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Introduction

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1.1 Technology Trends

1.1.1 Mobile Networks and the Wireless Internet of *Everything*

Mobile Communications are exponentially evolving to allow any electronic device wirelessly to connect to the Internet. The first decade of the 20th century saw how the computer and the phone have converged into a single concept of user terminal, making mobile telephony and nomadic computing facilities coexist in a single device: the smartphone. As smartphones have become a revolution in the wireless user's experience, a second revolution at the terminal side may be expected, and the future traffic growth rate will be huge, due to the extension of mobile data communications to machines, vehicles, sensors, and smart objects. All these heterogeneous wireless devices must be connected to each other in a massive moving data scenario that is already being called wireless internet of things (WIoTs).

Every WIoT scenario is essentially an smart environment (SE), i.e., a physical (layer) (PHY) space populated by sensors, actuators, embedded systems, user terminals, and any other type of communicating device, which cooperatively pursue given tasks by exchanging information and share all types of resources, such as radio spectrum or energy. Some examples of SEs are the human body, vehicles on a road, and a smart building or a smart city. Any of the SEs in mobile communications was seen as the raising of a new generation of wireless sensor networks (WSNs), either local or wide area, with coordination and communication entities and group mobility. Nowadays all those SEs are intended to be merged with the current and future mobile radio access networks (RANs). In some cases, like connected vehicles and body area networks (BANs), a coordinated group of sensors is intending to communicate with an infrastructure network or other mobile devices. In other scenarios, such as Smart City and Connected Home, a moving terminal is intended to get information from neighbouring wireless devices and sensors.

Cooperative Radio Communications for Green Smart Environments, 1–16.

It is then necessary to find ways to efficiently merge those types of SEs with the current and future mobile RANs.

SEs are delimited in space, but not in scope. For example, wireless devices on or inside the human body can improve everyday life for patients needing continuous health care (Smart Health), but can also help the professional sports-man/woman to improve his/her performance; inter-vehicular and vehicular-to-infrastructure (V2i) communications can assist the driver and increase road safety (Smart Cars) or enable the provision of Internet services in the car; wireless sensors in buildings can provide information helpful for energy control purposes (Smart Energy) or support rescue teams in emergency situations.

SEs can provide better safety and lifestyle, and can help reduce global energy consumption by contributing to an intelligent distributed management of the energy resource. SEs may be green smart environments (GSEs) because of their application: especially, in enabling energy efficient lifestyles, for example in enabling home working and teleconferencing to reduce the need for travel. However, they need to become green themselves. The impact on the environment and global energy consumption of information and communication technologies (ICT) must be minimised; SEs must be green also in the sense that their deployment and use must follow energy efficient paradigms, regardless of their goals and application areas. Progress will come from better hardware design, but also improved transmission techniques and protocols.

Moreover, GSEs need to be efficient overall, with better use of energy (Joule/bit), radio spectrum (bits/s/Hz/m^2), computing resources, etc. To achieve this goal, GSEs have to make proper use of the concept of cooperation among network nodes, both at link level to maximise end-to-end throughput between nodes, through relaying, network coding, or other forms of cooperation, and at network level to maximise network capacity in a dense heterogeneous environment. Cooperation also involves the proper detection, mitigation, and management of inter-network interference, which arises from the possibility of autonomous networks merging and splitting.

1.1.2 Mobile Communication Scenarios

Cars have been the first focus in those types of scenarios, with the development of some standards for V2i and vehicular to vehicular (V2V) communications along the last decade. Nowadays, the automotive industry is increasingly adapting wireless sensors and communication systems to improve the connectivity of their vehicles. Four main aspects benefit from radio communications to cars: infotainment services to passengers, vehicular cloud services, traffic safety, and traffic efficiency. In beyond 4G wireless communications, vehicles will be integrated parts of the system, not just end-nodes. In essence, vehicles can act as mobile base stations, which will be beneficial with respect to filling in coverage holes, supporting local capacity needs that appear unpredictably in time and space, and providing good quality of experience for passengers. In addition to serving as a mobile base station, a vehicle can sense its environment to support a multitude of applications. For instance, real-time traffic and environmental monitoring is truly enabled, which in turn enables real-time traffic management to increase the efficiency of the transport system and reduce its environmental impact. Connecting vehicles to the cloud with a stable, high-rate, low-latency wireless link will bring many benefits. Heavy calculations and storage can be off-loaded to the cloud, vehicle maintenance will be facilitated, and novel services can be delivered to vehicle customers with a very short time-to-market. Traffic safety and traffic efficiency applications require vehicles and road infrastructure-like road signs, traffic lights, toll booths, etc., to exchange information to make transport safer and more efficient, reducing accidents, traffic jams, fuel consumption, and emissions. Hence, wireless communications is a crucial enabling technology for these applications.

