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# Analysis and enhancements of 5G New Radio towards Non-Terrestrial Networks and Massive MIMO

By

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# Abstract

The deployment of 5G networks brings new solutions to world connectivity, addressing different services and devices. While it is not yet widespread, the trend is evident, and researchers and engineers are already concentrating on the next developments. Despite its potential, achieving seamless 5G coverage and high data rates in certain environments remains challenging due to signal attenuation, interference, user density and deployment costs. Moreover, some elements of the standard remain underexplored, and a thorough examination of potential limitations is essential to uncover new research opportunities. Therefore, this thesis aims to analyze the innovations of the physical layer of 5G New Radio, providing a set of performance results and designing and developing innovative techniques and applications.

In the first part of the thesis, we focus on link-level simulations for the study of the initial access in 5G New Radio and the new solutions for non-terrestrial networks, an extension of 5G to support satellite communications. Firstly, we provide an extensive overview of the synchronization procedure the user has to undertake before accessing the network, by considering aspects such as the frequency offset and different detection approaches. Initial access is a crucial step in guaranteeing user connection to the network and determining performance and possible limitations that can help in planning radio resources. Then, we derive an improved method specifically for the primary synchronization signal detection, considering typical 5G non-terrestrial networks scenarios, exploiting the frame structure and the presence of residual frequency offsets. The new detection metric proves to be promising and can enhance the receiver detection capabilities, particularly for land mobile satellite channels. Our study on 5G solutions for non-terrestrial networks proceeds with extensive link-level simulations on key performance as the achievable data rates and transmission latency, considering the impact of retransmission techniques. We show the results for different configurations and the drawbacks of using retransmission techniques designed for terrestrial networks. We also implement the novel orthogonal

time frequency space modulation scheme and compare it with the standard 5G waveform, considering 3GPP non-terrestrial networks channel models. This new modulation is gaining interest as a possible candidate for next-generation waveforms since represents the wireless channel in the delay-Doppler domain, and it proves to be an attractive alternative for certain scenarios.

In the second part of the thesis, we focus on system-level simulations to study and implement the new 3GPP 3D channel model. We exploit it to develop a multi-user multiple-input multiple-output system and evaluate its performance. This channel model captures the spatial characteristics of the environment and allows for the simulation of users in both outdoor and indoor conditions. Consequently, we can accurately assess beamforming techniques, crucial for enhancing network data rates. We also evaluate the use of a particular antenna pattern, i.e. cylindrical arrays. It is compared with the more common planar arrays showing promising results for decreasing the inter-sector interference and providing a more uniform antenna gain all over the mobile cell. Finally, we design an innovative application for a system of multiple distributed reconfigurable intelligent surfaces. An ad-hoc technique is developed to serve multiple users in parallel and reduce interference. We demonstrate the benefit of this new system, providing higher data rates when the signal from the network access point is obstructed by obstacles, avoiding the deployment of additional active antenna systems.

This set of findings proves the potential of the actual and new solutions for 5G and beyond, contributing to a better understanding of achievable performance and critical constraints. Finally, several future research directions have also been identified.

# Chapter 1

# Introduction

Telecommunications systems and networks have played an increasingly fundamental role in recent decades, revolutionizing technological innovation, economic growth, and social interaction. The use of networks is no longer just limited to computers and cell phones, but has also widened to sensors, household appliances, autonomous driving vehicles, and many other types of devices. We are heading to a world where every person has nearly two connected devices: with 10 billion devices expected in consumers' hands by 2027, this sector is experiencing impressive growth unlike any other [1]. The surge of connected devices, combined with the increase in data demand from new technologies and applications, requires a continuous effort to research innovative techniques and solutions to meet the requirements of these systems. Already some years ago, studies such as [2] and [3] displayed how the usage of mobile devices has changed our behavior in the social sphere.

Mobile networks are fundamental in the world of communication networks since they allow people and machines to connect to the Internet and communicate virtually anywhere with good coverage. They can reach remote areas of the world, as for satellite constellations, or they can serve high mobility environments, where wired links are not an option. Ericsson mobility report of November 2023 [4] shows that, while the rate of mobile data usage growth is expected to slow down (at least until 2029), the total amount of data consumed will continue to rise significantly. Moreover, more than 75% of the world population owns a mobile phone, and most of them have Internet access, even if strong inequalities are still affecting least developed countries, as explained by the International Telecommunication Union (ITU) in [5].

