosine similarity metric. Un-supervised machine learning techniques that automatically identify such clusters of correlated users is an emerging trend in the mmWave-NOMA literature.

2.4 Rate-optimal NOMA with Cooperative Communications

The merits of cooperative transmission schemes lie in their ability to extend the coverage area of the network and their ability to improve the users' SINR, consequently, the users' rate is improved. This happens by providing some users with multiple copies of the same message while utilizing some form of combining techniques such as the maximum ratio combining (MRC). Recently, the adoption of the user-assisted cooperative communications systems in conjunction with NOMA has received good research interest [79], [80], [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91]. This is due to the advantage of the spatial diversity gain in improving the users' rate while enhancing the spectral efficiency of the network [81].

A summary of the up-to-date work on the rate-optimal NOMA schemes in relay-assisted, user-assisted, and D2D cooperative communications systems is provided in Table VI in [10]. In this thesis, we only listed the related user-assisted cooperative communications works in Table 2.3. From the outlined works provided in Table 2.3,

Table 2.3: User-assisted Cooperative NOMA Communications Systems: Current Status of Rate Optimization Schemes [10].

[#]	Cooperation Type	Relaying Mode	System Model Note: the notion "nodes" here includes BS, relay, and users	Design Objective	Optimization Method
[79]	User-assisted	HD-DF	BS + two users, BS/strong user: multiple antennas, weak user: single antenna	Max. the strong user-rate	Iterative SDP and Lagrangian dual method
[80]		HD-DF	A two-stage MISO SWIPT NOMA cooperative transmission scheme, BS: multiple antennas/single antenna, users: single-antenna	Maximin user-rate	Semi-definite relaxation (SDR) and SCA techniques
[81]		FD-DF	BS + two users, single-antenna nodes, (No link between BS and weak user)	Maximin user-rate	Analytical method
[82]		HD-DF	A cooperative SWIPT-aided NOMA scheme, BS: multiple antennas, users: single antenna	Maximin user-rate	SCA and SDR techniques
[83]		HD-DF	A SWIPT-enabled cooperative NOMA scheme, BS: multiple antennas, users: single antenna	Max. the strong user-rate	SDR, S-procedure, and SCA techniques
[84]		HD-DF	Cooperative MIMO-NOMA scheme, multiple-antenna nodes	Max. the weak user-rate	CCCP-based algorithm and a search-based suboptimal algorithm
[85]		HD-DF (Uplink+downlink)	Cooperative HetNet NOMA scheme, single-antenna nodes	Max. ergodic sum rate	Three-sided matching algorithm
[86]		FD-DF	Downlink SWIPT cooperative relaying NOMA scheme, strong user: multiple antennas, BS/weak user: single antenna	Max. the strong user-rate	Alternative optimization-based algorithm
[87]		FD-DF with three cases for SI	A SWIPT cooperative NOMA scheme, BS: multiple antennas, users: two antennas	Max. sum rate	D.C. programming transformation
[88]		HD-DF, FD-DF, and hybrid-DF	Hybrid HD/FD cooperative NOMA scheme with transmit power adaptation, BS: single antenna, users: two antennas	Maximin user-rate	Transformation to quasi-concave then conversion into series of convex feasibility problems
[89]		HD-DF	A V2V mMIMO-NOMA system, BS: single antenna, users: multiple antennas	Max. sum capacity	Bisection algorithm
[90]		HD-AF	A dynamic vehicle clustering method and a power control strategy based on NOMA scheme, single-antenna nodes	Maximin user-rate	An interval-based dichotomy method
[91]		HD-DF	A joint channel estimation and power allocation cooperative NOMA system	Max. average effective SINR for the weak user	Sequential parametric convex approximation-based iterative algorithm

one can deduce that user-assisted cooperative works are investigated under two settings, (i) in the first setting, a BS transmits a superimposed signal through the NOMA scheme to two users that have different channel gains. The strong user uses DF or AF modes to forward the signal to the weak user which employs SIC to decode its own message. Such a model was studied in [80], [87], [82], [83], [84], [88], [86]. (ii) the second setting is similar to the previous one but without a direct link between the BS and the weak user. This model is useful to extend the network coverage and was

proposed by Zhang *et al.* [81].

■ Lessons Learnt

- The vast majority of the representative works in NOMA-enabled user-assisted cooperative communications systems considered half-duplex communication mode [79], [80], [82], [83], [84], [85], [88], [89], [90], [91]; since the half-duplex mode yields to lower implementation complexity and inherently avoids the self-interference as compared to the full-duplex (FD) mode. However, the recent advancements in SI cancellation technologies, the move towards short-range networks, and the low spectral efficiency of half-duplex (HD) mode paved the way for the adoption of FD mode in NOMA-enabled cooperative communications systems [81], [86], [87]. In order to further improve the system performance, by exploiting the tradeoff between the efficiency loss of the HD mode and the inherent self-interference of the FD mode, a hybrid half/full-duplex cooperative NOMA that dynamically switch between and HD and FD modes has been proposed by Liu *et al.* [88]. Overall, since NOMA and full-duplex are complementary in principle toward improving the spectral efficiency of a network without the need for additional bandwidth resources [92], we expect that the research in B5G networks will focus more on the integration of NOMA with full-duplex communication as compared to the integration of NOMA with half-duplex communication.
- As highlighted in the previous point, to enable the use of FD relaying some

advanced SI cancellation techniques should be adopted to reduce the SI to a tolerable level. This will increase the system complexity and require more signal processing power from the nodes. With FD relaying, it is intuitive from a practical point-of-view, to use relay-assisted cooperative communications as relay nodes have powerful signal processing capabilities. However, using a dedicated node for relaying increases the system cost. To avoid such cost and to utilize the network infrastructure, it is advisable, whenever applicable, to use user-assisted communications while equipping the users with energy harvesting technology to avoid draining user's batteries.

2.5 Rate-optimal NOMA with Visible Light Communications (VLC)

Although VLC systems have abundant free bandwidth, the current off-the-shelf LEDs have limited bandwidth which necessitates the adoption of spectrally efficient schemes like NOMA-enabled schemes to attain the desired high data rates. Moreover, indoor and low mobility VLC systems have the attractive features of quasi-static nature of the propagation channel and relatively high SNR conditions, especially for short-distance communications and clear LoS conditions, as these features allow more reliable estimation of the channel gains and SIC, respectively. A summary of the up-to-date work on the rate-optimal NOMA-enabled VLC systems is provided in Table 2.4 for different trans-receive configurations.

Table 2.4: VLC-NOMA Systems: Current Status of Rate Optimization Schemes [10].

[#]	Classification	System Model	Design Objective	Optimization Method
[93]	Single-cell (single-carrier)	Downlink VLC-NOMA scheme, one LED luminary+ K photo-diodes	Max. sum rate	KKT optimality conditions
[94]		Downlink VLC-NOMA scheme, one LED luminary+ two photo-diodes	Max. sum rate	SCA technique
[95]		Downlink VLC-NOMA scheme, one LED luminary+ K photo-diodes	Max. sum rate	Standard interior point method
[96]		Downlink VLC-NOMA scheme with beam steering, one LED luminary + K photo-diodes	Max. sum rate	An iterative algorithm based on majorization-minimization procedure
[97]		A downlink UAV-assisted VLC-NOMA system, one LED luminary + K photo-diodes	Max. sum rate	Harris Hawks optimization with artificial neural networks
[98]	Single-cell (multi-carrier)	Downlink OFDM-based VLC-NOMA scheme, four LED luminaries + K photo-diodes	Max. sum rate	Analytical method
[99]		A downlink power-line-fed VLC-NOMA scheme, one LED luminary + K photo-diodes	Max. sum rate	KKT optimality conditions
[100]	Multi-cell	Ultra-dense VLC hybrid OMA and NOMA scheme, eight LED luminaries + six photo-diodes	Max. sum throughput	A dynamic programming-based l th layer-recursion model
[101]		A user grouping-based VLC-NOMA scheme, four LED luminaries + K photo-diodes	Both max. sum rate and maxmin user-rate	Gradient projection algorithm (GPA)
[102]		A multiuser multi-cell VLC-NOMA scheme, four LED luminaries + eight photo-diodes	Both max. throughput and maxmin rate of cell-edge users	Interior point method

The early work in [93] has developed a convexified power allocation problem for an arrangement of one LED transmitter and M receiving photo-diodes and introduced an optimal power allocation algorithm that was shown to outperform both the gain ratio power allocation (GRPA) and the fixed power allocation (FPA) schemes. A similar approach was used in [95] where the convexified multiple factors power allocation problem was solved using CVX solvers. In [94], the Cuckoo Search (CS)

meta-heuristic optimization algorithm was utilized to solve a multi-objective optimization problem in terms of the achievable rate and the users received power and the optimized scheme was again shown to achieve a larger sum-rate than fixed power VLC-NOMA scheme. However, that gain was relatively small and the complexity of the used algorithm was not addressed. In [96], an iterative algorithm for the selection of the optimal NOMA pairs and then the determination of their allocated powers using the majorization-minimization (MM) procedure was utilized to maximize the sum-rate for VLC-NOMA with steerable beams. The rate maximization for integration of unmanned aerial vehicles (UAVs) in VLC-NOMA was considered in [97] where the Harris Hawks Optimizer (HHO), as a swarm intelligence technique, was utilized to jointly optimize the UAV's placement and power allocation.

For multi-carrier VLC-NOMA single-cell scenarios, in [98], an enhanced power allocation algorithm, as compared to fixed power allocation and gain ratio power allocation, for an OFDM-based VLC-NOMA system was shown to outperform these power allocation schemes in terms of sum rate and subcarrier loss rate. In [99], a joint power allocation strategy to maximize the sum-rate for a combined power line communications (PLC)-VLC network, where the data is fed by the PLC into the VLC network, was proposed and compared to the other power allocation schemes.

In multi-cell scenarios, a graph theory-based clustering strategy was proposed in [100] for layered asymmetrically clipped optical OFDM (LACO-OFDM) aided ultra-dense VLC networks and a hybrid NOMA-OMA scheme is adopted to reduce the excessive interference in such dense networks. A gradient projection (GP) algorithm was adopted in [101] for optimizing the power allocation for sum-rate maximization

where the users are assigned to the APs so that no inter-cell interference is there. The inter-cell interference was addressed in [102] where two variants of zero-forcing-based precoding in NOMA-VLC, where the cell-edge user is either associated with all the neighboring APs or associated with only the AP with the strongest channel gain, were introduced. The proposed schemes were shown to outperform both conventional ZF precoding and conventional NOMA schemes and the computational complexity of the different schemes considered in the paper was addressed in detail.

■ Lessons Learnt

- The optimization of VLC systems is in general more involved than RF systems due to the additional non-negative input signal and peak power constraints. The capacity-achieving inputs for amplitude-constrained multi-user multiple-access and broadcast VLC and optical channels are still, in general, open problems [103], [104], [105] and hence the capacity bounds and/or the modulation schemes such as pulse-amplitude modulation, on-off keying, and pulse-position modulation are widely used in optimizing the achievable rates in such channels.
- Although NOMA schemes are attractive for VLC systems and networks due to the typical high SNR conditions and the quasi-static channel characteristics especially for the LoS indoor scenarios, the additional signal design constraints, as highlighted in the item before, in VLC result in more involved rate optimization problems as compared to RF systems. So, the computational complexity of the utilized optimization methods and algo-

rithms becomes an issue and should have been addressed in all the papers in the table.

2.6 Rate-optimal NOMA with Mobile Edge Computing (MEC)

The representative works on MEC integrated NOMA systems is presented in Table 2.5. IoT devices usually have restricted memory and computational capabilities. Hence, offloading tasks in computational-intensive applications to a centralized location (such as base station) can be of great interest to maintain the IoT-enabled network. The transfer of these tasks to the MEC servers still has two main challenges, namely, (i) a large number of IoT devices can share the same MEC servers; therefore, ensuring the availability of computational resources in MEC servers that meet the processing requirements of the tasks is not an easy job. (ii) The IoT devices have limited battery capacity, the computation of tasks locally on the device or the transfer of data to a MEC server consume energy that could lead to quick depletion of the battery energy. Subsequently, the optimization of resource allocation in MEC-based networks is essential in real-time applications to ensure timely completion of the computational tasks and long-lasting use of the batteries of the IoT devices. In [106], a resource allocation problem in a downlink NOMA-enabled heterogeneous cloud radio access network (H-CRAN) that maximizes the weighted sum rate of NOMA users has been proposed. Later an extension to [106] that jointly optimizes the resource allocation and power allocation has been analyzed in [107]. In both works employing NOMA scheme

Table 2.5: MEC-NOMA Systems: Current Status of Rate Optimization Schemes [10].

[#]	Classification	System Model	Design Objective	Optimization Method
[106]	Mobile Edge Computing (MEC)	A downlink NOMA-enabled Fog radio access network, single antenna nodes	Max. weighted sum rate	A suboptimal solution: many-to-one matching algorithm and SCA technique
[107]		Similar to [106]	Max. weighted sum rate	The optimal solution: monotonic optimization and polyblock approximation method
[108]		A downlink multi-carrier NOMA-enabled Fog radio access network, single antenna nodes	Max. weighted sum rate	Hungarian-based method, multiple choice knapsack-based method, and alternating direction method of multipliers
[109]		A user-assisted HD cooperative MEC-enabled NOMA system, single antenna nodes	Max. sum offloaded data rate	Some mathematical simplification methods
[110]		A downlink cache-aided NOMA scheme with one BS + two users, single antenna nodes	Max. sum rate and min. file delivery time	Bisection search and an analytical method based on the optimality conditions

achieve better system weighted sum-rate performance as compared to equivalent systems that employ the OMA scheme; since NOMA allows multiple users to access the same subcarrier simultaneously. Both works have employed multiple fog APs/remote radio heads (RRHs) while enabling the reuse of the same subcarriers among the fog APs and between the fog APs and the RRHs. Hence, NOMA superiority comes at the expense of introducing (i) intra-cell interference (co-tier interference) among different fog APs' users and (ii) inter-cell interference (cross-tier interference) between the fog APs' users and the RRHs' users that caused by frequency reusing. Subsequently, both works utilized a mechanism to control this interference. This mechanism contributes in increasing the system complexity.

In [109], a sum-rate maximization problem for offloaded data that jointly optimizes the transmit power, the time allocation, and the task partition for users in a coop-

erative user-assisted MEC-enabled NOMA system has been proposed. The proposed system contains three nodes, namely, user, helper, and an AP integrated with a MEC server. The user can offload tasks to the helper and AP simultaneously using the NOMA scheme to exploit the idle computational resources in the helper. The helper can only offload tasks to AP and located between the user and the AP. Through simulation, the author demonstrated that the proposed scheme can achieve higher sum-rate performance for the offloaded data compared to the equivalent NOMA scheme without cooperation and TDMA scheme no matter where the physical location of the helper.

■ Lessons Learnt

- As mentioned in Section 1.2.7 and Section 2.6, the main goal in MEC-enabled networks with latency-sensitive applications is to support efficient task offloading for low-cost users. Hence, designing a suitable multiple-access scheme is crucial in such networks. With OMA schemes, the users sometimes need to wait for an available orthogonal resource block to grant access which is not acceptable in latency-sensitive applications. In contrast, NOMA schemes offer more flexible user scheduling opportunities while accommodating more users in each resource block. Hence, NOMA can be considered as an enabler for IoT-enabled networks at the expense of increasing the system complexity.

2.7 Summary

In this chapter, a comprehensive review of the literature is conducted on the integration of PD-NOMA scheme with some candidate communications schemes and technologies for high-data-rate future wireless networks including MISO, MIMO, mMIMO, mmWave and THz communications, cooperative communications, VLC, and MEC. Particularly, the chapter has investigated the system models and the various utilized optimization methods for each NOMA-enabled technology, and revealed the increased achievable rates as well as the associated trade-offs.

CHAPTER 3

ON THE ACHIEVABLE MAX-MIN USER RATES IN MULTI-CARRIER CENTRALIZED NOMA-VLC NETWORKS

VLC is gaining interest as one of the enablers of short-distance, high-data-rate applications, in future B5G networks. Moreover, NOMA-enabled schemes have recently emerged as a promising multiple-access scheme for these networks that would allow the realization of the target spectral efficiency and user fairness requirements. The integration of NOMA in the widely adopted orthogonal frequency-division multiplexing (OFDM)-based VLC networks would require an optimal resource allocation for

the pair or the cluster of users sharing the same subcarrier(s). In this chapter, the max-min rate of a multi-cell indoor centralized VLC network is maximized through optimizing user pairing, subcarrier allocation, and power allocation. The joint complex optimization problem is tackled using a low-complexity solution. At first, the user pairing is assumed to follow the divide-and-next-largest-difference user-pairing algorithm (D-NLUPA) that can ensure fairness among the different clusters. Then, subcarrier allocation and power allocation are solved iteratively through both the SA meta-heuristic algorithm and the bisection method. The obtained results quantify the achievable max-min user rates for the different relevant variants of NOMA-enabled schemes and shed new light on both the performance and design of multi-user multi-carrier NOMA-enabled centralized VLC networks.

3.1 Introduction

Wireless optical communications, particularly VLC, has emerged as a bandwidth-abundant, secure, and cost-effective communications technology. It complements the existing RF systems or even replaces them for some indoor and outdoor applications, such as conference and exhibition halls, office rooms, trains and airplane cabins, and so forth. It can also be deployed outdoors in V2V and V2X applications, as well as applications that are short-range, and which have a very high data rate in B5G networks. VLC is based on the principle of modulating light from LEDs without any adverse effects on the human eye and at the required illumination levels to transmit data. Clearly, this provides an excellent opportunity to utilize the existing illumination

infrastructure for very high-speed and secure wireless communications [41].

In a conventional distributed VLC architecture, a set of L transmit LEDs communicate with a set of N users in a way that each LED acts as an AP that serves its own subset of the N users. Besides, all the APs contain a base-band unit followed by an optical front-end and connect to each other through the data backbone, as well as the electrical grid. While in centralized light access network (C-LiAN) architecture, the base-band processing unit of each LED is retracted and grouped in a central pool that is managed by a centralized controller, where the LEDs are only responsible for the optical transmission/reception. In this way, the complexity and the associated cost of each VLC-enabled LED can be reduced. In addition, efficient joint-processing algorithms of signals from different LEDs can be implemented to enhance resource management, scheduling, interference management, handover, and so forth in the network. The centralized controller is responsible for collecting the channel state information (CSI) of the users, the traffic load status of the LEDs, and the QoS requirements of the users [111].

In the past generations of wireless networks, the wisdom of OMA schemes, such as TDMA, FDMA, CDMA, OFDMA, and wavelength-division multiple-access (WDMA) in both RF and VLC networks was dominant [112]. In these schemes, the different users are allocated orthogonal frequency channels or time slots or spreading codes, or wavelengths so that they do not interfere with one another as they access the network. However, the orthogonality requirement poses a limit on the number of users that may access the network resources, and hence reduces the overall spectral efficiency and increases the network latency. On the other hand, NOMA schemes allow several

users to share the same resource (e.g., a frequency/time resource block) and separate these users in other domains with additional receiver complexity. When the power domain is used to separate the users, it is referred to as the PD-NOMA [2] scheme. The NOMA concept was first introduced in [11] to enhance the spectral efficiency of wireless cellular networks, and it has its roots in broadcast channels in multi-user information theory [12], though with additional constraints on the users' target rates in addition to the typical transmit power constraint [10].

What makes NOMA interesting for adoption in indoor VLC networks are the followings [41]: (i) As the current off-the-shelf LEDs have limited bandwidth, this necessitates the adoption of spectrally efficient schemes, like the NOMA-enabled schemes, to attain the desired high data rates in VLC networks, (ii) under typical illumination constraints, VLC experiences relatively high SNR conditions where it is well-known that the NOMA scheme outperforms the orthogonal counterparts in that particular region, and (iii) the quasi-static nature of the propagation channel in low mobility and indoor VLC networks allows for more reliable estimation of the channel gains for subsequent NOMA scheme power allocation in the LEDs.

It is worth noting that applying NOMA to a large number of users in a single carrier system is not that feasible due to the error propagation, the high complexity of the architecture, and the additional system overhead for coordinating the users' CSI feedback. Hence, multi-carrier NOMA-enabled systems with efficient user-pairing techniques have emerged, where users are divided into clusters, and NOMA is applied among each cluster. Each cluster can be served through one or more subcarriers. In this chapter, user pairing, subcarrier allocation, and power allocation in direct-

current biased optical-OFDM (DCO-OFDM) indoor NOMA-enabled centralized VLC networks are investigated. Next, we provide a discussion for the most-utilized methods that can solve user pairing, subcarrier allocation, and power allocation problems, and we justify the use of the methods that we adopted in our proposed heuristic-based solution.

In the NOMA literature, there are different proposed user-pairing algorithms, such as (i) the random user-pairing algorithm [57], (ii) cognitive radio (CR)-inspired-NOMA pairing algorithm [113], (iii) next-largest-difference user-pairing algorithm (NLUPA) [113], (iv) divide-and-NLUPA (D-NLUPA) [57], (v) user-pairing algorithms that utilize the matching theory, such as the Hungarian method and Gale-Shapley algorithm [114], and (vi) the exhaustive search user-pairing algorithm [114]. Among these algorithms, the D-NLUPA algorithm is adopted in this work, as it is attractive for the max-min user rate requirement [57]. The reason is that by re-distributing the rate gains between the clusters and achieving cluster fairness, the rate gap between the users' rates will reduce and this reduces the search space, and thus the algorithm complexity, for reaching the max-min user rate point for all the users in the network.

The subcarrier allocation problem is typically a non-deterministic polynomial-time (NP)-hard optimization problem in both the number of users and the number of channels to be allocated [115]. The optimal resource allocation problem is known to be an NP-hard problem even for the single carrier case [115]. The NP class contains problems that have the characteristic that only non-deterministic algorithms can solve them in polynomial-time. However, we can verify a given solution to these problems in polynomial time. The non-deterministic algorithms solve a problem by evaluating

possible guesses of the solution. A problem is NP-hard if it is at least as hard as the hardest problem in NP, and all NP problems are reducible to it. In NP-hard problems, the search space size is so large that an exhaustive search is infeasible. Therefore, we determine approximate solutions to NP-hard problems. Evolutionary algorithms (EAs) are a popular approach to solve NP-hard problems [116]. Simulated Annealing (SA) is a well-known EA that has demonstrated excellent performance in solving optimization problems in various applications, including wireless communications [117], [118], [116]. In this work, we use the SA algorithm to allocate the subcarriers to user-pairs. For the power allocation, the bisection method is commonly used to optimally solve the power allocation problem for max-min user rate optimization in the NOMA literature [119], [120].

3.1.1 Related Work

When it comes to rate-optimal NOMA-enabled VLC networks, the majority of works have considered maximizing the system sum-rate metric [93], [94], [95], [96], [97], [98], [99], [100], and this is detailed in Table VIII of the survey by Maraqa et al. [10]. In particular, early works on rate-optimal NOMA-enabled VLC networks have considered a single-LED, single-carrier setup as in [93], [94], [95], [96], [97]. Then, the research evolved to consider a single-LED multi-carrier setup as in [98], [99]. Later, a few works have considered a multi-LED, multi-carrier setup as in [100], [101], [102]. Among those, only two works have considered the optimization of another common fairness measure, which is the max-min achievable user rate alongside maximizing the system sum-rate metric [101], [102]. This is referred to as the reason that the

optimization of the max-min user rate tends to reduce the total throughput of the users, as compared to sum-rate maximization; however, it guarantees fairness among the users. This is an appealing feature for the operation of ultra-massive machine-type communication (umMTC) and internet-of-everything (IoE) in B5G systems that need reliable connectivity with generally low data-rate requirements [121]. The work in [101] has considered the maximization of the minimum rate for NOMA-enabled VLC networks, where an approximation of the objective function was utilized to convexify the optimization problem, and a GP algorithm is used to adjust the power allocation coefficients. The maximization of the minimum user rate for the cell-edge users in NOMA-enabled VLC networks in [102], using hybrid NOMA and/or linear ZF precoding schemes, was approached by numerical convex optimization of the standard determinant maximization. However, both aforementioned works have considered the optimization of both the power allocation and user grouping. Neither of them has analyzed the effect of subcarrier allocation on the max-min user rate performance of NOMA-enabled VLC networks, which is the main objective of this work.

Our contributions can thus be summarized as follows:

- The optimization of the achievable max-min user rates for NOMA-enabled centralized VLC is investigated through formulating a joint problem for the user pairing, the subcarrier allocation, and the power allocation. Then, a low complexity solution is proposed.
- The development of SA-assisted algorithm for tackling the subcarrier allocation in the max-min user rate optimization problem. The obtained results are further

verified using the TS algorithm.

- The implementation of both of the NOMA-imposed schemes, where all the users are grouped into pairs, and the NOMA-not-imposed schemes; and besides these, the investigation of the effect of the different network parameters on the achievable max-min user rate.

The remainder of the chapter is organized as follows. In Section 3.2, we provide the system and channel models for the utilized C-LiAN architecture. The formulation of the proposed max-min user rate optimization problem is analyzed in Section 3.3. In Section 3.4, the details of the proposed heuristic-based solution for the formulated max-min user rate optimization are explained. Finally, simulation results and chapter conclusions are given in Section 3.5 and Section 3.6, respectively. Table 3.1 summarizes the notations used in this chapter.

3.2 System and Channel Models

A multi-user NOMA-enabled C-LiAN architecture [111] is shown in Figure 3.1. In this chapter, we assume that the ceiling of the room contains uniformly distributed LEDs denoted by $\mathcal{L} = \{l_0, l_1, \dots, l_{L-1}\}$, where L is the number of LEDs. Each LED is assigned up to K subcarriers that can be shared by several users, where the subcarriers of each LED are denoted as $\mathcal{K} = \{s_0, s_1, \dots, s_{K-1}\}$. In addition, the users are randomly located in the room, and denoted by $\mathcal{U} = \{u_0, u_1, \dots, u_{N-1}\}$; where the total number of users in the network is N . In multi-user systems, the transmission resources described in time, wavelength, and/or space are divided into resource units. A key challenge is

Table 3.1: List of Notations.

