1. Smart Propagation Environment

Vittorio Degli-Esposti[1], Matteo Albani[2]

[1]University of Bologna - Italy

[2]University of Siena - Italy

Abstract: *In the present chapter large intelligent surfaces are presented, with particular focus on their implementation using reflecting metasurfaces, and two possible macroscopic modelling approaches for the realistic simulation of their reflection characteristics are presented. The first one is a simple, Huygens-based, antenna-array-like macroscopic model, which is also suitable for realizations through reflectarrays. The second model is a ray-based, more rigorous approach that identifies the reflected and diffracted rays for a given couple of source and destination points. Some field computation examples are provided for both cases.*

1.1 Introduction: Large Intelligent Metasurfaces

Developed as the application of metamaterial technology to thin structures, metasurface technology is now finding widespread application, including the realization of novel antennas and microwave devices as well as the realization of smart electromagnetic environments. Since metasurfaces characteristics can also be changed in real-time, technology referred to as Reconfigurable Intelligent Surface (RIS) or Large Intelligent Surface (LIS, with reference to the large size), has emerged as a promising option to "customize" the environment and therefore the propagation channel [1]. Although RIS can also be implemented as arrays of antenna elements connectede to proper, variable reactive loads, low-cost technology is an important requirement for LIS, that might need to reach the size of multiple square meters. Metasurface tecnology is a promising solution for low-cost, passive intelligent surfaces, especially if high-performance reconfigurability is not required.

A metasurface is a thin structure, consisting of a substrate made of an insulating layer with a distribution of electrically small (i.e. smaller than the wavelength) metal or dielectric patches printed on it, called meta-atoms. Meta atoms can have various shapes, such as spiral, square, rectangular, H-shape, etc., and their shape or size varies over the surface in order to achieve a desired effect on the wavefront of the reflected or transmitted wave when the surface is illuminated by an incident wave. Metasurfaces aimed at reflecting an incident wave are defined "reflecting metasurfaces", whereas those conceived to transmit a wave are defined "transmitting metasurfaces" or "Huygens metasurfaces". In Both cases, thanks to their meta-atom arrangement on the surface, they can manipulate the phase-profile, and to some extent the amplitude-profile, of the reflected or transmitted wavefront in order to generate a different wavefront from what we can get from an ordinary surface. For instance, an ordinary surface will reflect an incident plane wave into

2. Beyond cellular Massive MIMO: User-centric Cell-Free Networks

Carmen D'Andrea[1], Giovanni Interdonato[1], Luca Sanguinetti[2]

[1]University of Cassino and Southern Latium - Italy

[2]University of Pisa - Italy

Abstract: Massive MIMO (multiple-input multiple-output) is no longer a promising concept for cellular networks - in 5G it became a reality, with 64-antenna fully digital base stations (BSs) being commercially deployed in many countries. However, this is not the final destination in a world where ubiquitous wireless access is in demand by an increasing population. It is, therefore, time for MIMO communication researchers to consider new multi-antenna technologies that might lay the foundations for beyond 5G networks. In particular, we need to focus on improving the uniformity of service quality. Among the different technologies, a promising one is represented by cell-free massive MIMO. In this type of network, all the user equipment (UE) in a large coverage area are jointly served by distributed access points (APs). All the APs are connected to a central processing unit (CPU) and this connection enables the division of the processing tasks for coherently serving all the active UEs. Recent papers have developed innovative signal processing and radio resource allocation algorithms to make this new technology possible, and the industry has taken steps towards its implementation. The aim of this chapter is to provide an overview of cell-free massive MIMO, discussing its main characteristics and applications in the present and future of wireless communications. Firstly, a general discussion on distributed multiple-antenna technologies is given, with particular emphasis on the different terminologies. Then, the cell-free massive MIMO technology is presented and its implementation constraints and challenges are discussed. Additionally, the different degrees of cooperation that can be envisioned in a cell-free network are detailed. Finally, some enabling technologies are discussed and some interesting use cases for future wireless networks are presented.