Another raising SE is the wireless body environment (WBE), which is supposed to revolutionise health monitoring, with its huge number of possible applications in the home and hospital, for elderly care and emergency cases. WBE communications will enable a new generation of services and applications that give the user an enhanced and intuitive interaction with surrounding technologies. This interaction is boosted by a network of body implanted or wearable devices, operating in the immediate environment around and inside the human body, that can exchange important data, health parameters, in real time. Moreover wireless body environment networks (WBENs) are expected to provide new functionalities for applications in people's every-day lives, such as sport, leisure, gaming, and social networks. As this service permits remote monitoring of several patients simultaneously, it could also potentially decrease health care costs. Health systems will also benefit from the integration of wireless on- and in-body sensors, with applications to healthcare, remote monitoring, wellness and assisted surgery. WBENs are developing as a more advanced and separate addition to wireless communications in general. While its basic operating characteristics are the same as all radio systems, there are many features and specific problems that justify dealing with it separately from other forms of wireless communication, such as battery life, low power, low cost, small size, body dynamics, and in-body propagation. Body environment applications are designed for short-range applications with relatively low power and are regulated by the telecommunication authorities. Also, the devices are operated in or close to a human body, which affects communication performance. Therefore, it is needed to find models to predict a reliable operating range for these systems, based on propagation characteristics, human posture, and movements.

The *Smart Cities* concept has been developed during recent years mainly, but not only, on the basis of urban sensor networks, which provide information either to a centralised management system or to the moving devices around them. The Smart City sensors are intended to help the control of lighting, temperature, pollution, flow of traffic, gas, water, and electricity parameters, as well as monitoring streets, pipes and bridges, emergency responses and public transportation, among others. This concept is an evolution of the intelligent room and intelligent building ideas, and is addressed to both people living and working in the city and people organising and administering the urban infrastructures. Current ongoing applications to provide the bases of the Smart City deployment are: optimised transportation, personalised services, community services, and management of big data. From the radio access deployment perspective, a huge set of advanced technologies is required for a full implementation of Smart Cities, and substantial effort to integrate them is essential. The same happens with manufacturers, operators, service providers, and city administrators, since close collaboration is envisaged among them. All the existing wireless networks (cellular 2G/3G/4G and beyond, point-to-point, wireless local area network (WLAN), wireless personal area network (WPAN), wireless metropolitan area network (WMAN), and mesh networks), and also user terminals, mostly smartphones, which are today's main moving transceivers, will play an important role to facilitate Smart City deployment. Their role as personal standalone network access devices is changing in future networks, when the handheld will be active as a cooperative networking node, and then be able to measure environmental parameters through its own sensors, as well as to geo-reference them, thus contributing to Smart City monitoring procedures.

On the basis mentioned above that every electronic device is to be wirelessly connected, future scenarios in radio communications will give rise to situations where a huge number of devices are located in PHY proximity (in the space domain, relative to radio coverage ranges), while generating independent traffic with different patterns and needing to share the same pool of radio resources to create some type of network topology. These situations come from static and low mobility devices, as in machine to machine (M2M) and machine to infrastructure (M2I) communications, which are to improve industrial automation; or the connected home multimedia systems and sensors, where revenues are expected because of the increase of wireless data traffic, while improving user experience within the concept of connected living.

