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Background and Introduction

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'Anything, anyhow, anywhere' – this statement is often used to express the desire that communications will connect all types of device (from subscriber terminals to sensors) through an array of different technologies wherever they are required. 'Anywhere' is certainly an expression of the need for wireless, mobile connectivity. A mere 10 years or so before the end of the last millennium, a 'killer app', in this case short-message service (SMS) text messaging, was required to launch the mobile telephony boom. In the first decade of this millennium, there has been demand for many forms of data communication using mobile telephones and the introduction of 'smart phones' has now made it clear that current networks (what are termed 3G and 3.5G networks) cannot satisfy user demand. The new networks currently being rolled out, called 3G long-term evolution (LTE), may prove to be only a stop-gap; a new generation of mobile, wireless networks is required to satisfy the increasing demand for all forms of data on the move.

The problem for wireless networks is that the medium of transmission to and from the user – the air interface – is necessarily shared. In order to increase the bandwidth available to each user, fewer users must share the resource, which leads, in general, to a requirement for the size of 'cells' to decrease. The problem, then, is providing large amounts of bandwidth to larger numbers of small cells. Over the last 30 years, optical-fiber transmission systems have been developed in a variety of forms, ranging from long-distance, ultra-high-bit-rate submarine cable systems to high-speed access and local area networks. Optical fiber can certainly provide high bandwidth to a fixed location. Undoubtedly, then, future communication networks need to marry the mobility offered by wireless connectivity to the high bandwidth provided by an optical distribution network. This book provides a vision for how this marriage will work, how an optical infrastructure can provide particular benefits to

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future mobile, wireless networks and how the requirements of the mobile, wireless network may define the choice of particular solutions in the optical infrastructure.

This first chapter explains the motivation for writing this book and the project on which the work reported in the book is based. We introduce, in very basic terms, the main motivation for using distributed antenna systems in next-generation wireless systems and the significance of a hybrid fiber-radio infrastructure to transparently connect remote antenna units to a central unit where joint processing can be performed.

The chapter is organized as follows. In Section 1.1, we present some trends related to the vision of 4th generation (4G) systems and discuss how they can be reached through the existence of an optical infrastructure connecting remote access units (RAUs) and enabling joint processing of the radio signals, which constitutes the fundamental concept of the project on which the work reported in the book is based. A short description of the project is given in Section 1.2. Section 1.3 is devoted to a brief overview of the contents of the book, providing an explanation of the approach taken in the presentation of the work and briefly discussing each chapter in turn.

1.1 The Trends and Challenges to Achieving 4G Wireless

1.1.1 Motivation

There is currently in the wireless arena considerable research aiming at what are commonly called ‘4G systems’. This research is spurred on by interdependent technical and economic or deployment trends. Such 4G systems should fulfil several goals including the provision of true broadband wireless access, for which a new air interface has to be developed, and system capacity that is enhanced in comparison to current 3G networks. To achieve generalized deployment, and therefore contribute to the development of the ‘information society’, all technical solutions are constrained by capital and operational expenditure. They should provide the required flexibility to allow upgradeability and reconfigurability in order to match the dynamics created by the different players in the field and the needs of the users, who demand more and more bandwidth and increasingly sophisticated services. Basically, three major factors can be identified: the quest for high bit rates in wireless communication; the system capacity; and the infrastructure costs, deployment and upgradeability constraints such a system would require.

1.1.2 The Quest for High Bit Rates in Wireless Communications

The provision of broadband services to everyone is considered one of the key components for enabling the so-called information society. Traditionally, the delivery of broadband connections to the end user has been targeted through the deployment of optical fiber. However, since 2002, the impact of wireless technologies has been such that liberation from a physical connection has created in the end user a new sense of freedom and autonomy in his or her relation to communications. It is obvious that everyone would like to have this freedom with any service and this has spurred considerable research into extending true broadband access to wireless communications. However, the provision of the high bit rates that are envisioned to be of interest to the end user, and might easily be provided with fixed optical connections, still represents enormous challenges to the wireless community. It is more or less agreed that achieving the targets outlined for systems beyond IMT-2000 [1] of providing around 1 Gbit/s

