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Analysis and Optimization for Robust Millimeter-Wave Communications

Cristian Tatino

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Norrköping 2021

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To my family

[IT] *"fatti non foste a viver come bruti, ma per seguir virtute e canoscenza"*.

[EN] *"you were not made to live your lives as brutes, but to be followers of worth and knowledge"*.

Dante Alighieri, La Divina Commedia, Inf.26.118-20.

Abstract

Spectrum scarcity is a longstanding problem in mobile telecommunications networks. Specifically, accommodating the ever-growing data rate and communications demand in the extensively used spectrum between 800 MHz and 6 GHz is becoming more challenging. For this reason, in the last years, communications in the millimeter-wave (mm-wave) frequency range (30-300 GHz) have attracted the interest of many researchers, who consider mm-wave communications a key enabler for upcoming generations of mobile communications, i.e., 5G and 6G. However, the signal propagation in the mm-wave frequency range is subject to more challenging conditions. High path loss and penetration loss may lead to short-range communications and frequent transmission interruptions when the signal path between the transmitter and the receiver is blocked.

In this dissertation, we analyze and optimize techniques that enhance the robustness and reliability of mm-wave communications. In the first part, we focus on approaches that allow user equipment (UE) to establish and maintain connections with multiple access points (APs) or relays, i.e., multi-connectivity (MC) and relaying techniques, to increase link failure robustness. In such scenarios, an inefficient link scheduling, i.e., over or under-provisioning of connections, can lead to either high interference and energy consumption or unsatisfied user's quality of service (QoS) requirements. In the first paper, we propose a novel link scheduling algorithm for network throughput maximization with constrained resources and quantify the potential gain of MC. As a complementary approach, in the second paper, we solve the problem of minimizing allocated resources while satisfying users' QoS requirements for mm-wave MC scenarios. To deal with the channel uncertainty and abrupt blockages, we propose a learning-based solution, of which the results highlight the tradeoff between reliability and allocated resource.

In the third paper, we perform throughput and delay analysis of a multi-user mm-wave wireless network assisted by a relay. We show the benefits of cooperative networking and the effects of directional communications on relay-aided mm-wave communications. These, as highlighted by the results, are characterized by a tradeoff between throughput and delay and are highly affected by the beam alignment duration and transmission strategy (directional or broadcast).

The second part of this dissertation focuses on problems related to mm-wave communications in industrial scenarios, where robots and new industrial applications require high data rates, and stringent reliability and latency requirements. In the fourth paper, we consider a multi-AP mm-wave wireless network covering an industrial plant where multiple moving robots need to be connected. We show how the joint optimization of robots' paths and the robot-AP associations can increase mm-wave robustness by decreasing the number of handovers and avoiding coverage holes. Finally, the fifth paper considers scenarios where robot-AP communications are assisted by an intelligent reflective surface (IRS). We show that the joint optimization of beamforming and trajectory of the robot can minimize the motion energy consumption while satisfying time and communication QoS constraints. Moreover, the proposed solution exploits a radio map to prevent collisions with obstacles and to increase mm-wave communication robustness by avoiding poorly covered areas.

Populärvetenskaplig sammenfatning

För telekommunikationsoperatörer är det avgörande att ha tillgång till frekvenser för att kunna överföra information, och det är en ständig konkurrens om att få använda nya frekvensband. Fram till den fjärde generationens mobilkommunikation (4G) har större delen av informationsöverföringen utförts genom att skicka signaler med frekvenser mellan 800 MHz och 2 GHz. Framtida kommunikationsbehov kräver att även andra, tidigare outnyttjade, frekvenser kan användas. Med anledning av detta har kommunikation med millimetervåg (mm-våg) intresserat många forskare, då dessa mm-vågor anses vara av stor betydelse för att kunna förbättra och utveckla nya sätt att kommunicera - det här berör t.ex. utvecklingen av 5G och 6G. En utmaning med mm-vågor, som innebär att relativt höga frekvenser används (30 GHz - 300 GHz), är dock att kommunikationsförutsättningarna blir mer besvärliga och signalerna når inte lika långt som om lägre frekvenser nyttjas.

Den första delen av den här avhandlingen fokuserar på att förbättra tillförlitligheten och räckvidden för mm-vågskommunikation. Detta är möjligt genom att tillämpa tekniker som ger förutsättningar för flera simultana anslutningar samt att signaler kan vidarebefordras på ett lämpligt sätt inom ett kommunikationsnätverk. Parallella anslutningar och vidarebefordring ökar antalet kommunikationsvägar som kan användas och minskar risken för att information inte når fram till avsedd mottagare. För ett tillfredsställande resultat krävs dock lämpliga principer för hur man nyttjar olika kommunikationsvägar. Olämplig hantering kan t.ex. resultera i att resurser används på ett ineffektivt sätt eller att kommunikationen upplevs vara av bristande kvalitet. I avhandlingen beskrivs den potential som finns med att

nyttja flera parallella kommunikationsvägar och ett tillvägagångssätt, baserat på maskininlärning, föreslås där avsikten är att med ett minimalt nyttjande av resurser tillhandahålla tillräcklig prestanda för lyckad kommunikation. Dessutom presenteras fördelar som kan erhållas om kommunicerande noder i ett nätverk samarbetar effektivt, för att därigenom uppnå en prestanda som ej är möjlig utan samarbete.

Det finns många kommunikationsutmaningar med koppling till industriella tillämpningar, och detta är något som avhandlingen också behandlar. Kommunikation till och från exempelvis robotar kan ställa höga krav på snabb, omfattande och tillförlitlig informationsöverföring. I avhandlingen föreslås en algoritm som har för avsikt att möjliggöra effektiv kommunikation i en industriell anläggning där mobila robotar färdas och mm-vågor används för att ansluta till och kommunicera med flertalet omkringliggande noder. Avhandlingen beskriver också hur robotar på ett effektivt sätt kan navigera och kommunicera i miljöer med färre noder, där kommunikationsavståndet kan vara förhållandevis långt. Det tillvägagångssätt som föreslås i detta fall är att nyttja intelligenta ytor som mm-vågor kan reflekteras mot för att därigenom färdas längre.

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Norrköping, February 2021
Cristian Tatino

Abbreviations

3GPP	3rd Generation Partnership Project
4G	fourth generation of mobile networks
5G	fifth generation of mobile networks
AF	amplify and forward
AP	access point
BIP	binary integer programming
CA	carrier aggregation
CG	column generation
CoMP	coordinated mutlipoint
D2D	device-to-device
DC	dual connectivity
DF	decode and forward
FCC	federal communications commission
FD	full-duplex
HD	half-duplex
IP	integer programming
ILP	integer linear programming
IRS	intelligent reflective surface

ITU	international telecommunication union
LB-BS	low-band base station
LP	linear programming
LTE	long term evolution
LOS	line-of-sight
mm-wave	millimeter-wave
mmAP	millimeter-wave access point
MC	multi-connectivity
ML	Machine learning
MIP	mixed integer programming
NC	network controller
NR	5G new radio
NLOS	non line-of-sight
QoS	quality of service
Rx	receiver
SC	single connectivity
SCO	successive convex optimization
SINR	signal-to-interference-plus-noise ratio
SNR	signal-to-noise ratio
Tx	transmitter
UAV	unmanned aerial vehicle
UE	user equipment
VAR	virtual and augmented reality
WLAN	wireless local area network
WPAN	wireless personal area network

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Part I

Introduction and Overview

Chapter 1

Introduction

1.1 Millimeter-Wave Communications Background

Wireless communications technologies have already changed the way to communicate and interact for billions of people. According to [1], over 70% of the global population will have mobile connectivity by 2023. Even more significant growth is expected by machine-type connections and autonomous vehicles, i.e., intelligent transportation systems, drones, and robots that will represent half of the globally connected devices by 2023. The tremendous increase of connections will be followed by the development of new data-hungry applications, e.g., virtual and augmented reality (VAR), that will generate a huge amount of traffic. This is estimated to grow at an annual rate of around 55 % between 2020 and 2030 reaching the incredible amount of 5,000 exabytes (EX) of data traffic [2]. Mainly three approaches are driving the research to accommodate this ever-growing connection and traffic demand: i) increase the number of antennas at the transmitter (Tx) and the receiver (Rx), ii) densification of radio base stations, and iii) increase the spectrum resources by using new frequency bands. The latter solution identifies millimeter-wave (mm-wave) communications as a key technology for the next generations of mobile communications. Specifically, mm-wave communications exploit the huge amount of frequency bands from 30 GHz to 300 GHz¹ to meet the rising demand for connections and traffic. However, as explained in more detail below, the signal propagation at

¹Note that also the 24-30 GHz band is usually considered in the mm-wave frequency range.

Figure 1.1: Mm-wave candidate bands to the mobile service by the international telecommunication union (ITU) [3], and mm-wave spectrum auctioned by the federal communications commission (FCC) [4].

mm-wave frequency ranges has some peculiarities that decrease the reliability of communications, especially for scenarios that are characterized by mobility and numerous physical obstacles.

Millimeter-wave Frequency Bands and Propagation Characteristics

Several frequency bands have been identified for accommodating mm-wave mobile communications, e.g., 24.25-27.5 GHz, 37-40.5 GHz, 47.2-50.2 GHz, 50.4-52.6 GHz, 66-76 GHz, and 81-86 GHz [3]. As shown in Fig. 1.1, some countries have already performed public auctions for allocating part of them [5], whereas the 60 GHz band is planned to be assigned to unlicensed mm-wave communications [6]. Measurements and tests at these frequency bands have shown that mm-wave communications can reach several Gbps of data rate [7, 8]. However, free space path loss and atmosphere absorption dramatically increase at such high frequencies, leading to shorter communication range [9, 10]. Moreover, mm-waves are characterized by high penetration loss that leads to frequent interruptions when an obstacle blocks the signal paths (blockage) [11, 12]. In general, the line-of-sight (LOS), or direct path, presents the highest channel gain in comparison to the reflected paths, whose channel gains could be 30 dB worse. However, good reflectors, e.g., metal smooth objects and tinted glasses, can lead to signal paths with higher gains [9].

Figure 1.2: Beam scanning for the alignment phase with a predefined set of beams (codebook) followed by directional uplink transmissions. Each beam is labelled with an ID.