Also high-dense traffic occurs in high mobility scenarios, such as public events, either planned or unexpected, and in others like the smart cities mentioned above, offices, smart grids, and smart metering. In any of these situations, the number of contenders for the radio resources can potentially be much higher than those manageable by traditional wireless architectures, protocols, and procedures. Such extreme situations do not occur often, but may happen in some cases in regular operation, for example in stadiums, in clothing stores (where thousands of radio frequency identification (RFID) tags may exist), or in a huge depot of some company. In all cases, the possibility of maintaining highly efficient connectivity using wireless communications can provide significant added value as it may solve many problems. In fact the huge number of moving connected devices in certain areas, either accessing centralised services or getting information from sensors in their surroundings, increases the interest in developing selfish *ad hoc* dynamic network configuration strategies. The popular term to describe these situations is "*Moving Networks*", where many new concepts in network coding, relaying, self-organisation, or opportunistic caching, among others, are to be developed.

1.2 RANs-Enabling Technologies

1.2.1 Small Cells in Very High-Dense Deployment

There is already a natural trend in the infrastructures of mobile networks to reduce the range, and hence the size and complexity of the base stations, while increasing the number and bandwidth of the PHY connections in between smaller cell sites. The reason for this is the continuously increasing data traffic demand, which generates new opportunities for the provision of new services, which at the end give rise to a further increase of traffic capacity and throughput requirements. The wide deployment of optical communications networks, with fibre connections closer to end users, makes sense also for those wideband connections in between small cells, changing the current basic concept of traffic-scaled cellular deployment to a modern view of opportunistic spectrum-access-based cooperative networking.

In RAN deployment, it is by now obvious that installing smaller cells in areas where the infrastructure can provide the required backhaul connectivity is the current natural evolution of the RAN infrastructure. The cost of its deployment versus the amount of data it can handle is beginning to be competitive compared to other solutions. But these small cells will also require new techniques for configuration, management and optimisation. Self-configuration of such elements of access networks is expected, as well as coordinated behaviour among groups of small cells, together with neighbouring network sites.

The deployment of new radio networks is based on facilitating access to devices by installing small cells or access nodes, which are interconnected in groups by high-speed backhaul networks, and cooperate within the group to manage the resources in a joint cooperative area. Small cells change the classical concept of the cellular network, from the traditional geometric approaches for coverage and service area analysis, and change also resource management concepts, such as "neighbour" to "partner" cell, the whole concept of "cellular" being progressively replaced by "*cooperative*", as the major infrastructure embodied in base stations evolves to a connected sub-network of small cells.

1.2.2 Moving and Relaying Nodes

In addition, terminals have ceased to be the edge of mobile and wireless communications networks, and are also becoming a local area communications node entity for many of the current scenarios, so the terminal acts as a local manager of radio communications, not only for the user but also for the surrounding smart devices. This concept, together with the reduction of cells size and the changes to the cellular based deployment concept mentioned above, leads to a view of a future convergence between a mobile device and a small base station, the terminal as a *local access enabler*, either via a fixed connection to the fibre loop or by a wireless connection to another access point or mobile device.

This scenario of wireless access enablers, both fixed and mobile, requires an inclusive approach of the current technologies on mobile opportunistic relaying, cooperative networking, distributed antenna systems (DASs), dynamic spectrum resources allocation, cognitive radio (CR), and massive and distributed multiple-input multiple-output (MIMO).

The evolution towards very dense small cells infrastructure brings radio network architectures to consider the roaming user device (on the bus, in the street, inside the car, at home, etc.) as a *relaying node* able to provide coverage extension and to act as an access point to the Internet for the "things" equipped with IP address; a similar service will be provided by urban radio backhauls, deployed using non-cellular low-energy and low-cost radio interfaces. This can make the IoT paradigm become true through a network of mobile and fixed gateways, interconnected according to the random mobility behaviour of humans.

1.2.3 Virtualisation, Cloud, and Ultra-Flexible RANs

Networks architectures are becoming more and more flexible, developing towards the Cloud RAN concept, based on technologies such as DASs, and evolving beyond it towards the so-called "Ultra-flexible RANs". The operation of a mobile network, which traditionally was based on a single owner of the Core and Radio Access infrastructures, who is at the same time the service provider for its customers, tends to become diffused in the virtual operation of shared RAN facilities, opening the door for Virtual Operators as service providers, Radio Resource Providers who own the spectrum and manage its access, RAN providers owning the infrastructure, etc. This scenario for Infrastructure Networks is in principle the basis for the future ultra-flexible RAN, in both technology and operation.