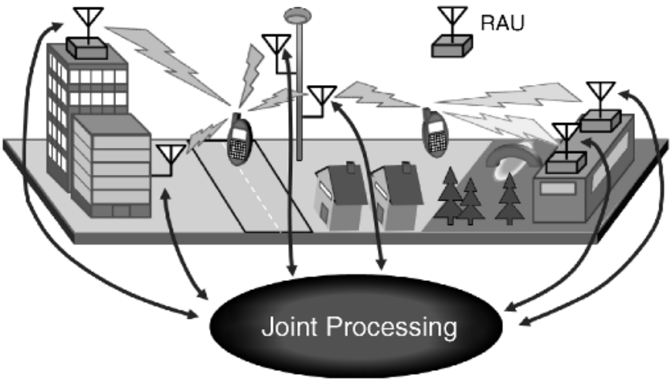

Figure 1.1 Joint processing of signals from multiple RAUs.

for pedestrian mobility and 100 Mbit/s for high mobility will require the use of multiple-input multiple-output (MIMO) technology based on multiple antennas at the transceivers to exploit the scattering properties of the wireless medium. The multiplexing gain provided by the very simple expression $\mathrm{R} = \min(\mathrm{N_R}, \mathrm{N_T})$, where $\mathrm{N_R}$ and $\mathrm{N_T}$ represent the number of receiving and transmitting antennas, respectively, is only achieved if the channel is richly scattered, which is seldom the case in outdoor environments, implying that the multiplexing gain can fall well below the theoretical bound. Furthermore, when more than one pair of MIMO users exists, there is interference between them, implying a requirement for joint processing of multiple pairs of MIMO links. Unfortunately, due to the physical limitations in the size of the transceivers, the number of antenna elements cannot be large and, furthermore, the spacing between them is limited. This implies that the scaling factor cannot be very high and (because the channels are highly correlated in a large number of scenarios, especially outdoor) that the gains obtained with MIMO technology fall well below the values achievable with fully uncorrelated channels. This has led to research into the use of virtual or distributed MIMO concepts [2–4], in which specific relay stations could act as antenna elements of a virtual array. Two concepts have emerged in infrastructure-based wireless systems concerning the use of distributed MIMO (D-MIMO): the first considers an extension of the existing architecture through the use of relays (fixed or mobile) to form virtual array antennas; the second consists of an architecture based on a distributed antenna system (DAS), where the mobiles communicate simultaneously with several antenna units (RAUs) that cooperate perfectly. Conceptually, this allows the antennas to be treated as physically distributed antennas of one composite base station, known as a central unit (CU). The key to achieving perfect cooperation is to have the radio signals transparently transported to a CU that performs all the signal processing, as depicted in Figure 1.1. We demonstrate through the work presented in this book that DAS has manifest advantages over conventional systems in terms of cost, flexibility, performance and capacity.

1.1.3 System Capacity

As the demand for wireless services increases, the solution to accommodating a higher number of users per square kilometre is, in a cellular architecture, the reduction of the cell size. However as the cell size becomes smaller and smaller, the path loss exponent is reduced and the interference does not undergo the same scaling effect, which means that the system capacity (users/km^2) does not increase linearly with the reduction of the cell size. One solution for coping with this problem is to apply intercell interference cancellation, which requires cooperation between the base stations and calls for the type of transport infrastructure identified in Section 1.1.2.

Both the link and the system capacity problems point to the same solution: perform joint processing of spatially separated radio signals. This requires deployment of an infrastructure that collects and distributes the radio signals from different antennas.

Due to its inherent broadband and low-loss characteristics, optical fiber is a suitable transmission medium for transporting radio signals to and from the RAUs, thus creating a radio-over-fiber (RoF) network. The use of RoF as the infrastructure to interconnect simplified remote antenna units for microcellular environments has been considered since the early 1990s [5] but, at that time, the cost of lasers with adequate characteristics was still too high and generalized deployment did not occur. Other target applications have been considered: simple fiber remoting of base stations to eliminate dead spots; WLANs [6] at millimetre-wave bands; broadband wireless access networks; and road vehicle communication networks for intelligent transportation systems [7]. One key aspect of the applications reported in the literature is that they deal with the concept of remoting or feeding radio signals to the antennas. The RoF infrastructure was not considered part of the architecture of the wireless system or as an enabler allowing the development of new architectural concepts or processing options. In the following sections, the vision of RoF shifts from a remoting one (in which a signal is delivered to a remote location) to an aggregating one, in which the infrastructure acts as a key enabler of several wireless technologies.