The 3rd Generation Partnership Project (3GPP) stands as the foremost standard organization guiding the definition and evolution of both past and future mobile networks. Since its establishment, 3GPP has played a central role in shaping the telecommunications landscape by defining globally recognized standards for mobile communication technologies. From the development of the earliest mobile standard, such as the Global System for Mobile Communications (GSM), Universal Mobile Telecommunications Service (UMTS), and Long Term Evolution (LTE), to the ongoing evolution towards 5th generation (5G) and beyond, 3GPP's collaborative efforts bring together industry stakeholders to define specifications, protocols, and architectures that establish mobile network deployments worldwide.

The transition to the current 5G standard has begun for a few years, and 5G subscriptions reached 1 billion in the first quarter of 2023, even better than some 2020 forecasts [6], while the coverage for the world population is expected to reach 85% in 2028 [7, 8]. Flexibility of communication systems is one of the main 5G objectives, providing adaptation to different scenarios, use cases and requirements. This is particularly relevant considering the vastness of existing applications and devices, as for example the multitude of Internet of Things (IoT) devices. Not all devices connected to the network will need to exchange large amounts of data, while others may require very limited delays. Precisely for this reason, 5G introduces more degrees of freedom in the configuration of various network parameters. The target of future networks beyond 5G will be the ability to seamlessly adapt to the wireless environment, creating highly resilient and user-centric experiences. With user-centric, the network paradigm will change by focusing and adapting to the user-specific conditions and requirements, more than on the system requirements. Furthermore, the role of upload data throughput is increasingly gaining importance, considering the spread of cloud storage services. The latency requirement will be further pushed by 3GPP to be lower than 1 ms, a critical parameter for Ultra-Reliable Low Latency Communications (URLLC) for autonomous vehicles, and other applications requiring immediate response time.

5G New Radio (NR) is the radio access technology of 5G. It defines the 5G physical layer, and so how devices communicate with mobile cells over the air interface. Key aspects of 5G NR are the frequency bands adopted, the waveform and the modulation and coding of the data. Actual and future communication systems face two major challenges: squeezing ever-increasing data demands into a finite pool of frequency bands (spectrum scarcity) and unpredictable signal distortions caused by varying environments and obstacles. Thus, the physical layer solutions have to target limited resources available and the adversities of the wireless channel, to evolve current technologies for systems optimization and for the adaptation to the different types of environments.

Several physical layer technologies have captured interest for future networks, and some of these are:

**Massive multiple-input multiple-output (MIMO)** Massive MIMO is an advanced wireless communication technology that leverages a large number of antennas at both the transmitter and receiver to produce significant enhancement to the performance of wireless communication systems. Deploying a significant number of antennas at the base station (BS) and potentially at the user devices, enables the use of many solutions that can target different performance goals, depending also on the environment:

- Spatial diversity: The large number of antenna elements in massive MIMO systems can provide spatial diversity, where each antenna element may receive significantly different signal replicas if they experience different propagation paths. If the signal at each antenna element is uncorrelated, the effect of fading and strong signal attenuation can be significantly reduced. The correlation of the antenna elements depends on the antenna's placement, and the richness of the environment, in terms of scatterers.

- Array gain and beamforming: The signal transmitted and received by different antennas can be properly combined to improve the overall signal quality. Beamforming techniques allow the direction of the signal transmission or reception in certain angular directions, to increase the gain of the array. This can be obtained by properly tuning the amplitude and phase shift of each antenna element, to combine the signal replica of each antenna.

- Spatial multiplexing: If the antennas experience uncorrelated channels, this diversity can also be used to transmit different streams of data over orthogonal spatial channels. The multiple streams of data can be transmitted to the same receiver or multiple receivers. Spatial multiplexing can thus almost linearly increase the capacity of the system as the total number of spatial channels. MIMO precoding and combining are the common terms used to refer to spatial multiplexing techniques at the transmitter and receiver sides, respectively. Note that in the 5G standard, the term beamforming is used also for spatial multiplexing.

**Reconfigurable intelligent surfaces (RIS)** RIS are thin, flat panels embedded with tiny antennas or other elements that can be adjusted to manipulate radio signals in real-time. They represent a new technology in wireless communications that is gaining momentum in the research community and are sometimes also referred to as intelligent reflecting surfaces (IRS) or metasurfaces, depending on the source. They are somehow related to massive MIMO, but with different objectives and functions. Different ways of implementation have been investigated, but one of the most promising is the one considering semi-passive elements. Semi-passive means that the RIS cannot perform signal processing or re-amplification of the signal, as the relays. RIS response can be properly adjusted via elements phase shift manipulation, possible in the analogue domain. The main purpose is to direct the signal in particular directions, for example, to improve the coverage of the network.