Variable Name	Variable Description
System Model's Variables	
$\mathcal{L} = \{l_0, l_1, \dots, l_{L-1}\}$	A set to describe the total number of LEDs
L	The total number of LEDs
$\mathcal{K} = \{s_0, s_1, \dots, s_{K-1}\}$	A set to describe the total number of subcarriers
K	The total number of subcarriers
$\mathcal{N} = \{u_0, u_1, \dots, u_{N-1}\}$	A set to describe the total number of users
N	The total number of users
N_0	The total number of users served by the LED l_0
φ_{l_0, u_s}	The angle of irradiance between the LED l_0 and the user u_s
ψ_{l_0, u_s}	The angle of incidence between the LED l_0 and the user u_s
u_s and u_w	A strong user and a weak user of the LED l_0
d_{l_0, u_s}	The distance between the LED l_0 and the user u_s
$\Psi_{1/2}$	The FoV semi-angle of the user u_s
m	The order of Lambertian emission
$\phi_{1/2}$	The semi-angle of the LED l_0
A_p	The area of the photo-diode (PD) for the user u_s
$T_s(\psi_{l_0, u_s})$	The optical filter gain
χ	The refractive index
h_{l_0, u_s}	The channel gain between the LED l_0 and the user u_s
a_s	The power allocation coefficient for the strong user
a_w	The power allocation coefficient for the weak user
P_e^k	The electrical signal power per subcarrier of a LED
P_e	The electrical signal power of a LED
P_o	The optical transmit power at the output of a LED
$\iota = P_o / \sqrt{P_e}$	The ratio between the electrical signal power and the optical transmit power
κ	The optical to electrical conversion efficiency of the PDs
$\sigma_k^2 = Z_o B_L / K$	The power of equivalent AWGN where Z_o denotes the noise power spectral density and B_L denotes the base-band modulation bandwidth
γ_s^k and R_s	The SINR and the achievable rate of the strong user
γ_w^k and R_w	The SINR and the achievable rate of the weak user
R_j	The achievable rate of an arbitrary user (j -th user) of an arbitrary LED in the network (i.e., R_j can be a strong user or a weak user in arbitrary user pair)
$S_{i,k} \in \{0, 1\}$	A binary variable to denote that a user is served by a LED l_i and a subcarrier k
$S_k \in \{0, 1\}$	A binary variable to denote that a user is served by a subcarrier k
$S_i^j \in \{0, 1\}$	A binary variable to denote the user u_j is served by LED l_i
$\mathbf{\Gamma}(l_i)$	A set of all user-pair combinations for an arbitrary LED l_i
K_{l_i}	The maximum number of subcarriers for an arbitrary LED l_i
Heuristic-based Solution's Variables	
$\lambda(u_j)$	The most suitable LED for a user $u_j \in \mathcal{N}$
$f_1(l_i)$	A function that returns the number of users assigned to the LED l_i
$f_2(u_j)$	A function that denotes the distance of the user u_j from the LED to which it is currently allocated
$f_3(u_j)$	A function that denotes the maximum distance of u_j from any LED
$\mathcal{N}_{l_i}, N_{l_i}$	A vector that store the users of LED l_i after binding, the number of users in $\mathcal{N}_{l_i}$
$\mathbb{P}_j$	A pair of users in $\mathbf{\Gamma}(l_i)$
X	A decision matrix that represents the solution of subcarrier allocation
$\mathcal{C} \in [0, 1]$	A predefined constant
$\mathcal{P}_1$ and $\mathcal{P}_2$	The penalty factors of the penalty method
Simulated Annealing Algorithm's Variables	
T_0 and T	The initial temperature and the current temperature
α	The rate of decrease in the temperature
M_0 and M	The initial and current value of the number of iterations in the Metropolis function
β	The rate of increase in the number of iterations of the Metropolis function
$X, X_{\text{current}},$ and X_{best}	The input solution, the current solution, and the best solution
$c_{\text{current}}, c_{\text{best}},$ and c_{new}	The costs (objection function value) of the current solution, the best solution, and the new solution created in the Metropolis function

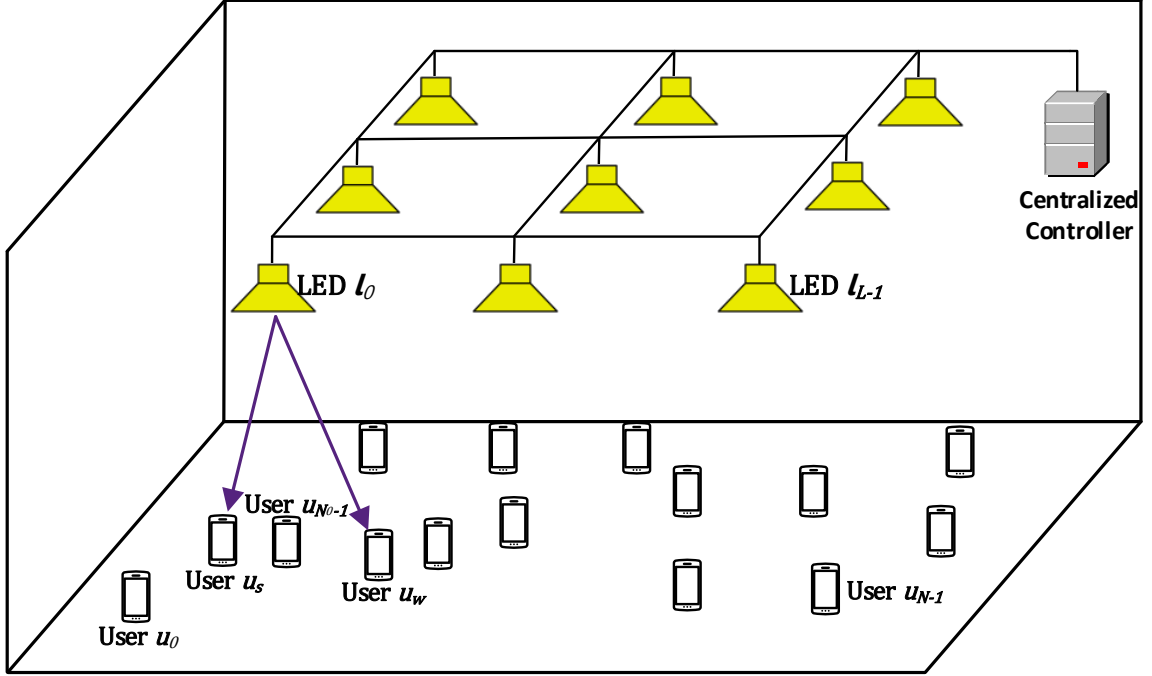


Figure 3.1: The C-LiAN architecture [111].

the allocation of the resource units in a way that key performance metrics, such as user fairness and spectral efficiency, are fulfilled. This motivates allowing the served users or a subset of them to share the subcarriers or a subset of them. Hence, in each signaling interval, we assume that each pair of users can occupy one or more subcarrier(s) in only one LED.

In this work, the LoS optical channel model is adopted, since in a typical indoor environment, the strongest diffuse component is usually much weaker than the LoS component [123]. Hence, the channel gain between the LED l_0 and user u_s is given by [118]:

$$h_{l_0, u_s} = \begin{cases} \frac{(m+1)A_p\chi^2 T_s(\psi_{l_0, u_s})}{2\pi d_{l_0, u_s}^2 \sin^2(\Psi_{1/2})} \cos^m(\varphi_{l_0, u_s}) \cos(\psi_{l_0, u_s}) & \text{if} \\ 0 \leq \psi_{l_0, u_s} \leq \Psi_{1/2} \\ 0, & \psi_{l_0, u_s} \geq \Psi_{1/2} \end{cases} \quad (3.1)$$

where φ_{l_0, u_s} and ψ_{l_0, u_s} denote, respectively, the angle of irradiance and angle of incidence between the LED l_0 and user u_s . As shown in Figure 3.2, d_{l_0, u_s} is the distance between the LED l_0 and user u_s . $\Psi_{1/2}$ is the FoV semi-angle of the user u_s . m is the order of Lambertian emission and is equal to $\frac{-1}{\log_2(\cos(\phi_{1/2}))}$, where $\phi_{1/2}$ is the semi-angle of the LED l_0 . A_p is the area of the PD for user u_s , $T_s(\psi_{l_0, u_s})$ is the optical filter gain, and χ denotes the refractive index.

We assume that served users by LED l_0 are ordered according to their channel

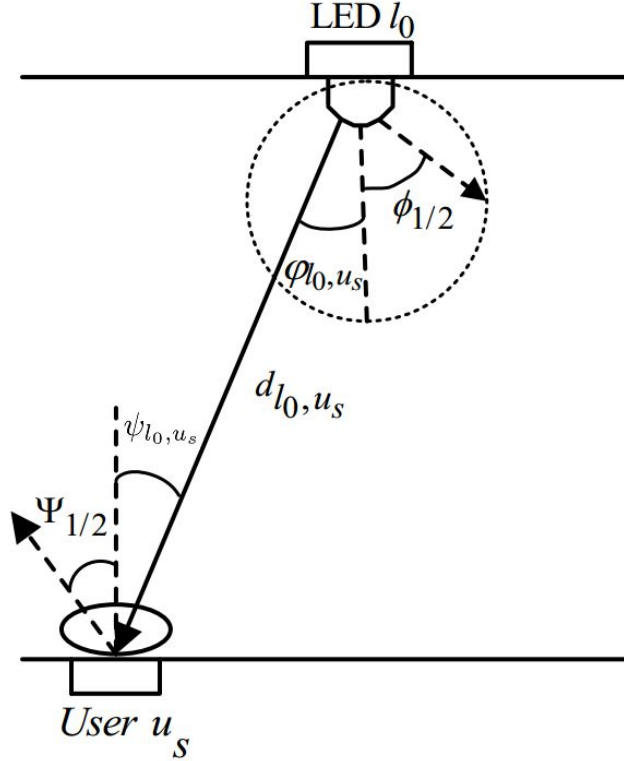


Figure 3.2: The LoS channel model between LED l_0 and user u_s [122].

gains in ascending order as $|h_{l_0,u_0}| \leq |h_{l_0,u_1}| \leq \dots \leq |h_{l_0,u_{N_0-1}}|$; where we assume here that the total number of served users by LED l_0 is N_0 . In general, if the user u_0 (i.e., the user that has the weakest instantaneous channel gain) of LED l_0 occupies an arbitrary subcarrier (for example, the k -th subcarrier), then the SINR of the user u_0 can be expressed as:

$$\gamma_{u_0,k} = \frac{|h_{l_0,u_0}|^2 \kappa^2 a_0 P_{o,k}^2}{I_1 + I_2 + \iota^2 \sigma_k^2}, \quad (3.2)$$

where a_0 represents the power allocation factors for the user u_0 that is attached to LED l_0 . $P_{o,k}$ is the LED optical transmit power per subcarrier and is equal to $P_o/(K-2)$ according to the DCO-OFDM principle, where P_o denotes the optical transmit power at the output of the LED. The ratio between the electrical signal power and the optical transmit power can be expressed as $\iota = \frac{P_o}{\sqrt{P_e}}$, where P_e denotes the electrical signal power. κ denotes the optical-to-electrical conversion efficiency of the PDs, σ_k^2 is the power of the equivalent additive Gaussian noise (practical indoor VLC networks are affected by both thermal noise due to the receiver pre-amplifier, and ambient light shot noise due to the possible sun-light through the windows and/or non-VLC indoor light sources. The total noise can be modeled as signal-independent Gaussian noise [124], [125]), whose variance is the sum of the variances of these two noise components and equals to $Z_o B_L/K$; where Z_o denotes the noise power spectral density. In the simulation section of this work, the value of Z_o accounts for both thermal noise and light shot noise. B_L denotes the base-band modulation bandwidth. In (3.2), the first term in the denominator, $I_1 = \sum_{i=1}^{L-1} S_{l_i,k} |h_{l_i,u_0}|^2 \kappa^2 P_{o,k}^2$, represents the interference induced

from the users that utilize the k -th subcarrier in the interfering LEDs (i.e., inter-LED interference) where $S_{l_i,k} \in \{0,1\}$ is a binary variable that denotes the user has received an interfering signal from a LED l_i on a subcarrier k . Likewise, the second term in the denominator, $I_2 = \sum_{j=u_1}^{N_0-1} |h_{l_0,j}|^2 \kappa^2 a_j P_{o,k}^2$, represents the interference that remains after SIC decoding (i.e., inter-user interference) where a_j represents the power allocation factors for the rest of the users that is attached to LED l_0 . It is worthy to note that we assume in the above equation that multiple users can be served by one subcarrier of LED l_0 (i.e., multiple users per cluster). For the rest of the chapter, we consider the case where two users are served by the same subcarrier(s) (i.e., two users per cluster). Studying the system performance while considering multiple users per cluster is left for future research.

For the two-user pairing case, we use the D-NLUPA scheme for pairing the users, as mentioned in Section 3.1, where the strong user (i.e., user u_s) is close to the LED with strong channel gain and the weak user (i.e., user u_w) is farther away from the LED with weak channel gain so that the strong user can successfully decode and subtract the weak user signal before decoding its own signal (i.e., performing SIC). In Figure 3.1, for LED l_0 , we can express the achievable rates of the strong and the weak users using a well-known lower bound for the capacity, given in [126], [122], as

$$R_s = \frac{B_L}{K} \sum_{k=0}^{K-1} S_k \log_2 \left(1 + \frac{e}{2\pi} \frac{|h_{l_0, u_s}|^2 \kappa^2 a_s P_{o,k}^2}{\sum_{i=1}^{L-1} S_{l_i, k} |h_{l_i, u_s}|^2 \kappa^2 P_{o,k}^2 + \iota^2 \sigma_k^2} \right), \quad (3.3)$$

$$R_w = \frac{B_L}{K} \sum_{k=0}^{K-1} S_k \log_2 \left(1 + \frac{e}{2\pi} \frac{|h_{l_0, u_w}|^2 \kappa^2 a_w P_{o,k}^2}{\sum_{i=1}^{L-1} S_{l_i, k} |H_{l_i, u_w}|^2 \kappa^2 P_{o,k}^2 + |h_{l_0, u_s}|^2 \kappa^2 a_s P_{o,k}^2 + \iota^2 \sigma_k^2} \right), \quad (3.4)$$

where $S_k \in \{0, 1\}$ is a binary variable to denote that the user is served by a subcarrier k , and it is assumed that the two-user pair (user u_s and user u_w) occupies one or more subcarrier(s) of the LED l_0 and the power allocation factors satisfy the condition $a_s + a_w = 1$. Noting that the analysis in (3.3) and (3.4) represents the rate equations for one user-pair of LED l_0 , the rate equations for the rest of the user-pairs of LED l_0 and for the user-pairs of any other LED in the network can be analyzed similarly.

3.3 The Max-Min User Rate Optimization Problem

In this section, we formulate a joint optimization problem for user pairing, subcarrier allocation, and power allocation that maximizes the minimum achievable rate of the served users. Let R_j denote the achievable rate of an arbitrary user (i.e, j -th user) of an arbitrary LED (i.e, LED l_i) in the network (i.e., R_j can be a strong user or a weak user in a user pair, as described in (3.3) and (3.4)). Then, the max-min optimization

problem can be expressed as:

$$\underset{\mathbf{\Gamma}(l_i), \mathcal{K}, a_s, a_w}{\text{maximin}} \quad R_j, \quad (3.5)$$

$$\text{subject to} \quad \sum_{k=0}^{K-1} S_k^j \geq 1, \quad \forall j, \quad 0 \leq j \leq N_{l_i} - 1 \quad (3.6)$$

$$0 \leq K_{l_i} \leq \frac{K}{2} - 1, \quad (3.7)$$

$$\sum_{i=0}^{L-1} S_{l_i}^j = 1, \quad \forall j, \quad 0 \leq j \leq N_{l_i} - 1 \quad (3.8)$$

$$a_s + a_w \leq 1, \quad \forall \text{pair} \in \mathbf{\Gamma}(l_i) \quad (3.9)$$

where $\mathbf{\Gamma}(l_i)$ is a set of all user-pair combinations of an arbitrary LED l_i . $S_k^j \in \{0, 1\}$ and $S_{l_i}^j \in \{0, 1\}$ are binary variables to denote that the user u_j is served by a subcarrier k and the user u_j is served by LED l_i , respectively. By (3.6), we ensure that any user attached to LED l_i is served by at least one subcarrier, noting that the weak user and the strong user in a user-pair are served by the same number of subcarriers according to the NOMA principle. By (3.7), the maximum number of subcarriers per LED is limited to $\frac{K}{2} - 1$ to be aligned with the DCO-OFDM principle. By (3.8), we ensure that each user attached to LED l_i is served only by LED l_i . By (3.9), we limit the values of the power allocation coefficients in a user-pair. The above optimization problem is of a combinatorial nature, for the user pairing and the subcarrier allocation, and has a non-linear objective function, and hence a non-convex NP-hard optimization problem [127], [115]. The optimal values of the power allocation coefficients can be determined using the bisection method [119].

3.4 The Heuristic-Based Solution for the Max-Min User Rate Optimization Problem

The optimization problem in (3.5)–(3.9) is an involved optimization problem, as stated before. Subsequently, the search space to handle the problem jointly is too large. Noting that performing an exhaustive search to solve this problem jointly is infeasible from a practical point-of-view, to reduce the complexity of this optimization problem, the user pairing is assumed to follow the D-NLUPA algorithm, as mentioned before, where that pairing algorithm is attractive for the max-min user rate requirement [57]. Hence, the optimization problem in (3.5)–(3.9) reduces to a joint subcarrier allocation and power allocation problem, which is still an NP-hard problem because of the remainder of the subcarrier allocation problem [127], [115], [128], though with less complexity as compared to the original optimization problem. Consequently, the proposed heuristic-based solution, that is discussed in this section, tackles the original optimization problem in three steps, as in Algorithm 1:

1. Binding of users to LEDs.
2. Determining the user-pairs for each LED (i.e., user pairing).
3. Optimizing subcarrier(s) allocation to user-pairs in each LED and power allocation within each pair (i.e., subcarrier allocation and power allocation).

As stated before, the max-min optimization problem in (3.5)–(3.9) involves both subcarrier and power allocation; however, since each of the NOMA users in each pair will share the same assigned subcarriers with a fixed power per subcarrier, then the

subcarrier allocation and the power allocation problems may be done attractively through both the SA algorithm and the bisection method. This is discussed in detail later in this section.

Algorithm 1: Overview of the proposed heuristic-based solution.

- 1 **Binding of users to LEDs:** Assign users to different LEDs in such a way that a user cannot be assigned to more than one LED;
 - 2 **Determining the user-pairs for each LED:** Apply the D-NLUPA algorithm to determine the user-pairs per LED. Store the user-pairs in $\Gamma(l_i)$;
 - 3 **Optimizing subcarrier(s) allocation to user-pairs in each LED and power allocation within each pair:** This task allocates the subcarriers to the user-pairs to maximize the minimum achievable rate of the served users. We apply the SA algorithm with an innovative objective function that allocates the users-pairs to the subcarriers while ensuring almost uniform data rates for all the served users.
-

3.4.1 Binding of Users to LEDs

Although a user can receive data using any number of subcarriers, all subcarriers should belong to a single LED. Therefore, it is necessary to bind users to LEDs. In the VLC literature, there are different approaches to attach users to LEDs [102]. In this work, we adopted the strategy to bind the users to the LEDs that have the channels of maximum strength with the users. We denote the most suitable LED for a user $u_j \in \mathcal{N}$ with $\lambda(u_j)$, and its value can be determined using the following equation:

$$\lambda(u_j) = \underset{\forall l_i \in \mathcal{L}}{\operatorname{argmax}} |h_{l_i, u_j}, u_j|. \quad (3.10)$$

The NOMA scheme imposition, termed in this work as the NOMA-imposed-scheme

(i.e., two users should share the available subcarrier(s)), requires that the number of users allocated to each LED should be even. Otherwise, it is not possible to impose NOMA fully, and as a result, some subcarriers are allocated to only one user (this scheme is termed in this work as the “NOMA-not-imposed scheme”). When the number of users allocated to any LED is odd, we can formulate a linear constrained optimization problem and solve it to ensure that each LED has an even number of users or zero users. Next, we describe the optimization problem. In (3.11), $\overline{|\cdot|}$ denotes a complement operation, and this operation returns one only when $|\lambda(u_j) - i| = 0$. The function $f_1(l_i)$ returns the number of users assigned to the LED l_i .

$$f_1(l_i) = \sum_{j=0}^{N-1} \overline{|\lambda(u_j) - i|}. \quad (3.11)$$

The distance of the users from their allocated LEDs can be given by:

$$f_2(u_j) = d(u_j, l_{\lambda(u_j)}), \quad (3.12)$$

$$f_3(u_j) = \max_{i \in \{0,1,\dots,L-1\}} d(u_j, l_i). \quad (3.13)$$

In (3.12) and (3.13), $f_2(u_j)$ denotes the distance of the user u_j from the LED to which it is currently allocated, and $f_3(u_j)$ denotes the maximum distance of u_j from

Algorithm 2: Algorithm for binding users to LED.

Input: $l_i \in \mathcal{L}$, $u_j \in \mathcal{N}$
Output: $\mathcal{N}_{l_i} = \{u_j, \text{s.t. } u_j \in \mathcal{N}, \text{ and, } \lambda(u_j) = l_i\}$ (a vector that stores the users of LED l_i),
 N_{l_i} (the number of users in $\mathcal{N}_{l_i}$)

- 1 Bind the users to the LEDs that have the channels of maximum strength with the users based on (3.10);
- 2 Store the set of users attached to each LED in a vector. For example, users attached to LED l_i are stored in vector $\mathcal{N}_{l_i}$, and their sum is stored in N_{l_i} ;
- 3 **if** NOMA-imposed scheme==TRUE $\exists f_1(l_i)$ is odd $\forall l_i \in \mathcal{L}$ **then**
- 4 **while** Stopping criterion is not reached **do**
- 5 Randomly choose a user currently attached to LED l_i and bind it to a new LED l_j (where, both LED l_i and LED l_j are randomly chosen);
- 6 Determine the cost of the new solution using (3.14) and (3.15);
- 7 **if** the cost of the new solution is worse than the previous one **then**
- 8 Revert the binding of the selected user to LED l_i
- 9 **end**
- 10 **end**
- 11 **end**
- 12 **return** $\mathcal{N}_{l_i}$, N_{l_i} ;

any LED. The linear constrained optimization problem is shown below:

$$\text{Minimize} \quad \sum_{j=0}^{N-1} \frac{f_2(u_j)}{f_3(u_j)}, \quad (3.14)$$

$$\text{subject to} \quad \sum_{i=0}^{L-1} (f_1(l_i) \bmod 2) = 0. \quad (3.15)$$

The above linear-constrained optimization problem can be solved using many methods, and in our work, we employed an iterative greedy algorithm [129] to solve it. The solution is represented by $\{\lambda(u_0), \lambda(u_1), \dots, \lambda(u_{N-1})\}$, where $\lambda(u_j) \in \{l_0, l_1, \dots, l_{L-1}\}$. Algorithm 2 summarizes the aforementioned approach followed for binding users to LEDs. The pseudo-code outlines an iterative method whose termination criterion could be the maximum number of iterations (e.g., 1000 iterations).

Algorithm 3: Algorithm to implement the D-NLUPA method of user-pairing.

Input: $l_i \in \mathcal{L}$, $\mathcal{N}_{l_i}$, N_{l_i}
Output: $\mathbf{\Gamma}(l_i)$ (a set of all user-pair for the LED l_i)

- 1 Sort the elements in $\mathcal{N}_{l_i}$ in the descending order based on the strength of their channels with LED l_i ;
- 2 **for** j in 0 to $\frac{N_{l_i}}{2}$ **do**
- 3 Create a pair $\mathbb{P}_j$ in which the user at index j is the strong user and the user at index $j + \frac{N_{l_i}}{2}$ is the weak user;
- 4 Insert $\mathbb{P}_j$ in $\mathbf{\Gamma}(l_i)$;
- 5 **end**
- 6 **if** NOMA-not-imposed scheme==TRUE **&&** N_{l_i} is an odd number **then**
- 7 Create a pair in which the user at index $N_{l_i} - 1$ is the strong user and a null value for the weak user, and insert it into $\mathbf{\Gamma}(l_i)$;
- 8 **end**
- 9 **return** $\mathbf{\Gamma}(l_i)$;

The iterative method makes a random change in the current binding of users and only lets the new solution replace the current one if the new binding is better than or equal to the current one using (3.14) and (3.15). The simulation results, shown in Section 3.5.1, illustrate that the above-described method is efficient in preventing the LEDs from having an odd number of users with a relatively low number of iterations.

3.4.2 Determining of the User-Pairs for Each LED

We used the D-NLUPA method [57] to determine the user-pairs for each LED. The D-NLUPA method is efficient in finding user pairs, and it creates pairs in which the first user has a strong channel (or strongest among users not already part of any pair) with a user of a relatively weaker channel. Algorithm 3 shows the D-NLUPA algorithm. The first step is to sort the users with respect to their channel gains. The second step is a loop that creates pairs of strong and weak users and stores them in $\mathbf{\Gamma}(l_i)$. The

actions on lines 6–7 only execute if the NOMA-not-imposed scheme is deployed and the number of users under any LED is odd. We should place the last user (i.e., the user having minimum channel strength) into a pair whose weak user is null.

3.4.3 Optimizing Subcarrier(s) Allocation to User-Pairs in Each LED and Power Allocation within Each Pair

In this subsection, we discuss the problem of allocating the subcarriers to user-pairs, as well as a solution method. As we mentioned in the previous subsection, for each LED, the user-pairs allocated to it are represented by $\Gamma(l_i)$, and each LED has up to K subcarriers. The allocation aims to maximize, as well as keep uniformness in the data rates of the users. We also propose a novel objective function to achieve the dual goals through applying a single function. In the following, we first discuss our proposed objective function and then discuss a solution method using the SA algorithm. We represent the solution of subcarrier allocation using the following notation:

$$X = \begin{bmatrix} x_{0,0}, x_{0,1}, \dots, x_{0,K-1} \\ x_{1,0}, x_{1,1}, \dots, x_{1,K-1} \\ \dots, \dots, \dots \\ x_{L-1,0}, x_{L-1,1}, \dots, x_{L-1,K-1} \end{bmatrix}, \quad (3.16)$$

where $x_{i,k}$ is an integer, and $k \in \{0, \dots, K-1\}$, $i \in \{0, \dots, L-1\}$, and $x_{i,k}$ denote the index of the user-pair of $\Gamma(l_i)$ assigned to the k -th subcarrier of the LED l_i . The objective of the subcarrier allocation is to maximize the minimum achievable rate of

the served users through finding a decision matrix (X), and is given by

$$\mathcal{O}(X) = \min_{j \in \{0,1,\dots,N-1\}} R_j, \quad (3.17)$$

$$\text{maximize } \mathcal{O}(X). \quad (3.18)$$

We propose two new constraints into the above objective function ($\mathcal{O}(X)$) to help the iterative heuristics to obtain a solution in which the data rates of all users have the following features:

1. The data rates of all users are closer to each other.
2. The users should not have a zero data-rate.
3. The data rate should be as maximal as possible considering the above two conditions.