1.1.4 Infrastructure Costs, Deployment and Upgradeability Constraints

As a consequence of the technical trends to provide higher bit rates, better quality of service (QoS), reconfigurability, and adaptability, the complexity of wireless systems is rapidly increasing. If one keeps with the current paradigm of a cellular architecture, the base stations will become more and more complex and this, coupled with the cell size reduction required to enhance the overall system capacity, implies that the deployment of sophisticated base stations will be a major factor in the overall network cost. Cell site location is critical. The location must have enough space to support the antennas and any ancillary equipment and should have available power, easy access for technicians and should be free of obstructions that would block coverage. The number of sites meeting all, or at least most, of these criteria grows smaller every day. Often, even if technically suitable sites are available, the site-owner's terms of use are unfavourable and providers are pushed toward less-desirable sites. Less-desirable sites create new coverage issues that force the provider to accept spotty coverage or find and populate an additional site. In addition to the decreasing number of acceptable sites, service providers face opposition from the same communities that demand better coverage. Many of these communities place severe limitations on the construction of wireless sites. As a result, stringent and costly requirements for location and appearance restrict available locations. With conventional sites limited and expensive, a new approach is required to fulfil the promise of anytime, anywhere access. One solution is to simplify the base stations as much as possible, reducing them to simple RAUs that just transmit and receive radio signals and are connected to a central unit that performs all the processing, bringing significant advantages both in terms of reduced capital expenditure (CAPEX, e.g. the installation costs) and operational expenditure (OPEX, e.g. maintenance costs).

The move to RAUs instead of full base stations has significant implications in terms of deployment flexibility and upgradeability. The current paradigm in the planning of cellular networks is one of keeping the intercell interference to acceptable levels. This task is becoming more and more complex as the number of heterogeneous services with different requirements increases. In terms of upgradeability, it implies that a significant re-planning has to be done each time the market demand requires network augmentation. Clearly, using simple RAUs does not place the same constraints when it comes to deciding if the network has to be augmented or not. The inclusion of new RAUs and dealing with the novel interference patterns they provoke can be performed dynamically at the algorithmic level.

Table 1.1 summarizes the issues identified in reaching such goals and how a transparent-fiber-based infrastructure can help in their solution.

Table 1.1 Issues in the wireless domain and benefits brought by a transparent radio transport

Issue	Solution and problems	How a transparent radio transport architecture can help
High link capacity	MIMO: In outdoor environments, using co-located antennas may not provide enough diversity.	Radio signals jointly processed at a central location enables the development of distributed MIMO.
System capacity	Reduce cell size: As the cell size is reduced, the system capacity does not increase linearly due to intercell interference. There are problems with cost and aesthetics in acquiring sites.	Transparent transport enables intercell interference cancellation and provides a higher degree of resource reuse.
Spectrum efficiency	Frequency-agile systems: Reliable sensing is needed to provide an accurate image of the spectrum usage in time and space.	RAUs transparently connected to a CU enables the deployment of sensors (dedicated or through in-band measurements) that allow the development of reliable fusion algorithms. This provides an accurate image of the spectral activity in the area where the RAUs are deployed.
Infrastructure costs	Increase number of base stations/antenna sites: They are very expensive in urban environments.	RAUs are much simpler than complete base stations and their location does not require such costly sites.
Public concern	Increase number of base stations/antenna sites: Large base stations may have a negative aesthetic effect.	RAUs have a limited processing and therefore are smaller in size and can be installed in existing facilities (e.g. lamp posts) without significant aesthetic impact.
	Increase number of base stations/antenna sites: There are concerns about the high density of electromagnetic radiation.	The distributed architecture of RAUs connected to a CU allows smoothing of the radiation density pattern.

1.1.5 Trends and Issues in Wired Broadband and Infrastructure Convergence

The development of optical and wireless communications have taken independent paths. Sometimes they were seen as competitors, at least for the access segment of the network; optical communication technology has been supporting the core of the networked society infrastructure for quite a number of years.

Currently, the trend in broadband optical communications is to bring fiber to the home (FTTH) or to the curb (FTTC), in what is more generally designated as Fiber-to-the-x (FTTx). This is spurred on by a combination of factors: the emergence of bandwidth-intensive applications and services; technology progress resulting in a reduction of the cost of equipment; and, to some extent, national policies – broadband access is viewed by governments as a tool for national competitiveness. The main hurdle in achieving the goal of FTTx comes in the huge investment in construction cost and the required access to homes and other buildings. For greenfield FTTH deployments, construction costs (civil engineering costs) comprise approximately 50% of the total costs in rolling out a FTTH network and constitute a large percentage of total network cost [8].