**Orthogonal time frequency space (OTFS) modulation** OTFS is a novel modulation scheme, introduced as an alternative solution to the well-known orthogonal frequency division multiplexing (OFDM), introduced by LTE and still used in 5G. OTFS distinguishes itself by exploiting the delay-Doppler domain, to achieve a more condensed and sparse channel representation. This characteristic renders OTFS particularly interesting in high-mobility wireless communication scenarios, where ensuring reliable communication poses notable challenges. Notably, vehicular environments stand out as representative cases, gaining prominence within the realm of communication systems, especially in conjunction with the rise of autonomous driving, a focal point for upcoming beyond 5G and 6th generation (6G) mobile standards.

**Non-terrestrial networks (NTN)** The mobile standards have historically focused on terrestrial networks. However, non-terrestrial networks are growing in relevance across diverse fields, and have already been introduced in the latest 5G standard releases. For those living in remote areas untouched by the terrestrial web, satellite Internet offers essential connectivity for education, business, and even personal connection. Beyond bridging the digital divide, satellites act as crucial backbones in densely populated regions, extending the Internet reach also to big cities and transportation corridors. Mega constellations of satellites are promising broader coverage and lower latency, the potential for satellite Internet to further evolve global connectivity. The race to conquer the world of satellite communications is gaining momentum, considering for example the popular Starlink, a satellite Internet constellation operated by the American aerospace company SpaceX, or the Iris[2], a new space-based secure communication system for EU citizens. The increasing demand for satellite-based services and applications worldwide is clearly noticeable given the growth of satellite activities: satellite launches were in the range of 200-500 from 2014 to 2019, and then started to drastically increase, up to 2911 launches in 2023, with a total of 9130 active payloads in orbit by 31 December 2023 [9].

## 1.1 Research objectives and contributions

This thesis aims to explore, analyze, implement, and evaluate novel approaches and techniques for the physical layer of emerging mobile networks, focusing on 5G and beyond. Given the complexity of 5G, arising from its diverse scenarios, use cases, and technologies, a comprehensive analysis can reveal potential limitations and identify promising avenues for future research and development.

Firstly, the thesis focuses on link-level simulations for the study of 5G NR synchronization procedure and 5G NTN physical data channels, providing also a new technique for signal detection in NTN. Of particular relevance in these studies is the adopted channel model. Then, the study of channel models and 5G NR is extended via system-level simulations, in the context of massive MIMO systems. Different types and configurations of antenna arrays are analysed and compared, considering a variety of scenarios and users conditions. Finally, the channel model for 5G and the MIMO system solutions are exploited to design a new application for the RIS.

The main research questions and contributions are separately described in the following sections.

### 1.1.1 The 5G NR synchronization procedure

Mobile networks allow plenty of devices to connect to a base station that provides access to the World Wide Web. The devices can be of different kinds and have very different characteristics and requirements. Smartphones, for example, are mobile devices that are used by static users, and pedestrians, or can be located inside vehicles that move at different speeds. Internet providers have the goal of serving as many clients as possible, and thus the base station should be able to reach devices as far as possible and in very harsh environments, such as indoor users, where the signal power is strongly weakened. Before actually transmitting and receiving a stream of data, the devices should be able to detect and be recognized by the particular mobile cell in the neighbouring area. This initial phase is called initial access, and it is crucial to the mobile network capabilities. The synchronization procedure is the first part of the initial access, and comprehends all the signal processing tasks that the user device should undergo to identify the available base stations, before initiating a connection with them. One of the 5G NR objectives is to improve the initial access, mainly for the probability of successful cell detection, but also to improve energy efficiency and system flexibility. Thus, 5G NR defines a new structure for the synchronization signals and flexible parameters, for example, to reduce the signalling overhead for energy saving. Even if 5G synchronization phases have been studied and evaluated in several studies, a comprehensive analysis of the entire process and exhaustive sets of results in different configurations were not available. Our interest is then the study via link-level simulations of the new 5G synchronization procedure in an extensive manner, and the comparison of detection approaches to provide useful insights for the receiver implementation. Moreover, we provide a comparison with LTE and some tests of the techniques used for simulations with real captures of 5G signals.