Directional Communications and Beamforming

Directional communications can be used to partially solve the high path loss for mm-waves. Specifically, the small wavelength allows constructing arrays of antennas with many elements in a limited space that can focus the energy in narrow beams towards adjustable directions. Although narrow beams provide high beamforming gain and can decrease the interference level [13], they are more sensitive to communication interruptions caused by blockages. Moreover, narrow beams introduce further complexity and delay when a connection needs to be established or recovered. Namely, to reach enough beamforming gain, both the receiver and the transmitter need to estimate the channel during the beam alignment phase. The performance of this procedure in terms of energy consumption, achieved beamforming gain, complexity, and duration, highly depends on which beamforming technique is used, i.e., digital, analog, or hybrid [14, 15]. Digital beamforming supports multi-stream transmissions, but each antenna is equipped with a radio frequency chain and channel between every pair of antenna elements at the transmitter and receiver must be estimated [15]. Although digital beamforming provides higher beamforming gains than analog beamforming, the former is characterized by higher energy consumption and cost than the latter, which supports single-stream transmissions. Specifically, in analog beamforming, all the antennas usually share the same radio frequency chain and the beam alignment phase involves a simpler procedure. As shown in Fig. 1.2, the transmitter and receiver search for the best Tx-Rx beam pair that maximizes the gain by sending pilots in a predefined set of directions (codebook) by adjusting the phase shifters for each antenna element [16, 17]. Finally, hybrid beamforming combines

analog and digital beamforming techniques by grouping multiple antenna elements into subarray modules to balance performance and cost tradeoffs. In general, in digital, hybrid, and analog beamforming, a beam alignment and a channel estimation involve transmissions of a sequence of pilot signals that consume power, time, and frequency resources.

Initial Access and Mobility Management

Initial access and mobility management are fundamental wireless network functionalities. The former aims to establish an initial connection between a user equipment (UE) and a cell or access point (AP), whereas the latter aims to trace UEs while changing their locations to provide continuous connectivity. At the initial access of a UE, several procedures must be performed, e.g., cell detection, access request, and channel estimation [18, 19, 20]. However, the use of narrow beams and the high path loss increase the complexity of initial access and mobility management procedures with respect to lower frequencies communications. Specifically, an omnidirectional cell detection may not be an appropriate solution for mm-wave communications, and the mobility of UEs can rapidly lead to beam misalignment [21] that dramatically reduce the beamforming gains of communications. Thus, channel estimations must be frequently repeated due to the UE movement. Moreover, the blockage sensitivity and high path loss cause a spottier coverage. This requires a dense deployment of mm-wave cells and APs. In such scenarios, the maximum signal-to-noise ratio (SNR) criteria for selecting the cell and AP association can lead to frequent handovers and costly beam alignment procedures [22]. Thus, optimized mobility management and association would lead to a significant enhancement of network performance at millimeter-wave communications.

Applications for Millimeter-wave Communications

For all these reasons, mm-wave wireless networks were initially studied for scenarios and applications that are characterized by short-range communications, low mobility, and LOS between the receivers and the transmitters. This view has led to technologies for providing access to wireless local area network (WLAN) and wireless personal area network (WPAN), such as the standards 802.11ad [23] and 802.15.3 [24], both operating in the 60 GHz band. Mm-waves

are also good candidates to provide access to networks in scenarios that are characterized by high data and density connection demand, e.g., data centers, malls, airports, and stadiums, for which intensive measurement campaigns have been performed [25, 26]. Moreover, the possibility to transmit a huge amount of data and directional communications make mm-waves ideal solutions for the deployment of low-cost wireless backhaulings [27, 28]. Directional communications have been also exploited to develop localization technologies and radars that work in mm-wave frequency bands [29, 30, 31].

The huge amount of bandwidth at mm-wave frequency bands is leading academic and industrial researchers to study and analyze mm-wave technology solutions also for other scenarios and applications that are characterized by mobility and non line-of-sight (NLOS) conditions, e.g., cellular access and industrial scenarios. Specifically, 5G new radio (NR) operating at mm-waves are under standardization by 3rd Generation Partnership Project (3GPP) and have been already tested successfully for the cellular access [32]. Moreover, mm-wave communications for industrial scenarios have recently attracted the interest of researchers [33, 34, 35, 36]. More precisely, real-time industrial applications, such as VAR for assisted manufacturing or mining, may require Gbps for peak data rates [37] that can be accommodated in the mm-wave frequency bands.

However, both industrial and outdoor cellular access applications require reliable and robust connections in dynamic environments that are characterized by high mobility and obstacle density. Indeed, the analysis and optimization of solutions for increasing the robustness in outdoor and industrial mm-wave wireless networks are the main topics of the five papers presented in this thesis.

1.2 Purpose and Scope

The aim of the thesis is to analyze and optimize techniques that enhance the robustness and reliability of mm-wave communications. This would allow the industry to exploit a huge amount of spectrum also for dynamic scenarios and applications with stringent quality of service (QoS) requirements. We focus on solutions that optimize mobility management or simultaneously provide multiple connections to UEs, i.e., multi-connectivity (MC), relaying, and intelligent reflective surface (IRS)s. With the above-mentioned goal, the following research questions are stated:

- Q1 What are the gains of MC in terms of throughput and reliability?
- Q2 What are the issues, the main tradeoffs, and costs that characterize MC and relaying techniques?
- Q3 What are the gains of cooperative relaying in terms of throughput and reliability for mm-wave wireless networks?
- Q4 What are the key system parameters and mm-wave propagation characteristics that mostly affect the performance of these techniques?
- Q5 How do optimized association and mobility management for mm-wave communications improve the robustness and affect robot trajectories in industrial scenarios?
- Q6 How do optimized robot trajectories improve the robustness for mm-wave communications in industrial scenarios?
- Q7 Finally, how does improving radio coverage to increase robustness enhance the robot energy efficiency in mm-wave industrial scenarios?

1.3 Thesis Outline and Organization

The thesis is divided into two parts. In Part I, we provide a general introduction to the concepts and problems of MC, cooperative relaying, IRSs, and mobility management for mm-wave communications. In Chapter 3, we introduce the mathematical tools we have used to approach the proposed problems. In Chapter 4, we describe the contributions of the five research papers that form Part II.

Chapter 2

Robust Connectivity in Millimeter-Waves

Robustness is the property of a system to withstand stresses, perturbations, and unpredictable variations in its operating environment without loss of functionality. Robustness is defined with respect to particular events that can disturb the operative conditions and is related to the design of the system. Otherwise specified, in this thesis we consider the robustness of mm-wave communications with respect to a connection (or link) failure. Another term that is often used in this thesis is *reliability*. This is a quantitative value that measures the success probability of a system in providing a service under certain quality constraints. Reliability is usually measured in percentage (%), e.g., for the fifth generation of mobile networks (5G), ultra reliable communications require the 99.999 % of successfully received packets. Reliability and robustness are different concepts, however, in many cases, by increasing the latter it is possible to enhance the former.

As introduced in Chapter 1, the peculiarities of mm-waves make the communications in this frequency range less reliable than lower frequencies and less robust with respect to blockages. Even a human body can block transmission by decreasing the received power by 30 dB [38]. However, the huge amount of frequency resources represent a big opportunity for telecom operators to provide high throughput transmissions and increase the number of served UEs. Therefore, researchers have proposed several solutions to increase robustness and reliability for mm-wave communications. This thesis analyzes the

performance gains and provides solutions to distinctive optimization problems that characterize some of these techniques.

Most of these above-mentioned techniques try to increase the number of available links and alternative signal paths between Tx and Rx. This can be combined with mechanisms that allow Tx-Rx pairs to fast switch link when the one that is used for the communication is interrupted. Communication interruptions may occur for several reasons, such as blockages, a beam misalignment that drastically decreases the beamforming gain due to mobility, and increasing Tx-Rx distance that causes a dramatic drop of the received power. Measurements and analysis have shown a dramatic performance gain when spatial diversity is used to enhance coverage in mm-wave communications [39, 40, 41]. By combining a proper coverage plan [42] and mechanisms for providing connections from multiple APs/cells, e.g., MC and relaying techniques, we can significantly improve throughput, reliability, and robustness in mm-wave communications [43, 44].

Another solution consists of rapidly re-establishing the communication in case of blockage by using alternative Tx-Rx signal paths, as proposed by [45]. More precisely, Tx and Rx nodes store several beam pairs, which are evaluated during the beam alignment phase. Then, if the beam pair that is used for the communications experiences a blockage, the Tx and Rx can quickly switch to alternative beams that exploit other signal paths. Note that the strongest path is represented by the LOS one, and, when this is blocked, alternative paths are provided by reflections. An example of beams that exploit direct and reflected paths, which are transmitted by a millimeter-wave access point (mmAP), is shown in Fig. 2.1. Contributions to the coverage provided by reflections and reflected beams are analyzed in [46, 47, 48].

As shown in [46], in some particular scenarios, the contributions of the reflected beams are not negligible and they can be used as alternative paths when the LOS one is blocked. However, in many cases, connections that are established mainly using reflected paths are unstable and unreliable depending on the obstacles' positions, sizes, orientation, and materials. In this regard, IRSs (also referred to as reconfigurable intelligent surfaces or metasurfaces) are attracting the interest of research as a breakthrough technology. Specifically, IRSs can efficiently control the reflections of the incident signals such that these can be either added coherently or destructively to Rx nodes for increasing the received power or suppress interference,

Figure 2.1: Example of direct and reflected beams.

respectively [49]. In the following sections, we will discuss in more detail the techniques, i.e., MC, relaying technology, and IRSs, that are related to our work. Finally, in the last section of this chapter, we will show how mobility management and association optimization can improve connectivity robustness and reliability by decreasing the number of handovers and avoiding coverage holes. These solutions are particularly effective when applied to autonomous vehicles for which we can control the mobility.

2.1 Multi-connectivity

Multi-connectivity (MC) is a technology that allows a UE to establish and maintain multiple connections at the same time. Together with a proper coverage planning, MC can increase mm-wave communication robustness. Multiple connections can be established either by using several resources of the same node (intra-site), e.g., different frequency bands, or with multiple cells/APs (inter-site). The latter exploits spatial macro-diversity to provide independent links [50, 39, 40, 43]. We can also distinguish between inter-frequency and intra-frequency MC, depending on whether the multiple connections use the same frequency band or not. These solutions can be combined, as in Fig. 2.2, which shows an example of an inter-site and inter-frequency MC scenario where the UE is connected to two mmAPs and one low-band base station (LB-BS). Moreover, MC can be either throughput or reliability oriented. More precisely, according to [51], MC is characterized by a tradeoff between reliability and throughput that are improved

Figure 2.2: Inter-site and Inter-frequency multi-connectivity scenario with two mmAPs and one LB-BS. These are connected to a centralized network controller (NC) co-located with the LB-BS.

by increasing multiplexing and diversity gain of the communication, respectively. The main purpose of the throughput oriented MC is to increase the data rate by transmitting different data on several established connections. These, in a reliability oriented approach, are used by Tx nodes to send the same data that are combined at the Rx node by using several possible combining techniques (e.g., maximum ratio combining and selection combining).

3GPP has defined for the fourth generation of mobile networks (4G) several versions of MC at different layers, e.g., dual connectivity (DC), carrier aggregation (CA), and coordinated multipoint (CoMP) [52]. For 5G, the technical specification [53] defines several possible solutions and architectures for both stand-alone and non-standalone MC scenarios. In the former case, 5G NRs are assisted by legacy standards, e.g., long term evolution (LTE), whereas, for stand-alone architectures, MC is performed by using only 5G NRs.