To include the above enhancements, we propose the objective function as follows:

$$\begin{array}{ll} \text{maximize} & \mathcal{O}(X), \\ & \mathcal{K}, a_s, a_w \end{array} \quad (3.19)$$

$$\begin{array}{ll} \text{subject to} & \frac{\max_{j \in \{0,1,\dots,N-1\}} R_j - \min_{j \in \{0,1,\dots,N-1\}} R_j}{\max_{j \in \{0,1,\dots,N-1\}} R_j} - \mathcal{C} \leq 0, \end{array} \quad (3.20)$$

$$R_j > 0, \quad \forall j \in \{0, 1, \dots, N-1\}. \quad (3.21)$$

In the above equations, (3.20) ensures that the percentage difference between the maximum and minimum data rates of any two users should be lesser than a predefined constant $\mathcal{C} \in [0, 1]$. Equation (3.21) ensures that no user suffers a service outage.

Finally, we convert the above constrained problem into an unconstrained optimization problem using the penalty method [130], as follows:

$$f_{\text{zero}}(R_j) = \begin{cases} 1, & \text{if } R_j = 0 \\ 0, & \text{otherwise} \end{cases} \quad (3.22)$$

$$f_{\text{cons}}(R_0, R_1, \dots, R_{N-1}) = \frac{\sum_{j=0}^{N-1} f_{\text{zero}}(R_j)}{N}, \quad (3.23)$$

$$f_{\text{max}}(R_0, R_1, \dots, R_{N-1}) = \max_{j \in \{0,1,\dots,N-1\}} R_j, \quad (3.24)$$

$$f_{\text{min}}(R_0, R_1, \dots, R_{N-1}) = \min_{j \in \{0,1,\dots,N-1\}} R_j, \quad (3.25)$$

$$f_{\text{diff}}(R_0, R_1, \dots, R_{N-1}) = \frac{f_{\text{max}} - f_{\text{min}}}{f_{\text{max}}} - \mathcal{C}. \quad (3.26)$$

The new objective function can be given by:

$$\mathcal{O}'(X) = \mathcal{O}(X) - \mathcal{P}_1 f_{\text{cons}} - \mathcal{P}_2 f_{\text{diff}}, \quad (3.27)$$

$$\text{maximize } \mathcal{O}'(X). \quad (3.28)$$

In the above equation, $\mathcal{P}_1$ and $\mathcal{P}_2$ denote the penalty factors. The function $\mathcal{O}(X)$ denotes a data-rate value of a user-pair, and hence it could be zero or positive, and the rates can vary between different user pairs. Therefore, $\mathcal{P}_1$ is set for the avoidance of solutions with zero minimum data rates (i.e., $f_{\text{cons}} > 0$), $\mathcal{P}_2$ is set for the avoidance of solutions in which the difference among the data rates of the users is more than the given value (i.e., $f_{\text{diff}} > 0$). We prioritize the two constraints by setting $\mathcal{P}_1 \gg \mathcal{P}_2$. The function $(\mathcal{O}'(X))$ is a non-linear integer programming (NLIP) problem, which

is NP-hard in general [131]. In this work, we adopted the SA algorithm, which is a popular method of solving NP-hard optimization problems [117], [118].

Now, we briefly describe the SA algorithm for finding an allocation of subcarriers to user-pairs in order to maximize the objective function (3.28). Algorithm 4 shows an overview of the SA algorithm. The input parameters are as follows: (i) T_0 is the initial temperature of the SA algorithm, and its value should be high; (ii) α is the cooling-rate and its value should be between $(0, 1)$, usually, its value is kept very close to 1, such as 0.97, 0.99; (iii) M indicates the number of iterations in the Metropolis function; (iv) β indicates the increase in the value of M . The first four lines in the SA algorithm initialize the variable and the current solution (X_{current}). The 'while' loop contains the main algorithm, and the termination criterion could be the maximum time or iterations. The 'while' loop in each iteration calls the Metropolis function, which is responsible for exploring the current solution's neighborhood to improve the current solution (X_{current}).

Algorithm 5 shows the Metropolis function. The Neighbor function in line 2 creates a new solution by mutating the current solution. In this work, we employ the random mutation that consists of the following two steps: (i) Randomly choose a LED and a subcarrier of it; and (ii) change the user-pair already allocated to the selected subcarrier to another user-pair attached to the same LED. The new solution (X_{new}) could replace the current solution based on comparing its objective function values with that of the current solution. The RANDOM in the pseudo-code indicates a random number between $(0, 1)$. The readers can refer to [116] for more details on the SA algorithm. For the optimal power allocation, the bisection method has been utilized,

Algorithm 4: Overview of the SA algorithm.

Input: T_0, α, β, M
Output: X

- 1 Initialize X to a random solution
- 2 $T = T_0, X_{\text{current}} = X, X_{\text{best}} = X$
- 3 $c_{\text{current}} = \mathcal{O}'(X)$
- 4 $c_{\text{best}} = c_{\text{current}}$
- 5 **while** stopping criterion is not reached **do**
- 6 Call Metropolis($X_{\text{current}}, c_{\text{current}}, X_{\text{best}}, c_{\text{best}}, T, M$)
- 7 Replace M by $\beta \times M$, and T by $\alpha \times T$
- 8 **end**
- 9 return X_{best}

Algorithm 5: Metropolis function.

Input: $c_{\text{current}}, X_{\text{current}}, X_{\text{best}}, c_{\text{best}}, T, M$
Output: X_{current}

- 1 **while** $M > 0$ **do**
- 2 $X_{\text{new}} = \text{Neighbor}(X_{\text{current}})$
- 3 $c_{\text{new}} = \mathcal{O}'(X_{\text{new}})$
- 4 $\Delta c = c_{\text{current}} - c_{\text{new}}$
- 5 **if** $c_{\text{best}} < c_{\text{new}}$ **then**
- 6 $c_{\text{best}} = c_{\text{new}}, X_{\text{best}} = X_{\text{new}}$
- 7 **else**
- 8 **if** $\text{RANDOM} < e^{-\frac{\Delta c}{T}}$ **then**
- 9 $X_{\text{current}} = X_{\text{new}}, c_{\text{current}} = c_{\text{new}}$
- 10 **end**
- 11 **end**
- 12 Decrease M by 1
- 13 **end**
- 14 return X_{current}

which can be found in [119].

3.4.4 The Complexity Analysis of the Proposed Heuristic-Based Solution

In this section, we briefly discuss the time complexity of the algorithms used to accomplish different tasks of the proposed heuristic-based solution. The binding method,

discussed in Section 3.4.1, requires the determination of the maximum value in an array which can be implemented using max-heap or linear determination [129]. The time complexity of the operation to find the maximum value is $O(L)$, and since the operation should be repeated for each user, therefore, the total complexity of the binding method is $O(NL)$. A brief analysis of the time complexity of the algorithm to implement the D-NLUPA method, discussed in Section 3.4.2, is as follows. The sorting can be accomplished using heapsort [129] that has a complexity of $O(N\log N)$, and the creation of user-pairs is a linear operation that has complexity equal to $O(N)$. The time complexity of this step is $O(LN\log N)$ because the heap-sort should be performed for each LED. The computation for each LED is independent of the others. Therefore, we can perform parallel computations, and in that case, the complexity reduces to $O(N\log N)$. We optimized the allocation of user-pairs to the subcarriers using the SA algorithm. The complexity of this algorithm is usually expressed in terms of the number of iterations needed for it to converge to its best solution [132]. In the Results and Discussions section, we analyzed the convergence aspects of the SA algorithm in detail.

3.5 Results and Discussions

In this section, the obtained results for the achievable max-min user rates in a C-LiAN architecture are presented. The user pairing, the sub-carrier allocation, and the power allocation were carried out using the D-NLUPA, the proposed SA algorithm, and the bisection method, respectively, as detailed before. To assess the performance

of the proposed heuristic-based solution, the Monte-Carlo simulation that is averaged over 100 different users' location realizations is used; specifically, each point in the performance curves is an average of implementations of 100 different users' location realizations. The proposed heuristic-based solution was implemented in R and C++ using R version 4.0.2, RStudio version 1.3.1, and Rcpp. We ran the simulations on a desktop computer with an Intel 2.6 GHz processor and 128 GB of memory. In the simulations, an empty room was considered, with a dimension of $5 \times 5 \times 3$, unless otherwise stated. The room was equipped with four LEDs, unless otherwise stated, mounted in the ceiling of the room with an equal distance between adjacent LEDs, in a square lattice topology, similar to [118], [133]. The users were distributed in the room according to the uniform random distribution [134]. The LoS optical channel model in (3.1) was considered, where the electrical signal power of each LED was set to 35 dBm unless otherwise stated, the default values for half the viewing angle of the LEDs and the FoV of the PDs were set to 60° and 85° , respectively, unless otherwise stated. The PDs faced upward towards the ceiling with an area of 1 cm^2 [122]. The number of subcarriers in each LED was set to either 16 or 32 subcarriers, and the number of users was set to 20 users unless otherwise stated. All system parameters used in the simulation are listed in Table 3.2. The SA algorithm parameters were chosen as, $\beta = 1.0005$, $\alpha = 0.995$, $M = 50$, and $T_0 = 1.0$. The penalty factors $\mathcal{P}_1$ and $\mathcal{P}_2$, in (3.27), were set to 1×10^5 and 10, respectively. The predefined constant $\mathcal{C}$ was set to 0.01.

Table 3.2: System Parameters.

Parameter name, notation	Value
The electrical power of the input signal, P_e	[30, 35, 40, 45, 50, 55] dBm [111], [100], [122]
Total number of users, N	[10, 20, 30, 40]
Total number of LEDs, L	[4, 9] [122], [133]
Total number of subcarriers, K	[16, 32] [122], [118]
Room height	[3, 5, 7, 9] meters
Semi-angle at half illumination of the LEDs, $\phi_{1/2}$	60° [118]
FoV of the PDs, $\Psi_{1/2}$	85° [122]
The base-band modulation bandwidth of each LED, B_L	20 MHz [122]
Electrical to optical conversion efficiency, ι	3.2 [118]
Area of the PD, A_p	1.0 cm ² [122]
Optical to electrical conversion efficiency, κ	0.53 A/W [133]
Equivalent noise power spectral density, Z_o	1×10^{-19} A ² /Hz [133], [135]
Refractive index, χ	1.5 [133]
Gain of optical filter, $T_s(\psi)$	1.0 [118]

3.5.1 Validation and Convergence of the Proposed Heuristic-Based Solution

In this subsection, to validate the results that the SA algorithm produces for the subcarrier allocation problem, the subcarrier allocation problem is solved using an-

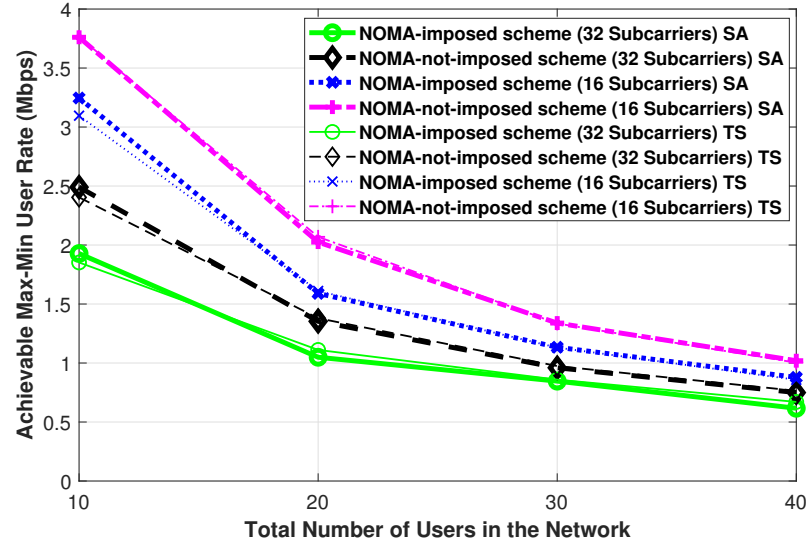
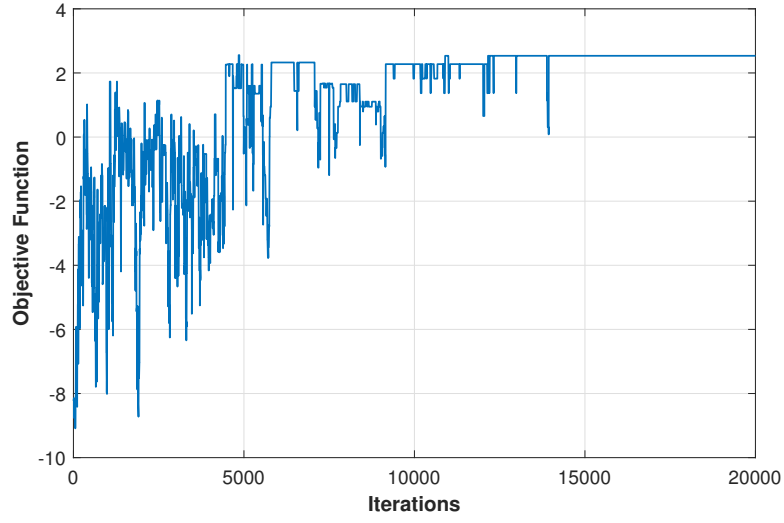


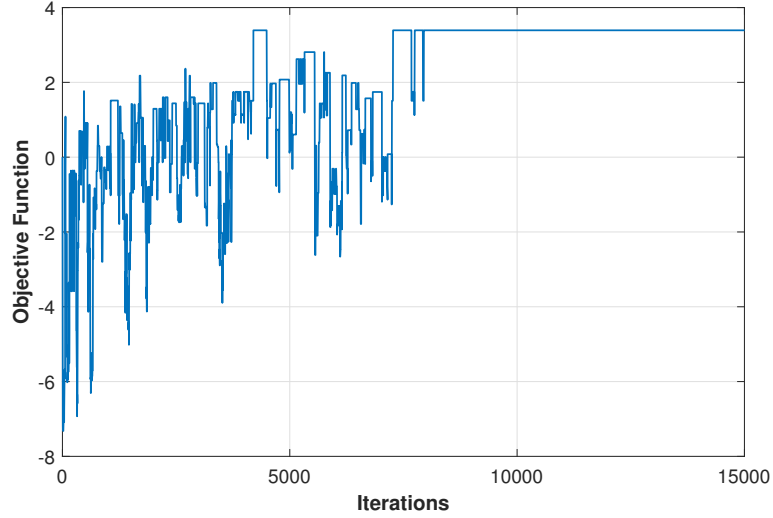
Figure 3.3: The achievable max-min user rate validation curve between the Simulated Annealing and the Tabu-search algorithms for both the NOMA-imposed scheme and the NOMA-not-imposed scheme obtained while changing the total number of users in the network.

other well-known meta-heuristic, which is the TS algorithm that is also efficient in solving non-linear optimization problems [136]. For validation purposes, both the SA and the TS algorithms are simulated under the same common parameters. It is worth mentioning that there are two specific parameters to the TS algorithm: (i) The “Tabu-search list” that includes the most recently visited solutions and is set to be 10, and (ii) the “Tabu-search-candidate list” that contains the examined subset of neighborhood solutions and set to be 4. In addition, we provide the convergence curves of the SA algorithm for both the NOMA-imposed and the NOMA-not-imposed schemes. Figure 3.3 represents a comparison figure between the Simulated Annealing and the Tabu-search algorithms for both the NOMA-imposed and the NOMA-not-imposed schemes, while changing the total number of users in the network. From this figure, it can be noticed that the obtained results of both algorithms are similar. This can verify that the design, the chosen parameters, and the obtained results for the Simulated Annealing algorithm are suitable and accurate.

Figure 3.4(a) and Figure 3.4(b) show the optimization convergence curves (i.e., objective function versus iterations) of the SA algorithm, for the parameter value just mentioned, for both the NOMA-imposed scheme and NOMA-not-imposed scheme, respectively. The curves indicate that the search process successfully skips through several locally optimal solutions and converges to a good-quality solution. The curve contains negative values due to the violation of constraints. The equations of the objective function (3.27) and (3.28) show that the violation of constraints causes it to return negative values. It should be noted that the number of iterations along the x-axis is equivalent to the number of function evaluations because we computed



(a) NOMA-imposed scheme.

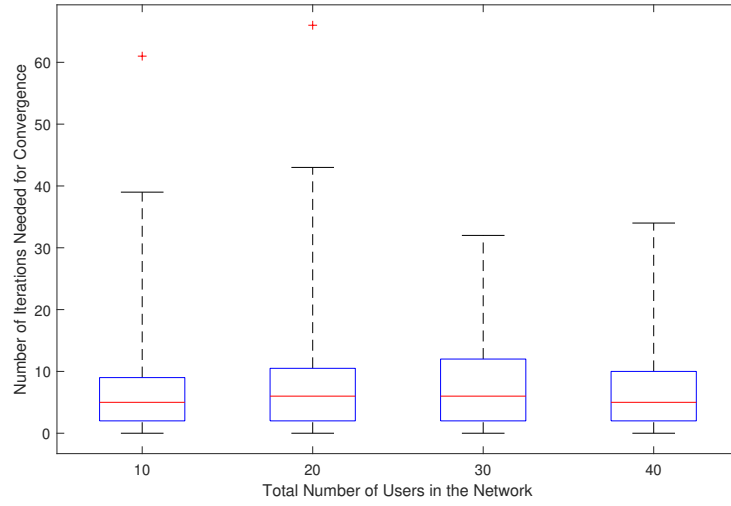


(b) NOMA-not-imposed scheme.

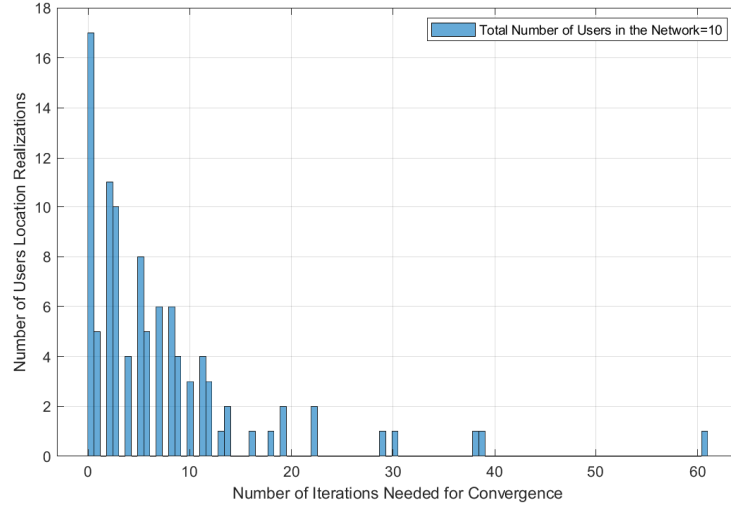
Figure 3.4: The optimization curves of the SA algorithm for both the NOMA-imposed scheme and the NOMA-not-imposed scheme for one users' location realization.

the objective function once in every iteration. The number of function evaluations is a metric used in evolutionary algorithms (EAs) to denote the convergence and time relationship of EAs [132].

In Figure 3.5, the convergence analysis of the user-binding iterative greedy algorithm is provided. As discussed in Section 3.4.1, this algorithm takes place only when



(a)



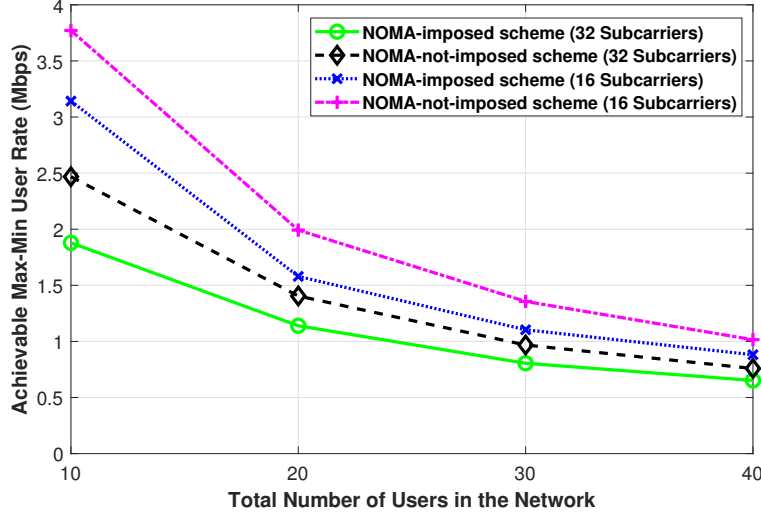
(b)

Figure 3.5: (a) Convergence analysis of the user-binding iterative greedy algorithm. (b) A detailed look into the number of iterations needed for convergence for the test case of $N = 10$ in Figure 3.5(a) for 100 different users' location realizations.

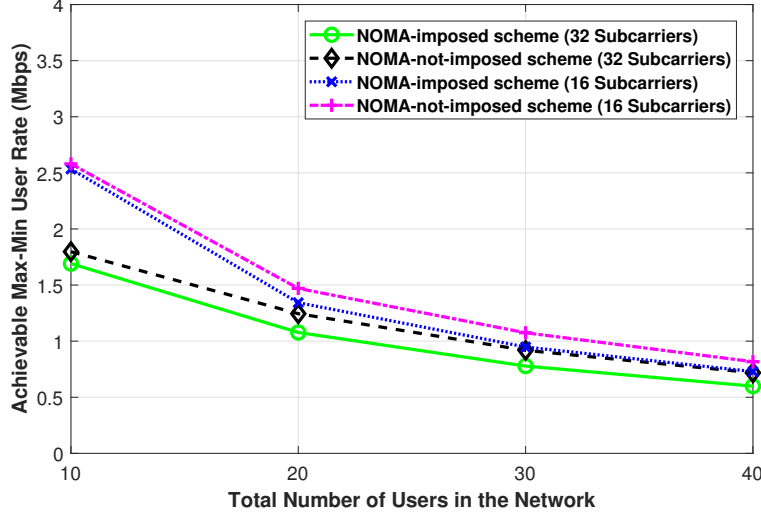
the NOMA-imposed scheme is in operation to make sure that the number of users under each LED in the network is even for forming NOMA user-pairs. In Figure 3.5(a), box-plot type is used to show the results; therefore, for the reader's convenience, it is necessary to briefly describe the main elements of the box-plot: (i) The median of

the number of iterations needed for convergence (y-axis values) is shown by the red line in the middle of the boxes, (ii) the ends of the boxes show the lower (Q1) and the upper (Q3) percentile of the y-axis values, (iii) the small horizontal lines above and beneath the boxes, called the whiskers, show the lowest and the highest value of the number of iterations needed for convergence excluding the outlier points, (iv) the outlier points are denoted here in a red plus sign and refer to the unexpected values. In Figure 3.5(a), the number of iterations needed for convergence considering a different number of users in the network, $[10,20,30,40]$ users, is demonstrated. One can observe from the figure that for all considered cases, the algorithm successfully prevents the LEDs from having an odd number of users with a relatively low number of iterations. Comparing the number of iterations needed for convergence in the SA algorithm, provided in Figure 3.4, and the number of iterations needed here, we can see that this algorithm converges with a much lower number of iterations. This is related to the reason that the search space for the sub-carrier allocation is much larger than the search space for user-binding. In Figure 3.5(b) we provide a detailed look into the number of iterations needed for convergence for the test case of $N = 10$. In this figure, the convergence is verified using a histogram plot, for 100 users' location realizations, where the number of iterations needed for convergence is shown in the x-axis versus the number of users' location realizations depicted in the y-axis. For example, when the x-axis value equals zero, this indicates that around 17 (out of 100) user realizations have an even number of users under each LED from the beginning (the iterative greedy algorithm is not needed). Next, when the x-axis value equals one, this indicates that 5 (out of 100) user realizations need only one iteration in

the iterative greedy algorithm to converge, and so on. This figure consolidates that the greedy algorithm always converges with a small number of iterations for all the considered 100 uniform random user realizations.



(a) For $L = 4$.



(b) For $L = 9$.

Figure 3.6: The achievable max-min user rate of the NOMA-imposed scheme and the NOMA-not-imposed scheme obtained while changing the total number of users in the network.

3.5.2 The Performance of the Proposed NOMA Schemes

Figure 3.6(a) and Figure 3.6(b) illustrate the achievable max-min user rate for the different total number of users, $[10, 20, 30, 40]$ users, and different total number of LEDs, $[4, 9]$, in the network. The LEDs are deployed in a square lattice topology, that is, 2×2 and 3×3 . The first observation here, and in the other max-min user rate curves in the other figures (i.e., Figures 3.7–3.10), is that the NOMA-imposed scheme tends to achieve lower rates as compared to the NOMA-not-imposed scheme. The reason for this is that the NOMA scheme's imposition might pair some users with their second-best LED in order to impose the NOMA scheme fully. The advantage of implementing the NOMA-imposed scheme comes from its ability to utilize the resources more efficiently (i.e., serving the users with fewer resources) than the NOMA-not-imposed scheme that might serve one user in a cluster. The second observation here is that as the number of users in the network increases, the achievable max-min user rate decreases. This is expected, as serving more users by the same resources increases the inter-LED interference in the network and results in decreasing the achievable max-min user rates. The third observation here is that the achievable max-min user rates with 32 subcarriers available per LED are less than the achievable max-min user rates with 16 subcarriers. This is because (i) the effect of the subcarrier allocation with 16 subcarriers is more apparent on the achievable max-min user rates compared to the network with 32 subcarriers; and (ii) there is a trade-off between the high utilization of subcarriers in the LEDs and the interference in the network, in which, if we allocate a high number of subcarriers to users, then the interference in the network

will be high, and subsequently, the achievable max-min user rate would decrease. The proposed subcarrier allocation with the SA algorithm takes into account this trade-off and eventually, for our setup, the simulations show that the SINR and the user rates are better with 16 subcarriers compared to 32 subcarriers. Notably, this observation is valid for small to medium values of LEDs' electrical signal power (i.e., $P_e < 45$ dBm); however, this trend will change for large P_e values, as discussed later in the discussion of Figure 3.9. Finally, one can observe from Figure 3.6b that the achievable max-min user rate decreases, again, as the number of subcarriers increases, leading to a more interference-limited scenario. Additionally, the performance of both the NOMA-imposed and the NOMA-not-imposed schemes become closer to each other compared to Figure 3.6(a), which is because for a larger number of active LEDs in the room, each user can receive strong channels from multiple LEDs, as LEDs become closer to each other. Subsequently, in the NOMA-imposed scheme, the binding of a user to another adjacent LED will not change its channel gain, and hence its data rate, much.