2.1 Introduction

The aim of nowadays mobile networks is to provide wireless access to a variety of devices anywhere in a wide geographical area. Hence, the service quality of contemporary networks is mainly determined by the throughput that can be delivered at different locations in the coverage area. Since the received signal power decays fast with the propagation distance, a traditional mobile network infrastructure consists of a set of geographically distributed transceivers, also referred to as APs, that the UE can choose between. These transceivers can be equipped with multiple antennas and the number of such antennas determines the dimensionality of the signals generated and processed. Current mobile

3. 6G Technologies for Localization

Davide Dardari[1], Monica Nicoli[2], Mattia Brambilla[2], Francesco Guidi[3]
Anna Guerra[3], Flavio Morselli[4], and Andrea Conti[4]

[1] Università di Bologna - Italy

[2] Politecnico di Milano - Italy

[3] CNR-IEIIT - Italy

[4] Università di Ferrara - Italy

Abstract: *This chapter discusses current research trends and perspectives on localization in future cellular networks towards 6th generation (6G). Emphasis is placed on how the technological enhancements can open new frontiers on precise and reliable localization and support the development of emerging sectors and applications.*

3.1 Introduction

Location awareness is an essential information both for enabling location-based services (LBSs) and for unleashing smart management of communication network resources [1]. Obtaining accurate location awareness is challenging in complex environments, yet mandatory for a number of emerging application verticals, which can no longer rely on ad-hoc fragmented positioning solutions. Seamless fusion of sensors and combination of heterogeneous network technologies is envisioned, particularly in indoor and harsh urban environments. While ultra-wideband (UWB) can be used in indoor, in urban environments positioning errors in the order of few centimeters cannot be guaranteed by global navigation satellite system (GNSS), neither by the most sophisticated augmentation systems such as real-time kinematics (RTK), due to sever multipath and blockage. It is precisely in this context that 5th generation (5G) and beyond cellular technologies promise to fill the performance gap in terms of accuracy and coverage, as depicted in Fig. 3.1. Location functionality is in fact getting embedded in new releases of the 3rd Generation Partnership Project (3GPP) cellular network standardization starting from Release 16 which introduces for the first time dedicated positioning reference signals.

Applications include autonomous unmanned aerial vehicles (UAVs), connected and autonomous vehicles (CAVs), cooperative robotics in industrial Internet of things (IoT), Internet of Senses, and augmented reality [2–4]. In cities, the envisioned density of 6G devices (up to 10^7 connections per km^2 [5]) will accelerate the delivery of LBSs requiring precise 6D positioning (i.e., 3D position and 3D orientation), letting the cellular infrastructure to complement the widely adopted GNSS technology for mass-market applications. It follows that sensing and communication are likely to be considered integrated and not independent functionalities that share a common wireless medium [6]. Such novelty will be a game-changer in location-based services and environmental mapping. The exploitation of the existing communication infrastructure (e.g., cellular networks)

4. Wireless Communications aided by Reconfigurable Intelligent Surfaces

Alessio Zappone[1], Stefano Buzzi[1,2]

[1]University of Cassino and Southern Lazio - Italy
[2]Politecnico di Milano - Italy

Abstract: *Reconfigurable intelligent surfaces (RISs) are planar or conformal structures made of a large number of controllable small sized elements capable of reflecting the impinging electromagnetic waves with a tunable phase shift. Thanks to this property, it is possible to modify and control the wireless propagation environment in order to improve the performance of a wireless communication system. RISs introduce a disruptive novelty element into the wireless communication landscape, since they permit to tune not only the transmitter and the receiver – as usually done since the birth of wireless communications – but also the communication medium.*
In wireless networking applications, RISs are mainly used or to extend coverage by overcoming – through reflection – obstacles that prevent direct illumination of certain areas, or to better concentrate the useful signals where needed, thus leading to an overall reduction of the interference levels.
This chapter provides an overview and one specific example of how a RIS-aided wireless communication system can be optimized.