Several studies, e.g., [54, 55, 56], have performed analysis of MC in mm-wave scenarios and have demonstrated the performance gain in terms of coverage, throughput, and reliability. Mm-waves can also be assisted by lower frequencies communications. A similar solution is proposed in [57] that considers a non-standalone mm-wave MC, with mmAPs and lower frequency technologies, e.g., LTE, that act as the data and the control planes, respectively. This is a common approach

for 5G systems and it is used also in [58] to improve and speed up the initial access and the beamforming alignment. Indeed, the latter represents a serious challenge for MC in mm-waves, where the UE needs to establish multiple connections and perform beam tracking with several mmAPs. The number of connections that can be established, the beamforming gain, and the duration of the initial access, highly depends on the beamforming techniques (i.e., digital, hybrid, or analog), the number of antennas, and radio frequency chains with which a node is equipped. These important aspects of the MC for mm-waves are analyzed in [20, 59]. In this regard, machine learning techniques can be used to reduce the complexity of the channel estimation and beam alignment with several mmAPs [60].

Another important aspect, on which we will focus in the first two papers of the thesis, is link scheduling. In an environment where a UE is in the coverage of several mmAPs, we need to decide which and how many connections the UE should use for the communications. The number of links and the selection of them can tremendously impact the network performance. In general, by serving a UE with multiple connections, we can increase the throughput and the reliability (by increasing either the diversity or multiplexing gain), but at the same time, the interference level and the consumed resources are increased. Resources here include frequency band, power budget, backhaul capacity, antennas, and radio frequency chains. Thus, we can observe that there is a clear tradeoff between the number of served UEs and the achieved throughput or reliability, or in general, between consumed resources and achieved QoS.

2.2 Relaying Technology

The main purpose of relaying techniques is to provide alternative paths to the direct one (source-destination) to increase robustness, reliability, coverage, and throughput of wireless networks. When the direct path either does not have enough channel gain or it is not available (e.g., out of coverage or blocked), the UE can transmit to an intermediate node called relay. This, in single-hop relaying, transmits the information to the destination node by either a wired or a wireless link, whereas, in the multi-hop relaying technique [61], several relays are used to reach the destination node. Relay nodes usually they do not have their own traffic and can be either stationary nodes, as powerful as a mmAP, or mobile devices with constrained energy capacity

Figure 2.3: Uplink directional mm-wave communications assisted by a buffer-aided relay. On the left, the UE transmits a packet directly to the mmAP (destination), whereas, on the right, the UE transmits a packet to the relay.

and limited computational power as in device-to-device (D2D) relaying techniques [62]. We can distinguish between full-duplex (FD) and half-duplex (HD) relays [63, 64, 65], depending on whether the relay node can receive and transmit simultaneously or not. Moreover, we can differentiate between amplify and forward (AF) [66] and decode and forward (DF) relays [67]. The latter decodes, re-modulates, and retransmits the received signal, whereas, the former simply amplifies and retransmits the signal without decoding. Although AF relays are simpler and cheaper, DF relays guarantee higher performance. Furthermore, relays can be equipped with a queue that allows them to store received packets and to transmit them when the wireless conditions are favorable [68, 69].

Given the blockage sensitivity and the high path loss of mm-wave communications, relays can represent a powerful tool. Specifically, relays can be used to decrease communication interruptions by providing alternative LOS paths [67, 70, 71, 72], or to overcome the severe penetration loss for outdoor-indoor communications [73]. When the relay is fixed, a proper relay placement is crucial to provide LOS links between the relay and the destination and the Tx nodes. However, the use of narrow beams in mm-waves introduces further complexity. More precisely, unlike omnidirectional communications, Tx nodes may not be able to simultaneously transmit to both the destination and the relay. As shown in Fig. 2.3, the Tx node chooses to send a packet either to the relay or to the destination. The effect of directional transmissions in relaying techniques for mm-waves is studied in the third paper of the thesis.

When multiple relays are available, multi-hop routing and relay selection are key functionalities that may highly affect network performance. In this regard, several schemes have been proposed and analyzed both for mm-wave and low-frequency communications [67, 70, 74, 75, 76, 77]. Moreover, given the high blockage sensitivity, it could be important for mm-wave wireless networks to account for the spatial correlation between the Tx-destination and the Tx-relay links during the relay selection procedure. Specifically, as shown in [78], an obstacle could block both of these links, and an optimal angular distance between the relay and the destination to maximize the success transmission probability can be computed.

2.3 Intelligent Reflective Surfaces

In recent years, intelligent reflective surfaces (IRSs) have been identified as a breakthrough technology for the next generations of mobile communications, e.g., 6G [79, 80]. IRSs consist of arrays of reflective elements that can be electronically controlled to adjust the angle and the phase of the reflected signals to be either added coherently or destructively to the receiver [49, 81]. The reflective elements can be made of several types of material, e.g., reflectarrays, liquid crystal surfaces, and software-defined meta-surfaces, that have specific electromagnetic characteristics [82, 83]. These reflective elements are electronically controlled by a controller to change the amplitude, phase, and even polarization of the incident signal to either increase the received power at the intended Rx or suppress interference at non-intended Rx nodes. These functions can be even selected through a software-defined interface for controlling the electromagnetic environment [84, 85] to enhance the coverage, throughput, reliability, and security.

Similarly to AF relays, IRSs are transparent with respect to Tx and Rx nodes. However, IRSs do not amplify the signals and they operate in a FD mode without introducing further noise or interference [82, 86]. In [87], the authors have performed a comparative performance analysis between IRSs and DF relays and the analysis has revealed the competitiveness of IRSs with respect to DF relays, especially when the number of reflective elements is sufficiently large. Furthermore, IRSs are nearly passive with a negligible energy consumption. All these characteristics make them a low-cost effective solution as an alternative to AF or DF relays.

Figure 2.4: Uplink IRS-assisted mm-wave communications. The controller is connected to both the AP and the IRS in order to jointly optimize the beamforming at the AP and the IRS. The terms G , h_d , and h_r represent the IRS-AP, UE-AP, and UE-IRS channels.

IRSs have also shown to be incredibly effective at mm-wave frequency bands and, similarly to relays, can provide alternative paths in NLOS conditions to overcome blockages and increase robustness of mm-wave communications [49, 88]. Moreover, IRSs have been recently tested successfully in the 28 GHz band by NTT DOCOMO [89], but research is still at the early stage and ongoing trends include: path loss modelling [81, 90], beamforming optimization [91, 92], designing and materials [93, 94], and AI controllable environments [95, 96].

Low-cost deployment and small energy consumption of IRSs make them attractive for improving throughput and reliability of unmanned aerial vehicle (UAV)-assisted communications [97, 98]. In this scenario, the possibility to control the position of UAVs requires a joint optimization of IRS beamforming and UAV's trajectory. A similar problem arises in mm-wave wireless networks in industrial scenarios with wirelessly connected robots that are considered in the fifth paper of this thesis.

2.4 Mobility Management and Association Optimization

Mobility management is a wireless network functionality that aims to trace mobile users while changing their locations to continuously provide connectivity. This is a critical functionality for mm-wave wireless networks operating in dynamic scenarios, where, beam alignments and channel estimations must be performed continuously to

Figure 2.5: A robot moving in an area covered by three mmAPs. The robot is connected to mmAP 1 and, given its trajectory, it is easy to predict blockages and handovers. For this scenario, an handover to mmAP 2 will lead to a blockage, whereas, an handover to mmAP 3 can guarantee a longer connection and more reliable communications.

avoid the degradation of the beamforming gain. More precisely, the high path loss and penetration loss decrease communication ranges and cause spottier coverage that requires denser cell deployments. Moreover, the mobility of the user and obstacles can create temporary blockages and strong reflections. In such scenarios, abrupt blockages make the maximum SNR criterion to perform associations highly inefficient leading to unnecessary handovers that cause frequent communication interruptions. These significantly decrease network performance, e.g., throughput, delay, and reliability, which can be enhanced with handover and blockage prediction and optimized associations. These schemes can be combined with methods that reduce the beam alignment and channel estimation overhead. As shown in [56, 99], MC can be used to avoid communication interruptions during a handover or a blockage by having multiple connections that are simultaneously active. Other solutions involve methods that use context information including SNR, beam ID, radio maps, users' position, and even camera images [100, 101, 102, 103]. Given such information, the network can predict possible blockages and select the optimal mmAP to perform a handover with, or reduce the duration of the initial access and beam alignment. Moreover, machine learning methods and context information can be jointly used to improve the performance of context-aware solutions. These methods can be

used to predict blockages and optimize handovers [104, 105], reduce beamforming complexity [60, 106], and both [107, 108].

As shown in Fig. 2.5, handovers and blockages in multi-mmAP scenarios are easier to predict for autonomous vehicles (such as robots) [109] with respect to conventional vehicles. Namely, robots' trajectory can be controlled. This introduces an additional degree of freedom to avoid coverage holes and minimize the number of handovers that has been fully exploited in the fourth paper of this thesis.

Chapter 3

Mathematical Modeling and Solution Tools

In this chapter, we briefly introduce the underlying theory of the main mathematical tools that have been used in the papers.

3.1 Mathematical Optimization

A general optimization problem can be defined as follows:

$$\min_{\mathbf{x}} f(\mathbf{x}) \tag{3.1a}$$

$$\text{s.t. } g_i(\mathbf{x}) \leq 0, \quad i = 1, \dots, p, \tag{3.1b}$$

$$h_j(\mathbf{x}) = 0, \quad j = 1, \dots, q, \tag{3.1c}$$

where, $\mathbf{x}$ represents the n -dimensional vector of optimization variables of the problem. Function $f(\mathbf{x})$ is the objective function, $g_i(\mathbf{x})$ and $h_j(\mathbf{x})$ represent inequality and equality constraints. The set of all the possible points $\mathbf{x}$ that satisfy these constraints is called *feasible region*. This model describes the problem of finding $\mathbf{x}^*$ in the feasible region that minimizes the objective function. If $f(\mathbf{x}^*) = -\infty$, then the problem is *unbounded*. The problem is *infeasible* if the feasible region is empty. Optimization problems can be classified according to the shape of objective function and constraints (linear, non-linear, convex, non-convex), and variables (continuous, discrete, binary).

3.1.1 Integer and Combinatorial Optimization

In integer optimization problems, also referred to as integer programming (IP), the variables are constrained to be integer values. If the objective function is linear, we have an integer linear programming (ILP) that can be formulated as follows:

$$IP : \min_{\mathbf{x}} \mathbf{c}^T \mathbf{x} \quad (3.2a)$$

$$\text{s.t. } \mathbf{A}\mathbf{x} = \mathbf{b}, \quad (3.2b)$$

$$\mathbf{x} \geq 0 \text{ and integer.} \quad (3.2c)$$

This is the same formulation of a linear programming (LP) in standard form, but with the integrality constraint of the variables. In this formulation, $\mathbf{A}$ is an m by n matrix, $\mathbf{c}^T$ is an n -dimensional row vector, and $\mathbf{b}$ is an m -dimensional column vector. Classes of IP problems are binary integer programming (BIP) and mixed integer programming (MIP) where the variables are binary or a mix of integer and continuous variables. Combinatorial problems are a class problems that are characterized by a discrete set of solutions and often formulated using IP models. Well-known combinatorial problems include minimum spanning tree, traveling salesman, and cutting stock.