Our contribution can be found in:

- [10] **R. Tuninato**, D.G. Riviello, R. Garello, et al. **"A comprehensive study on the synchronization procedure in 5G NR with 3GPP-compliant link-level simulator,"** *EURASIP J Wireless Com Network*, 2023.

### 1.1.2 5G NR advancements towards NTN

3GPP introduces NTN support in the latest releases. This new part of the standard defines the system rules for managing networks with satellite constellations and high altitude platforms. In satellite communications, different air interfaces have been adopted before 5G NTN, but the possibility of merging the terrestrial and non-terrestrial with a single standard is gaining a lot of interest. The extension of 5G networks to exploit satellite constellations can provide common ground for vendors and operators, leading to a synergy in technological advancements. This could permit the adoption of the same kind of receivers already available for user devices, without extreme changes. Nevertheless, 5G NR has been designed to address terrestrial networks. New solutions are required to cope with the challenges of typical satellite systems, such as large path losses, delays, and Doppler shifts. Firstly, we propose a novel method for initial signal detection in case of a typical NTN scenario, considering residual frequency offset and exploiting the NR signal frame structure to derive an optimized metric. Our proposed ad-hoc detection method for NTN shows encouraging results when applied to satellite communication channels. Other than the synchronization, also the 5G data channels may be affected by the peculiarities of NTN scenarios. This is the reason why we also analyse the physical downlink shared channel (PDSCH) performance for 5G NTN, considering the large delays, which require an evaluation of the impact of retransmission techniques on the system latency and complexity. In particular, we focus on the hybrid automatic repeat request (HARQ) and Radio Link Control (RLC) ARQ mechanisms, comparing their performance for different performance metrics. Moreover, we test the performance of OTFS modulation scheme in the same NTN scenario, to understand its benefit in the case of satellite links. In fact, by utilizing a two-dimensional delay-Doppler domain, OTFS offers a novel approach to wireless communication with the potential to enhance the performance and robustness of 5G and 6G networks. The adoption of this new solution can be particularly helpful in high-mobility scenarios, such as vehicular communications and satellite links. It is then fundamental to determine the conditions in which the system should exploit OTFS, and prove the performance gains for traditional 5G OFDM waveform.

Our contribution can be found in:

- [11] **R. Tuninato**, R. Garello. **"5G NTN primary synchronization signal: An improved detector for handheld devices,"** *IEEE Open Journal of the Communications Society*, 2024.

### 1.1.3 Massive MIMO and RIS-aided systems

Large antenna arrays are an effective technology that can hugely impact the mobile networks' capabilities, in different ways. Spatial multiplexing is one of the main solutions given by large antenna arrays that can boost the network capacities, to enhance the overall system throughput. However, one of the fundamental conditions for the implementation of such a technique is the wireless channel characteristics. The different antennas should experience uncorrelated channels to exploit more spatial channels. Our study is then focused on assessing the limits of this solution. To state the performance, the first research approach is to simulate the wireless environment through suitable channel models, able to emulate the stochastic behaviour of the signal propagation. 3GPP in [12] provides a new channel model that takes into account the 3-D environment, which is a cornerstone in 5G research and development. Its effectiveness lies in its robust foundation of real-world measurements, providing a highly accurate representation of diverse propagation environments. It is an evolution of well-established models, but also incorporating advancements essential for emerging technologies. This comprehensive approach makes this channel model an invaluable resource for researchers, engineers, and industry professionals working to optimize wireless communication systems. Its accuracy and versatility contribute significantly to the simulation tools for the development of reliable and efficient wireless networks.

Thus, our goal is to provide a study and implementation tutorial on this channel model, and then use it to evaluate the spatial multiplexing capabilities of large antenna arrays, via system-level simulations. In particular, many scenarios can be considered depending on the user status since they can be in line of sight (LOS), non-line of sight (NLOS) or indoors. Moreover, we are interested in the impact of the antenna array configuration on the base station performance. We then design and implement cylindrical antenna arrays, that are particularly interesting given the uniform antenna gain in the 360° area around them.