The huge investment required to roll out a fiber-based next-generation access (NGA) network leads to significant concerns in terms of regulation. Competition has been viewed as the main tool for developing effective access and foster innovation, investment and consumer benefits in communication markets. However, the cost of the roll-out of NGA networks has led to some experts arguing that the only sustainable solution (from an economic perspective) is a single next-generation, fiber-access network to end users. Therefore, as NGA networks develop, the regulatory and policy challenge is to maintain incentives to invest in a competitive environment. This concern has strong implications for the architectures that may be adopted, as some options are more appropriate for 'unbundling' than others. There are different variants for the optical deployment of NGA but one can recognize two main directions:

- Point-to-point FTTH (PtP-FTTH): The simplest approach is an active optical network (AON) where each subscriber is directly connected by a dedicated fiber to a central office (CO). The dedicated fiber allows for the specification of individual data rates and services but it is far from making use of the transmission capacity of the fiber. In the CO, the same number of line terminations needs to be installed as exist today for copper pairs (e.g. in digital subscriber line (DSL) technology).
- Passive optical networks (PON) FTTH: PON systems differ from PtP-FTTH in that they use one fiber to connect several customers – the fiber is shared by users. PON systems are less expensive than PtP-FTTH but PON central switches require more logic and encryption to integrate and separate customer streams. There have been three successive iterations for PON standards; current PON systems are able to share 1 Gbit/s in Ethernet-PON (EPON) and 2.5 Gbit/s in Gigabit-PON (GPON) of bidirectional capacity amongst the connected customers. GPON and EPON rely on time division multiplexing (TDM) technology to split signals between services and subscribers, offering a limited splitting factor (up to 64 subscribers) and a limited distance (around 20 kilometres) between a subscriber and their nearest network office. In order to avoid the above constraints, there is under discussion alternative solutions for the next-generation PON (NGPON) within the Open Lambda

> Initiative (OLI) [9] and the full service access node (FSAN) groups. The standardization of NGPONs is currently under discussion, with various alternatives being pushed by the various member organizations (including suppliers and operators). One of the proposed solutions is next-generation optical access (NGOA) based on an ultra-dense wavelength division multiplexing (WDM) PON with coherent detection that allows for an unprecedented split ratio (up to approximately 1000) or a very long unamplified reach (of approximately 100 km) [10, 11].

Given the main trend in the deployment of optical NGA or NGOA and the deployment constraints as well as the regulatory concerns, one needs to consider how the integration of wireless and optical technologies can facilitate the deployment of the infrastructure.

The most common view is to consider wireless access as a competitor to optical access but, in fact, it can be used as a facilitator. Wireless communications can be used as an extension of the fixed broadband network allowing for a gradual deployment, helping to phase the investments needed and also to overcome the asymmetries in access between urban and rural scenarios. This option also helps in terms of openness – even if the incumbent operator only deploys fiber up to the node, new entrants can provide services by deploying wireless from the node to the subscriber, if regulation allows.

The existence of an optical infrastructure combined with the progress in WDM technology (coarse WDM (CWDM), dense WDM (DWDM) and ultra dense WDM (UDWDM)) may also allow its use as a backhaul for existing wireless networks and the development of new architectural concepts for future networks. The ability to share the wired distribution of broadband signals and the transport of radio signals to and from RAUs in the same infrastructure is therefore a key aspect for a global operator, since it allows leverage of the investments needed in the deployment of NGA by sharing its costs through several networks. It is expected that, at least in urban environments, the convergence of the technologies could provide significant benefits. This implies that in metropolitan areas (see Figure 1.2) there is, or there will be, a high density of fiber deployed with enough capacity to transport the wireless radio signals, enabling a transparent transport of the radio signals to a central location