IPs are more challenging to solve than LPs, and global optimality is hard to achieve in general. Methods that aim to optimally solve IPs include cutting plane, branch-and-bound, and branch-and-cut algorithms. However, the complexity of these methods grow exponentially with the number of variables. In this regard, computational complexity theory classifies problems according to their tractability, and several classes have been identified. Without going into details (these can be found in [110]), we can first distinguish two classes of problems: non-deterministic polynomial (NP) and NP-hard problems. The former is a class of *decision problems* for which there is a polynomial-size proof of the answer for any instance for which the answer is "yes", whereas, a problem is NP-hard if any problem in NP can be reduced to it in polynomial time. If a problem is NP-hard and its decision problem is NP, then the latter is NP-complete (NP-C). Finally, polynomial (P) is a class of decision problems in NP that can be optimally solved in polynomial time. This class of problems is the easiest to solve, whereas, for NP-hard problems, global optimality is often hard to achieve, and other methods must be used. These usually aim to rapidly find a suboptimal solution that is close enough to the optimal one. In this regard, it is crucial to derive good optimality

bound for the solution of the problem. Specifically, we distinguish between primal and dual bounds that, for a minimization problem, provide upper and lower bounds, respectively. Primal bounds can be obtained by any feasible solution, whereas, dual bounds involve complex relaxation techniques (e.g., linear, combinatorial, and Lagrangian) [110]. We now present the column generation (CG) method that has been initially applied to LPs to deal with a large number of variables. However, as explained in the following, CG can be used for providing sub-optimal solutions for some IPs that suffers from large dimensionality.

Column Generation

In Papers I and IV, we have used heuristics that are based on a CG algorithm for solving two combinatorial optimization problems. CG is a decomposition technique that can be used for solving LPs that present a large number of variables. At an LP optimum, only a small subset of variables contribute to the final solution, and these can be iteratively generated starting from an initial feasible solution. Specifically, a CG-based algorithm starts from a subset of variables that correspond to columns of $\mathbf{A}$. This restricted problem is called *master problem* that is solved to obtain the optimal dual values for each constraint. These are used to construct the *pricing problem*, of the which solution provides the new variable and corresponding column of $\mathbf{A}$ to be included in the master problem.

The above process is iteratively repeated until no new improving column can be generated by the pricing problem. Note that CG requires the variables to be continuous, but we can apply CG to IPs by considering the continuous relaxation. When the generation of columns is terminated, we proceed by solving the master problem that, at this stage, provides an optimal solution for LPs. However, this does not hold for IPs, for which the variables of the master problem must be converted to be integer. The resulting problem does not guarantee optimality and, in some cases, can lead to infeasibility. For this reason, CG-based algorithms for IP usually include further steps to generate a final integer solution.

For further detail on IP and CG, the reader is referred to [110, 111, 112].

3.1.2 Convex Optimization

In a convex optimization problem (COP), $f(\mathbf{x})$ and $g_i(\mathbf{x})$ are convex functions, and $h_j(\mathbf{x})$ are affine, i.e., $h_j(\mathbf{x}) = \mathbf{a}_j^T \mathbf{x} - b_j$. Given these conditions, the feasible set is a convex set. Maximization of a concave function with convex inequality constraint functions and affine equality constraints is also a convex optimization problem. A fundamental property of COPs is that any locally optimal point is also globally optimal. Moreover, strong duality holds for COPs, and necessary and sufficient conditions to the optimality can be easily found, i.e., the Karush-Kuhn-Tucker (KKT) conditions [113]. More precisely, in any COP with differentiable objective and constraint functions, any primal and dual optimal points satisfy the KKT conditions and have zero duality gap. These properties make COPs particularly easy to solve and fast algorithms have been developed, e.g., interior point methods [114].

It is possible to use methods developed to solve COPs to tackle non-convex problems. However, in these cases, optimality is not guaranteed and the optimization can provide a locally optimal solution that may be far from the global optimum. In this regard, in Paper V, we have used a successive convex optimization (SCO) algorithm [115]. This technique is particularly effective to solve non-convex problems by exploiting convex programming.

Successive Convex Optimization

SCO is an heuristic that leverages convex programming to solve non-convex problems. The goal of SCO techniques is to find a local tightly convex approximation to a given optimization problem with possibly non-convex objective and constraint functions. Specifically, consider problem (3.1), and assume $f(\mathbf{x})$ and $g_i(\mathbf{x})$ are non-convex functions. Then, in a small neighbourhood (trust region) of an initial point $\mathbf{x}_0$, we can find convex upper bounds to $f(\mathbf{x})$ and $g_i(\mathbf{x})$, i.e., $\hat{f}_0(\mathbf{x}, \mathbf{x}_0)$ and $\hat{f}_i(\mathbf{x}, \mathbf{x}_0)$, respectively. These are used to replace $f(\mathbf{x})$ and $g_i(\mathbf{x})$ in (3.1) to obtain a local convex approximation of the original problem. This can be easily solved by using techniques for solving COPs and the solution is used as next local point to construct the successive local approximation. The above process is repeated until the convergence is reached. It is possible to prove that, under certain conditions [115], the algorithm converges to a KKT point of the original problem. For further details of COP and SCO, the reader is referred to [113, 115].

3.2 Machine Learning

Machine learning (ML) is an application of artificial intelligence that aims to automatically derive models by extracting patterns directly from raw data (dataset) to perform prediction, classification and clustering tasks. The main benefits include lower costs for human interventions and the possibility to derive models that describe complex phenomena. Algorithms that can be classified as ML techniques have been developed since the 1950s, but nowadays ML is experiencing a golden age thanks also to wireless communications and pervasive sensor networks that have dramatically increased the possibility and decreased the cost of obtaining large datasets. ML applications are countless and include object detection, image classification, speech recognition, anomaly detection, stock market prediction, and disease diagnosis. Specifically, ML represents a key enabler technology for several fields, e.g., robotics, automotive, and image and video processing. Starting from 5G, ML has been gradually used for developing algorithms to enhance wireless communication performance [60, 106, 108] and it is expected that the role of ML will be even more crucial for next generations of mobile networks [2, 37].

ML algorithms usually consist of a learning (or training) and a prediction phase. During the learning phase, the model is inferred from a set of training examples (training dataset) to maximize the prediction accuracy (minimize the prediction error). Each example of the training set usually consists of several *features*. During the prediction phase, the model is used to perform one of the following tasks:

- Regression tasks aim to predict quantitative values, e.g., stock market value and SNR predictions.
- The output of classification tasks is a qualitative response and takes on values in one of a discrete set of classes. Example of classification tasks are disease diagnosis, fault and anomaly detection, and object classification.
- Clustering is the task of finding subgroups (clusters) in a dataset, where, the elements belonging to a cluster present certain similarities in the features. Clustering is used in data compression, pattern recognition, and market research.

Moreover, it is possible to identify two main learning strategies [116]:

- In a supervised learning strategy, the dataset for training the model includes a set of input training examples and the cor-

responding true values (label) that must be predicted by the model. Examples of ML techniques that use supervised learning strategy are linear regression, logistic regressions, neural networks (NN), decision trees, and support vector machines for classification and regression tasks. During the learning phase, the error between the predicted value provided by the model and the true value is minimized by using several gradient descent-based algorithms.

- Unsupervised learning consists of inferring unknown patterns and regularities of the data from an unlabeled training set. Possible applications for this type of learning techniques include clustering and segmentation by using NNs, K-means clustering algorithm, and principle component analysis (PCA).
- Semi-supervised learning strategy combines labeled and unlabeled training examples.

Although reinforcement learning uses one of the above-mentioned strategies, it can be considered a fourth approach because the learning phase is performed online. Specifically, the training examples are gradually acquired and, when a new observation is obtained, the model performs a prediction that is evaluated according to a reward function and the system learns by experience [117].

Several tradeoffs characterize ML techniques e.g., flexibility (or complexity)/interpretability and bias/variance tradeoffs. Specifically, more flexible models are able to learn to describe more phenomena, however, the interpretation of the model results is more complex. Moreover, higher and lower flexibility increase the variance and the bias of the model, respectively, which contribute to the prediction error.

3.2.1 Decision Trees and Random Forests

Decision trees are ML techniques that can be applied to both regression and classification tasks. During the learning phase, a decision tree divides the features space of the training examples into several regions. For an observation that belongs to a certain region, the average value and the most representative class of the region are used to perform the regression and classification tasks, respectively. Despite the high interpretability of this method, decision trees suffer from high variance. This can be reduced by training several decorrelated decision trees (random forests) on different subsets of the training

dataset. During the prediction phase, the results of the different decision trees are averaged. For further detail on ML, decision trees, and random forests, the reader is referred to [116, 118, 119].

3.3 Queuing Theory

Queuing theory represents a powerful mathematical tool with a large number of applications, e.g., transportation, finance, logistic, and communication networks. Specifically, queuing analysis can be used to study dynamic systems and obtain the following key performance parameters (KPIs): system stability, average queue size, average throughput, average delay, and outage probability. To derive this information, we first describe the queuing system by defining the following characteristics: arrival statistics (A), service or departure statistics (B), number of servers (c), queue size (n), and customer population size (p). These form what is called Kendall's notation $A/B/c/n/p$ that, together with the service discipline, e.g., FIFO (first-in, first-out) or LIFO (last-in, first-out), completely describes the queuing system.

We can obtain the above-mentioned KPIs by studying the evolution of the state, which is usually represented by the queue size, at discrete time steps or in continuous time. Moreover, arrival and service processes can be deterministic or represented by random processes. We consider the latter case, where arrival and departures are described either by Poisson or Bernoulli random processes for continuous and discrete time, respectively. In this setup, it is possible to prove that the evolution of the state is a Markovian process. More precisely, the future state of the queue depends only on the present state and not on its past one.

3.3.1 Discrete Time Markov Chain

In this thesis, we focus on discrete time and discrete states of the queue, of which the evolution can be modeled by a discrete time Markov chain (DTMC). Specifically, a DTMC is a discrete-time random process that takes values from a discrete set ($\mathcal{S}$). Let define $\mathbf{s}(k)$ as a vector, of which the n -th element is the probability to be in state n at timeslot k . This vector is called the state distribution vector. Then, we can distinguish between periodic and aperiodic Markov chains. In the former case, $\mathbf{s}(k)$ repeats its values at regular intervals of time. Moreover, Markov chains can be either irreducible and

reducible depending on whether or not it is possible from a state to reach any other state. For an aperiodic and irreducible Markov chain, the goal is to compute the steady-state distribution $\mathbf{s}$:

$$\mathbf{s} = \lim_{k \rightarrow \infty} \mathbf{s}(k). \quad (3.3)$$

This can be obtained by computing the transition probabilities between all the possible states in $\mathcal{S}$ that form the transition probability matrix $\mathbf{P}$. Specifically, element ij of $\mathbf{P}$ represents the probability to transit from state j to state i (p_{ij}). For a DMTC, these probabilities are fixed and do not depend on the previous history, but only on the current states, and the arrival and departure processes. Given $\mathbf{P}$ and $\mathbf{s}(k-1)$, we can obtain $\mathbf{s}(k)$ by using the following relation:

$$\mathbf{s}(k) = \mathbf{P}\mathbf{s}(k-1), \quad \forall k. \quad (3.4)$$

At the equilibrium, the state distribution assumes values that does not vary according to k and satisfies the following equation:

$$\mathbf{P}\mathbf{s} = \mathbf{s}. \quad (3.5)$$

There are several methods to derive $\mathbf{s}$ including repeated multiplication of $\mathbf{P}$, $\mathbf{P}$ eigenvector, difference equations, Z -transform, and numerical techniques. For further details of queuing theory and Markov chains, the reader is referred to [120, 121].