A first step in the evolution of network infrastructures has been the use of DASs for mobile access in small areas, mainly – but not only – indoors, which largely eliminates the concept of "cell". This occurs at least in the sense that cells will not be the stable projection of the service area created by some radiating elements from a single site, but a dynamic set of positions to which a service connection is provided by a combination of signals generated in a cooperative manner from several distributed antennas.

The approach that makes RANs even more efficient is referred to as cloud radio access network (C-RAN), a centralised processing, collaborative radio, real-time cloud computing, and clean RAN systems. Based on real-time virtualisation technology, C-RAN minimises CAPEX and OPEX costs. It enables the fast, flexible, and optimised deployment and upgrade of RANs, supporting pay-per-use models. It also eases the flexible and on-demand adaptation of resources to non-uniform traffic. Besides this, the centralised processing of a large cluster of remote radio units (RUs) also enables the efficient operation of inter-cell interference reduction, and coordinated multi-point (CoMP) transmission and reception mechanisms, and eases mobility between RUs.

To make the future mobile networks sustainable from an economic viewpoint, it should provide more and cost less, both metrics being equally important. Flexible architecture concepts like Cloud RAN address these challenges, although in many cases the research effort highlights the performance enhancement aspect only. However, beyond 4G mobile services provision in a 2020 time horizon also requires cost-effective technologies for ubiquitous coverage, together with the flexible management of centralised resources. With this dual *performance–cost* goal in mind, the Cloud RAN concept is being expanded to include not only the RAN but also many of the evolved packet core (EPC) functionalities, in the so-called *Network Virtualisation*.

Network Virtualisation refers to the capability of partitioning and/or pooling underlying PHY resources (e.g., sites, racks, and base band cards) or logical elements (e.g., RAN and EPC nodes) in a network, and it is usually associated with the concepts of software-defined networking (SDN) and cloud services. Some operators consider Network Virtualisation as a fundamental tool for making the network manageable, and a lever for modifying (opening) the mobile network infrastructure ecosystem, without precluding the incorporation of performance-enhancement technologies, such as CoMP or interference management, which is not necessarily a primary goal.

The role of Operators is also evolving, from the current RAN sharing approaches to a full virtual operation concept. In fact, the operation of mobile networks, which traditionally was based on a single owner of the Core and Radio Access infrastructures, who is at the same time the service provider for its customers, tends to become diffused in virtual operation of shared RAN facilities, opening the door for a combined architecture with Virtual Network Operators as service providers, Radio Resource Providers who own the spectrum and manage its access, RAN providers owning the infrastructure, etc. This has a large impact on the development of novel integrated and flexible services based on RAN-as-a-service (RANaaS). The scenario of Infrastructure Networks is in principle the basis for a future ultra-flexible RAN, in both technology and operation.

1.2.4 Energy- and Spectrum-Efficient Networking

From the mobile communications perspective, and looking also to other related disciplines, the user interface revolution is crucial for the required evolution of terminals and networks. A factor that changed dramatically with the launch of touch-screen terminals was the "user latency". If the "time-to-type" a command in a mobile keyboard in previous years is compared to the "time-to touch" in today's tablets, a factor of 10 is easy to reach. Hence, the time between uplink packet transmissions from these new generation terminals has greatly decreased, and previous traffic models for uplink load have become obsolete. The activity of the user when accessing wireless services might give rise to a new revolution in the coming decade, since other interfaces are under development, such as gestural (in glasses or lenses), muscular (using on-skin sensors), or even brain activity sensors in the long term. Any such human interfaces will boost a new era of applications and services, started to be referred as “Tactile Internet” which, of course, give rise to new requirements for wireless connectivity and mobile networking. The only way to make the coming services and applications efficient at the RAN side is to reduce the signalling load, and latency, to enrich user experience, and to maximise spectrum efficiency.