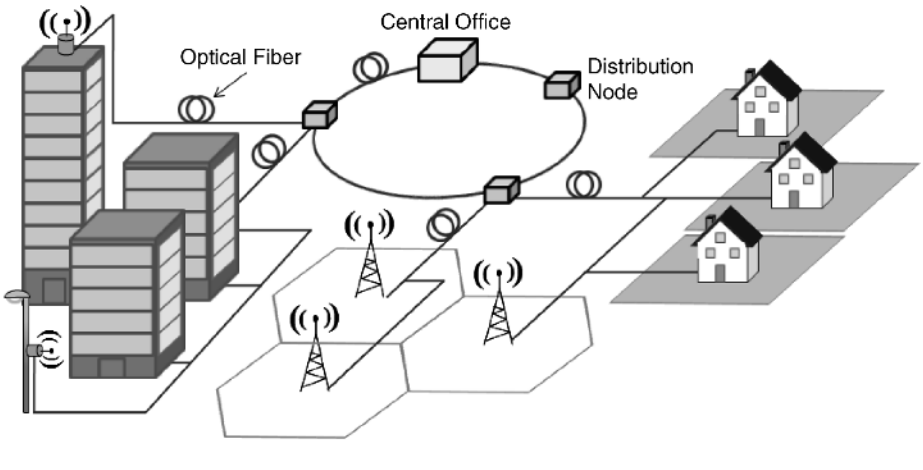

Figure 1.2 Converged fixed-wireless network.

Table 1.2 Issues and benefits from optical–wireless interaction in the deployment of NGOA

Issues	How wireless technology can help
Generalized access is difficult to achieve.	Wireless communication can be used to provide the last mile in low-density areas. This allows for quick access with gradual fiber deployment.
Incumbent operators are not willing to deploy to the home to avoid local loop unbundling.	If the regulator allows, new entrants can deploy wireless connections from the node to the home.
It is risky to make large investments when facing competition from wireless networks.	Synergies between wireless and optical technologies can be exploited: • The optical infrastructure can be designed to transport the radio signals and therefore can be used as the mobile backhaul. • Wireless architecture and technologies can exploit the huge bandwidth and low loss provided by fiber to enhance features and capabilities. • The fiber infrastructure is an enabler for the deployment of DAS.

where joint processing is performed. Such a scheme should enable the simplification and profusion of compact plug-and-play base stations or remote access units.

It is clear from the previous points that for both wired NGA and future wireless systems, the infrastructure costs will be a major issue and therefore the more rational option should be to devise technology and architectures that can share the same infrastructure. Table 1.2 summarizes the main issues and benefits of wireless and optical interaction in the deployment of NGA using FTTH to provide broadband access to everyone, despite investment (especially construction) costs being very high.

The economic and deployment constraints identified so far call for the same type of transport infrastructure. With multiband RAUs, the availability of radio signals from heterogeneous systems at the same point opens new doors at both the technical and business levels:

- At the technical level, processing of multiple systems at a single location will facilitate the design of efficient cross-system algorithms, protocols and the interoperability of heterogeneous systems, generalizing the concept of cross-layer to cross-system and enabling the development of efficient common radio resource management algorithms.
- At the business level, the owner of RoF can be a third party and the existence of an infrastructure that can be rented will facilitate the entrance of new service providers, as well as providing an extra source of revenue for conventional operators if they intend to develop such an architecture. Another option is that the RoF infrastructure will be deployed and owned by public authorities.

1.2 The FUTON Concept for Next-Generation Distributed and Heterogeneous Radio Architectures

The fiber-optic networks for distributed, extendible heterogeneous radio architectures and service provisioning (FUTON) project is an international collaborative research project, partially supported by the European Commission, to investigate distributed antenna system (DAS) architectures targeting the demanding objectives for future wireless systems. The investigated and implemented FUTON architecture consists of an optical infrastructure that transparently connects multiple RAUs with a CU that is responsible for the joint processing of all radio signals, as depicted in Figure 1.1. Taking advantage of the centralized joint processing and the DAS infrastructure, FUTON has developed signal-processing concepts for virtual MIMO and intercell interference cancellation to achieve broadband wireless transmission and efficient cross-system algorithms for the vast panoply of heterogeneous systems, enabling the interoperability sought in 4G. In this section, we present an overview of the FUTON concept and its main features and the FUTON consortium.

1.2.1 Global Architecture and the Main Evolutionary Scenarios

Figure 1.3 illustrates the global architecture of FUTON. The geographical area to be covered is divided into serving areas (or 'super cells'), where multiband RAUs are deployed. They are linked to a central unit through optical-fiber connections that transport the radio signals transparently. The multiband RAUs are able to transmit and receive the radio signals from different wireless systems. An illustration of the deployment in a serving area is shown in Figure 1.4.