3.3.2 $M^N/M/1$ Queue

In Paper III, we have studied the performance of the queue at the relay that can be modeled as a $M^N/M/1$ queue. Specifically, the arrival and departures are Markovian processes (Bernoulli random processes) and there are N source nodes and one server. Given discrete time and discrete states, the evolution of the queue can be studied by considering a DMTC whose transition probability matrix is a lower Hessenberg matrix:

$$\begin{pmatrix} a_0 & b_0 & 0 & 0 & \dots \\ a_1 & b_1 & b_0 & 0 & \dots \\ a_2 & b_2 & b_1 & b_0 & \dots \\ a_3 & b_3 & b_2 & b_1 & \dots \\ a_4 & b_4 & b_3 & b_2 & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}. \quad (3.6)$$

The elements of the matrix can be derived according to the arrival and departure processes. The steady-state distribution and the main KPIs of this queue can be obtained by using the Z -transformation method as explained in detail in [120].

Chapter 4

Contributions of the Thesis

The thesis analyzes several performance aspects of techniques for increasing the robustness of wireless communications at mm-wave frequencies and deals with specific optimization problems of these techniques. In the first part, we analyze and quantify the benefits of providing multiple connections to the UEs in mm-wave communications. We provide rigorous mathematical formulations of two fundamental link scheduling problems in MC scenarios that are solved by using combinatorial optimization and machine learning methods. These highlight the potential gains of MC in terms of throughput and reliability and their tradeoffs with the allocated resources addressing research questions Q1 and Q2. In the third paper, we focus on Q2-Q4 and use queueing theory to provide a mathematical analysis of the performance of relay-aided mm-wave communications. Simulation results show the benefits and the effect of directional communications on cooperative networking for mm-waves.

Finally, in the second part of the thesis, we address research questions Q5-Q7 and exploit the possibility to control the mobility of robots in industrial scenarios. Specifically, in the fourth paper, we consider a problem that aims to jointly optimize the robots' paths and the robot-mmAP associations. Then, in the fifth paper, we consider the problem of minimizing the motion energy consumption of a robot with QoS-constrained mm-wave communications that are aided by an IRS. Numerical results highlight the importance of the proposed

problems and corresponding solutions in order to increase robustness and satisfy QoS requirements for robots connected using mm-wave communications.

The main ideas presented in the five research papers are the result of discussions among all the authors. The author of this dissertation has contributed to Papers I-V as the first author working on modeling, mathematical analysis, problem formulation, implementation of algorithms, simulation, and numerical results along with the writing of the papers. Papers I-V and the corresponding main scientific contributions are summarized in Section 4.1.

The thesis is an extension of the author's Licentiate thesis:

- C. Tatino, "Performance Aspects in Millimeter-Wave Wireless Networks," Linköping: Linköping University Electronic Press, 2018. Linköping Studies in Science and Technology. Licentiate Thesis, 1821.

4.1 Papers Included in the Thesis

Paper I: Maximum Throughput Scheduling for Multi- Connectivity in Millimeter-Wave Networks, co-authored with I. Malanchini, N. Pappas, and D. Yuan. This paper has been published in Proceedings of International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), May 2018.

In the first paper, we deal with the link scheduling problem in a low frequency assisted mm-wave MC scenario with multiple UEs. Namely, we consider a downlink inter-frequency reliability oriented MC scheme, where the control and the data planes are transmitted by using LB-BS and mmAPs, respectively. Although multiple connections increase the reliability of the communication, at the same time, they utilize resources in terms of frequency bands, backhaul capacity, energy, and antennas. For this reason, we consider several MC schemes that allow a mmAP to be prepared for communication with a UE at different levels (states) without transmitting and consuming significant resources. A centralized network controller (NC) has the goal to set the state of several links along with a certain time window according to the channel conditions and resource constraints to maximize the network throughput.

This paper addresses research question Q1 stated in Chapter 1. To do so, we first derive a rigorous mathematical formulation of the constrained throughput maximization problem as a non-linear binary integer problem. To solve the latter, we propose a column generation algorithm that can deal with the exponential growth of combinatorial solutions. The results highlight the potential gain of the proposed MC architectures that, in some scenario, can increase the network throughput of almost the 30 % with respect to a single connectivity (SC) scheme. Moreover, we show that the proposed algorithm can numerically approach the optimal solution. In conclusion, the results highlight that a MC scheme with predictive link preparation provides high throughput without significantly increasing resource utilization with respect to a SC scheme.

Paper II: Learning-Based Link Scheduling in Millimeter-wave Multi-connectivity Scenarios, co-authored with N. Pappas, I. Malanchini, L. Ewe, and D. Yuan. This paper has been published in Proceedings of IEEE International Conference on Communications (ICC), June 2020.

In the second paper, we consider a complementary approach to the first paper. Specifically, we solve the problem of minimizing allocated resources while satisfying user's QoS requirements in low frequency assisted mm-wave MC scenarios. We consider a single user downlink outdoor scenario with several mmAPs and one LB-BS. These jointly provide coverage and connectivity to a mobile user and are connected by high-speed backhauling links to an NC. The user needs to receive a certain amount of data within a deadline. These can be transmitted by using several links simultaneously including both mm-wave and low-frequencies communications. In such scenarios, the network performance is highly affected by the number and the selection of transmitting links that depend on several parameters, e.g., type of user (vehicle or pedestrian), QoS requirements, and blockage frequency.

In this paper, we focus on research questions Q1 and Q2. To deal with abrupt blockages and channel uncertainty, we propose a learning-based solution for link scheduling. The proposed method is a *random forest classifier* that can learn the optimal selection of links with respect to users' location and QoS requirements to achieve the following goals: i) satisfying users' QoS requirements, ii) minimizing failed transmissions that represent wasted allocated resources, and iii) offloading low-frequency communications. We show the performance of the learning-based model for several mobility types, i.e., pedestrians and vehicles. We compare the obtained results with a genie-aided solution and two baseline methods. The results highlight how the proposed learning method for predicting mm-wave channel conditions and corresponding resource allocation is able to optimize the tradeoff between allocated resources and reliability. Specifically, the performance evaluation shows that the random forest classifier outperforms all the considered baseline methods and, for some scenarios, it approaches the optimum by minimizing failed transmissions and satisfying QoS requirements.

Paper III: On the Benefits of Network-level Cooperation in Millimeter-wave Communications, co-authored with N. Pappas, I. Malanchini, L. Ewe, and D. Yuan. This paper has been published in IEEE Transactions on Wireless Communications, 2019.

In the third work, we analyze the throughput and delay of mm-wave wireless networks that are assisted by a relay to increase robustness, reliability, and communication range. Specifically, we consider a symmetric multi-UE scenario with a FD network cooperative relay and a mmAP, which represents the destination. The UEs have saturated queues of infinite size and, in each timeslot, transmit with a certain probability. We study the effect of directional communications on cooperative networking by defining two UE transmission strategies: directional and broadcast. By using the former, the UEs send either a packet to the destination or the relay by using narrow beams. Whereas, by using the broadcast transmission, UEs use wider beams, with lower beamforming gain, to send a packet to both the mmAP and the relay in the same timeslot. The relay stores, in an infinite size queue, the successfully received packets.

We obtain closed-form expressions of the network aggregate and per UE throughput and packet delay by evaluating the stability condition, the arrival, and service rate of the queue at the relay. These are numerically evaluated for several scenarios by varying the system parameters, e.g., the number and position of nodes, transmit probability, and signal-to-interference-plus-noise ratio (SINR) threshold. To provide answer to research questions Q2 and Q3, we show that cooperative networking is characterized by a tradeoff between throughput and delay and, in some scenarios, can increase the throughput and the transmission success probability of 25%. Furthermore, we address research question Q4 by showing how the duration of the beam alignment phase and directional communications significantly impact the performance affecting the optimal strategy. This depends also on the network topology. Namely, we can observe that, for short distances between the UEs, the relay, and the mmAP, it is often beneficial to transmit by using a wider beam. Although this provides a lower beamforming gain, it gives the possibility to transmit to both the mmAP and the relay in the same timeslot. However, when the distances and the SINR threshold increase, a directional transmission becomes preferable.

Parts of the work have been published and presented in the following conference:

- C. Tatino, N. Pappas, I. Malanchini, L. Ewe and D. Yuan, "Throughput Analysis for Relay-Assisted Millimeter-Wave Wireless Networks," in IEEE Globecom Workshops (GC Wkshps), December 2018.

Paper IV: Multi-Robot Association-Path Planning in Millimeter -Wave Industrial Scenarios, co-authored with N. Pappas, and D. Yuan. This paper has been published in IEEE Networking Letters, November 2020.

In this work, we define and solve multi-robot association-path planning (MAPP) problems that, in contrast to conventional multi-robot path planning, aim to jointly optimize the robots' paths and the robot-AP associations in mm-wave industrial scenarios. The robots need to move from their starting positions to their goals within a time horizon. In this regard, mm-wave can provide high data rates for new industrial applications, but they are characterized by spotty coverage requiring dense radio deployments. In such scenarios, coverage holes and numerous handovers may decrease the communication throughput and reliability of moving robots. We focus on the type of MAPP with the goal of i) selecting paths for reaching the destinations in the shortest possible time, ii) minimizing the number of handovers, and iii) avoiding AP overloading.

To solve this problem, we use a graph-based method. Specifically, the robot can move on a directed graph that is defined by using a radio map on positions that are free from obstacles and covered by at least an AP. Then, we define the cost of the edges to include association and time information. Thanks to this choice, we can guarantee the connections of the robot and solve MAPP problems by using path-based formulations. Although we prove the NP-hardness of the problem, and we propose a column generation-based algorithm (PGCP) that can solve MAPP in polynomial time. To provide answers to research questions Q5 and Q6, we show that paths and the associations resulting from the optimization of MAPP problems avoid coverage holes, AP overloading, and dramatically reduces the number of handovers without increasing significantly the traversal time of the paths. These results highlight the importance of MAPP problems to reach fully wireless and automated factories for Industry 4.0.

Paper V: QoS Aware Robot Trajectory Optimization with IRS-assisted Millimeter -Wave Communications, co-authored with N. Pappas, and D. Yuan. This paper has been submitted to IEEE Transactions on Wireless Communications, 2020.