Figure 3.7 and Figure 3.8 show the achievable max-min user rate performance while changing the semi-angle at half illumination of the LEDs and changing the FoV of the PDs, respectively, for both the NOMA-imposed scheme and the NOMA-not-imposed scheme. In both figures, as the viewing semi-angle of the LED and the FoV of the PDs increase, a slight decrease in the max-min user rate is observed. This is because, when the viewing semi-angle of the LED, as in Figure 3.7, is increased, the coverage region of that LED increases, and hence the possibility of binding users that are far from the LED increases. On the other hand, in Figure 3.8, as the FoV of the

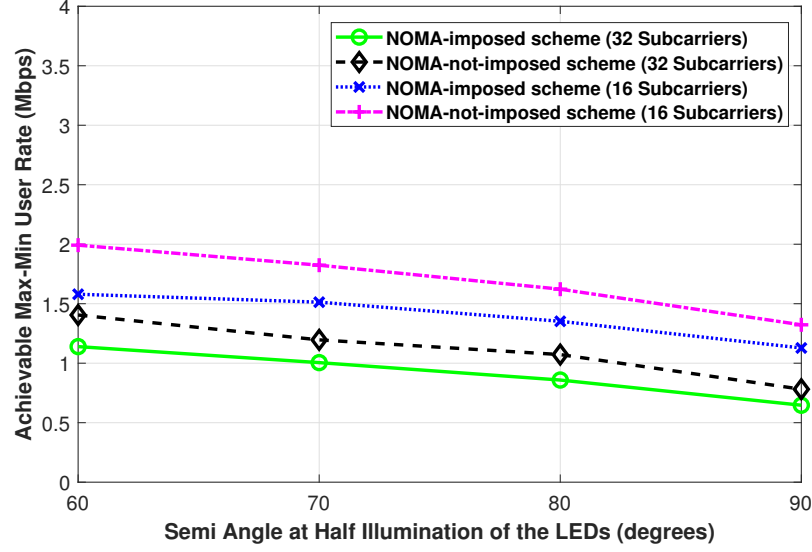


Figure 3.7: The achievable max-min user rate of the NOMA-imposed scheme and the NOMA-not-imposed scheme while changing the semi-angle at half illumination of the LED.

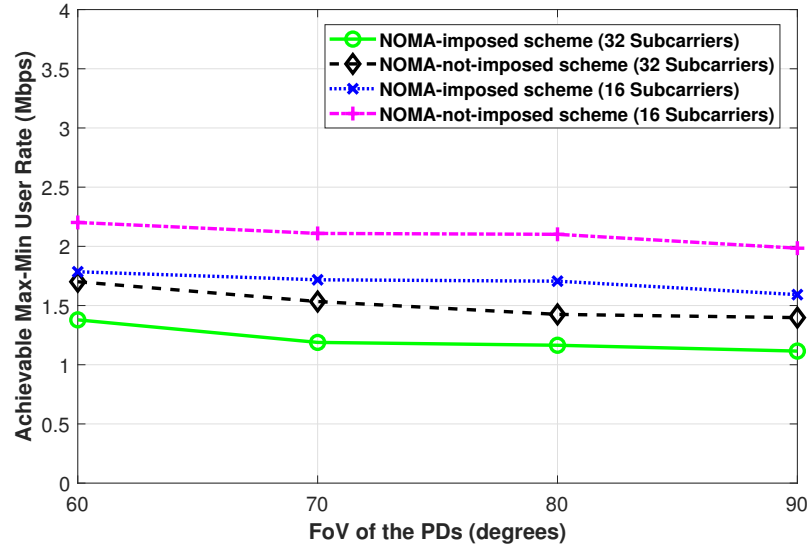


Figure 3.8: The achievable max-min user rate of the NOMA-imposed scheme and the NOMA-not-imposed scheme while changing the FoV of the PD.

PDs increases, the possibility of binding a user with a LED that is far from the user increases. Besides, with a large LED viewing angle, the signal intensity that the user receives from the LED is reduced. Likewise, with a large user FoV, the user becomes more susceptible to interference from neighbor LEDs. A similar trend (i.e., as the

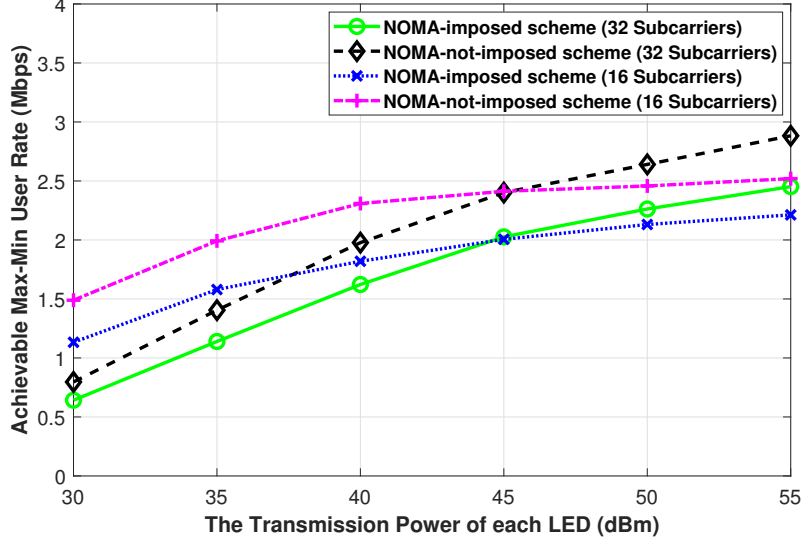


Figure 3.9: The achievable max-min user rate of the NOMA-imposed scheme and the NOMA-not-imposed scheme while changing LEDs electrical signal power.

FoV increases the achievable rate decreases) is reported in [100] for the one-to-many case considering the sum-rate performance metric (in this chapter, we consider the max-min user rate metric) in a multi-user VLC network.

In Figure 3.9, we present the achievable max-min user rate performance while changing the LEDs' electrical signal power (i.e., $P_e = [30, 35, 40, 45, 50, 55]$ dBm) for both the NOMA-imposed scheme and the NOMA-not-imposed scheme. In this figure, on the x -axis, we show the electrical signal power P_e but the users' rate equations (i.e., (3.3) and (3.4)) are written in terms of the LED optical transmit power P_o . Therefore, we transform the electrical signal power values to optical transmit power values through the following relation $\iota = \frac{P_o}{\sqrt{P_e}}$ to substitute these values in the simulations. From Figure 3.9, one can observe that for small to medium P_e (i.e., $P_e < 45$ dBm) both NOMA-imposed and NOMA-not-imposed schemes with 16 subcarriers have a better achievable max-min user rate performance compared to the equivalent schemes

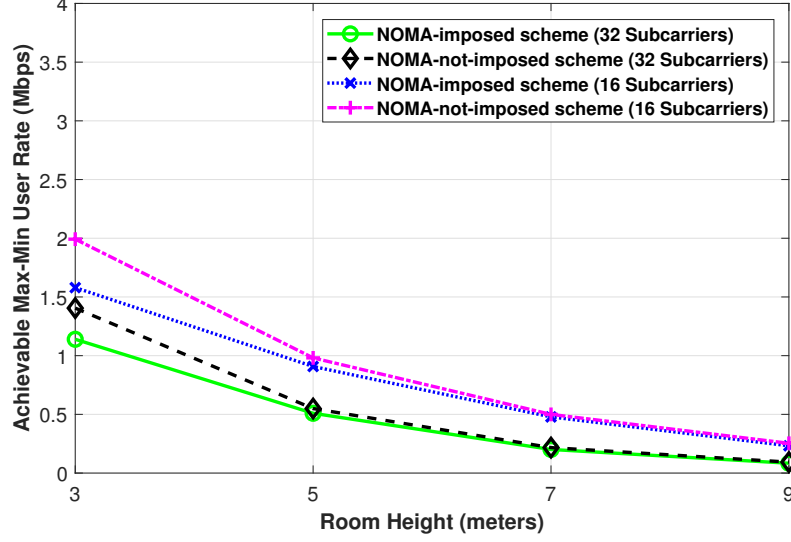


Figure 3.10: The achievable max-min user rate of the NOMA-imposed scheme and the NOMA-not-imposed scheme while changing the room height.

with 32 subcarriers, while the opposite is true for large P_e values (i.e., $P_e \geq 45$ dBm).

The reason is that as the power of the interfering signals gets larger, the achievable max-min user rate tends to have a larger decrease for a smaller number of the allocated subcarriers. A similar trend in RF channels, for the secrecy user rate metric, was reported in [120].

Finally, in Figure 3.10, we illustrate the achievable max-min user rate performance while changing the room height. It is intuitive to see that when the room height increases, the channel gains of the users get weaker and subsequently, the achievable max-min user rate decreases. Besides, with a large room height, the achievable max-min user rates become comparable for both the NOMA-imposed scheme or the NOMA-not-imposed scheme and with 32 subcarriers per LED or with 16 subcarriers per LED. This is since the users become prone to weak signal power and weak interference power due to the comparable weaker channel gains.

3.6 Conclusions

As both VLC technology and NOMA-enabled schemes are envisioned to be among the enablers of a high data rate and low-latency future wireless networks, the achievable max-min user rates of NOMA-enabled centralized multi-carrier VLC networks were investigated in this chapter. The D-NLUPA and the bisection method were utilized for user pairing and the power allocation per pair, respectively, and a simulated annealing-based algorithm was developed for the subcarrier allocation. The obtained results, for two variants of the proposed NOMA-enabled scheme, have quantified the maximum achievable max-min user rates and shed lights on the effect of the different network parameters, such as (i) The number of served users, (ii) the number of LEDs in the room, (iii) the semi-angle at half illumination of the LEDs, (iv) the FoV of the PDs, (v) the LED power, and (vi) the indoor space dimensions on the achievable max-min user rates.

CHAPTER 4

ENERGY-EFFICIENT COVERAGE ENHANCEMENT OF THZ-MISO SYSTEMS: AN FD-NOMA APPROACH

THz communication is gaining more interest as one of the envisioned enablers of high-data-rate short-distance indoor applications in B5G networks. Moreover, NOMA-enabled schemes are promising schemes to realize the target spectral efficiency, low latency, and user fairness requirements in future networks. In this chapter, an energy-efficient CNOMA scheme that guarantees the minimum required rate for the cell-edge users in an indoor THz-MISO communications network is proposed. The proposed cooperative scheme consists of three stages: (i) beamforming stage that allocates BS beams to THz cooperating cell-center users using analog beamforming with the aid of

the cosine similarity metric, (ii) user pairing stage that is tackled using the Hungarian algorithm, and (iii) power allocation stage for both the BS THz-NOMA transmit power and the cooperation power of the cooperating cell-center users, which are optimized sequentially. The obtained results quantify the energy efficiency (EE) of the proposed scheme and shed new light on the performance of multi-user THz-NOMA-enabled networks.

4.1 Introduction

Emerging B5G networks are witnessing revolutionary enhancement of data rate transmission for various innovative communication technologies and applications, including virtual reality (VR), extended reality (XR), streaming 8K videos over wireless links, etc. In addition to that, the immersion of mMTC and IoE in future wireless networks, that need ultra-reliable connectivity, are expected to become a reality in this decade [22]. Particularly, the vision of providing users with a 1 Tbps peak data rate, up to 10 Gbps experience data rate, and almost perfect reliability is foreseen [121]. Nowadays, the trend of operating at high-frequency bands is apparent, for example, in 5G NR standard (i.e., 3GPP release 16) some mmWave communications bands (i.e., between 24.25 GHz to 52.6 GHz) have been officially adopted. Nevertheless, for satisfying the aforementioned B5G networks demands, these mmWave communication bands might not be sufficient. Consequently, operating at higher frequency bands, sub-THz (0.1-0.3 THz) and THz (0.3-3 THz) bands, where very large available contiguous bandwidth that spans from tens to even hundreds of GHz is one of the

promising solutions for this problem [22], [23].

Traditionally, THz-band applications have been restricted to sensing, imaging, and localization. This was due to the lack of compact high-power signal transmitters and high-sensitivity detectors [137] at this band. Recent advancements in THz transceiver devices have paved the way for THz communications [22]. Those advancements can be grouped into four technology paths, namely, electronic, photonic, integrated hybrid electronic-photonic, and plasmonic transceiver designs [137], [22]. The main merits of each transceiver design can be summarized as follows; (i) Electronic solutions can generate high transmission power, (ii) photonic solutions are superior to the electronic ones in term of achieving high data rates; as modulating and processing photonic signals are done at very high speeds, (iii) the integrated hybrid solutions can be programmed and efficiently designed for various emerging system-level properties, (iv) plasmonic solutions have compact and reconfigurable array designs, can support large communication bandwidths, and can operate directly at THz frequencies; contrary to electronic solutions that generally depend on the up-conversion of microwave signals and to the photonic solutions that depend on the down-conversion of optical signals [137], [22].

Operating at sub-THz and THz frequency bands come at the cost of high propagation losses. In [23], Rappaport *et al.* highlight the additional challenges for wave propagation at frequencies beyond 100 GHz, particularly that the free-space path loss and penetration loss increase significantly as we go to high frequencies, leading to shorter coverage areas. However, at these frequency bands, the wavelength and consequently the size of the antennas are very small, allowing for the use of highly

directional antennas for ultra-precise beamforming [22].

Over the past few years, researchers have started investigating NOMA as a promising multiple access technique for accommodating more users in the same resource blocks [10], [138]. Most of the research has focused on PD-NOMA scheme which utilizes superposition coding (SC) at the transmitter and SIC decoding at the receiver. In the PD-NOMA scheme, multiple users share the same frequency and time resources and the channel gain differences are exploited at the receiver to separate the multiplexed user's signals using the SIC decoding [10], which offers significant improvements in connectivity and spectral efficiency. Also, the in-band user-assisted cooperative side links are proposed in the literature to enhance the spectral efficiency for the cell-edge users as well as the network energy efficiency [27].

In this work, by utilizing the NOMA principle along with FD cooperative side links, we propose an energy-efficient user cooperative scheme that guarantees the minimum required rate for cell-edge users in an indoor THz-MISO communications network. Particularly, due to the high propagation losses in THz networks, cell-edge users might receive very weak THz beams from the BS and eventually suffer from a low data rate experience that is below their expected minimum required rate. Hence, with the aid of user-assisted cooperative side links and FD-NOMA scheme, this minimum required rate for cell-edge users can be guaranteed. The proposed cooperative scheme consists of three stages: (i) a beamforming stage that allocates beams to THz cooperating cell-center users using analog beamforming with the aid of the cosine similarity metric, (ii) a user pairing stage of THz cell-center users and user-assisted cell-edge users where a common matching algorithm, the Hungarian algorithm, that pairs users based on

the Euclidean distance, is utilized and (iii) a power allocation stage where both the THz-BS NOMA transmit power and the cooperation power of the cooperating cell-center users are optimized sequentially. Each of the aforementioned stages is designed to contribute to decreasing the consumed power in the network to make our proposed scheme energy-efficient.

The amount of work in the THz-NOMA-enabled networks is still limited [76], [77], [78]. In [76], in order to maximize the network throughput, the authors solved an optimization problem that involves beamforming, power allocation, and sub-band assignment. Through numerical simulations, the authors demonstrated the superiority of the proposed scheme compared to the THz-OMA counterpart. In [77], a downlink heterogeneous THz-NOMA cache-enabled system with imperfect SIC is proposed. An EE maximization problem that includes user clustering, beamforming, and power allocation is formulated and then solved by dividing the original problem into three sub-problems. Through simulations, the authors show that the proposed enhanced K-means algorithm for user clustering and the proposed alternating direction method of multipliers for power allocation can achieve high EE performance for the proposed network. In [78], a machine-type communication downlink sub-THz-NOMA enabled system to enable massive connectivity of devices has been analyzed. An EE maximization problem has been solved via unconstrained then constrained optimization. Through simulations, the authors show that the proposed system attains better performance compared to its counterpart in the mmWave band. To the best of the authors' knowledge, there is no existing work that combines multi-user indoor MISO-NOMA in THz band with user-assisted cooperative side links for coverage enhancement of

cell-edge users.

The main contributions can thus be summarized as follows;

- Proposing an energy-efficient user-assisted full-duplex cooperative NOMA scheme that guarantees the minimum required rate for cell-edge users in multi-user indoor THz-MISO systems.
- Developing the proposed scheme in three stages: (i) analog beamforming stage with the aid of the cosine similarity metric, (ii) user pairing stage for THz co-operating cell-center users and cell-edge users, and (iii) a power allocation stage for both the BS transmit power and the cooperation power of the cooperating cell-center users.
- Investigating the effect of changing different network parameters through simulations, such as the BS transmit power levels and cell-edge users' minimum required rate on the EE of the network. The obtained results are bench-marked with the mmWave-NOMA counterpart scheme.

The remainder of this chapter is organized as follows. In Section 4.2, we provide the channel model and the system model of the proposed THz-MISO NOMA-enabled scheme. The details of the proposed scheme are presented in Section 4.3. Simulation results are provided in Section 4.4. Finally, chapter conclusions and future research directions are given in Section 4.5. For the reader's convenience, the list of used notations is summarized in Table 4.1.

Table 4.1: List of Notations.

Variable Name	Variable Description
Channel Model's Variables	
$\mathcal{N} = [1, \dots, n, \dots, N]$	A set that denotes the number of antenna-phased arrays at the BS
$\mathcal{K}_{\text{THz}} = [1, \dots, K_{\text{THz}}]$	A set that denotes the number of users served in the THz band
$\mathcal{K}_{\text{Coop}} = [1, \dots, K_{\text{Coop}}]$	A set that denotes the number of users served with cooperative side-links
$\mathcal{PL}(f, d)$	The path loss determined by THz frequency f and distance d between the BS and a user, where $d \in (0, d_{\text{THz}}]$ and d_{THz} is the maximum transmission range of the THz system
Ω	The antenna gains
$\mathcal{L}_{\text{spread}}(f, d)$	The spreading loss in the LoS path determined by THz frequency f and distance d between the BS and a user
$\mathcal{L}_{\text{abs}}(f, d)$	The molecular absorption loss in the LoS path determined by THz frequency f and distance d between the BS and a user
$\alpha(\varphi)$	The array steering vector
$k_{\text{abs}}(f)$	The frequency-dependent medium absorption coefficient
c	The speed of light in free space
e	The Euler's number and equal to 2.718281828
System Model's Variables	
$\mathbf{w}_{k,i}$	The antenna weight vector (AWV) formed by the BS transmitted on beam- k towards user- i
$\mathbf{s}_{\text{THz}}$	The overall transmit signals from the BS
$\mathbf{s}_{k,\text{THz}}$	The transmit superimposed signal towards the i -th THz user of the k -th user pair
$s_{k,i}, s_{k,j}$	The transmit signals toward the i -th THz user and the j -th cooperative side-link user for the k -th user pair
$\hat{s}_{k,ii}$	The self-interference signal of the full-duplex link that arrives at the i -th user
$\beta_{k,i}, \beta_{k,j}$	The power fractions assigned by the BS for user- i and user- j , respectively, of the k -th user pair
$\mathbf{h}_{k,i}$	The channel gain vector of the i -th user for the k -th user pair
$h_{k,ii}$	The self-interference channel gain for the i -th user of the k -th user pair
$h_{k,ij}$	The cooperative side-link channel gain between the user- i and user- j of the k -th user pair
$p_{k,u}$	The transmit power of the i -th user of the k -th user pair
$n_{k,i}, n_{k,j}$	The noise at user- i and user- j , respectively, of the k -th user pair
$\sigma_{k,i}^2, \sigma_{k,j}^2$	The noise power at user- i and user- j , respectively, of the k -th user pair
$y_{k,i}^{\text{THz}}, y_{k,j}^{\text{Coop}}$	The received signals at user- i and user- j , respectively, of the k -th user pair
$\gamma_{k,j}^{i,\text{THz}}$	The SINR when decoding user- j at user- i of the k -th user pair
$\gamma_{k,i}^{i,\text{THz}}$	The SINR when decoding user- i own signal
$\gamma_{k,i}^{j,\text{Coop}}$	The SINR when decoding user- j own signal
$R_{k,i}^{\text{THz}}, R_{k,j}^{\text{Coop}}$	The achievable rates of user- i and user- j of the k -th user pair
EE	The global energy-efficiency performance metric measured in (bits/Joules)
ξ	The power amplifiers inefficiency at the BS
P_{loss}	The power losses at the BS
R_0^{min}	Users minimum required rate
$\ \cdot\ _2$	The Euclidean norm of a vector

4.2 Channel Model and System Model

The system model of the proposed multi-user indoor THz-MISO CNOMA scheme is depicted in Figure 4.1. Consider a downlink system with a single BS equipped with one RF chain and N -antenna phased arrays serving (i) K_{Center} cell-center users through analog beamforming (ABF) and (ii) K_{Edge} cell-edge users through user-assisted full-duplex DF cooperative side links by a subset of $K_{\text{Coop}} \subset K_{\text{Center}}$ cooperating users. All the users are equipped with a single antenna element. To facilitate the investigation of the proposed CNOMA scheme, this chapter assumes that K_{Coop} equals K_{Edge} . In

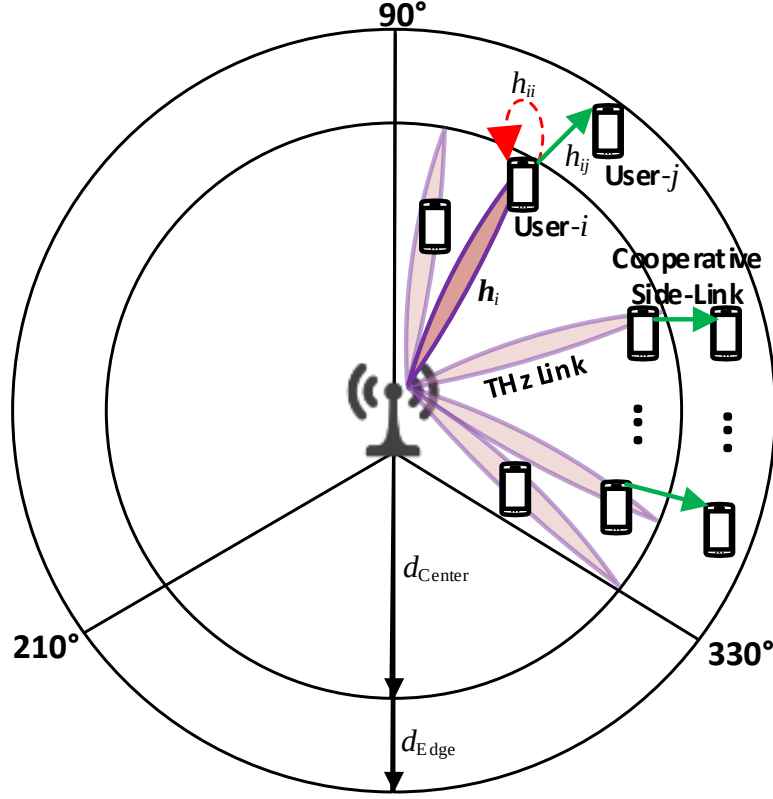


Figure 4.1: An illustration of the proposed multi-user indoor THz-MISO NOMA-enabled scheme with user-assisted cooperative side links.

this work, due to the requirement of low power consumption and hardware cost, we consider the ABF structure in the BS, which utilizes the single-phase shifter (SPS) implementation [21]. Also, for decreasing the computational complexity, it is assumed that the BS has full CSI and distance information for all users in the network, this assumption is also adopted by [76], [77]. In the BS, each antenna is driven by a phase shifter (PS) and a power amplifier (PA). The elements of the precoding vectors are complex numbers, its phase is controlled by the phase shifters and its modulus is controlled by the power amplifiers [21].

4.2.1 Indoor THz Channel Model

In this subsection, we discussed the indoor THz channel model. In the THz band, the high path loss resulting from spreading loss and molecular absorption loss limits the scattering phenomenon. This makes THz communication links sensitive to obstacles blockage such as walls, and leads to large path loss difference between the direct paths and blocked paths. For example, in an indoor THz system, Priebe and Kurner [139] reported that when the LoS exists, the first-order reflections are attenuated on average more than 10 dB, and the second-order reflections are attenuated on average more than 20 dB. From this, one can conclude that the non-line-of-sight (NLoS) paths of THz channels are very limited. Therefore, in this work similar to [77], we consider the LoS paths only. Hence, the channel gain vector of the i -th user on the k -th user pair can be expressed as

$$\mathbf{h}_{k,i} = \sqrt{N} \left(\sqrt{\frac{1}{\mathcal{PL}(f,d)}} \Omega \mathbf{a}(\theta_{k,i}) \right), \quad (4.1)$$

$$\mathcal{PL}(f,d) = \mathcal{L}_{\text{spread}}(f,d) \mathcal{L}_{\text{abs}}(f,d) = \left(\frac{4\pi f d}{c} \right)^2 e^{k_{\text{abs}}(f)d}, \quad (4.2)$$

where $\mathcal{PL}(f,d)$ denotes the path loss incurred by the THz signal that is transmitted from the BS on frequency f to the i -th user that is d meters apart from the BS. Ω and $\mathbf{a}(\theta_{k,i})$ denote the antenna gains of the BS and the array steering vector toward user- i of the k -th user pair, respectively. Equation (4.2) shows the two multiplicative factors that contribute to the path loss of THz signals, namely, the spreading loss $\mathcal{L}_{\text{spread}}$ and the molecular absorption loss $\mathcal{L}_{\text{abs}}$. The term $k_{\text{abs}}(f)$ denotes the frequency-dependent absorption coefficient for different isotopologues of water vapor molecules. It is worthy

to note that, in a regular medium, the main contributor of the total absorption loss comes from water vapor molecules and its loss far exceeds the contribution of other air molecules [77]. The speed of light is denoted by c . The term $\mathbf{a}(\theta_{k,i})$ represents the array steering vector for uniform linear array (ULA) and can be represented as [77]

$$\mathbf{a}(\theta_{k,i}) = \frac{1}{\sqrt{N}}[1, \dots, e^{j\pi[n \sin(\theta_{k,i})]}, \dots, e^{j\pi[(N-1) \sin(\theta_{k,i})]}]^T, \quad (4.3)$$

where $\theta_{k,i}$ denotes the physical angle-of-departure of the THz beam. The cooperative side-link channel model also follows the one in (4.1); since in-band user-assisted cooperative communications paradigm is adopted [27], [140].

4.2.2 System Model and Formulation

In this subsection, we present the details of the proposed multi-user indoor THz-MISO NOMA-enabled system and its energy-efficiency formulation. For mathematical convenience, we focus the analysis on the signaling within one NOMA user pair (i.e., the cooperating cell-center user- i and cell-edge user- j), the remaining user pairs can be analyzed similarly, since in this work, each THz cooperating cell-center user is served by one precoding vector on an orthogonal channel which can be a time slice or a sub-carrier frequency channel. With the adoption of the PD-NOMA scheme, the BS transmits superimposed signal towards the k -th user pair is

$$\mathbf{s}_k = \mathbf{w}_k s_k = \mathbf{w}_k (\sqrt{\beta_{k,i}} p_k s_{k,i} + \sqrt{\beta_{k,j}} p_k s_{k,j}), \quad (4.4)$$

where $\mathbf{w}_k$ represents the precoding vector formed toward k -th user pair, s_k represents the SC signal for the k -th user pair, $\beta_{k,i}$ and $\beta_{k,j}$ denote the power fractions assigned by the BS for cooperating cell-center user- i and cell-edge user- j , respectively. $s_{k,i}$ and $s_{k,j}$ denote the transmit messages of cooperating cell-center user- i and cell-edge user- j . p_k denotes the BS transmit power for the k -th user pair (i.e., per-channel use).