To date, the improvement of user’s experience has been achieved by widening the network, the inclusion of new infrastructures, new frequency bands, and additional transmission systems. Three generations of Radio Access already coexist in 3GPP mobile networks, and little effort has been expended to improve the overall energy and spectrum efficiency. Thus, the metric of Joules per Bit per user is so far useless in RAN deployment. Moreover, even with the deployment of 4G technology, RANs continue to offer broadband access to a limited percentage of locations. This is true even in densely populated areas, where broadband radio access is available, but where interference limits capacity to well below its theoretical maximum. This means that overall the deployed RAN is still making sub-optimal use of the spectrum and energy (bits/Joule), mainly because it is based on fixed spectrum allocation and hierarchical network infrastructure. In the current decade, and beyond 2020, new terminals, devices, applications and services will continuously surge onto the market, forcing RANs to offer extreme levels of throughput, capacity, coverage, and ubiquity. This boosts a fundamental review of the basis of the current RANs, leading to the above mentioned Ultra-flexible architectures, combined with extremely efficient RATs and new approaches for a smarter spectrum management and sharing strategies.

The above-mentioned scenarios of WIoT require dramatically reduced energy consumption, to enable long-endurance self-powered nodes, or nodes powered by energy harvesting, while radio spectrum and overall energy resources remain strictly limited. Especially for IoT, total energy requirements in the order of 1 pJ/bit/node, including all contributions to node energy consumption, will probably be necessary.

To achieve such goals, the implementation technology has to be based on low-power hardware architecture and energy-efficient signal processing. *Multihop cooperative networks* have the capability to greatly increase capacity density and reduce energy consumption, by bringing the access network closer to the end-user. Anyway, the existing “layered” protocols, with their requirements for retransmissions, and multiple acknowledgements, may be highly inefficient, and in multihop networks result in bottlenecks that prevent them scaling as required both for high capacity density access networks and large scale IoT networks. wireless network coding (WNC) – a.k.a. physical layer network coding (PLNC), is a technique that has potential to become a "disruptive" technology for such networks. It has the capability of naturally solving problems related to dense, cloud-like, massively-interacting networks of nodes. It can also be regarded as an example of the more general concept of the "network-aware physical layer", in which functions conventionally performed at high layers of the protocol, such as routing, are more efficiently carried out at the PHY layer, which alone has the capability of processing signals directly, without loss of information. These networks will nevertheless need to be self-managing to optimise their efficiency and adapting to varying demands and resource availability.

1.2.5 New Spectrum Bands for Mobile Broadband

Spectrum availability is always crucial for the evolution of Radio Communications. There is no doubt that for mobile operation in open areas the UHF band is the best possible allocation, but these bands are becoming overloaded under the current access technologies, RAN infrastructures and services provision schemes. Some spectrum bands were already identified by international telecommunications union (ITU) during the World Radio communication Conference of 2012 in Geneva [ITU2012] as potential allocations for spectrum sharing technologies. More recently, the 2015 edition [ITU2015] has confirmed additional spectrum allocations to mobile services on a primary basis, and identified additional frequency bands above 1 GHz for international mobile telecommunications (IMTs) to facilitate the development of future terrestrial mobile broadband applications.

Assuming that the amount of data traffic is to grow by two orders of magnitude in the coming decade, no matter what will be the type of traffic and the "killer" applications or services in these future networks, the need for more resources to deal with even more than 100 times more mobile data traffic in the 2020s is apparent. These "resources" could of course come from additional spectrum, although this is already scarce below 3 GHz and less feasible after the second digital dividend, but obviously still available in higher frequency bands for short-range broadband connections.

While UHF remains being the main allocation for mobile services, with many thousands of moving terminals per square kilometre, new concepts for efficient spectrum usage will have to appear. Among other approaches, opportunistic access to certain frequency bands, CR, co-primary usage in shared bands, and massive and distributed MIMO are already under deployment. *Sharing spectrum* requires consideration not only of technologies but also of regulatory policies, and the effect on applications and services for the end users derived from such approaches.

In addition, exploitation the mm waves band for the next generation of mobile communication standards (5G) has started to gain considerable traction within the wireless industry, EU's Horizon 2020 such as the 5G PPP initiative [5GPPP], regulators and the ITU. Study Groups of the ITU keep working on potential IMT at higher frequencies, above 6 GHz, as part of the preparations for next World Radio Conference (WRC'19). Propagation measurements and channel modelling in the higher frequency bands are also part of the objectives of the ITU SGs after the WRC'15 and for the coming 4 years.