Finally, the fifth paper considers the joint optimization of trajectory and beamforming for a wirelessly connected robot using IRS-assisted mm-wave communications. The goal is to minimize the motion energy consumption of a robot moving in an area that is partially occupied by obstacles. The robot needs to transmit uplink data by satisfying a minimum average data rate requirement to an IRS-assisted AP using mm-waves. This is a fundamental problem in fully automated factories that characterize Industry 4.0, where robots may have to perform tasks with given deadlines while maximizing battery autonomy and communication efficiency. In such scenarios, the low-cost deployment of IRSs represents an efficient solution for enhancing robustness and reliability at mm-wave frequencies.

To solve the problem, we account for the mutual dependence between trajectory and beamforming (at the AP and IRS) optimization. Specifically, the latter depends on the robot trajectory that must be optimized to avoid collisions and satisfy time and QoS constraints. Thus, we first provide a rigorous mathematical formulation as a non-linear and non-convex problem. Then, we exploit mm-wave channel characteristics to decouple beamforming and trajectory optimization. The latter is solved by using a modified successive-convex optimization algorithm (RMAP) that accounts for the obstacles' positions and a radio map to avoid collisions and satisfy QoS requirements. We prove that the algorithm can converge to a solution satisfying the Karush-Kuhn-Tucker (KKT) conditions, and simulation results show the fast convergence of RMAP.

The proposed algorithm is able to provide solutions that dramatically reduce the motion energy consumption with respect to methods that aim to find maximum-rate trajectories. Moreover, in this paper, we focus on research questions Q6 and Q7. More precisely, we first show how RMAP, thanks to the radio map information, can provide trajectories that avoid poorly covered areas. Then, we show how the IRS and the beamforming optimization increase the motion energy efficiency of the robot by increasing mm-wave coverage and robustness.

4.2 Papers not Included in the Thesis

- C. Parera, Q. Liao, I. Malanchini, C. Tatino, A. E. C. Redondi and M. Cesana, "Transfer Learning for Tilt-Dependent Radio Map Prediction," in *IEEE Transactions on Cognitive Communications and Networking*, vol. 6, no. 2, pp. 829-843, June 2020.
- C. Parera, A. E. C. Redondi, M. Cesana, Q. Liao, L. Ewe, and C. Tatino "Transferring Knowledge for Tilt-Dependent Radio Map Prediction," in *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC)*, April 2018.
- N. Pappas, E. Fountoulakis, C. Tatino, V. Angelakis, and D. Yuan, "Pursuing the Potential of New Mechanisms for Performance Engineering of 5G," in *Proceedings of IEEE 22nd International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, June 2017.
- C. Tatino, N. Pappas, and D. Yuan, "Beam Based Stochastic Model of the Coverage Probability in 5G Millimeter-wave Systems," in *Proceedings of 15th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt)*, May 2017.

4.3 Conclusions and Future Research

Our research has shown that MC can increase robustness, throughput, and reliability of mm-wave communications at the cost of additional allocated resources (e.g., number of connections). An optimized allocation of the resources can lead to efficient MC solutions, of which the performance can dramatically increase if combined with methods aiming to predict channel conditions. These can be implemented by using machine learning algorithms that show high performance in minimizing the percentage of failed transmissions and satisfying minimum QoS requirements. Moreover, we show that the number of available links, the type of users, and the scattering environment are the main parameters that affect the performance of MC techniques. Cooperative networking represents another technique to increase throughput and reliability, but, as shown by the results, at the cost of additional delay introduced by queue-aided relays. Directional communications and beam alignments highly affect the performance of this type of technique, as well as the network topology and the number of UEs.

Additional results show that the possibility to optimize robot tra-

jectory can make robot-AP communications more robust by selecting paths that avoid coverage holes and poorly covered areas. Moreover, by jointly optimizing robot-AP associations and robots' trajectory, it is possible to minimize handovers without increasing significantly the traversal time. Furthermore, we show that the deployment of IRSs improves radio coverage that increases the energy efficiency of robots under communication QoS constraints. In this regard, radio maps are a fundamental tool to achieve the required QoS.

MC solutions present further tradeoffs that have not been deeply analyzed in this thesis and in literature. Specifically, MC increases backhauling traffic and needs accurate coordination between the APs and the NC, and proper coverage planning, which introduce additional delay, complexity, and deployment cost, respectively. Moreover, emerging technologies for 6G will introduce new possible MC schemes e.g., with terahertz and satellite communications. The analysis in Paper III has shown whether to transmit to the relay or to the AP or both. However, the optimal strategy for a UE depends on the network topology and selected strategies of possible interferers. Thus, joint optimization of the transmission strategy at multiple UEs can improve throughput and reliability. Moreover, IRSs are efficient alternatives to relays, of which the pros and cons are still not fully analyzed at mm-wave frequencies. Finally, new problems arise for robotic systems that will represent important use cases for 6G and beyond. Joint coverage planning and trajectory optimization and beam tracking for mobile robots can represent promising research directions for mm-wave communications.

Bibliography

- [1] Cisco, “Cisco annual internet report (2018-2023),” Tech. Rep., Mar. 2020.
- [2] F. Tariq, M. R. A. Khandaker, K. K. Wong, M. A. Imran, M. Bennis, and M. Debbah, “A speculative study on 6G,” *IEEE Wireless Communications*, vol. 27, no. 4, pp. 118–125, 2020.
- [3] ITU, “ITU radio regulations,” Tech. Rep., 2020.
- [4] FCC, “Use of spectrum bands above 24 GHz for mobile radio services,” Tech. Rep., 2019.
- [5] G. Kang, S. Jiang, and Z. Zhao, “Research on millimeter wave spectrum planning for 5G,” *Journal of Physics: Conference Series*, vol. 1345, p. 032040, Nov. 2019.
- [6] X. Lu et al., “Integrated use of licensed- and unlicensed-band mmwave radio technology in 5G and beyond,” *IEEE Access*, vol. 7, pp. 24 376–24 391, 2019.
- [7] S. Rangan, T. S. Rappaport, and E. Erkip, “Millimeter-wave cellular wireless networks: Potentials and challenges,” *Proceedings of the IEEE*, vol. 102, no. 3, pp. 366–385, Mar. 2014.
- [8] T. S. Rappaport, Y. Xing, G. R. MacCartney, A. F. Molisch, E. Mellios, and J. Zhang, “Overview of millimeter wave communications for fifth-generation (5G) wireless networks-with a focus on propagation models,” *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 12, pp. 6213–6230, Dec. 2017.
- [9] H. Zhao et al., “28 GHz millimeter wave cellular communication measurements for reflection and penetration loss in and around

-
- buildings in new york city,” in *IEEE International Conference on Communications (ICC)*, Jun. 2013, pp. 5163–5167.
- [10] G. R. MacCartney and T. S. Rappaport, “73 GHz millimeter wave propagation measurements for outdoor urban mobile and backhaul communications in new york city,” in *IEEE International Conference on Communications (ICC)*, Jun. 2014, pp. 4862–4867.
- [11] T. Bai, R. Vaze, and R. W. Heath, “Analysis of blockage effects on urban cellular networks,” *IEEE Transactions on Wireless Communications*, vol. 13, no. 9, pp. 5070–5083, Sept. 2014.
- [12] M. Gapeyenko et al., “On the temporal effects of mobile blockers in urban millimeter-wave cellular scenarios,” *IEEE Transactions on Vehicular Technology*, vol. 66, no. 11, pp. 10 124–10 138, Nov. 2017.
- [13] H. Shokri-Ghadikolaei and C. Fischione, “The transitional behavior of interference in millimeter wave networks and its impact on medium access control,” *IEEE Transactions on Communications*, vol. 64, no. 2, pp. 723–740, Feb. 2016.
- [14] Y. Niu, Y. Li, D. Jin, L. Su, and A. V. Vasilakos, “A survey of millimeter wave communications (mmwave) for 5G: Opportunities and challenges,” *Wireless Networks*, vol. 21, no. 8, pp. 2657–2676, Nov. 2015.
- [15] M. Xiao et al., “Millimeter wave communications for future mobile networks,” *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 9, pp. 1909–1935, Sept. 2017.
- [16] J. Wang et al., “Beam codebook based beamforming protocol for multi-Gbps millimeter-wave wpan systems,” *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 8, pp. 1390–1399, 2009.
- [17] H. Shokri-Ghadikolaei, L. Gkatzikis, and C. Fischione, “Beam-searching and transmission scheduling in millimeter wave communications,” in *IEEE International Conference on Communications (ICC)*, 2015, pp. 1292–1297.

-
- [18] M. Giordani, M. Mezzavilla, and M. Zorzi, "Initial access in 5G mmwave cellular networks," *IEEE Communications Magazine*, vol. 54, no. 11, pp. 40–47, Nov. 2016.
- [19] C. N. Barati, S. A. Hosseini, M. Mezzavilla, T. Korakis, S. S. Panwar, S. Rangan, and M. Zorzi, "Initial access in millimeter wave cellular systems," *IEEE Transactions on Wireless Communications*, vol. 15, no. 12, pp. 7926–7940, Dec. 2016.
- [20] M. Giordani, M. Polese, A. Roy, D. Castor, and M. Zorzi, "A tutorial on beam management for 3GPP NR at mmwave frequencies," *IEEE Communications Surveys Tutorials*, vol. 21, no. 1, pp. 173–196, 2019.
- [21] S. Hur, T. Kim, D. J. Love, J. V. Krogmeier, T. A. Thomas, and A. Ghosh, "Millimeter wave beamforming for wireless backhaul and access in small cell networks," *IEEE Transactions on Communications*, vol. 61, no. 10, pp. 4391–4403, Oct. 2013.
- [22] H. Shokri-Ghadikolaei, C. Fischione, G. Fodor, P. Popovski, and M. Zorzi, "Millimeter wave cellular networks: A MAC layer perspective," *IEEE Transactions on Communications*, vol. 63, no. 10, pp. 3437–3458, 2015.
- [23] IEEE, "IEEE standard for information technology–telecommunications and information exchange between systems–local and metropolitan area networks–specific requirements–part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications amendment 3: Enhancements for very high throughput in the 60 GHz band," *IEEE Std 802.11ad-2012 (Amendment to IEEE Std 802.11-2012, as amended by IEEE Std 802.11ae-2012 and IEEE Std 802.11aa-2012)*, pp. 1–628, 2012.
- [24] T. Baykas, C. S. Sum, Z. Lan, J. Wang, M. A. Rahman, H. Harada, and S. Kato, "IEEE 802.15.3c: the first IEEE wireless standard for data rates over 1 Gb/s," *IEEE Communications Magazine*, vol. 49, no. 7, pp. 114–121, Jul. 2011.
- [25] M. Z. Zaaimia, R. Touhami, L. Talbi, M. Nedil, and M. C. E. Yagoub, "60-GHz statistical channel characterization for wireless data centers," *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 976–979, 2016.