As depicted in Figure 4.1, the received signal at the i -th cooperating cell-center user on the k -th user pair while considering FD relaying mode for the cooperative side link is

$$y_{k,i}^{\text{Coop}} = \underbrace{\mathbf{h}_{k,i}^H \mathbf{w}_k \sqrt{\beta_{k,i} p_k} s_{k,i}}_{\text{Desired Signal for User}_i} + \underbrace{\mathbf{h}_{k,i}^H \mathbf{w}_k \sqrt{\beta_{k,j} p_k} s_{k,j}}_{\text{Intended Signal for User}_j} + \underbrace{h_{k,ii} \sqrt{p_{k,u}} \hat{s}_{k,ii}}_{\text{Self Interference}} + \underbrace{n_{k,i}}_{\text{Noise}}, \quad (4.5)$$

where $h_{k,ii}$ represents the SI channel gain for the i -th user of the k -th user pair. $\hat{s}_{k,ii}$ represents the SI signal of the full-duplex link that arrives at the i -th user. $p_{k,u}$ represents the cooperative transmit power of the i -th user of the k -th user pair. $n_{k,i}$ denotes the noise seen at user- i of the k -th user pair. The second term in (4.5), represents the intended signal for the j -th user of the k -th user pair that will be extracted by performing the SIC decoding procedures. On the other hand, the received signal at the j -th cell-edge user on the k -th user pair can be expressed as

$$y_{k,j}^{\text{Edge}} = \underbrace{h_{k,ij} \sqrt{p_{k,u}} \hat{s}_{k,ij}}_{\text{Desired Signal}} + \underbrace{n_{k,j}}_{\text{Noise}}, \quad (4.6)$$

where $h_{k,ij}$ denotes the cooperative side-link channel gain between user- i and user- j of the k -th user pair. $\hat{s}_{k,ij}$ represents the transmit signal from user- i to user- j of the

k -th user pair. $n_{k,j}$ denotes the noise seen at user- j of the k -th user pair. Now, we can express the SINR when decoding the j -th user signal at the i -th user of the k -th user pair as

$$\gamma_{k,j}^{i,\text{Coop}} = \frac{\beta_{k,j} p_k |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2}{\beta_{k,i} p_k |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2 + p_{k,u} \kappa |h_{k,ii}|^2 + \sigma_{k,i}^2}, \quad (4.7)$$

where κ denotes the SI parameter, and its value ranges between $[0, 1]$. When $\kappa = 0$, this refers to the perfect SI cancellation scheme. On the other hand, when $\kappa = 1$, this refers to the scheme where there is no SI cancellation at the i -th cooperating cell-center user. $\sigma_{k,i}^2$ denotes the noise power. After performing the SIC decoding procedures, the SINR when user- i decodes its own signal can be expressed as

$$\gamma_{k,i}^{i,\text{Coop}} = \frac{\beta_{k,i} p_k |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2}{p_{k,u} \kappa |h_{k,ii}|^2 + \sigma_{k,i}^2}. \quad (4.8)$$

The SNR seen at the cell-edge user- j on the k -th user pair can be represented as

$$\gamma_{k,j}^{j,\text{Edge}} = \frac{p_{k,u} |h_{k,ij}|^2}{\sigma_{k,j}^2}. \quad (4.9)$$

At this point, we can represent the achievable rate of decoding user- j signal at user- i and the achievable rate when user- i decodes its own signal as

$$R_{k,j}^{i,\text{Coop}} = W \log_2(1 + \gamma_{k,j}^{i,\text{Coop}}), \quad (4.10)$$

$$R_{k,i}^{\text{Coop}} = W \log_2(1 + \gamma_{k,i}^{i,\text{Coop}}), \quad (4.11)$$

where W is the available contiguous bandwidth of the THz channel window. According

to [141], the achievable rate when user- j decodes its own signal can be expressed as

$$R_{k,j}^{\text{Edge}} = \min\{W \log_2(1 + \gamma_{k,j}^{i,\text{Coop}}), W \log_2(1 + \gamma_{k,j}^{j,\text{Edge}})\}. \quad (4.12)$$

In the following, we express the energy efficiency of the system that can be defined as “the ratio between the achievable sum rate and the total power required to achieve this rate (Bits/Joule)” [142] for the K_{Coop} orthogonal channels

$$\begin{aligned} \text{EE} &= \frac{\sum_{k=1}^{K_{\text{Coop}}} (R_{k,i}^{\text{Coop}} + R_{k,j}^{\text{Edge}}) / K_{\text{Coop}}}{\xi((\sum_{k=1}^{K_{\text{Coop}}} p_k + p_{k,u}) / K_{\text{Coop}}) + P_{\text{loss}}} \\ &= \frac{\sum_{k=1}^{K_{\text{Coop}}} (R_{k,i}^{\text{Coop}} + R_{k,j}^{\text{Edge}})}{\xi(\sum_{k=1}^{K_{\text{Coop}}} p_k + p_{k,u}) + K_{\text{Coop}} P_{\text{loss}}}, \end{aligned} \quad (4.13)$$

where ξ is the power amplifiers’ inefficiency at the THz BS as well as at the cooperating cell-center users. P_{loss} is the circuit power consumption and can be expressed as [77]

$$P_{\text{loss}} = P_B + N_{RF} P_{RF} + N_T P_A + N_T P_P, \quad (4.14)$$

where P_B is the base-band power consumption, N_{RF} is the number of RF chains at the BS, P_{RF} is the RF chain power consumption, N_T is the number of power amplifier/phase shifters at the BS, P_A is the power consumption of each power amplifier, and P_P is the power consumption of each phase shifter.

4.3 The Proposed Energy-Efficient CNOMA Scheme

In this section, we discuss in detail the proposed energy-efficient cooperative communication scheme. A summary of the proposed scheme is provided in Algorithm 6.

4.3.1 Cooperating Cell-center User Scheduling Stage: Analog Beamforming with the Cosine Similarity Metric

Typically, in small-cell and indoor-cell deployments, a low hardware cost and power consumption are essential [143]. Hence, ABF is adopted in this work to meet such demand. The BS applies ABF that has a fixed set of beams uniformly distributed over the sector coverage area. In this work, the indoor cell is assumed to have three sectors of 120° each. With one RF chain available at the BS, only one beam can be transmitted at a time, which we equate to forming one beam to serve one NOMA user

Algorithm 6: A summary of the proposed cooperative scheme

(-) **Initialization:** (i) distribute the cooperating cell-center and cell-edge users, (ii) calculate the channel gain of each cooperating cell-center user, (iii) build the BS available beams set;

(A) **Cooperating cell-center user scheduling stage:** find the best beam for each cooperating cell-center user based on analog beamforming with the aid of the cosine similarity metric;

(B) **Cooperating cell-center and cell-edge user pairing stage:** (i) pair each cooperating cell-center user with each cell-edge user based on the Euclidean distance, (ii) in each formed pair, calculate the channel gain between the paired cooperating cell-center user and the cell-edge user;

(C) **Power optimization stage:** In each pair, sequentially, (i) calculate the cooperation power of the cooperating cell-center user, and (ii) calculate BS NOMA power fractions for the cooperating cell-center user and the cell-edge user;

pair per channel use. Since we use ABF that can only generate one beam at a time, we use a time-division strategy to alternate between the different user pairs. Figure 4.1 illustrates the entire angular coverage region that is divided into three sectors. In here, we consider a specific sector, $\bar{\theta}$, from $-\pi/6$ to $\pi/2$ or 330° to 90° , other sectors can be analyzed similarly. In this sector, the 120° area is covered by a set of $B + 1$ beams. Each beam- b of the available beams has the following steering vector [143]:

$$\mathbf{w}_b = \mathbf{a}(\bar{\theta}_b), \forall b \in [0, B], \quad (4.15)$$

where the parameter $\bar{\theta}_b$ is

$$\bar{\theta}_b = -\pi/6 + (b \times \frac{2\pi}{3B}). \quad (4.16)$$

In this way, this entire sector region is divided into B equal angles, effectively forming a set of $B + 1$ beams. The $B + 1$ beams can be thought of as a choice of $B + 1$ different steering vectors based on (4.15), such that collectively, the steering vectors of the $B + 1$ candidate precoding vectors uniformly cover the entire sector region of $\bar{\theta} = -\pi/6$ to $\pi/2$.

The cosine similarity metric is utilized to determine the level of correlation among THz cooperating cell-center users and the BS available beams that are formed through analog beamforming. Several works in mmWave-NOMA systems have used the cosine similarity metric to determine the correlations among the users channels [144] or between the users' channels and the fixed beams [143] and this concept can be similarly used here in the context of THz-NOMA systems. In particular, we use the result from [143] where it is shown that the cosine similarity metric between the user- i of

the k -th user pair with channel $\mathbf{h}_{k,i}$ and a beam- b with precoding vector $\mathbf{w}_b$ can be expressed as follows:

$$\cos(\mathbf{h}_{k,i}, \mathbf{w}_b) = \frac{|\mathbf{h}_{k,i}^H \mathbf{w}_b|}{\|\mathbf{h}_{k,i}\| \|\mathbf{w}_b\|} = \frac{|\mathbf{a}(\phi_{k,i})^H \mathbf{a}(\phi_b)|}{N} = F_N(\pi[\phi_{k,i} - \phi_b]), \quad (4.17)$$

where $\phi_{k,i} = \sin(\theta_{k,i})$ and $\phi_b = \sin(\bar{\theta}_b)$ are the normalized directions of the user channel and the candidate beam, respectively, and F_N represents the Fejer Kernel. The properties of Fejer Kernel dictate that as $|\phi_{k,i} - \phi_b|$ increases, $\cos(\mathbf{h}_{k,i}, \mathbf{w}_b) \rightarrow 0$. In other words, if a beam and a cooperating cell-center user direction are well aligned, the cosine similarity metric is high and it reflects that it is suitable to schedule this user on that beam. This process is done to schedule each cooperating cell-center user with its best THz beam.

4.3.2 Cooperating Cell-center and Cell-edge User Pairing: Hungarian Algorithm

At this stage, the BS knows the best THz beam for scheduling each cooperating cell-center user. It is now the time to pair each cooperating cell-center user with the cell-edge user that has the shortest Euclidean distance to it. To achieve this, a well-known one-to-one assignment matching algorithm entitled the Hungarian method [145] is adopted. Noting that the computational complexity of the Hungarian method here is $O(K_{\text{Coop}}^3)$. This computational complexity is significantly simpler than the computational complexity of the brute-force algorithm, i.e., $O(K_{\text{Coop}}!)$.

4.3.3 Power Optimization Stage: Sequential Optimization of NOMA BS Power Coefficient and Cooperating Cell-center Users Cooperation Power

At this stage, the BS has calculated the user pairs for all users in the network. Now, we calculate both the cooperation power of each THz cooperating cell-center user and the BS NOMA power fractions. In each user pair, the cooperation power of the THz cooperating cell-center user has to be determined such that the minimum required rate, $R_0^{\min}$, of the cell-edge user in a user pair is met. This can be achieved by equating $\gamma_{k,j}^{j,\text{Edge}}$ with $\gamma_0^{\min}$. Noting that $\gamma_0^{\min} = 2^{(R_0^{\min}/W)} - 1$. By doing this, $p_{k,u}$ for the k -th user pair can be obtained as

$$p_{k,u} = \frac{\gamma_{k,j}^{j,\text{Edge}} \sigma_{k,j}^2}{|h_{k,ij}|^2}, \quad \forall k \in \text{all user pairs.} \quad (4.18)$$

Next, the BS NOMA power fractions for the cooperating cell-center user and the cell-edge user in a user pair have to be determined such that we guarantee a successful SIC decoding of cell-edge user signal at the cooperating cell-center user. Consequently, in each user pair, we equate $\gamma_{k,j}^{i,\text{Coop}}$ with $\gamma_{k,j}^{j,\text{Edge}}$. After some simple manipulations, $\beta_{k,i}$ (eventually $\beta_{k,j}$ that is equal to $1 - \beta_{k,i}$) can be obtained as

$$\beta_{k,i} = \frac{p_{k,u}^2 \kappa |h_{k,ii}|^2 |h_{k,ij}|^2 + \sigma_{k,i}^2 p_{k,u} |h_{k,ij}|^2 - p_k |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2 \sigma_{k,j}^2}{-p_k |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2 \sigma_{k,j}^2 - p_k p_{k,u} |h_{k,ij}|^2 |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2}, \quad \forall k \in [1, \dots, K]. \quad (4.19)$$

It is worthy to highlight here how each stage in the proposed scheme reduces the consumed power in the network, which makes this scheme energy-efficient: (A) in

stage one, when the cooperating cell-center user in each pair is scheduled in its best beam, this reduces the BS transmit power consumption, (B) in stage two, pairing the users based on the Euclidean distance will reduce the required cooperation power at the cooperating cell-center users, and (C) in stage three, optimizing the cooperation power just to satisfy the minimum required rate for the cooperating cell-edge users will reduce the cooperation power consumption.

4.4 Simulation Results and Discussions

In this section, we evaluate the performance of the proposed cooperative scheme through MATLAB simulations, using the system parameters in Table 4.2. Monte-

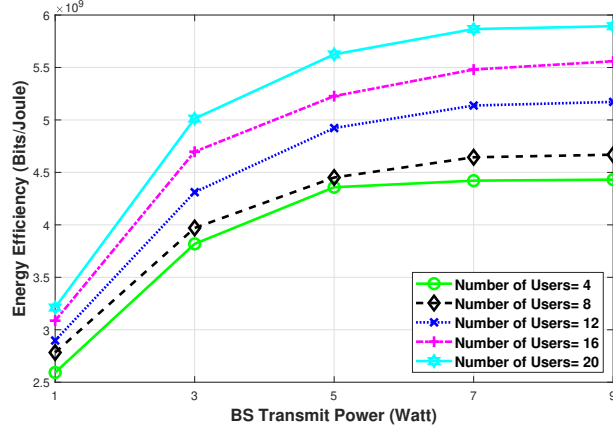
Table 4.2: System Parameters

Parameter name, notation	Value
BS transmit power per-channel use, p_k	[1, 3, 5, 7, 9] Watt [77]
Power consumption of base-band, P_B	200 mWatt [77]
Power consumption of RF chain, P_R	160 mWatt [77]
Power consumption of each phase shifter, P_P	40 mWatt [77]
Power consumption of each power amplifier, P_A	20 mWatt [77]
Inefficiency of power amplifier, ξ	1/0.38 [77]
Users minimum required rate, $R_0^{\min}$	[5, 10, 15, 20] Gbps [76]
Number of antennas at the BS, N	4 [143]
BS antenna gains, Ω_{BS}	20 dBi [146]
Cell-center user antenna gain, Ω_{User}	3 dBi [147]
Number of available beams, B	20
Beam-width angles, $\bar{\theta}_b$	6° [148]
BS sector angular coverage, $\bar{\theta}$	120°
Self-interference parameter, κ	0.4
Center frequency of the considered THz window, f	3.42 THz [149], [77]
Contiguous Bandwidth of the considered THz window, W	137 GHz [149]
water vapor molecules absorption coefficient, $k_{abs}(f)$	0.28 m ⁻¹ [150]
Number of users, $K_{Coop} + K_{Edge}$	4 – 20 users [77]
User distribution	Uniform random [143]
BS coverage region, $d_{Center} + d_{Edge}$	7 meters

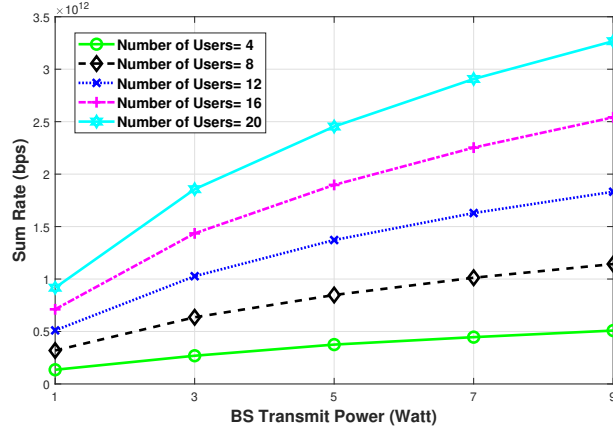
Carlo simulations that are averaged over 10^4 users' locations realizations are used for each point in the performance curves. Beyond the listed parameters in Table 4.2, the noise power is $\sigma^2 = 10 \log_{10}(W) + N_f - 174$ dBm, where the noise figure $N_f = 10$ dB [143]. Since this work focuses on achieving the minimum required rate for the cell-edge users, we assume that the subset of the cell-center users that are capable of helping the cell-edge users, with the minimum required cooperation power and hence the better energy efficiency of the proposed scheme, are the ones that are located in the farthest 20% of cell-center users coverage region. Such a scenario can take place in exhibition halls, conferences, restaurants, etc. that most likely have dense user deployment.

Figure 4.2 illustrates the energy efficiency, sum-rate, and network-consumed-power performance of the proposed cooperative scheme with different BS transmit power levels and with different number of users in the network. The first observation here is that as the BS transmit power increases the network EE increases then starts to saturate as can be seen in Figure 4.2(a). Such a trend in the network can be justified by the following argument; the increase in the BS transmit power is reflected as (i) logarithmic increase in the network sum rate (Figure 4.2(b)) and as (ii) linear increase in the total network consumed power (Figure 4.2(c)). The second observation here is that as the number of considered users in the network increases both the network EE and the users' sum-rate increase; this is evident in the EE formula (4.13).

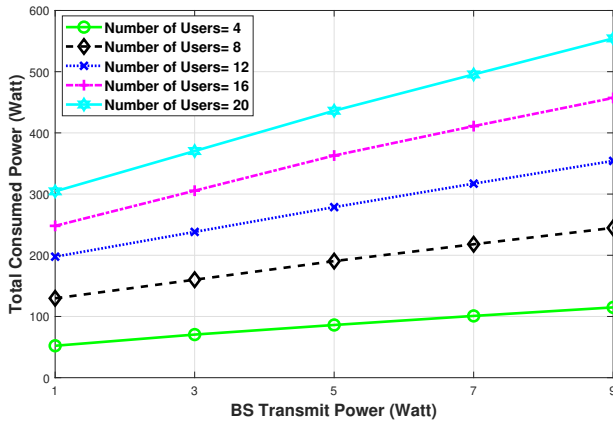
In Figure 4.3(a), we present the achievable EE performance of the system while changing the minimum user required rate, $R_0^{\min} = [5, 10, 15, 20]$ Gbps. We provide this figure to support the effectiveness of the proposed cooperative scheme in improving the



(a)

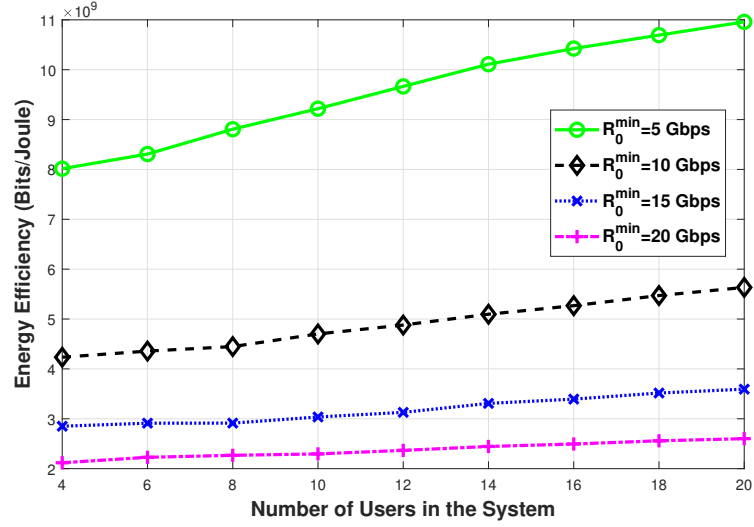


(b)

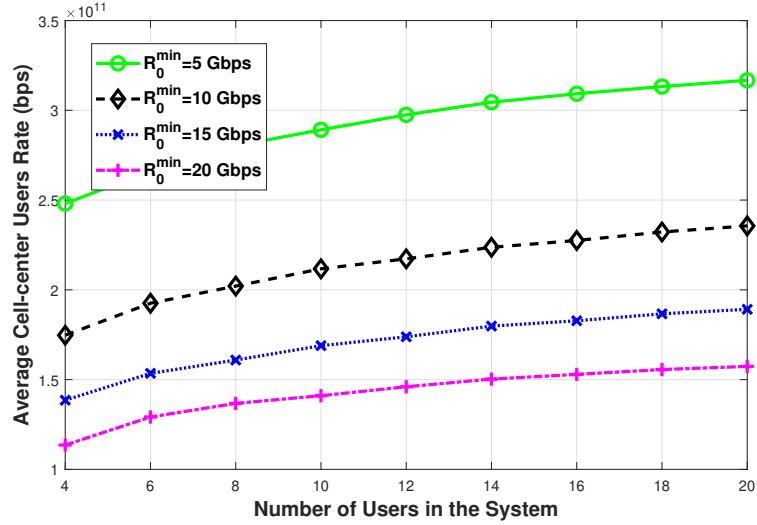


(c)

Figure 4.2: (a) The energy efficiency, (b) sum-rate, and (c) network-consumed-power performance of the network with different BS transmit power levels.



(a)



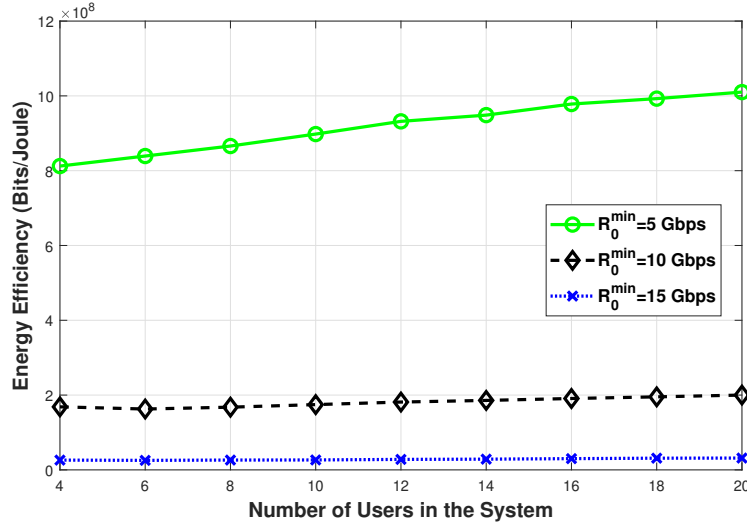
(b)

Figure 4.3: (a) The achievable EE, and (b) the average cooperating cell-center users' rate performance of the network while changing the cell-edge user minimum required rate, $R_0^{\min}$.

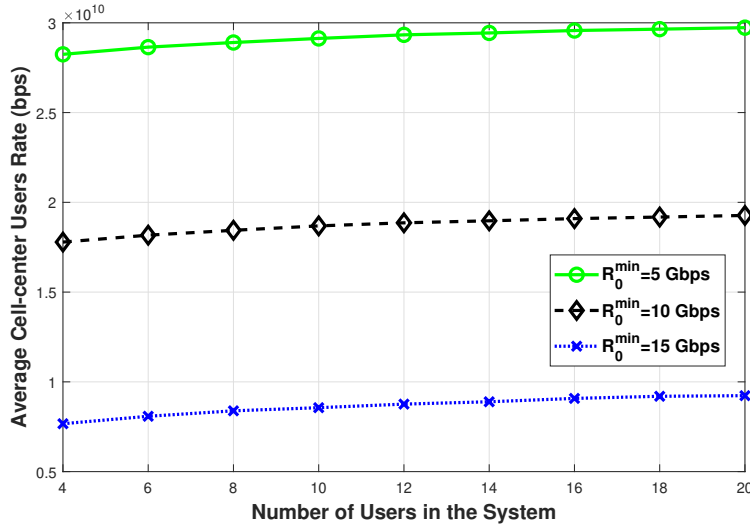
network EE while guaranteeing a minimum rate requirement for the cell-edge users.

From this figure, one can see that as the minimum user required rate increases the network EE performance decreases; this is because with this increase in the minimum user required rate, the cooperation power at the cooperating cell-center users increases,

consequently, the total consumed power in the system increases and the network EE of the system decreases. In Figure 4.3(b), we provide the average cooperating cell-center users' rate performance of the network while changing $R_0^{\min}$. This figure demonstrates the ability of the proposed cooperative scheme in achieving high data rate for the



(a) mmWave-NOMA counterpart scheme.



(b) mmWave-NOMA counterpart scheme.

Figure 4.4: (a) The achievable EE, and (b) the average cooperating cell-center users' rate performance of mmWave-NOMA counterpart scheme while changing cell-edge user minimum required rate, $R_0^{\min}$.

cooperating cell-center users, which are between 0.1-0.3 Tbps, while guaranteeing a minimum user required rate for all the cell-edge users.

For benchmarking purposes, in Figure 4.4, we provide the achievable EE and the average cooperating cell-center users' rate performance of the mmWave-NOMA counterpart scheme. We assume that the mmWave carrier frequency is $f_{\text{mmWave}} = 28$ GHz with a contiguous bandwidth of $W_{\text{mmWave}} = 2$ GHz [144]. Comparing Figure 4.3 with Figure 4.4, it is evident that both the achievable EE and average cooperating cell-center users' rate have a large gain as a consequence of operating in the THz band compared with the mmWave band.

4.5 Conclusions

As both operating at the THz bands and NOMA-enabled scheme are envisioned to be among the enablers of high data-rate applications in future wireless networks, an energy-efficient scheme of multi-user indoor THz-MISO NOMA-enabled system with user-assisted cooperative side links is proposed and its performance investigated in this chapter. Analog beamforming with the aid of the cosine similarity metric has been adopted to allocate cell-center users to BS THz beams, then the user-pairing problem between cooperating cell-center users and cell-edge users has been tackled through the Hungarian algorithm that pairs users based on the Euclidean distance, finally, the power allocation of the BS transmit power as well as the cooperation power of the cooperating cell-center users has been sequentially optimized. The obtained results demonstrate the energy efficiency and illustrate the effect of changing different

network parameters, such as changing the BS transmit power levels and changing cell-edge users' minimum required rate on the EE of the network.