4.1 Introduction and Motivation

Reconfigurable Intelligent Surfaces (RISs) are planar (or conformal) structures made of special materials, known as meta-materials, that contain elementary electromagnetic units. Such electromagnetic units do not adhere to conventional reflection and diffraction laws, but they are able to modify the phase and wavefront of the radio waves impinging on them, in a fully customizable way. They can be thus used to modify the propagation environment, either by concentrating the electromagnetic radiations where needed, or by extending coverage by illuminating through specific reflections areas where the direct propagation link is blocked by some obstacle. Figures 4.1 and 4.2 depict representative scenarios of both the above situation. In particular, in Fig. 4.1 a group of UEs are in a no-coverage area, since a macroscopic obstacle prevent direct communication between the base station (BS) and the UEs. The deployment of the RIS provides thus an additional way to reach the users through a two-hop path. Morever, the controllable nature of the RIS elements introduces additional degrees of freedom that permit realizing an additional beamforming operation to concentrate the signal where needed and reduce globally the interference level. Fig. 4.2 represents a situation where there is a direct (not necessarily Line-of-Sight, though) link between the BS and the UEs, and the RIS is used in this

5. Terahertz communications

Giampaolo Cuozzo[1], Gianni Pasolini[1]

[1]CNIT Nat. Lab. of Wireless Communications -WiLAB- and Univ. of Bologna - Italy

Abstract: *The terahertz (THz) frequency band is envisioned as a promising candidate to support ultra-high-speed and low-latency communications for beyond fifth-generation (5G) mobile networks, bridging the gap between millimeter wave and optical frequency ranges. The purpose of this chapter is to provide a comprehensive review of the benefits, the challenges, the key technologies, and the latest developments in the THz communications field. Starting with a discussion of the peculiarities of the signal propagation at THz frequencies, we continue by providing an overview of the physical layer issues, along with the envisioned solutions and technologies. We then focus on the medium access control layer, as well as on the resource allocation strategies, and we finally conclude with a brief description of the first standard targeted to THz communication systems.*

5.1 Introduction

Cellular systems have experienced substantial revolutionary advances in the last years, the most recent being the fifth generation (5G) technology with the introduction of paradigm-defining techniques, such as softwarization and network virtualization, massive multiple-input multiple-output (MIMO), ultra-densification and the introduction of new frequency bands. However, as society's needs continue to evolve, a plethora of use cases have emerged that cannot be met by 5G [1].

For example, augmented reality and virtual reality visions are being extended towards 3D holographic videos, which require microsecond-level latency and Tbps-level data rates that cannot be achieved by 5G, even by leveraging the newly introduced millimeter wave (mmWave) frequency bands. The target peak data-rate and minimum end-to-end latency for 5G systems are, in fact, 20 Gbps and 1 ms, respectively. Similarly, increasing industrial automation and the shift from Industry 4.0 to the upcoming Industry X.0 paradigm will push communication requirements well beyond those currently envisioned by 5G: for instance, *Digital Twin* applications will be possible only provided that both extremely high throughput (tens of gigabits per second) and ultra low latency communications (< 1 ms) are provided [2].

More in general, a number of emerging use cases (e.g., holographic teleportation, real-time remote healthcare, autonomous cyber-physical systems, smart infrastructures, ...) require a further evolution of the cellular technology, which motivates the research on 6G. At the time of writing, the key performance indicators (KPIs) that will guide the design of 6G systems have not yet been fully defined, nevertheless tentative values of the expected performance levels are appearing [1, 3], clearly showing that significant advances will be needed in many areas of wireless communications. Table 5.1 [3] shows, for instance, the comparison between the target performances for 5G and those envisioned

6. Role of photonics in next generation fronthaul/backhaul links

Piero Castoldi[1], Luca Valcarenghi[1], and Roberto Sabella[2]

[1] Scuola Superiore Sant'Anna, Pisa, Italy

[2] Ericsson Research, Italy

Abstract: *The centralisation of some mobile network functions and the increase of the maximum achievable cell capacity (e.g., through Massive MIMO) call for the utilization of photonic technologies in the fronthaul and in the backhaul. This chapter highlights the role of photonics in these new network segments. In addition, it highlights other possible elements and functions of the mobile network where the introduction of photonic technologies can be beneficial.*

6.1 Introduction

The 5G and beyond network architecture implements a very scalable and flexible network technology that provides a resilient cloud-native mobile network with end-to-end support for network slicing. It aims to support new services based on three major usage scenarios, namely: (i) enhanced mobile broadband (eMBB) supporting higher broadband access capabilities, faster connections, and higher resolution; (ii) massive machine-type communications (mMTC) for high density connections of low cost and energy efficient IoT devices; and (iii) ultra-reliable low-latency communications (URLLC), which support mission critical applications requiring very low latency and high reliability [1].