-
- [26] mmMAGIC, “Deliverable d2.1: Measurement campaigns and initial channel models for preferred suitable frequency ranges,” Tech. Rep., 2016.
- [27] C. Dehos, J. L. Gonzalez, A. D. Domenico, D. Ktenas, and L. Dussopt, “Millimeter-wave access and backhauling: the solution to the exponential data traffic increase in 5G mobile communications systems?” *IEEE Communications Magazine*, vol. 52, no. 9, pp. 88–95, 2014.
- [28] W. Feng, Y. Li, D. Jin, L. Su, and S. Chen, “Millimetre-wave backhaul for 5G networks: Challenges and solutions,” *Sensors*, vol. 16, pp. 892–908, Jun. 2016.
- [29] Y. Golovachev, A. Etinger, G. Pinhasi, and Y. Pinhasi, “Millimeter wave high resolution radar accuracy in fog conditions-theory and experimental verification,” *Sensors*, vol. 18, pp. 2148–2159, Jul. 2018.
- [30] S. Sugimoto, H. Tateda, H. Takahashi, and M. Okutomi, “Obstacle detection using millimeter-wave radar and its visualization on image sequence,” in *Proceedings of the 17th International Conference on Pattern Recognition (ICPR)*., vol. 3, 2004, pp. 342–345.
- [31] F. Lemic et al., “Localization as a feature of mmwave communication,” in *Proceedings of the 12th IEEE International Conference on Wireless Communications and Mobile Computing (IWCMC’16)*, Sept. 2016.
- [32] Ericsson, “Ericsson, Qualcomm and U.S. cellular achieve extended-range 5G data call over mmwave,” Tech. Rep., Sept. 2020. [Online]. Available: <https://www.ericsson.com/en/press-releases/2020/9/ericsson-qualcomm-and-u.s.-cellular-achieve-extended-range-5g-data-call-over-mmwave>
- [33] M. Cheffena, “Industrial wireless communications over the millimeter wave spectrum: opportunities and challenges,” *IEEE Communications Magazine*, vol. 54, no. 9, pp. 66–72, Sept. 2016.
- [34] J. Sachs, K. Wallstedt, F. Alriksson, and G. Eneroth, “Boosting smart manufacturing with 5G wireless connectivity,” Ericsson Technology Review, 2019.

-
- [35] C. Pielli, T. Ropitault, and M. Zorzi, “The potential of mmwaves in smart industry: Manufacturing at 60 GHz,” in *17th International Conference on Ad Hoc Networks and Wireless (AD HOC-NOW)*, 2018, pp. 64–76.
- [36] S. Saponara, F. Giannetti, B. Neri, and G. Anastasi, “Exploiting mm-wave communications to boost the performance of industrial wireless networks,” *IEEE Transactions on Industrial Informatics*, vol. 13, no. 3, pp. 1460–1470, 2017.
- [37] M. Giordani, M. Polese, M. Mezzavilla, S. Rangan, and M. Zorzi, “Toward 6G networks: Use cases and technologies,” *IEEE Communications Magazine*, vol. 58, no. 3, pp. 55–61, 2020.
- [38] G. R. MacCartney, S. Deng, S. Sun, and T. S. Rappaport, “Millimeter-wave human blockage at 73 GHz with a simple double knife-edge diffraction model and extension for directional antennas,” in *the 84th IEEE Vehicular Technology Conference (VTC-Fall)*, Sept. 2016, pp. 1–6.
- [39] G. R. MacCartney and T. S. Rappaport, “Millimeter-wave base station diversity for 5G coordinated multipoint (CoMP) applications,” *IEEE Transactions on Wireless Communications*, vol. 18, no. 7, pp. 3395–3410, 2019.
- [40] J. Choi, “On the macro diversity with multiple BSs to mitigate blockage in millimeter-wave communications,” *IEEE Communications Letters*, vol. 18, no. 9, pp. 1653–1656, Sept. 2014.
- [41] E. Hriba and M. Valenti, “Correlated blocking in mmwave cellular networks: Macrodiversity, outage, and interference,” *Electronics*, vol. 8, p. 1187, Oct. 2019.
- [42] F. Devoti and I. Filippini, “Planning mm-wave access networks under obstacle blockages: A reliability-aware approach,” *IEEE/ACM Transactions on Networking*, vol. 28, no. 5, pp. 2203–2214, 2020.
- [43] M. Gerasimenko, D. Moltchanov, M. Gapeyenko, S. Andreev, and Y. Koucheryavy, “Capacity of multiconnectivity mmwave systems with dynamic blockage and directional antennas,” *IEEE Transactions on Vehicular Technology*, vol. 68, no. 4, pp. 3534–3549, 2019.

-
- [44] G. Yang and M. Xiao, "Performance analysis of millimeter-wave relaying: Impacts of beamwidth and self-interference," *IEEE Transactions on Communications*, vol. 66, no. 2, pp. 589–600, 2018.
- [45] X. An et al., "Beam switching support to resolve link-blockage problem in 60 GHz WPANs," in *IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, Sept. 2009, pp. 390–394.
- [46] C. Tatino, I. Malanchini, D. Aziz, and D. Yuan, "Beam based stochastic model of the coverage probability in 5G millimeter wave systems," in *the 15th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt)*, May 2017, pp. 1–6.
- [47] N. A. Muhammad, P. Wang, Y. Li, and B. Vucetic, "Analytical model for outdoor millimeter wave channels using geometry-based stochastic approach," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 2, pp. 912–926, Feb. 2017.
- [48] A. Narayanan, T. V. Sreejith, and R. K. Ganti, "Coverage analysis in millimeter wave cellular networks with reflections," in *IEEE Global Communications Conference (GLOBECOM)*, 2017, pp. 1–6.
- [49] P. Wang, J. Fang, X. Yuan, Z. Chen, and H. Li, "Intelligent reflecting surface-assisted millimeter wave communications: Joint active and passive precoding design," *IEEE Transactions on Vehicular Technology*, pp. 1–1, 2020.
- [50] A. Wolf, P. Schulz, M. Dörpinghaus, J. C. S. Santos Filho, and G. Fettweis, "How reliable and capable is multi-connectivity?" *IEEE Transactions on Communications*, vol. 67, no. 2, pp. 1506–1520, 2019.
- [51] A. Wolf, P. Schulz, D. Öhmann, M. Dörpinghaus, and G. Fettweis, "Rate-reliability tradeoff for multi-connectivity," in *IEEE Wireless Communications and Networking Conference (WCNC)*, Apr. 2018, pp. 1–6.
- [52] 3GPP, "Evolved universal terrestrial radio access (E-UTRA) and evolved universal terrestrial radio access network (E-

-
- UTRAN); overall description (release 16), 3GPP TS 36.300,” Tech. Rep., Jan. 2020.
- [53] —, “Evolved universal terrestrial radio access (E-UTRA) and NR; multi-connectivity (release 16), 3GPP TS 37.340 V16.3.0,” Tech. Rep., Sept. 2020.
- [54] D. Moltchanov, A. Ometov, S. Andreev, and Y. Koucheryavy, “Upper bound on capacity of 5G mmwave cellular with multi-connectivity capabilities,” *Electronics Letters*, vol. 54, no. 11, pp. 724–726, 2018.
- [55] M. Gapeyenko, V. Petrov, D. Moltchanov, M. R. Akdeniz, S. Andreev, N. Himayat, and Y. Koucheryavy, “On the degree of multi-connectivity in 5G millimeter-wave cellular urban deployments,” *IEEE Transactions on Vehicular Technology*, vol. 68, no. 2, pp. 1973–1978, 2019.
- [56] V. Petrov et al., “Dynamic multi-connectivity performance in ultra-dense urban mmwave deployments,” *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 9, pp. 2038–2055, 2017.
- [57] D. Aziz, J. Gebert, A. Ambrosy, H. Bakker, and H. Halbauer, “Architecture approaches for 5G millimetre wave access assisted by 5G low-band using multi-connectivity,” in *IEEE Globecom Workshops (GC Wkshps)*, Dec. 2016, pp. 1–6.
- [58] M. Polese, M. Giordani, M. Mezzavilla, S. Rangan, and M. Zorzi, “Improved handover through dual connectivity in 5G mmwave mobile networks,” *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 9, pp. 2069–2084, Sept. 2017.
- [59] M. Giordani, M. Mezzavilla, S. Rangan, and M. Zorzi, “Multi-connectivity in 5G mmwave cellular networks,” in *Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net)*, Jun. 2016, pp. 1–7.
- [60] A. Alkhateeb, S. Alex, P. Varkey, Y. Li, Q. Qu, and D. Tujkovic, “Deep learning coordinated beamforming for highly-mobile millimeter wave systems,” *IEEE Access*, vol. 6, pp. 37 328–37 348, 2018.

-
- [61] X. Lin and J. G. Andrews, "Connectivity of millimeter wave networks with multi-hop relaying," *IEEE Wireless Communications Letters*, vol. 4, no. 2, pp. 209–212, 2015.
- [62] M. N. Tehrani, M. Uysal, and H. Yanikomeroglu, "Device-to-device communication in 5G cellular networks: challenges, solutions, and future directions," *IEEE Communications Magazine*, vol. 52, no. 5, pp. 86–92, May 2014.
- [63] D. Kim, H. Lee, and D. Hong, "A survey of in-band full-duplex transmission: From the perspective of PHY and MAC layers," *IEEE Communications Surveys Tutorials*, vol. 17, no. 4, pp. 2017–2046, Fourthquarter 2015.
- [64] N. Shende, O. Gurbuz, and E. Erkip, "Half-duplex or full-duplex relaying: A capacity analysis under self-interference," in *the 47th Annual Conference on Information Sciences and Systems (CISS)*, Mar. 2013, pp. 1–6.
- [65] Z. Wei, X. Zhu, S. Sun, Y. Huang, L. Dong, and Y. Jiang, "Full-duplex versus half-duplex amplify-and-forward relaying: Which is more energy efficient in 60-GHz dual-hop indoor wireless systems?" *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 12, pp. 2936–2947, Dec. 2015.
- [66] L. Jiang and H. Jafarkhani, "Mmwave amplify-and-forward mimo relay networks with hybrid precoding/combining design," *IEEE Transactions on Wireless Communications*, vol. 19, no. 2, pp. 1333–1346, 2020.
- [67] K. Belbase, Z. Zhang, H. Jiang, and C. Tellambura, "Coverage analysis of millimeter wave decode-and-forward networks with best relay selection," *IEEE Access*, vol. 6, pp. 22 670–22 683, 2018.
- [68] N. Nomikos, T. Charalambous, I. Krikidis, D. N. Skoutas, D. Vouyioukas, M. Johansson, and C. Skianis, "A survey on buffer-aided relay selection," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 2, pp. 1073–1097, 2016.
- [69] N. Pappas, M. Kountouris, A. Ephremides, and A. Traganitis, "Relay-assisted multiple access with full-duplex multi-packet reception," *IEEE Transactions on Wireless Communications*, vol. 14, no. 7, pp. 3544–3558, 2015.