CHAPTER 5

ENERGY MINIMIZATION IN MEC-ASSISTED COOPERATIVE THZ-SIMO NOMA SYSTEMS

The various requirements in terms of data rates and latency in beyond 5G and 6G networks have motivated the integration of a variety of communications schemes and technologies to meet these requirements in such networks. Among these schemes are THz communications, cooperative NOMA-enabled schemes, and MEC. THz communications offers abundant bandwidth for high-data-rate short-distance applications. NOMA-enabled schemes are promising schemes to realize the target spectral efficiency and low latency requirements in future networks, while MEC would allow distributed processing and data offloading for these networks. In this chapter, an energy-efficient MEC-assisted cooperative THz-SIMO NOMA scheme is proposed to allow the uplink transmission of offloaded data from the far cell-edge users to the computing resources

in the BS through the cell-center users. The proposed cooperative scheme comprises three stages: (i) a user pairing stage that forms NOMA user pairs based on the well-known Hungarian algorithm, (ii) a receive beamforming stage in the BS to schedule each NOMA user pair in the system, and (iii) a joint time and power allocation optimization problem that aims to minimize the total energy consumption of all the users in the system, which is tackled using the Lagrange duality method. The obtained results reveal new insights into the performance and design of MEC-assisted cooperative THz-SIMO NOMA systems. Particularly, with relatively high offloading rate demands (several Gbits/user), we illustrate that the proposed scheme can handle such demands while satisfying a predefined latency constraint.

5.1 Introduction

The emerging high-data-rate and ultra-low latency applications in B5G and 6G networks such as mobile augmented reality (MAR) applications [151] require larger corresponding bandwidths with more strict latency constraint than the ones offered by 5G networks [152]. This has spurred the interest in the THz bands to realize the required data rates. Moreover, the large amount of data to be processed in such networks has motivated MEC, also known as Multi-Access Edge Computing, for remote computation of intensive-tasks limited-battery mobile devices. In MEC-assisted networks, the BS is equipped with MEC server(s) that can receive and execute offloaded tasks from the network mobile devices. Later, the results are sent to these mobile devices after execution.

There are three computing offloading models in MEC-assisted networks, namely, binary, partial, and full offloading [30]. In the binary offloading model, a user tasks can be either locally computed at the mobile device or remotely computed at the MEC server and cannot be partitioned. In the partial offloading model, a user tasks are divided into two parts: the local computing part and the offloading part. While in the full offloading model, the whole user tasks are offloaded and remotely accomplished by the MEC server(s) [10]. In this era of B5G networks, a wide range of mobile-initiated applications that require complex computation such as machine learning (ML) and signal processing algorithms are on the rise. These applications impose a heavy computation burden on the limited-battery user devices. With the full offloading model, a user device can be responsible only for collecting the input/output data and displaying the computation results on the screen. As such, the full offloading model can be considered the most effective solution in conserving mobile devices' resources. For this reason, in this chapter, we adopted the full offloading model.

The amount of work in user-assisted cooperative MEC NOMA networks is still limited when it comes to the adopted system model [109], [153], [154], [155], [156], [157], [158], [159]. Specifically, all these works have analyzed a cooperative uplink SISO systems and they are different in where the NOMA scheme is adopted (i.e., at the far-user side [109], [153], [154], [155], or at the near-user side [156], or at both near-user and far-user sides [157], [158], or at both BS and near-user sides [159]). In particular, in [156], a three-nodes system that comprises of a far-user, a near-user, and a BS has been analyzed to minimize the users' sum-energy consumption. The authors solved an optimization problem that involves a joint transmission time assignment and

power allocation for users. Through numerical simulations, the authors demonstrated the superiority of the proposed scheme compared to (i) the THz-OMA counterpart, (ii) the direct transmission scheme, and (iii) an equivalent system with random time and power allocation. In this chapter, motivated by [156], we adopt the NOMA scheme at the cell-center users, but on the contrary to [109], [153], [154], [155], [156], [159], [157], [158], (i) our work focuses on the cooperative uplink SIMO system model, (ii) the adopted band in the previous mentioned works was sub-6 GHz band compared to our work that embraces the THz band, (iii) our work is based on a multi-user system model, in contrast, all the works in [109], [156], [159], [153], [155], [157] have adopted three-nodes systems, except for [154], [158] that adopted a device-assisted multi-helper MEC system which differs from our proposed multi-user model.

In this chapter, an energy-efficient MEC-assisted cooperative THz-SIMO NOMA scheme is proposed to allow the uplink transmission of offloaded data from the far cell-edge users to the BS. The proposed cooperative scheme comprises three stages: (i) a user pairing stage that forms NOMA user pairs, where a cell-edge user is paired with a cell-center user, based on the well-known Hungarian algorithm, (ii) a receive beamforming stage in the BS to schedule each NOMA user pair in the system, and (iii) a joint time and power allocation optimization problem that aims to minimize the total energy consumption of all the users in the system, which is tackled using the Lagrange duality method. Thus, our contributions can be summarized as follows:

- Proposing an energy-efficient MEC-assisted cooperative THz-SIMO NOMA scheme for allowing the far cell-edge users to transmit their offloading data

to the BS through cooperating cell-center users.

- Developing the proposed cooperative scheme in three stages, namely, (i) cooperating cell-center and cell-edge user pairing stage, (ii) cooperating cell-center user scheduling stage, and (iii) users' energy minimization stage.
- Illustrating through simulations that the proposed scheme can handle relatively high offloading rate demands (several Gbits/user) within a predefined latency constraint. Also, to support the effectiveness of the proposed cooperative scheme, the proposed THz-NOMA scheme is benchmarked with several baseline schemes (i.e., (i) THz-NOMA scheme with partial offloading model and without offloading, (ii) mmWave-NOMA scheme with full offloading, and (iii) THz-OMA scheme with full offloading).

The rest of this chapter is organized as follows. In Section 5.2, the THz channel model and the offloading model of the proposed MEC-assisted cooperative THz-SIMO NOMA scheme are presented. In Section 5.3 the details of the proposed scheme are specified. Detailed Simulation results are provided in Section 5.4, which is followed by the chapter conclusions in Section 5.5. For the reader's convenience, the list of used notations is summarized in Table 5.1.

5.2 Channel and System Models

An uplink communication scheme where a BS, that is equipped with N antennas, receives and executes offloading data from a set of K single-antenna NOMA user

Table 5.1: List of Notations

Notion	Description	Notion	Description
N	Number of antenna-phased arrays at the BS	$y_{k,i}^j$	Received signal at the i -th user that is transmitted from the j -th user for the k -th pair
K	Number of NOMA user pairs in the system	$y_{k,BS}$	Receive superimposed signal at the BS from the i -th cooperating cell-center user
K_{Coop}	Number of cell-center users in the system	$(p_{k,j}, p_{k,i})$	Transmit power of (j -th, i -th) users for k -th pair
K_{Edge}	Number of cell-edge users in the system	$\hat{s}_{k,j}$	Transmit offloading data from the j -th user
$(L_{k,j}, L_{k,i})$	Task input-bits of (j -th, i -th) users for the k -th pair	$n_{k,i}$	Noise seen at the i -th user
$(L_{k,j}^{\text{off}}, L_{k,i}^{\text{off}})$	Offloaded bits of (j -th, i -th) users for the k -th pair	σ^2	The noise power
$(L_{k,j}^{\text{loc}}, L_{k,i}^{\text{loc}})$	Locally-computed bits of (j -th, i -th) users for the k -th pair	$R_{k,i}^j$	Achievable offloading data rate of the j -th user at the i -th user
$t_{k,j}$	Time needed for the data to be sent from the j -th user to the i -th user for the k -th pair	$R_{k,BS}^j$	Achievable offloading data rate at the BS for the j -th user
$t_{k,i}$	Time needed for the data to be sent from the i -th user to the BS	$R_{k,BS}^i$	Achievable offloading data rate at the BS for the i -th user
T	Delay-tolerance of the system	$(E_j^{\text{off}}, E_i^{\text{off}})$	Energy consumption for data offloading of the (j -th, i -th) users
$\mathbf{h}_{k,i}$	Channel gain receive vector between the i -th user and the BS for the k -th pair	$(E_j^{\text{loc}}, E_i^{\text{loc}})$	Energy consumption for data local-computing of the (j -th, i -th) users
$h_{k,ji}$	Cooperative side-link channel gain between j -th user and i -th user	$\mathbf{w}_k$	Receive vector at the BS antenna array
$\mathcal{PL}(f, d_i)$	Path loss incurred by the signal that is transmitted from the i -th user to the BS on frequency f with d_i meters distance separation between them	$(\beta_{k,j}, \beta_{k,i})$	The NOMA power fractions allocated to transmit the (j -th, i -th) users offloaded data bits
$\theta_{k,i}$	Physical angle-of-arrival of the THz beam	$(s_{k,j}, s_{k,i})$	Transmit offloaded data messages of (j -th, i -th) users for k -th pair
$\mathbf{a}(\theta_{k,i})$	Array steering vector toward i -th user for the k -th pair	c_j	Number of central process unit (CPU) cycles needed to execute one bit in a task at the j -th user
$(G_{t,j}, G_{t,i})$	The (j -th, i -th) user antenna transmission gain	κ_j	Effective capacitance coefficient at the j -th user
$G_{r,i}$	The i -th user antenna reception gain	$f_{j,a}$	CPU frequency at the a -th cycle
$G_{r,BS}$	The BS antenna reception gain	$(\bar{\theta}, B)$	Coverage sector area θ is divided into B parts, which the BS uses to generate $B + 1$ candidate beams
c	Speed of light in free space	$\phi_{k,i}$	Normalized directions of the i -user channel for k -th pair
$\mathcal{L}_{\text{spread}}$	Spreading loss in the LoS path	ϕ_b	Normalized directions of the candidate beam
$\mathcal{L}_{\text{abs}}$	Molecular absorption loss in the LoS path	$\boldsymbol{\lambda}$	Lagrangian dual factor vector
$k_{\text{abs}}(f)$	Frequency-dependent medium absorption coefficient	W	Contiguous bandwidth of the THz window

pairs is depicted in Figure 5.1. The users are classified into K_{Coop} cell-center users and K_{Edge} cell-edge users. The links between the BS and the cell-edge users are assumed to be very weak due to the high attenuation in THz bands. Subsequently, the cell-center users perform HD DF cooperation to relay the cell-edge users' offloading data to the BS for processing. Each cooperating cell-center user is paired with a cell-edge user using the Hungarian algorithm, which will be discussed in Section 5.3.1, to form a NOMA user pair. In each pair, the cell-center user utilizes the NOMA scheme to superimpose the offloading data of his paired cell-edge user alongside his own offloading data. Then, this superimposed signal is transmitted to the BS. Each

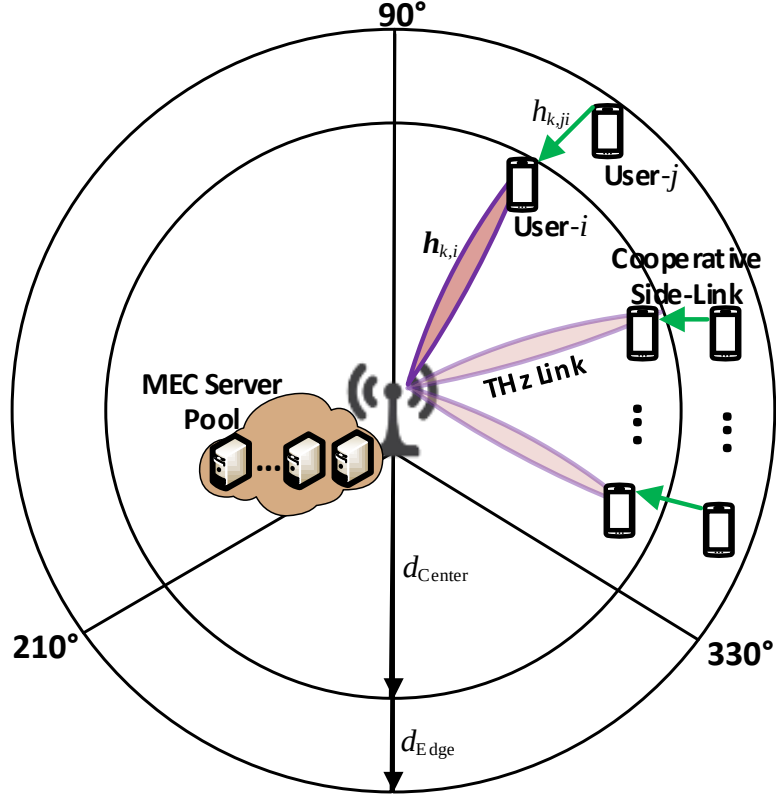


Figure 5.1: The proposed model for multi-user MEC-assisted cooperative THz-SIMO NOMA systems.

NOMA user pair (e.g., j -th cell-edge user and i -th cooperating cell-center user) utilizes an orthogonal channel, which can be a time slot or a sub-carrier frequency channel, to transmit to the BS. From the BS side, each NOMA user pair is served by one receive precoding vector on an orthogonal channel as ABF is adopted [42]. The remaining user pairs can be analyzed similarly.

As explained in the introduction, we adopt the full offloading model to meet the high demands in next-generation networks. For the operation of this model, it is assumed that there is a central controller in the BS that can collect computation-related information, global CSI, and distribute the computation-related policies for all users [160]. At this point, we focus the analysis on the k -th NOMA user pair that

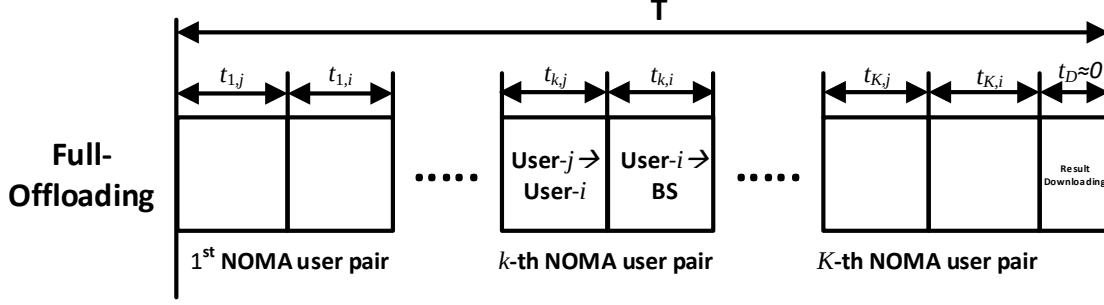


Figure 5.2: Full offloading model for the proposed multi-user MEC-assisted cooperative THz-SIMO NOMA system.

contains the i -th and j -th users. In this NOMA user pair, and similarly on all other NOMA user pairs, we assume that the j -th user has a data-size of $L_{k,j} > 0$ (in bits) computation tasks to execute. Likewise, the i -th user has a data-size of $L_{k,i} > 0$ (in bits) computation tasks to execute. In this NOMA user pair, we denote the time needed for the data to be sent from the j -th user to the i -th user as $t_{k,j}$, and the time needed for the data to be sent from the i -th user to the BS as $t_{k,i}$. At the BS, the time consumed for the task computation and result downloading can be ignored because of the powerful computation at the MEC server pool and the small data size of the result [109], [156]. Considering latency-critical applications, all offloaded data need to be executed within one time block with duration $T > 0$, (i.e., $\sum_{k=1}^K (t_{k,j} + t_{k,i}) \leq T$). In Figure 5.2, an illustration of the full offloading model is provided to show how the block duration T is divided between all the NOMA user pairs. Moreover, we assume that the channel coherence time is larger than the block duration T , so that the channel gain remains constant during T [160].

Next, we discuss the THz channel model and the details of offloading model for the considered multi-user MEC-assisted cooperative THz-SIMO NOMA system.

5.2.1 THz Channel Model

In the THz band, transmitted signals suffers from a high path loss due to existence of the spreading and molecular absorption losses. This makes THz communication links sensitive to the LoS obstacles blockage such as walls. For example, it was reported in [139] that when the LoS exists between a transmitter and a receiver, the first-order reflections are attenuated on average by more than 10 dB, and the second-order reflections are attenuated on average more than 20 dB. Therefore, in this chapter, similar to [77], we assume the existence of the LoS path only. Subsequently, the channel gain receive vector between the i -th user in the k -th NOMA user pair and the N -antenna array at the BS can be expressed as

$$\mathbf{h}_{k,i} = \sqrt{N} \left(\sqrt{\frac{G_{t,i} G_{r,BS}}{\mathcal{PL}(f, d_i)}} \mathbf{a}(\theta_{k,i}) \right), \quad (5.1)$$

$$\mathcal{PL}(f, d_i) = \mathcal{L}_{\text{spread}}(f, d_i) \mathcal{L}_{\text{abs}}(f, d_i) = \left(\frac{4\pi f d_i}{c} \right)^2 e^{k_{\text{abs}}(f) d_i},$$

where $\mathcal{PL}(f, d_i)$ denotes the path loss incurred by the THz signal that is transmitted from the i -th user to the BS on frequency f with d_i meters distance separation between them. $\mathbf{a}(\theta_{k,i})$ denotes the array steering vector towards the i -th user of the k -th user pair. $G_{t,i}$ and $G_{r,BS}$ respectively denote the i -th user antenna transmission gain and the BS antenna reception gain. In this chapter, we assume that all users have the same antenna transmission and reception gains, and the users and the BS are equipped with directive antennas to countermeasure the channel attenuation in the THz links [161]. c denotes the speed of light. The path loss of THz signals consists of two multiplicative factors, namely, (i) the spreading loss $\mathcal{L}_{\text{spread}}$ and (ii) the molecular absorption loss

$\mathcal{L}_{\text{abs}}$. The term $k_{\text{abs}}(f)$ denotes the frequency-dependent absorption coefficient for different isotopologues of water vapor molecules. In a typical medium, water vapor molecules contribute to most of the total absorption loss as compared to the little contributions of the other air molecules [77]. The array steering vector for ULA can be expressed as [77]

$$\mathbf{a}(\theta_{k,i}) = \frac{1}{\sqrt{N}} [1, \dots, e^{j\pi[n \sin(\theta_{k,i})]}, \dots, e^{j\pi[(N-1) \sin(\theta_{k,i})]}]^T, \quad (5.2)$$

where $\theta_{k,i}$ denotes the physical angle-of-arrival of the THz beam. The channel model of cooperative side-links, between cell-edge users and cell-center users, also follows the one in (5.1); since in-band user-assisted cooperative communications paradigm is adopted [27]. Hence, the cooperative side-link channel gain between the j -th user and the i -th user can be expressed as [162]

$$h_{k,ji} = \sqrt{\frac{G_{t,j}G_{r,i}}{\left(\frac{4\pi f d_{ji}}{c}\right)^2 e^{k_{\text{abs}}(f)d_{ji}}}}. \quad (5.3)$$

5.2.2 Offloading System Model

In this subsection, we focus on the offloading data delivery from users to the BS that involves two phases, (i) an orthogonal channel transmission from each cell-edge user to each cell-center user, and (ii) a NOMA transmission from each cell-center user to the BS. Also here, let's focus the analysis on the k -th NOMA user pair and all other NOMA user pairs can be analyzed in similar manner; as, in this chapter, the analog beamforming at the BS is assumed since it is a more energy-saving option compared

to digital and hybrid beamforming [21]. During the first phase, the received signal at the i -th user, that is transmitted from the j -th user, can be written as

$$y_{k,i}^j = \underbrace{h_{k,ji}\sqrt{p_{k,j}}\hat{s}_{k,j}}_{\text{Data from User-}j} + \underbrace{n_{k,i}}_{\text{Noise}}, \quad (5.4)$$

where $h_{k,ji}$ denotes the cooperative side-link channel gain between j -th user and i -th user, $p_{k,j}$ represents the transmit power of the j -th user, $\hat{s}_{k,j}$ represents the transmit offloading data from the j -th user, and $n_{k,i}$ denotes the noise seen at the i -th user with a power σ^2 . Consequently, the achievable offloading data rate of the j -th user at the i -th user can be expressed as

$$R_{k,i}^j = W \log_2 \left(1 + \frac{p_{k,j}|h_{k,ji}|^2}{\sigma^2} \right), \quad (5.5)$$

where W is the available contiguous bandwidth of the adopted THz channel window. In this NOMA user pair, the duration of the first phase is $t_{k,j}$. Subsequently, the energy consumption for data offloading of the j -th user is $E_j^{\text{off}} = t_{k,j}p_{k,j}$.

During the second phase, the receive superimposed signal at the BS from the i -th cooperating cell-center user of the k -th user pair is

$$y_{k,\text{BS}} = \underbrace{\mathbf{h}_{k,i}^H \mathbf{w}_k \sqrt{\beta_{k,i} p_{k,i}} s_{k,i}}_{\text{Data from User-}i} + \underbrace{\mathbf{h}_{k,i}^H \mathbf{w}_k \sqrt{\beta_{k,j} p_{k,j}} s_{k,j}}_{\text{Data from User-}j} + \underbrace{\mathbf{n}_k^H \mathbf{w}_k}_{\text{Noise}}, \quad (5.6)$$

where $\mathbf{w}_k$ represents the receive vector at the BS antenna array, s_k represents the NOMA superimposed signal of the k -th user pair, $\beta_{k,i}$ and $\beta_{k,j}$ denote the NOMA

power-fractions allocated to transmit the i -th cooperating cell-center user and j -th cell-edge user offloaded data bits, respectively, in which $\beta_{k,j} + \beta_{k,i} = 1$ [156]. $s_{k,i}$ and $s_{k,j}$ denote the transmit offloaded data messages of the i -th cooperating cell-center user and j -th cell-edge user. $p_{k,i}$ denotes the transmit power of the i -th user. $\mathbf{n}_k$ denotes the N -dimensional Gaussian white noise vector seen at the BS with a power σ^2 . The second term in (5.6), represents the sent offloading data from the j -th user to the BS that was extracted by the i -th user through the SIC decoding procedures. In this NOMA user pair, the duration of the second phase is $t_{k,i}$. Consequently, the achievable offloading data rate at the BS for the i -th user and j -th user can be, respectively, expressed as

$$R_{k,\text{BS}}^i = W \log_2 \left(1 + \frac{\beta_{k,i} p_{k,i} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2}{\beta_{k,j} p_{k,i} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2 + \sigma^2} \right), \quad (5.7)$$

$$R_{k,\text{BS}}^j = W \log_2 \left(1 + \frac{\beta_{k,j} p_{k,i} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2}{\sigma^2} \right). \quad (5.8)$$

Recall that the duration of the second phase is $t_{k,i}$. Hence, the energy consumption for data offloading of the i -th user is $E_i^{\text{off}} = t_{k,i} p_{k,i}$. According to [160], by combining the two phases, the offloaded data that are processed by the MEC server pool at the BS for i -th user and j -th user can be, respectively, written as

$$L_{k,i}^{\text{off}} = t_{k,i} R_{k,\text{BS}}^i, \quad (5.9)$$

$$L_{k,j}^{\text{off}} = \min\{t_{k,j} R_{k,i}^j, t_{k,i} R_{k,\text{BS}}^j\}. \quad (5.10)$$

5.3 The Proposed MEC-assisted Cooperative THz-SIMO NOMA Scheme

In this section, we discuss the proposed MEC-assisted cooperative THz-SIMO NOMA scheme in detail. Algorithm 7 provides a summary of the proposed scheme.

5.3.1 Cell-edge and Cooperating Cell-center User Pairing Stage: Hungarian Algorithm

In the beginning, the users in the system are distributed according to the uniform random distribution [143] and each cell-edge user is paired with a cooperating cell-center user by considering the shortest Euclidean distance. To achieve this, the Hungarian algorithm is adopted, which is a well-known one-to-one assignment matching algorithm [145]. Noting that the computational complexity of the brute-force algorithm is $O(K_{\text{Coop}}!)$, which is much more involved than the adopted Hungarian algorithm

Algorithm 7: A summary of the proposed scheme

- (-) **Initialization:** (i) distribute the cell-edge and cooperating cell-center users, (ii) calculate the channel gain of each cooperating cell-center user, (iii) build the BS available beams set;
 - (A) **Cell-edge and cooperating cell-center user pairing stage:** (i) pair each cell-edge user with each cooperating cell-center user based on the Hungarian algorithm, (ii) in each formed pair, calculate the channel gain between the paired users;
 - (B) **Cooperating cell-center user scheduling stage:** find the best beam for each cooperating cell-center user based on receive analog beamforming with the aid of the cosine similarity metric;
 - (C) **Users' energy minimization stage:** determine the optimal time and power allocation that minimize the total energy consumption of all the users in the system;
-

that has a computational complexity of $O(K_{\text{Coop}}^3)$. After conducting the NOMA user pairing, a calculation of the channel gain between each paired cell-edge user and co-operating cell-center user is performed.

5.3.2 Cooperating Cell-center User Scheduling Stage: Analog Beamforming with the Cosine Similarity Metric

As low hardware cost and power consumption are essential for energy-efficient future wireless networks, the hybrid and analog beamforming schemes, where the number of the RF chains at the BS is reduced, have gained interest over the last decade [143], [42], [77], [163], [21]. Hence, ABF is adopted here where the BS performs receive ABF using a set of fixed beams that are uniformly distributed over each sector coverage area. So, the cell is assumed to have three 120° sectors as shown in Figure 5.1. With one RF chain available at the BS, only one beam can be selected at a time, and hence one beam to serve one NOMA user pair per channel use. A time-division strategy is used to alternate among the different user pairs so that ABF can only generate one beam at a time. So, considering a specific sector, $\bar{\theta}$, from $-\pi/6$ to $\pi/2$ or 330° to 90° , the 120° area is covered by a set of $B + 1$ beams and similarly for the other sectors. Each beam- b of the available beams has the following steering vector [143]:

$$\mathbf{w}_b = \mathbf{a}(\bar{\theta}_b), \forall b \in [0, B], \quad (5.11)$$

where the parameter $\bar{\theta}_b = -\pi/6 + (b \times \frac{2\pi}{3B})$. In this way, this entire sector region is divided into B equal angles, effectively forming a set of $B + 1$ beams. The $B + 1$

beams can be thought of as a choice of $B + 1$ different steering vectors based on (5.11), such that collectively, the steering vectors of the $B + 1$ candidate precoding vectors uniformly cover the entire sector region of $\bar{\theta} = -\pi/6$ to $\pi/2$.