With the constant evolution of 5G networks, Network Function Virtualization (NFV) is explored to provide rapid and cost-effective deployment, upgrade, and scaling of network services and functions in an integrated fronthaul/backhaul network infrastructure. NFV aims to implement the following improvements: (i) decoupling software from hardware, allowing separate timelines and maintenance for software and hardware; (ii) flexible function deployment, where software and hardware can perform different functions at various times; and (iii) dynamic scaling of the Virtualized Network Function (VNF) performance [2]. Virtualization prevents network service providers from investing on expensive hardware components. It can also accelerate the installation time, thereby providing faster services to customers. Photonics can be beneficial in supporting 5G and beyond networks in several network segments. Since the introduction of the concept of cloud RAN (C-RAN) photonics was considered for carrying digital fronthaul interfaces. Indeed, if most of the baseband functions are centralized (e.g., lower layer split options) optical networks are the only networks capable of supporting the huge capacity required.

Photonics will play a role also in other elements of the distributed 5G and beyond network. In 5G and beyond transport it will allow the transmission and routing of huge

7. Co-designed Communication and Sensing

Elisabetta Matricardi[1], Lorenzo Pucci[1], Dario Tagliaferri[2], Marouan Mizmizi[2], and Andrea Giorgetti[1]

[1]WiLab - CNIT, DEI - University of Bologna, Italy

[2]Politecnico di Milano - Italy

Abstract: Sixth-generation (6G) wireless systems will offer a multitude of new applications besides connectivity to an unprecedented number of users and devices. It is widely recognized that one of 6G's most revolutionary innovations will be its ability to enable the localization of non-cooperative objects and, more generally, the sensing of the physical environment via RF signals. This functionality will be a key added value for future mobile radio systems and for which the term *perceptive networks* has been recently coined. This chapter aims at exploring the main co-design aspects that enable the network to operate both as a communication system and as a radar system for sensing purposes. Then, it presents the main signal processing techniques for object localization, with emphasis on two main modulation techniques: the orthogonal frequency division multiplexing (OFDM) modulation, one of the most successful communication signals, and the orthogonal time frequency space (OTFS) modulation, which is among the candidates for next generation wireless systems. For both waveforms, the chapter focuses on the key aspects that enable radar functionality, highlighting the pros and cons in terms of performance and complexity. Finally, an innovative approach that combines both waveforms' benefits, named dual-domain waveform superposition, is outlined.

7.1 Introduction and Use Cases

The upcoming sixth-generation (6G) wireless networks have been envisioned as key enablers for many emerging services with high-quality wireless connectivity requirements and sensing capabilities. A variety of visionary speculations about what 6G will be, among the most common is the usage of high communication frequencies, such as millimeter wave (mmWave) ($30-100$ GHz) and sub-THz (> 100 GHz) [1, 2], and empowering the network and mobile devices with radio sensing capabilities [3]. Indeed, communication and sensing systems are both evolving towards higher frequency bands and larger antenna arrays. Although they have been advancing independently for decades, they share several commonalities in terms of hardware architectures and signal processing, which offers an exciting opportunity of integrating sensing into wireless infrastructures, thereby potentially sharing the frequency-time-space-hardware resources in the so-called co-design communication and sensing, also referred to as integrated sensing and communication (ISAC), systems [4]. Radio sensing and communication systems also tend to have similar channel characteristics, as their operation frequencies reach the mmWave

8. Massive Multiple Access for 6G

Enrico Paolini, Lorenzo Valentini, Muhammad Usman Khan[1], Fulvio Babich, Massimiliano Comisso[2], Velio Tralli[3]

[1]University of Bologna - Italy

[2]University of Trieste - Italy

[3]University of Ferrara - Italy

Abstract: *This chapter addresses the connectivity problem between a massive number of intermittently active devices contending for transmission of short uplink packets to a single base station. Such a context, usually referred to as "massive multiple access", deviates sharply from traditional multiple access due to the extremely large device population size, random devices' activity, transmission of short packets, and bursty nature of transmissions from the generic device. Massive multiple access problems have fostered a revival of random access theory and techniques as well as the development of sophisticated grant-free access schemes featuring a tight interaction between the the physical and the medium access control layers. The chapter describes massive multiple access challenges towards sixth-generation mobile networks and overviews promising technologies and research directions.*