Finally, systems at 60 GHz and above, even up to 400 GHz, are currently under consideration as the natural way of providing wireless Gigabit links, but this is limited to short-range radio access to infrastructure, focussing the wireless "networking" problem on managing the location of terminals and the distribution of services though access points over wired infrastructure.

The inclusion of several new bands in simultaneous operation for the same network access tends to increase very much the complexity at the terminal side. In fact, the heterogeneity of the RAN spectrum and access modes has been enforced by the rapid increase in demand for mobile data, but it is nowadays becoming a drawback for the design of radio terminals, and its energy efficiency. If the future of mobile communications evolves through the inclusion of new spectrum bands on current cellular infrastructures, terminals and antenna systems may reach their limit of reliability.

1.2.6 Radio Channels and Propagation Modelling

The radio channel is central to the paradigm of the current and future mobile communications scenarios: multiple antenna systems, interference recognition and the high degree of cooperation among separate network nodes, require a multi-dimensional description of the radio channel characteristics, jointly modelling of space, time, frequency, polarisation, etc. Moreover, the deployment contexts include the human body, the vehicular environment, dense urban areas, indoors, and many other where characterisation of radio propagation is complex. All this motivates the need for accurate models describing radio propagation in a multi-dimensional fashion, and proper evaluation of how the radio channel characteristics affect the link and network performance, and vice-versa.

Radio propagation for wireless networks has been extensively investigated for over 20 years, mainly towards networks planning for 2G, 3G, and 4G mobile communications. Simple and sophisticated models have been developed in COST IC1004, and some of them incorporated into standards, following the activities of COST 207, 231, 259, 273, 2100, WINNER, and METIS in Europe, as well as of bodies such as 3GPP, ETSI, and IEEE 802 among others. There was a strong body of knowledge for outdoor, rural, and urban channels, covering "classical" use cases of communication between, e.g., a mobile terminal and a base station. However emerging cases, such as BANs, vehicle-to-vehicle links or wireless sensor networks, were much less known from the radio channel point of view, and have been studied in IC1004. The same case applies to cooperation and relaying, being one of the major mitigation techniques to combat channel attenuation and consequent power consumption, and in which IC1004 has assessed multi-link radio channels. There was also a significant lack of knowledge in radio propagation for the more unusual environments considered for the above mentioned SEs, about transitions from one kind of SE to another, models for heterogeneous communication systems, models for the behaviour of real world terminals in real environmental conditions and an interference model for the crowded spectrum conditions determined by a very large number of co-existing wireless objects. Many of these lacks have been covered in COST IC1004.

Also in the *development of RANs*, the supporting knowledge required is that of the radio channel. The requirement for robust and resilient wireless access requires that the characteristics of the propagation channel are addressed in a more complete manner than before, when link outage could be accepted by the user to some extent. Site specific *network planning* will tend to be used much more than at present, in order to provide adequate access in cases that would previously be treated as poorly-performing outliers, not specifically addressed. Thanks to the widespread availability of computing power, PHY propagation tools that make use of digital terrain and building maps will be used within operational networks in order to better optimise the allocation of resources and ensure correct access in the worst cases and in quasi real time. Obviously, further progress in the validity and accuracy of such tools are required, and drives research in this area so as to find a suitable trade-off between precision and computation time. In addition, the possibly distributed character of the nodes challenges the traditional cellular model, with concepts such as stationarity and shadowing becoming less well defined than before. This calls radio channel modelling research to move away from base-station centric approaches and take a whole new range of concepts into account.

Finally, according to the current trend in the Wireless Industry, future wireless networks are expected to operate not only in the allocated frequency bands below 6 GHz, but also in the higher frequency bands between 30 and 90 GHz (the millimetre wave (mmW) frequency range), where the availability of large contiguous blocks of spectrum could be exploited, enabling the possibility of very significant increase in bandwidth. In these higher frequency bands, the wavelength and, consequently, antenna elements are smaller, which facilitate the implementation of large array antennas for beamforming to compensate for propagation losses, and achieve significant system capacity and throughput gains. Although initial results and trials on the use of mmW for mobile broadband access look extremely promising, a number of important challenges need to be overcome, and radio channel modelling in such new bands is one of extreme importance.