The cosine similarity metric is utilized to determine the level of correlation among THz cooperating cell-center users and the BS available beams that are formed through analog beamforming. Several works in mmWave-NOMA systems have used the cosine similarity metric to determine the correlations between the users' channels and the fixed beams [143] or among the users channels [144]. Similarly, this concept can be used herein in the context of THz-NOMA systems. In particular, we use the result from [143], where it is shown that the cosine similarity metric between the channel $\mathbf{h}_{k,i}$ of the i -th user, in the k -th user pair, and a beam- b with beamforming vector $\mathbf{w}_b$ can be expressed as follows:

$$\begin{aligned} \cos(\mathbf{h}_{k,i}, \mathbf{w}_b) &= \frac{|\mathbf{h}_{k,i}^H \mathbf{w}_b|}{\|\mathbf{h}_{k,i}\| \|\mathbf{w}_b\|} \\ &= \frac{|\mathbf{a}(\phi_{k,i})^H \mathbf{a}(\phi_b)|}{N} \\ &= F_N(\pi[\phi_{k,i} - \phi_b]), \end{aligned} \tag{5.12}$$

where $\phi_b = \sin(\bar{\theta}_b)$ and $\phi_{k,i} = \sin(\theta_{k,i})$ are the normalized directions of the candidate beam and the user channel, respectively, and F_N represents the Fejer Kernel. The properties of Fejer Kernel dictate that as $|\phi_{k,i} - \phi_b|$ increases, $\cos(\mathbf{h}_{k,i}, \mathbf{w}_b) \rightarrow 0$. So, each cooperating cell-center user is scheduled with its best THz beam by guaranteeing that the selected beam and the cooperating cell-center user direction are well aligned, as reflected through the large value of the cosine similarity metric.

5.3.3 Users' Energy Minimization Stage

In this subsection, we formulate and optimally solve a joint time and power allocation optimization problem that aims to minimize the total energy consumption of all the users in the proposed scheme. Somehow similar problems have been investigated in [109] and [156], but (i) for two users only, (ii) with cooperative SISO models, (iii) with a direct link between the cell-edge user and BS, and (iv) for the partial offloading model. These four aforementioned differences between this chapter and the literature make the formulation and solution of the optimization problem in our model unique. For the solution of the optimization problem, a Lagrange duality method has been adopted inspired by the solution provided in [156].

In the k -th NOMA user pair, one can define the energy consumption of the j -th user and the i -th user as $E_{k,j}^{\text{off}} + E_{k,i}^{\text{off}}$. As discussed in Section 5.2, a common latency constraint is adopted in the proposed system to ensure that all users can receive the results of their offloading data within a given time (i.e., $\sum_{k=1}^K (t_{k,j} + t_{k,i}) \leq T$). Consequently, for the k -th NOMA user pair, the latency constraint is $t_{k,j} + t_{k,i} \leq T/K$. For the data offloading, the energy consumption of users depend on both the users' transmit power and time duration for offloading data [156]. Therefore, the

optimization problem can be defined as

$$(P1): \min_{\{t_{k,j}, t_{k,i}, p_{k,j}, p_{k,i}\}} E_{k,j}^{\text{off}} + E_{k,i}^{\text{off}}, \quad (5.13)$$

$$\text{s.t.} \quad L_{k,j}^{\text{off}} \geq L_{k,j}, \quad k \in [1, \dots, K] \quad (5.14)$$

$$L_{k,i}^{\text{off}} \geq L_{k,i}, \quad k \in [1, \dots, K] \quad (5.15)$$

$$t_{k,j} + t_{k,i} \leq T/K, \quad k \in [1, \dots, K] \quad (5.16)$$

$$L_{k,j}^{\text{off}}, L_{k,i}^{\text{off}} > 0, \quad k \in [1, \dots, K] \quad (5.17)$$

$$L_{k,j}^{\text{loc}}, L_{k,i}^{\text{loc}} = 0, \quad k \in [1, \dots, K] \quad (5.18)$$

where by (5.14) and (5.15) we ensure that all the users' tasks are accomplished remotely in the MEC server pool. Equation (5.16) represents the latency requirement for the k -th NOMA user pair. Equations (5.17) and (5.18) are set as the full offloading model is adopted. It is worth noting that the above optimization problem is for one NOMA user pair, the optimization of other NOMA user pairs can be performed similarly, and then the total energy consumption of all NOMA user pairs is summed and reported.

Proposition 5.1 *The optimal time and power allocation that minimize the energy consumption of one NOMA user pair are given by*

$$\begin{aligned} t_{k,j}^* &= \frac{T}{K} - \frac{L_{k,i}}{W \log_2(1 + \frac{\beta_{k,i}}{\beta_{k,j}})}, \quad t_{k,i}^* = \frac{L_{k,i}}{W \log_2(1 + \frac{\beta_{k,i}}{\beta_{k,j}})}, \\ p_{k,j}^* &= \frac{\sigma^2(2^{L_{k,j}/W t_{k,j}^*} - 1)}{|h_{k,ji}|^2}, \quad p_{k,i}^* = \frac{\sigma^2(2^{L_{k,j}/W t_{k,i}^*} - 1)}{\beta_{k,j} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2}. \end{aligned} \quad (5.19)$$

Proof. See Appendix A. I

5.4 Results and Discussions

In this section, we present detailed numerical results to evaluate the performance of the proposed MEC-assisted cooperative THz-SIMO NOMA system. In these performance curves, Monte-Carlo simulations that are averaged over 100 different users' location realizations are used. A list of the default used parameters is provided in Table 5.2. Beyond this list, the noise power is $\sigma^2 = 10 \log_{10}(W) + N_f - 174$ dBm, with noise figure $N_f = 10$ dB [143]. For comparison purposes, we consider the following baseline schemes:

1) **THz-NOMA scheme with partial offloading model and without offloading:** As discussed in the introduction, in the partial offloading model, the user

Table 5.2: System Parameters

Parameter name, notation	Value
CPU cycles for each one bit at users, c_j, c_i	1 cycle/bit [109]
Effective capacitance coefficient for users, κ_j, κ_i	10^{-27} [160]
The length of the time block, T	0.25 second [160]
Number of input computation bits per user, $(L_{k,j}, L_{k,i})$	(1, 1) Gbits
Number of antennas at BS, N	4 [143]
The antenna transmission and reception gains of any user, (e.g., $G_{t,i}$ and $G_{r,i}$)	3 dBi [164]
BS antenna reception gain, $G_{r,BS}$	26 dBi [163]
Number of available beams, B	20 [42]
Beam-width angles, $\bar{\theta}_b$	6° [148]
BS sector angular coverage, $\bar{\theta}$	120° [42]
Power allocation factor per cell-edge user, $\beta_{k,j}$	0.3 [156]
Power allocation factor per cell-center user, $\beta_{k,i}$	0.7 [156]
Water vapor molecules absorption coefficient, $k_{\text{abs}}(f)$	0.28 m^{-1} [150]
Center frequency of the considered THz window, f	3.42 THz [149]
Contiguous bandwidth of the considered THz window, W	137 GHz [149]
Speed of light, c	$3 \times 10^8 \text{ m/s}$
Number of users, $K_{\text{Coop}} + K_{\text{Edge}}$	4 – 20 users [77]
User distribution	Uniform random [143]
BS coverage region, $d_{\text{Center}} + d_{\text{Edge}}$	$3 + 2 = 5$ meters

tasks are partitioned into a local computing part and a remote offloading part. While for the system without offloading the tasks are only locally computed at the user-side. The energy consumption analysis for these baseline schemes is provided next.

■ *Local computing for the partial offloading model*

In here, we provide the analysis of the energy consumption at the users that arise from the local computation of the tasks that are not offloaded. The local computation at users can be executed during the whole time duration T . In the k -th NOMA user pair, we can express the local computing energy consumption for the j -th user as [156], [160]

$$E_{k,j}^{\text{loc}} = \sum_{a=1}^{c_j L_{k,j}^{\text{loc}}} \kappa_j f_{j,a} = \frac{\kappa_j c_j^3 (L_{k,j}^{\text{loc}})^3}{(t_{k,j} + t_{k,i})^2}, \quad (5.20)$$

$$f_{j,a} = \frac{c_j L_{k,j}^{\text{loc}}}{t_{k,j} + t_{k,i}}, \forall a \in \{1, \dots, c_j L_{k,j}^{\text{loc}}\}, \quad (5.21)$$

where c_j is the number of CPU cycles needed to execute one bit in a task at the j -th user. κ_j is the effective capacitance coefficient at the j -th user. $f_{j,a}$ is the CPU frequency at the a -th cycle, where $a \in \{1, \dots, c_j L_{k,j}^{\text{loc}}\}$. In (5.21), to facilitate the calculation similar to [156], [160], we assume that the CPU frequencies of different CPU cycles to be identical. In a similar manner, we can write the local computing energy consumption for the i -th user as [156], [160]

$$E_{k,i}^{\text{loc}} = \frac{\kappa_i c_i^3 (L_{k,i}^{\text{loc}})^3}{(t_{k,j} + t_{k,i})^2}. \quad (5.22)$$

Overall, the energy consumption for the data offloading and the local computing of users data in the k -th NOMA user pair is $E_{k,i}^{\text{loc}} + E_{k,i}^{\text{off}} + E_{k,j}^{\text{loc}} + E_{k,j}^{\text{off}}$. This formula

is substituted in (P1) as an objective function, then we followed the same steps mentioned in Appendix A to find the optimal time and power allocation that minimize the total energy consumption of all the users in the system.

■ *Local computing for the system without offloading*

In this scheme, $t_{k,j}$ and $t_{k,i}$ are set to zero. Subsequently, $E_{k,j}^{\text{off}}$ and $E_{k,i}^{\text{off}}$ become zero. Both $E_{k,j}^{\text{loc}}$ and $E_{k,i}^{\text{loc}}$ are calculated based on (5.20) and (5.22), respectively.

2) **mmWave-NOMA scheme with full offloading:** In this baseline scheme, we set the center frequency of the considered mmWave channel to $f_{\text{mmWave}} = 28$ GHz with a contiguous bandwidth of $W_{\text{mmWave}} = 2$ GHz [144]. Also, we set the noise power to $\sigma_{\text{mmWave}}^2 = -40$ dBm.

3) **THz-OMA scheme with full offloading:** In this baseline scheme, we assume that the transmission is performed in three phases. Similar to the analysis in Section 5.2, let us focus on the k -th user pair, and all other user pairs can be analyzed similarly. During the first phase, the j -th cell-edge user transmits its offloading data to the i -th cell-center user within $t_{k,j}$. During the second phase, the i -th cell-center user transmits its offloading data to the BS within $t_{k,i-1}$. Finally, during the third phase, the i -th cell-center user transmits the received cell-edge's offloading data to the BS within $t_{k,i-2}$. Subsequently, one can express the achievable offloading data rate of the j -th user at the i -th user and the achievable offloading data rate at the BS for the i -th user and j -th user, respectively, as [16]

$$R_{k,i}^{j,\text{OMA}} = W \log_2 \left(1 + \frac{p_{k,j}^{\text{OMA}} |h_{k,ji}|^2}{\sigma^2} \right), \quad (5.23)$$

$$R_{k,BS}^{i,OMA} = 0.5W \log_2 \left(1 + \frac{p_{k,i}^{OMA} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2}{0.5\sigma^2} \right), \quad (5.24)$$

$$R_{k,BS}^{j,OMA} = 0.5W \log_2 \left(1 + \frac{p_{k,i}^{OMA} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2}{0.5\sigma^2} \right). \quad (5.25)$$

Also, the offloaded data processed by the MEC server pool at the BS for the i -th user and j -th user are given as

$$L_{k,i}^{\text{off},OMA} = t_{k,i-1} R_{k,BS}^{i,OMA}, \quad (5.26)$$

$$L_{k,j}^{\text{off},OMA} = \min\{t_{k,j}^{OMA} R_{k,i}^{j,OMA}, t_{k,i-2} R_{k,BS}^{j,OMA}\}. \quad (5.27)$$

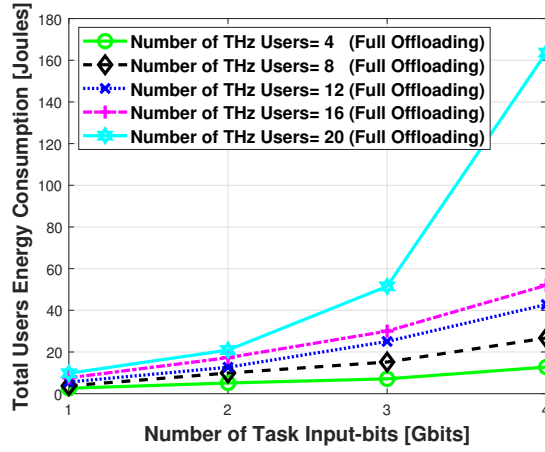
Moreover, the energy consumption for data offloading of the i -th user and the j -th user can be expressed, respectively, as

$$E_i^{\text{off}} = (t_{k,i-1} + t_{k,i-1}) p_{k,i}^{OMA}, \quad (5.28)$$

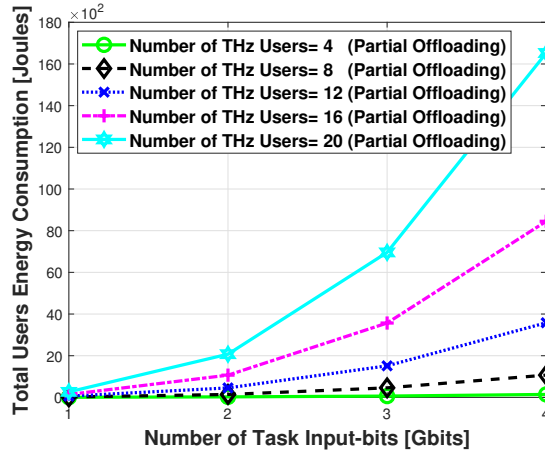
$$E_j^{\text{off}} = t_{k,j}^{OMA} p_{k,j}^{OMA}. \quad (5.29)$$

By substituting (5.23)-(5.29) into (P1) and following the same steps mentioned in Appendix A, one can find the optimal time and power allocation that minimize the total energy consumption of all the users in the OMA counterpart scheme. For a fair comparison between the proposed THz-NOMA scheme with full offloading and this baseline scheme we assume that $t_{k,i} = t_{k,i-1} + t_{k,i-2}$.

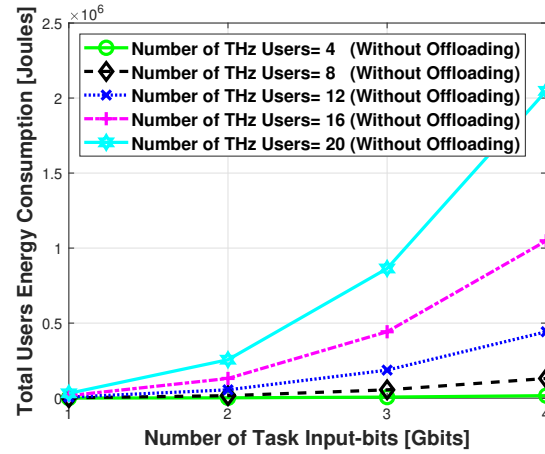
Figure 5.3 illustrates the total energy consumption of the users, in Joules, for the proposed THz-NOMA system with the full offloading model compared to the counter-



(a)



(b)

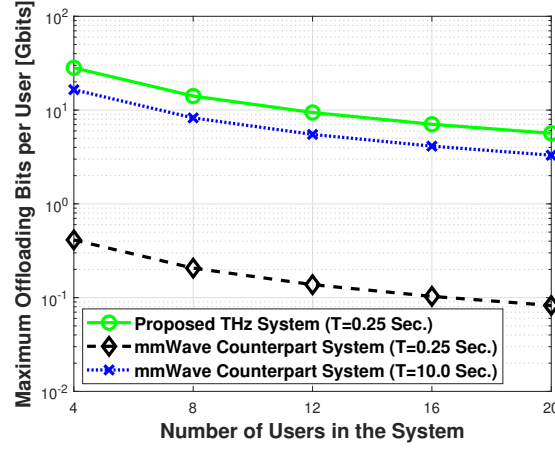


(c)

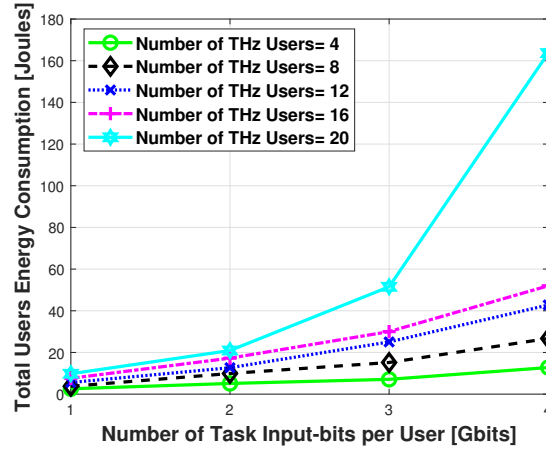
Figure 5.3: The total users' energy consumption of the proposed THz-NOMA system for different offloading models, (a) full offloading model, (b) partial offloading model, and (c) without offloading model.

part THz-NOMA system with the partial offloading model as well as the counterpart system without offloading. For the partial offloading model, we assume that 80% of the task input-bits for each user are offloaded and 20% of the task input-bits are locally computed. The first observation here for the three systems (i.e., Figure 5.3(a) - Figure 5.3(c)), is that as the number of users in these systems increases the total energy consumption increases. Likewise, as the number of task input-bits for each user increases, a somehow exponential increase in the total energy consumption of the users in these systems is observed; this is referred to the reason that with increasing the number of task input-bits, each user needs more power to transmit (offload) its bits to the BS for remote computation. The second observation here is that for the systems with partial offloading and without offloading models, a tremendous amount of energy is required to offload the task input-bits in each user (e.g., when there are 20 users in the system and each user has 4 Gbits data to offload, the total energy consumption of the users: (i) for the system with the full offloading model is 163.66 Joules, (ii) for the system with the partial offloading model is 16.53 KJoules, and (iii) for the system without offloading is 2.05 MJoules). In reality, this required energy might be unfeasible. Hence, our proposed THz-NOMA system with the full offloading model has significant energy reduction for the systems that need several Gbits offloading data to process.

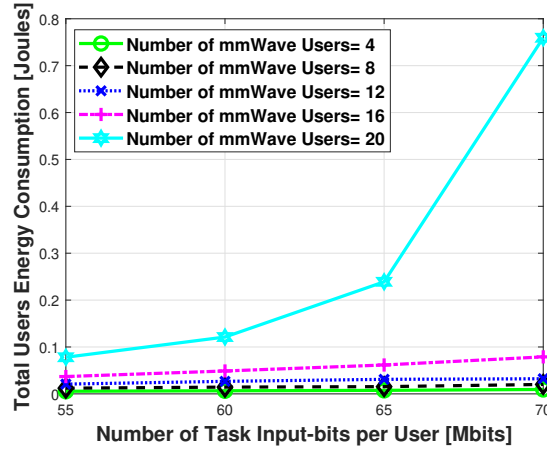
In Figure 5.4, we present the maximum offloading bits per user, in Gbits, as well as the total energy consumption of the users for the proposed THz-NOMA system compared to its mmWave-NOMA counterpart system. From Figure 5.4(a), one can see that for the same latency constraint (i.e., $T = 0.25$ second), the proposed THz-



(a)



(b)



(c)

Figure 5.4: (a) Maximum offloading bits per user in the proposed THz-NOMA system as well as in its mmWave-NOMA counterpart. The total energy consumption of the users for different systems, (b) proposed THz-NOMA system, (c) mmWave-NOMA counterpart system.

NOMA system can offload considerably larger amount of data bits from each user to the BS (See the green and black curves in Figure 5.4(a)). On the other hand, at the expense of increasing the latency constraint 40 times (i.e., from $T = 0.25$ second to $T = 10.0$ seconds) the mmWave-NOMA counterpart system becomes closer performance-wise to the proposed THz-NOMA system. Still, with that increase in the latency constraint, the proposed THz-NOMA system can offload 1.7x more bits compared to its mmWave-NOMA counterpart. If we compare Figure 5.4(b) to Figure 5.4(c), we can see that despite that the total users' energy consumption of mmWave-NOMA counterpart system is much smaller compared to the proposed THz-NOMA system, but the mmWave-NOMA counterpart system is only capable of offering tens of Mbits of data for each user to offload, while the proposed THz-NOMA system can offer several Gbits of data for each user to offload.

In Figure 5.5, the total energy consumption of all users is provided for the proposed THz-NOMA system compared to its THz-OMA counterpart. In this figure, we notice that the total users' energy consumption of the proposed THz-NOMA system is slightly smaller, few Joules, than the total users' energy consumption of the THz-OMA counterpart. This is because, with the assumption $t_{k,i} = t_{k,i-1} + t_{k,i-2}$, the time allocation of the THz-NOMA system and its THz-OMA counterpart are the same. Also, there is no change in the values of $p_{k,j}$, $\forall k \in [1, \dots, K]$. The only change occurs in the values of $p_{k,i}$, $\forall k \in [1, \dots, K]$. These $p_{k,i}$ values approximately increase by 7.8x and this increase, in turn, increases the total users' energy consumption of the THz-OMA counterpart system slightly. Keeping in mind that the THz-NOMA system is more resource-efficient than the THz-OMA system, as one transmission is

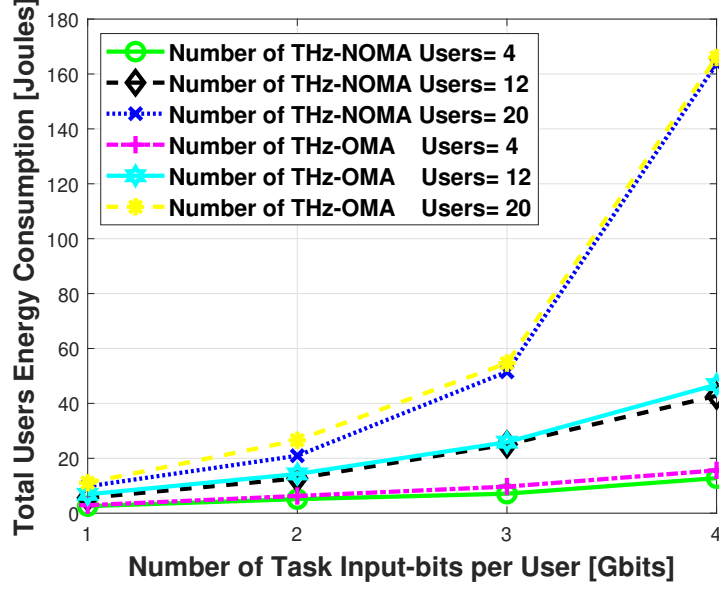
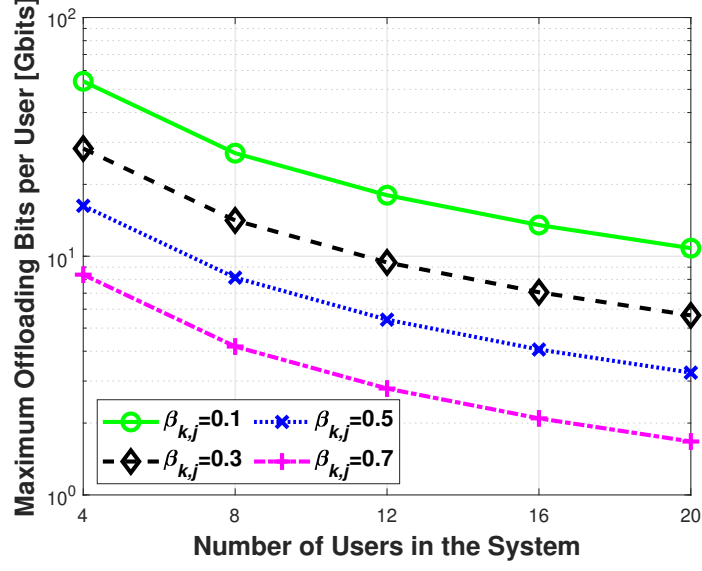


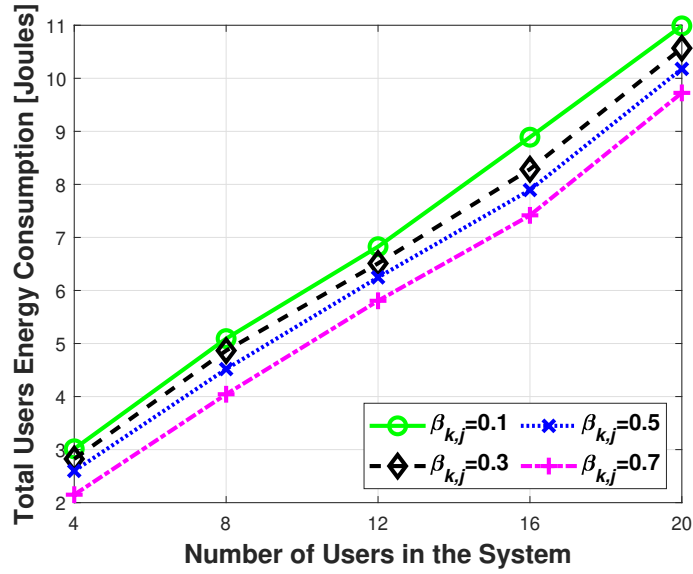
Figure 5.5: The total energy consumption of all users for the proposed THz-NOMA system compared to its THz-OMA counterpart.

made towards the BS compared to two transmissions for the THz-OMA system.

Figure 5.6 represents the maximum offloading bits per user as well as the total energy consumption of all users for the proposed THz-NOMA system while changing the value of the NOMA power-fractions $\beta_{k,j}$. In Figure 5.6(a), the maximum offloading bits per user in the system decreases as we, (i) increase the number of served users in the system, and (ii) increase the value of $\beta_{k,j}$. Such decrease can be deduced by looking at (A.15), where the increase in the number of users in the system is reflected by a decrease of the maximum transmission (offloading) time for each user (Recall that $t_{k,j} + t_{k,i} = T/K$). On the other hand, when the value of $\beta_{k,j}$ increases, the value inside the logarithm, in (A.15), decreases which consequently decreases the maximum offloading bits per user. Figure 5.6(b) is simulated while assuming that the required offloading bits for cell-edge users and cell-center users are equal (i.e., $L_{k,j} = L_{k,i} = 1$ Gbits). In Figure 5.6(b), as we increase the value of $\beta_{k,j}$ for a specific number of



(a)



(b)

Figure 5.6: Changing $\beta_{k,j}$ v.s. (a) maximum offloading bits per user, and (b) total energy consumption of all users.

users, the total users' energy consumption decreases. This is since, based on (5.9) and (5.10), as $\beta_{k,j}$ increases we allocate more time, $t_{k,i}$, to offload the cell-center and cell-edge users data, through the NOMA scheme, with less required power, $p_{k,i}$, for that offloading process.