-
- [70] S. Biswas, S. Vuppala, J. Xue, and T. Ratnarajah, "On the performance of relay aided millimeter wave networks," *IEEE Journal of Selected Topics in Signal Processing*, vol. 10, no. 3, pp. 576–588, Apr. 2016.
- [71] Z. Lin, X. Peng, F. Chin, and W. Feng, "Outage performance of relaying with directional antennas in the presence of co-channel interferences at relays," *IEEE Wireless Communications Letters*, vol. 1, no. 4, pp. 288–291, Aug. 2012.
- [72] S. Singh, F. Ziliotto, U. Madhow, E. Belding, and M. Rodwell, "Blockage and directivity in 60 GHz wireless personal area networks: from cross-layer model to multihop MAC design," *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 8, pp. 1400–1413, Oct. 2009.
- [73] K. Ntontin and C. Verikoukis, "Relay-aided outdoor-to-indoor communication in millimeter-wave cellular networks," *IEEE Systems Journal*, vol. 14, no. 2, pp. 2473–2484, 2020.
- [74] Z. Zhang, X. Chai, K. Long, A. V. Vasilakos, and L. Hanzo, "Full duplex techniques for 5G networks: self-interference cancellation, protocol design, and relay selection," *IEEE Communications Magazine*, vol. 53, no. 5, pp. 128–137, May 2015.
- [75] H. Cui, M. Ma, L. Song, and B. Jiao, "Relay selection for two-way full duplex relay networks with amplify-and-forward protocol," *IEEE Transactions on Wireless Communications*, vol. 13, no. 7, pp. 3768–3777, Jul. 2014.
- [76] Y. Xu, H. Shokri-Ghadikolaei, and C. Fischione, "Distributed association and relaying with fairness in millimeter wave networks," *IEEE Transactions on Wireless Communications*, vol. 15, no. 12, pp. 7955–7970, Dec. 2016.
- [77] K. Belbase, C. Tellambura, and H. Jiang, "Two-way relay selection for millimeter wave networks," *IEEE Communications Letters*, vol. 22, no. 1, pp. 201–204, 2018.
- [78] S. Kwon and J. Widmer, "Relay selection for mmwave communications," in *the 28th IEEE Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Oct. 2017, pp. 1–6.

-
- [79] Z. Zhang et al., “6G wireless networks: Vision, requirements, architecture, and key technologies,” *IEEE Vehicular Technology Magazine*, vol. 14, no. 3, pp. 28–41, 2019.
- [80] Q. Wu and R. Zhang, “Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network,” *IEEE Communications Magazine*, vol. 58, no. 1, pp. 106–112, 2020.
- [81] W. Tang et al., “Wireless communications with reconfigurable intelligent surface: Path loss modeling and experimental measurement,” *IEEE Transactions on Wireless Communications*, 2020.
- [82] E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M. Alouini, and R. Zhang, “Wireless communications through reconfigurable intelligent surfaces,” *IEEE Access*, vol. 7, pp. 116 753–116 773, 2019.
- [83] C. Liaskos, S. Nie, A. Tsioliaridou, A. Pitsillides, S. Ioannidis, and I. Akyildiz, “A new wireless communication paradigm through software-controlled metasurfaces,” *IEEE Communications Magazine*, vol. 56, no. 9, pp. 162–169, 2018.
- [84] C. Liaskos, S. Nie, A. Tsioliaridou, A. Pitsillides, S. Ioannidis, and I. Akyildiz, “A novel communication paradigm for high capacity and security via programmable indoor wireless environments in next generation wireless systems,” *Ad Hoc Networks*, vol. 87, pp. 1 – 16, 2019.
- [85] A. C. Tasolamprou et al., “Exploration of intercell wireless millimeter-wave communication in the landscape of intelligent metasurfaces,” *IEEE Access*, vol. 7, pp. 122 931–122 948, 2019.
- [86] E. Björnson, Ö. Özdogan, and E. G. Larsson, “Reconfigurable intelligent surfaces: Three myths and two critical questions,” 2020. [Online]. Available: <https://arxiv.org/abs/2006.03377>
- [87] E. Björnson, Ö. Özdogan, and E. G. Larsson, “Intelligent reflecting surface versus decode-and-forward: How large surfaces are needed to beat relaying?” *IEEE Wireless Communications Letters*, vol. 9, no. 2, pp. 244–248, 2020.

-
- [88] W. Khawaja, O. Ozdemir, Y. Yapici, I. Guvenc, and Y. Kakishima, "Coverage enhancement for mm wave communications using passive reflectors," in *11th Global Symposium on Millimeter Waves (GSMM)*, 2018, pp. 1–6.
- [89] NTT DOCOMO, "Docomo conducts world's first successful trial of transparent dynamic metasurface," Tech. Rep., Jan. 2020. [Online]. Available: https://www.nttdocomo.co.jp/english/info/media_center/pr/2020/0117_00.html
- [90] Ö. Özdoğan, E. Björnson, and E. G. Larsson, "Intelligent reflecting surfaces: Physics, propagation, and pathloss modeling," *IEEE Wireless Communications Letters*, vol. 9, no. 5, pp. 581–585, 2020.
- [91] Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming," *IEEE Transactions on Wireless Communications*, vol. 18, no. 11, pp. 5394–5409, 2019.
- [92] S. Hu, F. Rusek, and O. Edfors, "Beyond massive MIMO: The potential of data transmission with large intelligent surfaces," *IEEE Transactions on Signal Processing*, vol. 66, no. 10, pp. 2746–2758, 2018.
- [93] A. Pitilakis et al., "A multi-functional reconfigurable meta-surface: Electromagnetic design accounting for fabrication aspects," *IEEE Transactions on Antennas and Propagation*, pp. 1–1, 2020.
- [94] A. Zappone, M. Di Renzo, X. Xi, and M. Debbah, "On the optimal number of reflecting elements for reconfigurable intelligent surfaces," *IEEE Wireless Communications Letters*, pp. 1–1, 2020.
- [95] Q. Zhang, W. Saad, and M. Bennis, "Millimeter wave communications with an intelligent reflector: Performance optimization and distributional reinforcement learning," 2020. [Online]. Available: <https://arxiv.org/abs/2002.10572>
- [96] M. Di Renzo et al., "Smart radio environments empowered by ai reconfigurable meta-surfaces: An idea whose time has come," *EURASIP Journal on Wireless Communications and Networking*, p. 129, May 2019.

-
- [97] L. Ge, P. Dong, H. Zhang, J. Wang, and X. You, "Joint beamforming and trajectory optimization for intelligent reflecting surfaces-assisted UAV communications," *IEEE Access*, vol. 8, pp. 78 702–78 712, 2020.
- [98] S. Li, B. Duo, X. Yuan, Y. Liang, and M. Di Renzo, "Reconfigurable intelligent surface assisted UAV communication: Joint trajectory design and passive beamforming," *IEEE Wireless Communications Letters*, vol. 9, no. 5, pp. 716–720, 2020.
- [99] M. Giordani, M. Mezzavilla, S. Rangan, and M. Zorzi, "An efficient uplink multi-connectivity scheme for 5G millimeter-wave control plane applications," *IEEE Transactions on Wireless Communications*, vol. 17, no. 10, pp. 6806–6821, 2018.
- [100] R. Parada and M. Zorzi, "Context-aware handover in mmwave 5G using ue's direction of pass," in *24th European Wireless Conference*, 2018, pp. 1–6.
- [101] I. Filippini, V. Sciancalepore, F. Devoti, and A. Capone, "Fast cell discovery in mm-wave 5G networks with context information," *IEEE Transactions on Mobile Computing*, vol. 17, no. 7, pp. 1538–1552, 2018.
- [102] Y. Koda, K. Nakashima, K. Yamamoto, T. Nishio, and M. Morikura, "Handover management for mmwave networks with proactive performance prediction using camera images and deep reinforcement learning," *IEEE Transactions on Cognitive Communications and Networking*, vol. 6, no. 2, pp. 802–816, 2020.
- [103] M. Alrabeiah, A. Hredzak, and A. Alkhateeb, "Millimeter wave base stations with cameras: Vision-aided beam and blockage prediction," in *IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*, 2020, pp. 1–5.
- [104] Y. Sun, G. Feng, S. Qin, Y. Liang, and T. P. Yum, "Reinforcement learning based handoff for millimeter wave heterogeneous cellular networks," in *IEEE Global Communications Conference (GLOBECOM)*, 2017, pp. 1–6.
- [105] A. Alkhateeb, I. Beltagy, and S. Alex, "Machine learning for reliable mmwave systems: Blockage prediction and proactive

-
- handoff,” in *IEEE Global Conference on Signal and Information Processing (GlobalSIP)*, 2018, pp. 1055–1059.
- [106] Y. Wang, A. Klautau, M. Ribero, A. C. K. Soong, and R. W. Heath, “Mmwave vehicular beam selection with situational awareness using machine learning,” *IEEE Access*, vol. 7, pp. 87 479–87 493, 2019.
- [107] M. Alrabeiah and A. Alkhateeb, “Deep learning for mmwave beam and blockage prediction using sub-6 GHz channels,” *IEEE Transactions on Communications*, vol. 68, no. 9, pp. 5504–5518, 2020.
- [108] S. Khosravi, H. S. Ghadikolaie, and M. Petrova, “Learning-based handover in mobile millimeter-wave networks,” *IEEE Transactions on Cognitive Communications and Networking*, pp. 1–1, 2020.
- [109] Y. Lu, M. Gerasimenko, R. Kovalchukov, M. Štůsek, J. Urama, J. Hosek, M. Valkama, and E. S. Lohan, “Feasibility of location-aware handover for autonomous vehicles in industrial multi-radio environments,” *Sensors*, vol. 20, Nov. 2020.
- [110] G. L. Nemhauser and L. A. Wolsey, *Integer and Combinatorial Optimization*. Wiley-Interscience, 1988.
- [111] D.-S. Chen, R. Batson, and Y. Dang, *Applied Integer Programming: Modeling and Solution*. John Wiley & Sons, 2011.
- [112] D. Bertsimas and J. Tsitsiklis, *Introduction to Linear Optimization*. Athena Scientific, 1998.
- [113] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge University Press, 2004.
- [114] Y. Nesterov and A. Nemirovski, *Interior-point Polynomial Algorithms in Convex Programming*. Siam studies in applied mathematics, 1994.
- [115] B. R. Marks and G. P. Wright, “A general inner approximation algorithm for nonconvex mathematical programs,” *Operations Research*, vol. 26, no. 4, pp. 681–683, 1978. [Online]. Available: <http://www.jstor.org/stable/169728>

-
- [116] T. Hastie, R. Tibshirani, and J. Friedman, *The Elements of Statistical Learning – Data Mining, Inference, and Prediction*. Springer–Verlag New York, 2009.
- [117] R. S. Sutton and A. G. Barto, *Introduction to Reinforcement Learning*, 1st ed. MIT Press, 1998.
- [118] K. P. Murphy, *Machine Learning: a Probabilistic Perspective*. MIT Press, 2012.
- [119] I. Goodfellow, Y. Bengio, and A. Courville, *Deep Learning*. MIT Press, 2016, <http://www.deeplearningbook.org>.
- [120] F. Gebali, *Analysis of Computer and Communication Networks*. Springer-Verlag, 2010.
- [121] D. Bertsekas and R. Gallager, *Data Networks (2nd Ed.)*, 1992.

Part II

Papers

Papers

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