1.3 Scope of the Book

This book is structured into twelve chapters.

Chapter 2 provides an understanding of the propagation phenomena in the diverse urban environments, to enable the design of efficient wireless networks in future bands and scenarios. The chapter includes results of studies related to 4G and future 5G radio systems for both outdoor and outdoor to indoor, while scenarios include rural and highway, base station to pedestrian users, vehicular-to-vehicular, V2i, container terminals, vegetation and high-speed mobility such as trains.

Chapter 3 addresses aspects of radio link and system design in indoor scenarios for supporting ubiquitous indoor data connectivity and location and tracking services. In particular, the chapter deals with modelling of the complex indoor radio channels for effective antenna deployment, evaluation of mmW radios for supporting higher data rates, and indoor localisation and tracking techniques.

Chapter 4 focuses on key issues in vehicular to any (communications) (V2X), including propagation, antennas, and Medium access control (MAC) and MAC layer algorithms. The chapter includes reports on measurements, characterisation, and modelling of vehicular radio channel for road, railway, and special environments.

Chapter 5 provides an overview of the last advances in research on WBANs, carried out in the framework of COST IC1004, and proposes a radio channel model for these particular types of scenarios. Given the wide range of applications of WBAN communications, the chapter is organised in the analysis of both antennas and propagation aspects for In-Body, On-Body and Off-Body cases, as well as some insights on the Body-to-Body communications scenario.

Chapter 6 deals with the evolution of RANs, and summarises advances done by COST IC1004 researchers on advanced resource management ecosystem, considering resource scheduling, interference, power, and mobility management. The chapter also describes the recent energy efficiency new strategies in 3G and 4G RANs, as well as on Spectrum Management in Cognitive Networks, specifically for TV white spaces (TVWS). Virtualised and Cloud architectures for realistic scenarios are proposed and analysed in this chapter, as well as reconfigurable radio for Heterogeneous Networks (HetNets).

Chapter 7 addresses PLNC, machine-to-machine (M2M), Relaying and CR networks, which will be key enabling technologies for 5G and beyond. Among other techniques, this chapter covers the virtual MIMO, RA distributed processing, interference analysis and cancellation algorithms in relay-assisted (RA) wireless transmissions, network coded modulation (NCM), hierarchical network code (HNC) maps, and relay/destination decoding techniques.

Chapter 8 discusses the progress on the PHY layer for next generation wireless systems, covering the range of "SEs". The topics in chapter 8 include interference characterisation and alignment, models for the energy consumption of wireless terminals, energy efficient relaying, MIMO precoding for adaptation on realistic channels, beam-space MIMO and spatial modulation, iterative methods in modulation and coding and models of the PHY layer to incorporate into system-level simulations.

Chapter 9 is dedicated to radio channel measurement and modelling techniques for beyond 4G Networks. In particular, this chapter includes new measurement techniques not only targeting radio channels, but also material properties in new frequency bands, improved PHY models, covering full-wave as well as ray-based methods, with a specific sub-section dealing with diffuse scattering and complex surfaces, progress in analytical models, new channel estimation tools for model development based on channel sounding data. The COST2100 channel models are updated and presented here, enabling to include new features, such as massive and distributed MIMO aspects.

Chapter 10 deals with recent advances and innovations in antenna systems for communications. The contents include the design of multiple antenna systems, the optimisation of antenna performance using decoupling techniques, smart reconfigurable antennas, RFID and sensor antenna innovations, holistic characterisation and measurement of antenna patterns and performance, including mmW frequencies.

Chapter 11 gives first an insight on general underlying concepts of the state of the art of MIMO over-the-air (testing) (OTA) technologies, and then describes four specific methods for MIMO terminals testing proposed by COST IC1004 to standardisation bodies: multi-probe anechoic, reverberation, two-stage, and decomposition.

Finally, Chapter 12 attempts to risk a vision on the future challenges and developments in mobile and wireless communications, on a time scale of about 5 years. This is based on the results obtained by the COST IC1004 network of scientific experts, and on the three main “pillars” of the success story of follow-up Radio communication COST Actions, which are antennas and channels, signal processing, and device networking.