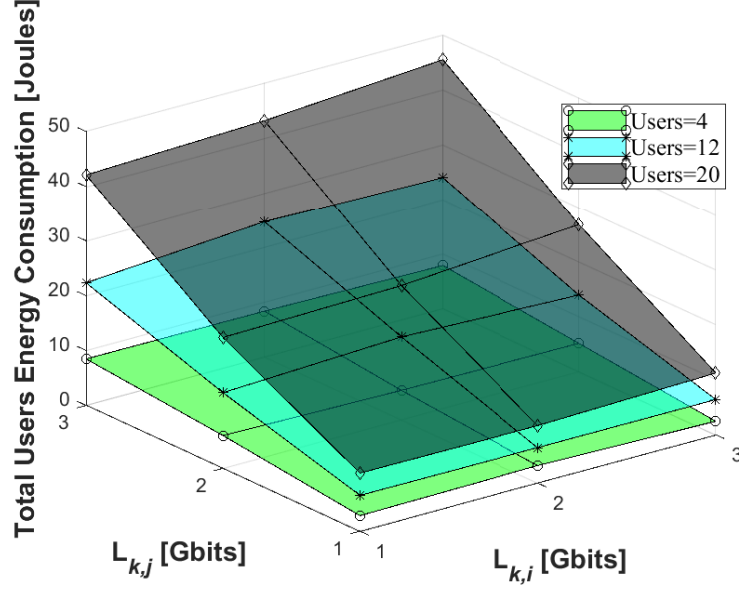


Figure 5.7: Variable offloading bits for the cell-center and cell-edge users in each NOMA user pair (i.e., $[L_{k,i}, L_{k,j}]$, $\forall k \in [1, \dots, K]$) v.s. energy.

Figure 5.7 shows the total users' energy consumption performance of the proposed THz-NOMA system while considering a variable offloading bits for the cell-edge users and the cell-center users in each NOMA user pair. In this figure, the increase in the offloading data of the cell-center users (i.e., $L_{k,i}$, $\forall k \in [1, \dots, K]$) does not affect the total users' energy consumption much as compared to the effect of increasing the offloading data of the cell-edge users (i.e., $L_{k,j}$, $\forall k \in [1, \dots, K]$). This is referred to as the reason that the offloading bits of each cell-edge user is transmitted twice, (i.e., (i) the first time is from each cell-edge user to each cell-center user, and (ii) the second time is from each cell-center user to the BS) compared to the offloading bits of each cell-center user which is transmitted only once (i.e., from each cell-center user to the BS). The increase in the total users' energy consumption for both cases of increasing $L_{k,i}$ or increasing $L_{k,j}$ is related to the reason that the required users' transmission power needed to offload all these offloading bits add-up and subsequently increase

Table 5.3: Potential THz Channel Windows.

	Center frequency (THz) [149]	Contiguous bandwidth (GHz) [149]	Absorption coefficient (m^{-1}) [150]	$\mathcal{PL}(f, 5)$ (dB)
f1	1.51	169	0.1432	113.1102
f2	2.52	82	0.48	124.8723
f3	3.42	137	0.28	123.1818
f4	4.91	113	0.32	127.1915
f5	5.72	126	0.32	128.5178
f6	6.57	120	0.34	130.1555
f7	7.19	246	0.1344	126.4743
f8	8.83	217	0.1033	127.5835
f9	9.57	230	0.0779	127.7310

the total users' energy consumption in the system (recall that the total users' energy consumption is $E_{k,i}^{\text{off}} + E_{k,j}^{\text{off}} = t_{k,i}p_{k,i} + t_{k,j}p_{k,j}$, $\forall k \in [1, \dots, K]$).

In [149], a sensitivity analysis for the THz spectrum that ranges between 0.3 – 10.0 THz has been conducted. Based on this sensitivity analysis, Singh and Sicker [149] have identified various THz channel windows that are 1.0 THz apart. In Table 5.3, a summary of these channel windows that includes its, (i) center frequencies, (ii) contiguous bandwidths, (iii) absorption coefficients, and (iv) the total path loss with 5 meters separation between a user and the BS (i.e., $\mathcal{PL}(f, 5)$). These total path loss values are calculated based on (5.1). From this table, we can see that the total path loss in the THz channel is affected by (i) the THz center frequencies (that contributes to the spreading loss), and (ii) the value of the absorption coefficient at that center frequency (that contributes to the molecular absorption loss). Figure 5.8 provides the maximum offloading bits per user as well as the total energy consumption of all users for the proposed THz-NOMA system for different THz channel windows. From Figure 5.8(a), one may observe that the maximum offloading bits per user is changing based on the contiguous bandwidth available in each THz channel window. Figure 5.8(b) is also simulated while assuming that the required offloading bits for cell-edge users and cell-center users are equal (i.e., $L_{k,j}=L_{k,i}= 1$ Gbits). In this figure, for

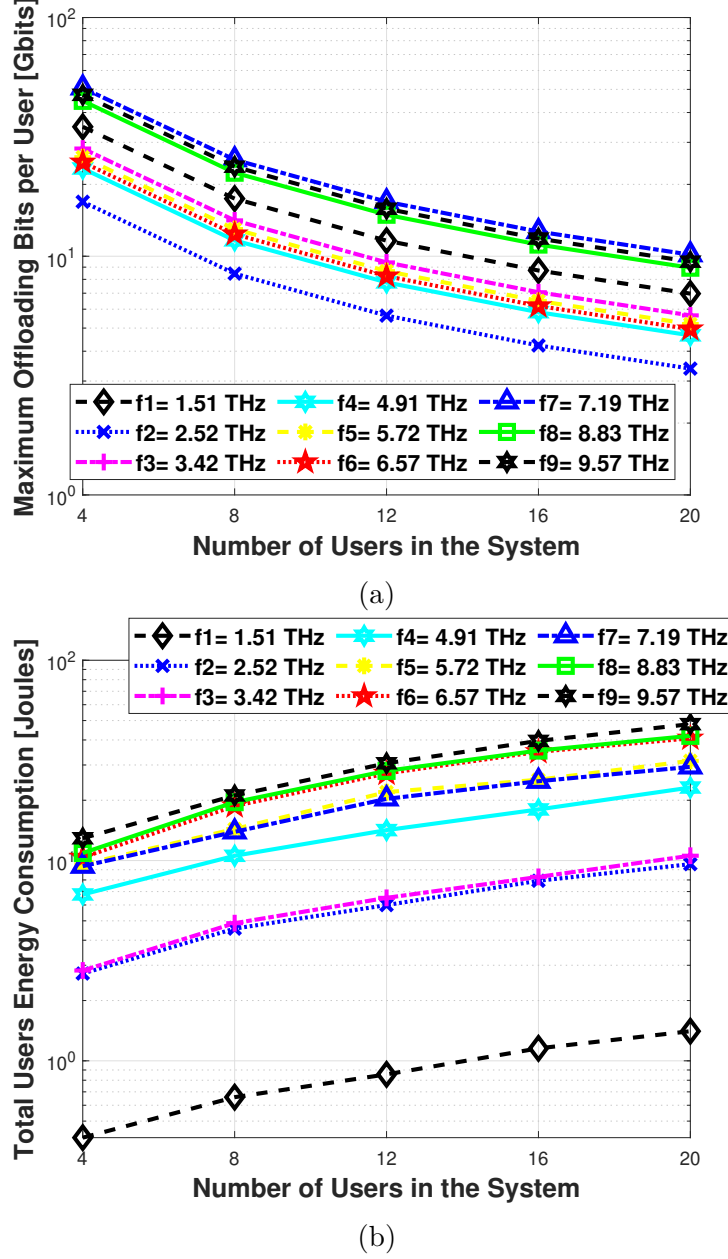


Figure 5.8: Changing THz frequency windows v.s. (a) maximum offloading bits per user, and (b) the total energy consumption of all users.

the frequencies that are at the lower end of the THz spectrum (i.e., f1-f4), we can see that as the center frequency decreases the total users' energy consumption decreases. On the other hand, for the upper end of the THz spectrum (i.e., f5-f9), the effect of increasing the center frequency does not always decrease the total users' energy

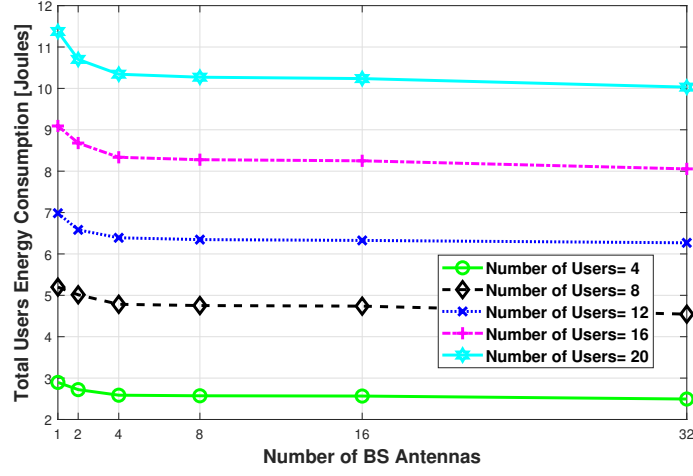


Figure 5.9: The total energy consumption of all users for the proposed THz-NOMA system while changing the number of antennas in the BS.

consumption in the system. For example, if we look at the curves of (f5-f7), despite that f7 has a larger center frequency than f5 and f6, its total users' energy consumption is lower than f5 and f6. This is because f7 has a larger contiguous bandwidth as well as a smaller absorption loss compared to f5 and f6 (See Table 5.3).

Figure 5.9 illustrates the total energy consumption of all users while changing the number of antennas in the BS. This figure is presented to show the benefit of adopting a multi-antenna BS compared to a single-antenna BS. As apparent in the figure, the total energy consumption of all users decreases as the number of antennas in the BS increases. This is since, based on (5.9) and (5.10), as the number of antennas in the BS increases the required transmission power for the cell-center users ($p_{k,i}$, $\forall k \in [1, \dots, K]$) decrease while the values of $t_{k,j}$, $t_{k,i}$, and, $p_{k,j}$, $\forall k \in [1, \dots, K]$ remain the same.

5.5 Conclusions

The growing interest in THz communications as an enabler of high-data-rate low-latency applications in B5G networks has spurred the research on the integration of various promising communication schemes. In this chapter, a cooperative scheme for the MEC-assisted THz-SIMO NOMA system is proposed and investigated. This cooperative scheme allows the uplink transmission of offloaded data from the far cell-edge users to the BS and comprises three stages: (i) a user pairing stage, (ii) a receive beamforming stage, and (iii) a joint time and power allocation optimization stage that aims to minimize the total energy consumption of all the users in the system. The proposed scheme is benchmarked with several baseline schemes and is shown to outperform them in terms of the successful handing of several Gbits/user offloaded data, with a reasonable total users' energy consumption within a predefined latency constraint. Then, the obtained results of the proposed scheme quantified the total energy consumption of all users as well as the maximum offloading bits per user for different system parameters, such as (i) the number of served users, (ii) the number of task-input bits, (iii) the NOMA power-fractions allocated to transmit the users offloaded data bits, (iv) the variable input-bits for cell-edge and cell-center users, (v) the different potential THz channel windows, and (vi) the number of BS antennas.

CHAPTER 6

CONCLUSION AND FUTURE RESEARCH DIRECTIONS

6.1 Conclusion

The main aim of this thesis is to tackle some emerging problems that resulted from the integration of PD-NOMA scheme with some of the enabling communications schemes and technologies for future wireless networks. In particular, the thesis investigated the performance of (i) a multi-user multi-carrier centralized NOMA-VLC system, (ii) a multi-user downlink cooperative THz-MISO NOMA system, and (iii) a multi-user uplink MEC-assisted cooperative THz-SIMO NOMA system. Those systems are studied while optimizing, respectively, the following objective functions, (i) the max-min user rate, (ii) the system EE, and (iii) the total user energy consumption. Also, different design variables are considered while optimizing those systems, namely, user scheduling, NOMA user pairing, subcarrier allocation, power allocation, antennas beamforming, and offloading time allocation. Moreover, through Monte Carlo simulations those

systems are evaluated in terms of the achievable Max-Min user rate in Mbps, system energy efficiency in Bits/Joule, users sum rate in bps, system total consumed power in Watts, average cell-center users rate in bps, total users energy consumption in Joules, and maximum offloading bits per user in Gbits. More insights and details about the content of the thesis as outlined as follows.

In Chapter 2, we survey the integration of PD-NOMA scheme with some of the enabling communications schemes and technologies that are expected to meet the various requirements of B5G networks. In particular, this chapter surveys the different rate optimization scenarios studied in the literature when PD-NOMA scheme is combined with some candidate schemes and technologies for B5G networks including MISO, MIMO, mMIMO, higher frequency mmWave and THz communications, cooperative communications, VLC, and MEC. The considered system models, the optimization methods utilized to maximize the achievable rates, and the main lessons learnt on the optimization of these NOMA-enabled schemes and technologies are discussed in detail. One can conclude from the presented literature in Chapter 2 that PD-NOMA scheme is a promising multiple access scheme for future wireless networks because of its ability to (i) improve the network spectral efficiency, (ii) achieve user fairness in the network, (iii) achieve low transmission latency for delay-sensitive applications, and (iv) achieve high throughput for cell-edge users, this is at the cost of increasing the receiver complexity.

In Chapter 3, the max-min user rate of a multi-cell indoor centralized VLC network is maximized through optimizing user pairing, subcarrier allocation, and power allocation. The joint complex optimization problem is tackled using a low-complexity

solution. At first, the user pairing is assumed to follow the D-NLUPA that can ensure fairness among the different clusters. Then, subcarrier allocation and power allocation are solved iteratively through both the SA meta-heuristic algorithm and the bisection method. The obtained results quantify the achievable max-min user rates for the different relevant variants of NOMA-enabled schemes (i.e., NOMA-not-imposed scheme (hybrid NOMA-OMA scheme) and NOMA-imposed scheme) and shed new light on both the performance and design of multi-user multi-carrier NOMA-enabled centralized VLC networks. One conclusion out of the work presented in this chapter is as follows, while varying different network parameters (i.e., (i) the number of served users, (ii) the number of LEDs in the room, (iii) the semi-angle at half illumination of the LEDs, (iv) the FoV of the PDs, (v) the LED power, and (vi) the indoor space dimensions) the performance of the NOMA-not-imposed scheme outperforms the performance of the NOMA-imposed scheme in terms of the max-min user rate. The reason for this is that the NOMA scheme's imposition might pair some users with their second-best LED. This max-min user rate improvement comes at the cost of lower spectrum efficiency in the NOMA-not-imposed scheme.

In Chapter 4, an energy-efficient CNOMA scheme that guarantees the minimum required rate for the cell-edge users in an indoor THz-MISO communications network is developed. The developed cooperative scheme consists of three stages: (i) beamforming stage that allocates BS beams to THz cooperating cell-center users using analog beamforming with the aid of the cosine similarity metric, (ii) user pairing stage that is tackled using the Hungarian algorithm, and (iii) power allocation stage for both the BS THz-NOMA transmit power and the cooperation power of the co-

operating cell-center users, which are optimized sequentially. The obtained results quantify the EE of the developed scheme and shed new light on the performance of multi-user THz-NOMA-enabled networks. One conclusion out of the work presented in this chapter is as follows, despite the high path loss in the THz band, the developed THz-NOMA cooperative scheme achieves around 9-20 times increase in average cell-center users rate compared to its mmWave-NOMA counterpart.

In Chapter 5, an energy-efficient MEC-assisted cooperative THz-SIMO NOMA scheme is developed to allow the uplink transmission of offloaded data from the far cell-edge users to the computing resources in the base station. The developed cooperative scheme consists of three stages: (i) a user pairing stage that forms NOMA user pairs based on the well-known Hungarian algorithm, (ii) a receive beamforming stage in the BS to schedule each NOMA user pair in the system, and (iii) a joint time and power allocation optimization problem that aims to minimize the sum of energy consumption of the users in the system, which is tackled using the Lagrange duality method. The obtained results reveal new insights into the performance and design of MEC-assisted cooperative THz NOMA systems. Particularly, with relatively high offloading rate demands (several Gbits/user), we illustrate that the developed scheme can successfully handle such demands with a reasonable total users' energy consumption within a predefined latency constraint. Other baseline schemes cannot cope with such demands for the following reasons, (i) for the THz NOMA scheme with partial offloading model and without offloading, a tremendous amount of energy is required to offload the task input-bits in each user which might be unfeasible in reality. (ii) For the mmWave-NOMA scheme with full offloading, more than 40 times increase in

the latency constraint is needed to offload such demands which might be unrealistic for delay-sensitive applications. (iii) For the THz-OMA scheme with full offloading, despite that only a slight increase in the total users' energy consumption is foreseen as compared to the developed THz-NOMA scheme with full-offloading, but our developed scheme is more resource-efficient as one transmission is made towards the BS in our developed scheme compared to two transmissions for the THz-OMA counterpart scheme.

6.2 Future Research Directions

In this section, we highlight some possible directions of future research on the integration of PD-NOMA scheme with enabling technologies and schemes of future wireless networks based on our achieved thesis work.

- The current VLC-NOMA work in Chapter 3 can be extended in the following different directions:
 1. By exploiting illuminating LED-arrays, one can enable the utilization of MIMO/mMIMO in indoor VLC networks to extend the network coverage, and further increase the system capacity [165]. Investigating the max-min user rate optimization for indoor MIMO/mMIMO-VLC networks can be considered as a possible direction of future research. However, the performance gains may be limited due to the effect of the peak-to-average-power-ratio (PAPR) problem [166].

2. An important practical consideration in indoor VLC networks is user mobility. The Random Way-Point (RWP) model is the most commonly used one for user mobility in indoor VLC literature [167]. In indoor multi-user centralized VLC networks, there are different solutions worth studying which can be adopted to accommodate user mobility: (a) Horizontal handover while adopting fractional frequency reuse (FFR) scheme or the use of red, green, and blue (RGB) LEDs, or allowing for a coordinated multi-point (CoMP) transmission scheme between different LEDs, (b) vertical handover that involves RF/VLC network or WiFi/VLC network or PLC/VLC network, (c) cell-zooming strategies that dynamically adjust the coverage areas of the LEDs based on user mobility profiles, and (d) utilizing algorithms that can accommodate for user mobility by determining solutions within the coherence time of the channel [118].

3. A consequence of user mobility in indoor VLC networks is LoS link blockage [167]. Thus, some novel solutions need to be adopted—for example, a multi-directional receiver or omni-directional receiver where PDs are embedded at different sides or all sides, respectively, of a smartphone. Another possible solution for the LoS link blockage can be considered by utilizing intelligent reflecting surfaces (IRSs) inside the indoor environment. Investigating the max-min user rate optimization with such solutions can be an interesting direction for future research.

- The current THz-NOMA work in Chapter 4 and Chapter 5 can be extended in

the following different directions:

1. Since the work in Chapter 4 adopts a MISO setup and the work in Chapter 5 adopts a SIMO setup, the investigation of adopting a MIMO/mMIMO setup is an interesting extension to these works to check if the MIMO/mMIMO setup can improve further the performance of these developed systems.
2. Both works in Chapter 4 and Chapter 5 depend on the analog BF. Hybrid BF is also adopted in the literature in energy-efficient systems. Checking the performance of these developed systems with the hybrid BF technique is an attractive topic for future research.
3. Obtaining full CSI comes with additional cost and overhead. Extending the works in Chapter 4 and Chapter 5 to the partial CSI enabled system or a system with no CSI are directions that need further research.

APPENDIX A

PROOF OF PROPOSITION 1 IN CHAPTER 5

In here, the energy consumption minimization problem (P1) has be tackled. Firstly, (P1) needs to be reformulated (i) by replacing the optimization variables $p_{k,j}$ and $p_{k,i}$ with the variable vector $\mathbf{E} = \{E_{k,j}^{\text{off}} = t_{k,j}p_{k,j}, E_{k,i}^{\text{off}} = t_{k,i}p_{k,i}\}$, (ii) by replacing $t_{k,j}$ and $t_{k,i}$ with the variable vector $\mathbf{t} = \{t_{k,j}, t_{k,i}\}$, and (iii) by substituting (5.9) and (5.10) into (P1). The resultant reformulated problem can be expressed as

$$(P2): \min_{\{\mathbf{t}, \mathbf{E}\}} E_{k,j}^{\text{off}} + E_{k,i}^{\text{off}}, \quad (\text{A.1})$$

$$\text{s.t. } t_{k,j}R_{k,i}^j \geq L_{k,j}, \quad k \in [1, \dots, K] \quad (\text{A.2})$$

$$t_{k,i}R_{k,\text{BS}}^j \geq L_{k,j}, \quad k \in [1, \dots, K] \quad (\text{A.3})$$

$$t_{k,i}R_{k,\text{BS}}^i \geq L_{k,i}, \quad k \in [1, \dots, K] \quad (\text{A.4})$$

$$t_{k,j} + t_{k,i} \leq T/K, \quad k \in [1, \dots, K] \quad (\text{A.5})$$

where (P2) is jointly convex with respect to $\mathbf{E}$ and $\mathbf{t}$. The convexity of (P2) can be proved in a similar way to the one proved in the Appendix of [156]. Secondly, as (P2) is convex, the Lagrangian dual function (P3) can be expressed, while assigning $\boldsymbol{\lambda} = \{\lambda_1, \lambda_2, \lambda_3, \lambda_4\}$ to be the dual factor variables, as

$$(P3): \min_{\{t_{k,j}, t_{k,i}, E_{k,j}^{\text{off}}, E_{k,i}^{\text{off}}\}} \mathbb{L}(t_{k,j}, t_{k,i}, E_{k,j}^{\text{off}}, E_{k,i}^{\text{off}}),$$

where $\mathbb{L}(t_{k,j}, t_{k,i}, E_{k,j}^{\text{off}}, E_{k,i}^{\text{off}}) = E_{k,i}^{\text{off}} + E_{k,j}^{\text{off}}$

$$\begin{aligned} & + \lambda_1(L_{k,j} - t_{k,j}R_{k,i}^j) \\ & + \lambda_2(L_{k,j} - t_{k,i}R_{k,BS}^j) \\ & + \lambda_3(L_{k,i} - t_{k,i}R_{k,BS}^i) \\ & + \lambda_4(t_{k,j} + t_{k,i} - T/K). \end{aligned} \tag{A.6}$$

Thirdly, as (P2) is a convex problem and satisfies the Slater's conditions, then (P2) and (P3) has strong duality. By applying the KKT conditions and solving the equations listed below, the optimal solution can be obtained [34]:

$$\frac{\partial \mathbb{L}}{\partial t_{k,j}} = \lambda_4 - \lambda_1 W \log_2(1 + \frac{E_{k,j}|h_{k,ji}|^2}{\sigma^2 t_{k,j}}) + \frac{\lambda_1 W E_{k,j}|h_{k,ji}|^2}{(\sigma^2 t_{k,j} + E_{k,j}|h_{k,ji}|^2)\ln 2} = 0, \tag{A.7}$$

$$\begin{aligned}
\frac{\partial \mathbb{L}}{\partial t_{k,i}} &= \lambda_4 - \lambda_2 W \log_2 \left(1 + \frac{\beta_{k,j} E_{k,i} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2}{\sigma^2 t_{k,i}} \right) + \frac{\lambda_2 W \beta_{k,j} E_{k,i} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2}{(\sigma^2 t_{k,i} + \beta_{k,j} E_{k,i} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2) \ln 2} \\
&\quad - \lambda_3 W \log_2 \left(1 + \frac{\beta_{k,i} E_{k,i} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2}{\beta_{k,j} E_{k,i} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2 + \sigma^2} \right) \\
&\quad + \frac{\lambda_3 t_{k,i} W \beta_{k,i} E_{k,i} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2 \sigma^2}{(\beta_{k,j} E_{k,i} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2 + \sigma^2 t_{k,i} + \beta_{k,i} E_{k,i} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2) (\beta_{k,j} E_{k,i} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2 + \sigma^2 t_{k,i}) \ln 2} = 0,
\end{aligned} \tag{A.8}$$

$$\frac{\partial \mathbb{L}}{\partial E_{k,j}} = 1 - \frac{\lambda_1 t_{k,j} W |h_{k,ji}|^2}{(E_{k,j} |h_{k,ji}|^2 + \sigma^2 t_{k,j}) \ln 2} = 0, \tag{A.9}$$

$$\begin{aligned}
\frac{\partial \mathbb{L}}{\partial E_{k,i}} &= 1 - \frac{\lambda_2 t_{k,i} W \beta_{k,j} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2}{(\sigma^2 t_{k,i} + \beta_{k,j} E_{k,i} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2) \ln 2} \\
&\quad - \frac{\lambda_3 t_{k,i}^2 W \beta_{k,i} \sigma^2 |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2 \sigma^2}{(\beta_{k,j} E_{k,i} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2 + \sigma^2 t_{k,i} + \beta_{k,i} E_{k,i} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2) (\beta_{k,j} E_{k,i} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2 + \sigma^2 t_{k,i}) \ln 2} = 0,
\end{aligned} \tag{A.10}$$

$$\frac{\partial \mathbb{L}}{\partial \lambda_1} = L_{k,j} - t_{k,j} W \log_2 \left(1 + \frac{E_{k,j}^{\text{off}} |h_{k,ji}|^2}{\sigma^2 t_{k,j}} \right) = 0, \tag{A.11}$$

$$\frac{\partial \mathbb{L}}{\partial \lambda_2} = L_{k,j} - t_{k,i} W \log_2 \left(1 + \frac{\beta_{k,j} E_{k,i}^{\text{off}} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2}{\sigma^2 t_{k,i}} \right) = 0, \tag{A.12}$$

$$\frac{\partial \mathbb{L}}{\partial \lambda_3} = L_{k,i} - t_{k,i} W \log_2 \left(1 + \frac{\frac{\beta_{k,i} E_{k,i}^{\text{off}} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2}{t_{k,i}}}{\frac{\beta_{k,j} E_{k,i}^{\text{off}} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2}{t_{k,i}} + \sigma^2} \right) = 0, \tag{A.13}$$

$$\frac{\partial \mathbb{L}}{\partial \lambda_4} = t_{k,j} + t_{k,i} - T/K = 0. \quad (\text{A.14})$$

Finally, the optimal solution of $t_{k,i}^*$ can be found by approximating (A.13) in the high SNR region, $\frac{\beta_{k,i} E_{k,i}^{\text{off}} |\mathbf{h}_{k,i}^H \mathbf{w}_k|^2}{t_{k,i}} \gg \sigma^2$, and solving the following approximated expression

$$\frac{\partial \mathbb{L}}{\partial \lambda_3} \approx L_{k,i} - t_{k,i} W \log_2 \left(1 + \frac{\beta_{k,i}}{\beta_{k,j}} \right) = 0, \quad (\text{A.15})$$

after getting $t_{k,i}^*$, the remaining optimal values for $t_{k,j}^*, E_{k,j}^*, E_{k,i}^*$ can be obtained by solving (A.14), (A.11), and (A.12), respectively. Subsequently, one can get $p_{k,j}^*, p_{k,i}^*$ by substituting $p_{k,j}^* = E_{k,j}^*/t_{k,j}^*$ and $p_{k,i}^* = E_{k,i}^*/t_{k,i}^*$. With this, the proof is completed.

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- *Journal Papers (Published/Submitted)*
 - [1] **Omar Maraqa**, Aditya S. Rajasekaran, Hamza U. Sokun, Saad Al-Ahmadi, Halim Yanikomeroglu, and Sadiq M. Sait, “Energy Minimization in MEC-

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- *Patents (Filed)*

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