Regarding RIS, they are also devices that exploit many elements to improve the transmission means of the network. Differently from large antenna arrays, they offer a low-power consumption solution, since they are made by semi-passive elements. Thus, RIS holds significant potential and paves the way for a future where these devices are integrated into various environments. Our idea is then to exploit a possible scenario with multiple RIS distributed in the area, to serve multiple users in parallel where the mobile cell coverage would not be able to provide connectivity. Similar to a distributed antenna system, strategically placing RIS in different locations is favourable for getting uncorrelated channels. We designed a new iterative optimization technique for multiple RIS which leverages the uncorrelation of the spatial channels to serve multiple users in parallel.

Our contribution can be found in:

- [13] D.G. Riviello, F. Di Stasio, **R. Tuninato**, **"Performance analysis of multi-user MIMO schemes under realistic 3GPP 3-D channel model for 5G mmWave cellular networks"**, *Electronics*, 2022.
- [14] D.G. Riviello, **R. Tuninato** and R. Garello, **"Assessment of MU-MIMO schemes with cylindrical arrays under 3GPP 3-D channel model for B5G networks"**, *2023 IEEE 20th Consumer Communications & Networking Conference (CCNC)*, Las Vegas, NV, USA, 2023.
- [15] **R. Tuninato**, G. Alfano, F. Daneshgaran, R. Garello and M. Mondin, **"A study on multi-RIS for multi-user distributed MIMO systems,"** *2023 IEEE International Mediterranean Conference on Communications and Networking (MeditCom)*, Dubrovnik, Croatia, 2023.

## 1.2 Organization

This thesis is organized as follows.

**Chapter 2** contains a detailed and in-depth investigation of the 5G NR synchronization procedure for the initial access of 5G user devices. A 3GPP-compliant link-level simulator is adopted to test and analyze the critical issues a receiver must face when recovering the first info on the network it wants to connect to. The impact of many impairments as the frequency offset is analyzed and different detection techniques are compared. Results on real-captures of the 5G signal are also provided.

**Chapter 3** expands the 5G synchronization study and presents a new primary synchronization signal detection technique for handheld devices in 5G NTN. It exploits the 5G synchronization signal characteristics and the presence of residual frequency offset to optimize the detection probability. The land mobile satellite channel is adopted to better characterize the signal propagation in NTN communications.

**Chapter 4** shifts the NTN analysis to the 5G physical and MAC layers. The performance of the physical transport channel is evaluated for typical land mobile satellite channels, and the impact of retransmission techniques is investigated, considering the new challenges posed by the large satellite distances. Moreover, OTFS is implemented and compared to OFDM to determine the possible benefits of this new modulation scheme.

**Chapter 5** broadens the study of 5G systems with system-level simulations for terrestrial networks based on MIMO. In particular, the focus is on the new 3GPP 3-D channel model, designed as a powerful simulation tool. In this chapter, this channel model is then used to evaluate the performance of a multi-user multi-layer MIMO system. The key point is to study the capabilities of large antenna arrays under various user conditions and with different channel scattering richness.

**Chapter 6** is an extension of MIMO systems analysis by giving an outlook on the possible advantages of deploying different kinds of antenna arrays, such as uniform cylindrical arrays. They are particularly interesting since they provide a uniform gain in any direction, and they do not suffer the typical inter-sector interference affecting mobile cells.

**Chapter 7** introduces a new application for the RIS, in the context of system-level simulations for MIMO systems. The idea is to exploit multi-RIS distribution in the environment to obtain a variety of spatial channels to serve multiple users, as for distributed antenna systems, with the advantage of lower power consumption and costs.

**Chapter 8** offers a concise recap of the presented work, emphasizing the significant results obtained. Concluding remarks synthesize the research milestones and offer valuable considerations for continued advancement.

## 1.3 List of publications

The complete list of publications regarding the content of this thesis is the following:

- Chapter 2: [10] **R. Tuninato**, D.G. Riviello, R. Garello, et al. **"A comprehensive study on the synchronization procedure in 5G NR with 3GPP-compliant link-level simulator,"** *EURASIP J Wireless Com Network*, 2023.
- Chapter 3: [11] **R. Tuninato**, R. Garello. **"5G NTN primary synchronization signal: An improved detector for handheld devices,"** *IEEE Open Journal of the Communications Society*, 2024.
- Chapter 5: [13] D.G. Riviello, F. Di Stasio, **R. Tuninato**, **"Performance analysis of multi-user MIMO schemes under realistic 3GPP 3-D channel model for 5G mmWave cellular networks"**, *Electronics,* 2022.
- Chapter 6: [14] D.G. Riviello, **R. Tuninato** and R. Garello, **"Assessment of MU-MIMO schemes with cylindrical arrays under 3GPP 3D channel model for B5G networks"**, *2023 IEEE 20th Consumer Communications & Networking Conference (CCNC)*, Las Vegas, NV, USA, 2023.
- Chapter 7: [15] **R. Tuninato**, G. Alfano, F. Daneshgaran, R. Garello and M. Mondin, **"A study on multi-RIS for multi-user distributed MIMO systems,"** *2023 IEEE International Mediterranean Conference on Communications and Networking (MeditCom)*, Dubrovnik, Croatia, 2023.