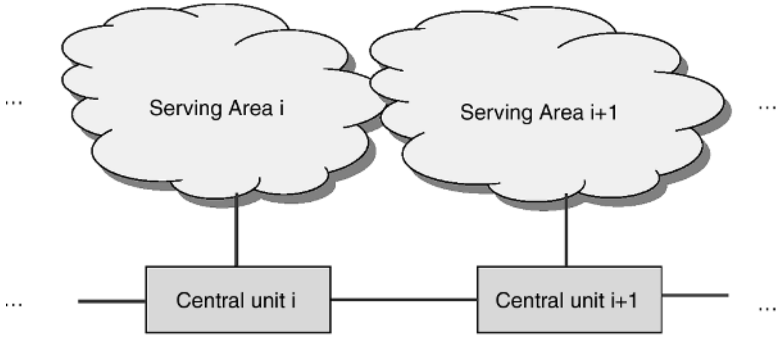

Figure 1.3 Global architecture of FUTON.

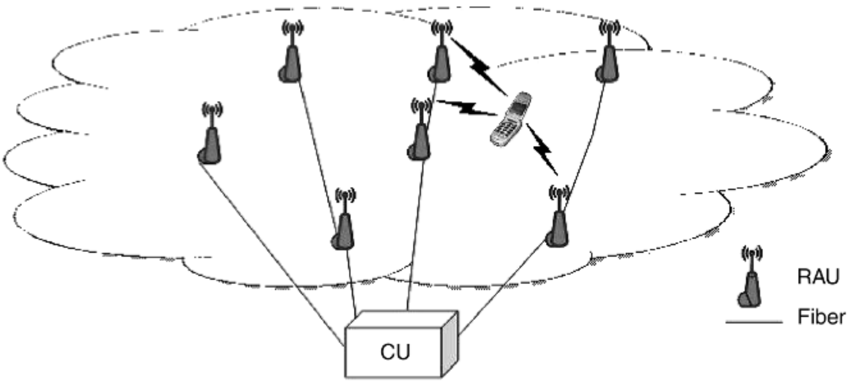

Figure 1.4 Deployment in a serving area.

The processing related to all communications in a serving area is done at the central unit of that serving area. The CU encompasses functions at least up to Layer 3 of the Open Systems Interconnection (OSI) model. For distributed wireless systems, the availability of the radio signals allows joint processing of the signals to and from the different RAUs, enabling the realization of distributed MIMO (D-MIMO) links (see Figure 1.4). Even for single-attachment systems, one can go beyond conventional processing since the availability of the radio signals at the location where the higher-layer processing is performed enables the development of efficient cross-layer algorithms to optimize the usage of the radio resources. Figure 1.5 shows a more detailed illustration for a single serving area, where the planes indicate the different systems that can coexist in a serving area and can be connected to the same central unit. Logically, it consists of a fixed infrastructure designed with enough flexibility that its resources are not necessarily allocated to a single cellular system; rather, they can be shared by several wireless systems and also by fixed optical connections.

The FUTON infrastructure is able to support a wide range of wireless systems and fixed connections:

- legacy systems for which the infrastructure can be used either as a simple remoting system or (for cellular systems) to enable intercell interference cancellation;
- outdoor distributed broadband wireless systems (DBWS) for which the infrastructure acts as a virtual D-MIMO enabler to achieve the target high bit rates;
- indoor distributed broadband wireless systems in which a simplified RAU (the indoor RAU in Figure 1.5) is attached to a home with pre-installed fiber to form a distributed in-house MIMO system;
- remoting of dedicated radio systems.

The basic RAU in Figure 1.5 can be shared between legacy systems and outdoor DBWSs.