8.1 Introduction

The advent of the Internet of things (IoT) [1] has boosted the attention on machine-type communications (MTC), i.e., autonomous communication between physical objects that are not directly operated by humans [2]. As a consequence of the fast growing pervasiveness of IoT in several application domains, including transportation, healthcare, agriculture, logistics, and many others, the number of "smart objects" and, above all, their density has become so large that the terminology massive machine type communication (mMTC) has been coined [3, 4]. Generally speaking, mMTC refers to wireless networking among a massive number of devices that are physically located in the same geographic area, hence, whose density in terms of devices per square meter is very large. In mMTC applications, devices are usually battery-driven. Each device generates data in a very discontinuous and intermittent way, with short activity periods separated by long periods in which the device is inactive. Activity periods are usually aimed at transmitting a message, in the form of a short or relatively-short packet (e.g., with a payload that may range from tens of bytes to one thousand bytes), to another device or to a remote server through the network.

A very common situation in the context of mMTC is the one in which a massive number of devices access the network wirelessly through the same gateway or, equivalently, access point (AP) or base station (BS). In the uplink, i.e., in the wireless link from the

9. High-resolution SAR imaging for urban mobility

Stefano Tebaldini[1], Dario Tagliaferri[1], Marco Manzoni[1], Marco Rizzi[1]
Andrea Monti Guarnieri[1], Claudio Prati[1], Monica Nicoli[1], Umberto Spagnolini[1]
Ivan Russo[2], Christian Mazzucco[2]

[1]Politecnico di Milano - Italy

[2]Huawei Technologies Italia - Italy

Abstract: The use Synthetic Aperture Radar (SAR) technologies in the context of automotive applications has drawn increasing attention in the last years. The interest in SAR technology derives from the possibility to generate Radar images of the surrounding environment at a resolution much finer than allowed by conventional automotive Radars, which indicates strong potential for what concerns detection, localization, and characterization of the targets. Still, for SAR imaging to become a reality in the automotive context it is necessary that proper resources are made available, not just in terms of computing capabilities, but also for what concerns radio-frequency bandwidth and duration of the transmissions. In this sense, future 6G vehicular communications are expected to play the role of enabling technology for the advent of automotive SAR, in that the capability of exchange massive amounts of data among neighboring vehicles allow to further enhance SAR resolution even in scarce bandwidth conditions, e.g., in interference-limited scenarios. Under these assumptions, in this chapter we aim at providing a discussion of the potentials of automotive SAR imaging as applied to high-resolution mapping of urban scenarios. The discussion is complemented by showing the outcomes of recent experimental demonstrations on open roads.

9.1 Introduction

The advent of fully Autonomous Driving (AD), foreseen for 2030, is expected to provide a safe, comfortable and efficient driving experience. According to SAE [1], AD can be conceptually and technologically split into six different levels. In the first three (0-2), the human driver is only assisted by basic functionalities, e.g., lane changing detection, blind spot warning, emergency braking, etc, keeping the full control of the vehicle. Levels from 3 to 5, instead, envision a driver-less system, where humans are not even required to take over-driving. Currently we are living the early phase of the self-driving revolution, where fully Autonomous Vehicles (AVs) are developed for controlled/private environments (e.g., industrial fleets for logistics, farming, airports, etc.) Over the next decade, the paradigm shift will face the consumers to spend travelling time in working, relaxing or accessing entertainment. The rush to level 5 requires AVs to be able to accurately, seamlessly and reliably *sense* the environment, in order to take real-time decisions and drive over all

10. Semantic and goal-oriented communications

Sergio Barbarossa, Francesco Pezone [1]