# Chapter 2

# Final Considerations

The number of topics involved in the thesis shows how wide can be the umbrella of techniques and technologies associated with 5G. Even considering mostly the physical layer, the amount of aspects to be considered in analysing such complex systems requires extensive studies and performance assessments. The objective of this thesis is to shed light on at least part of the most relevant features of 5G networks and to address novel solutions for the networks of the future.

Firstly, the initial access in 5G NR is analysed in Chapter 2, presenting an extensive overview of the entire procedure. We considered different approaches for signal detection and provided a large set of link-level simulation results that can be seen as a guideline for other researchers or even for non-academic subjects. Moreover, we proved that the new synchronization signals adopted by 5G NR outperformed the previous solutions for LTE, and we also tested the detection techniques with real 5G signal captures. This is particularly important since the synchronization procedure is probably one of the most critical phases in providing connectivity to users who may experience harsh signal propagation conditions.

From this study and the understanding of the synchronization signal structure of 5G NR, we designed a new PSS detection technique addressing a typical 5G NTN scenario, as described in Chapter 3. By exploiting the type of symbols surrounding the PSS, and evaluating the impact of inter-carrier interference, we developed a detection metric that outperforms the noncoherent correlation, usually adopted by receivers, with a limited complexity increase. Moreover, it proved robust under realistic NTN downlink scenarios.

In Chapter 4, a second study on 5G NTN focused on the new solutions for the physical layer of 5G NTN, and in particular for the PDSCH, the physical channel for user data transfer. Our goal was to implement a 5G NTN scenario and assess the PDSCH performance, with a particular focus on the retransmission techniques. We identified the limitations of HARQ due to large RTT in land mobile satellite links, and we compared it with RLC ARQ. We determined that HARQ can provide better performance but, with an ideal adaptive MCS, the gap with RLC ARQ can be reduced. Future studies should investigate alternative solutions or adaptions to HARQ for robust transmissions in 5G NTN. We also evaluated the possible benefits of adopting an OTFS modulation scheme for 5G NTN, which is promising in the case of channel response diversity in the delay domain, as the NTN TDL-D channel, that can be exploited to improve the received signal power.

The previous works focused on link-level simulations. Nevertheless, the performance of 5G systems should be evaluated also from a system-level point of view. In this case, suitable wireless channel models must be considered, to better characterize the signal propagation. Thus, we presented and described the implementation of the new 3GPP 3-D channel model in Chapter 5. Based on this novel tool, we studied the new massive MIMO technology, that requires spatial considerations of the signal propagation. We developed a multi-layer multi-user MIMO system, based mostly on well-known precoding techniques, and investigated the achievable system capacity. From this system basis, new techniques for smart and dynamic resource and user allocation may be researched in the future, also leveraging machine learning models.

Our interest then moved to cylindrical arrays, and their comparison with the common planar arrays, in Chapter 6. We showed that this particular antenna pattern can provide some advantages by limiting the interference and antenna gain loss at the inter-sector edges. Moreover, we considered the impact of imperfect channel estimation on the overall performance.

The last work, in Chapter 7, leveraged our knowledge of the 3-D channel model and multi-user precoding techniques, to develop a new application for RIS. RIS are an interesting and relatively cheap solution to improve signal propagation when obstacles can produce signal blockage. We designed an application for this new technology to provide multi-user capabilities and thus increase the overall system capacity. The study of an analytical model for this system is still missing, and new techniques may be developed, reducing the complexity and optimising the RIS-user allocation.

To conclude, this thesis provided an exhaustive analysis and new solutions for the physical layer of 5G and beyond networks. Through link-level and system-level simulations, we implemented and tested a variety of systems and scenarios. Many research directions are still open, and further real-world tests may be carried out with actual systems and devices.

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