[1]Sapienza University of Rome - Italy

Abstract: *One of the biggest challenges of next generation networks is sustainability. The current predictions about the data traffic increase, especially in view of the introduction of virtual/augmented reality applications or holographic communications, show an exponential behavior, which is clearly unsustainable. In parallel, the concern about energy consumption is becoming more and more pressing. Overcoming these big challenges requires a paradigm shift from current network architectures to a new model aimed at providing more by consuming less. One possibility is to promote a paradigm shift from Shannon theoretic framework toward semantic and goal-oriented communication, where the focus is not just to transport bits from source to destination in a reliable manner, regardless of what those bits represent. Conversely, a new network design based on semantic and goal-oriented communication must focus on the meaning underlying the exchange of data and the motivations underlying this exchange. This change of perspective is made possible by the integration of artificial intelligence tools within the communication layers, including not only machine learning, but also novel knowledge base systems and generative models. This chapter offers an attempt to promote this paradigm shift direction by exploiting the information bottleneck as one of the possible driving principles.*

10.1 Introduction

5G networks represent a breakthrough in Information and Communication Technologies (ICT) as a single platform enabling a variety of services, from enhanced mobile broadband (EMB), mission-critical communications (MCC), and massive Internet-of-Things (IoT). Besides making smartphones faster in sharing information through the Internet, EMB will enable new immersive experiences such as Virtual Reality (VR) and Augmented Reality (AR). At the same time, still using the same platform, but combining the physical resources in a different way, MCC enables ultra-reliable low-latency links useful for remote control of industrial processes or critical infrastructures, autonomous driving and medical procedures. Finally, making again a different usage of the same platform, massive IoT makes possible the connection of a massive number of embedded sensors through the ability to scale down data rates and power, providing extremely lean and low-cost connectivity solutions. The above three services are characterized by fundamentally different specifications and constraints, in terms of data rate, latency, reliability, number of connected devices, etc. 5G networks have been able to tackle the challenge of designing a single platform enabling such a variety of services in a very effective way by resorting to network function virtualization (NFV) and exploiting a dense deployment of radio access nodes, massive Multiple-Input/Multiple Output (MIMO) systems, and wideband links

11. Physical layer security for 6G systems

Stefano Tomasin[1], Lorenzo Mucchi[2], Diana Moya Osorio[3], Dania Marabissi[2]

[1]University of Padova, Dep. of Information Engineering - Italy

[2]University of Florence, Dept. of Information Engineering - Italy

[3]Centre for Wireless Communications, University of Oulu - Finland

Abstract: *The sixth generation (6G) of cellular networks envisions a large variety of new services and types of connected devices (from Internet of Things devices to unmanned aerial vehicles), with a significant attention to power efficiency. Traditional cryptographic security may not fit the new scenario due to its complexity and new rising challenges, such as quantum computing. Moreover, securing wireless sensing in 6G (e.g., for localization purposes) will be even more challenging. Physical layer security (PLS) is an approach to security operating directly on the wireless signals and exploiting the propagation characteristics to provide confidentiality, integrity, and authentication. While being a research topic for a while, PLS is now developing practical approaches that may be suited for 6G networks due to its low-power and low-complexity features and its easy integration with sensing techniques. The chapter will give an overview of existing solutions and research perspectives on PLS for 6G networks.*

11.1 Introduction

Although current research on security in cellular communications is mainly focused on 5th generation (5G) core network, the improvements on security required by the 6th generation (6G) are becoming of critical importance. Recently, cyber attacks are becoming more sophisticated on the wireless edge with lower implementation cost, e.g., using 1000 USD software defined radio device [1, 2]. Moreover, artificial intelligence (AI) and machine learning (ML) tools are expanding the set of attacks [3]. At the same time, network slicing and, in general, the flexible infrastructure, paved the way to multi-domain orchestration, often implemented with ML approaches [4, 5]. In addition, the research is moving slowly from a client-server networking approach to a true end-to-end quality of service (QoS) approach, thus the service-level agreement will include quality of security (QoSec) in the next future [6]. The ingredients of QoSec in 6G are currently under investigation, including the definition of its security level with the proposition of adaptive risk-aware solutions.

Future 6G networks are envisioned to include new tools to sense and interpret the context of the communication [7]. Multiple sources can be used not only to reach a high accurate sub-cm localization, but also for extracting additional but essential details about the information, e.g., time, type, and age. Context awareness incorporated into QoSec