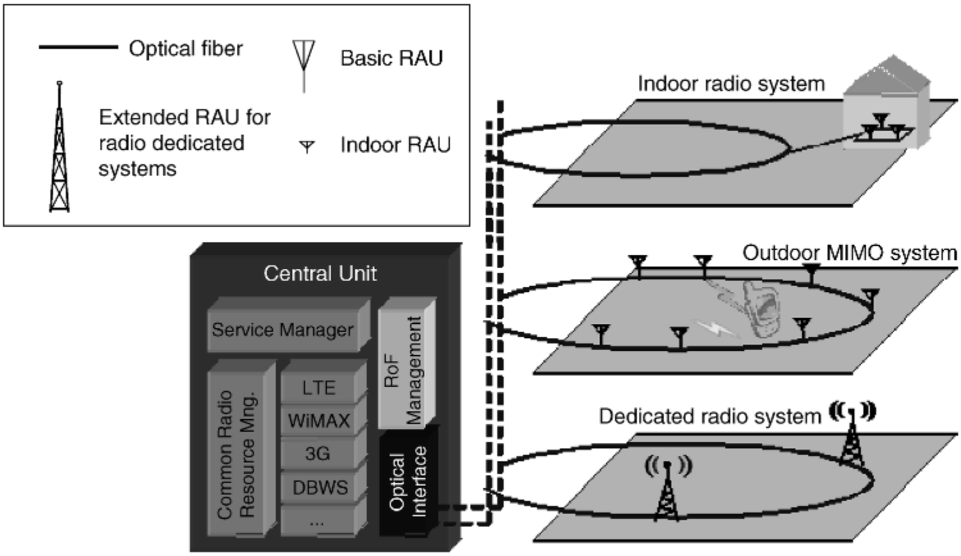

Figure 1.5 Systems coexisting in a serving area and connected to one central unit.

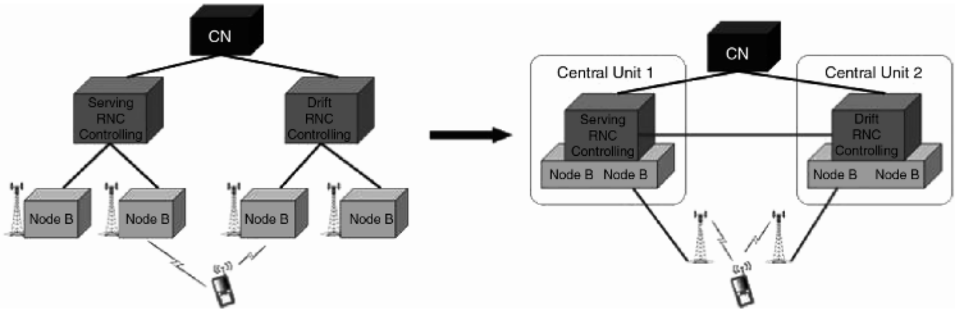

Figure 1.6 Evolutionary path for the Universal Mobile Telecommunication System (UMTS).

A key aspect for the operators is to provide an 'evolutionary roadmap', so that the existing infrastructure can be reused. Although, as pointed out in Section 1.1.4, the goal is to move to simple RAUs that can, for example, be installed on lamp posts, the proposed architecture can be used in an evolutionary way with current wireless networks. Figure 1.6 shows Core Network (CN) and the Node B functionalities located jointly with the radio network controller (RNC), thereby allowing the implementation of intercell interference cancellation algorithms and more efficient cross-layer procedures, leading to an enhanced system capacity of the existing 3G network.

1.2.2 Optical Infrastructure Signalling

The scenarios and infrastructure will be described in detail in subsequent chapters. Here, we point out only the main assumptions.

The optical infrastructure is a set of optical links where the RAUs and optical network units (ONUs) are connected to the central unit through optical fiber. The key aspects of this hybrid infrastructure are reliability, flexibility and low cost. To achieve these goals, the FUTON project proposes a combination of radio frequency (RF) with subcarrier multiplexing (SCM) and low-cost forms of wavelength division multiplexing (WDM) for the optical distribution network.

From the wireless systems' viewpoint, the optical infrastructure should act as a transparent medium allowing the formation of a reliable network for joint processing of the radio signals. As shown in Figure 1.5, the optical links are managed by the RoF manager in the central unit.

There is interaction between the radio resource management (RRM) layer of the wireless system and the RoF manager so that the space (antenna) resources assigned to a specific radio channel are mapped into the appropriate optical resources at the infrastructure (see Chapters 6 and 11).

1.2.3 The FUTON Consortium

The FUTON consortium was assembled from 11 countries (nine European Union countries, Brazil and Japan). The distribution by organization type was as follows:

- Operators:
  - Hellenic Telecommunications (Greece),
  - Portugal Telecom (Portugal),
  - VIVO (Brazil).

- Large industrial companies:
    - Alcatel-Thales (France),
    - Motorola (France),
    - Nokia-Siemens Networks (Portugal and Germany).
- Small and medium enterprises (SMEs):
    - Acorde (Spain),
    - Sigint (Cyprus),
    - Wavecom (Portugal).
- Research centres
    - CEA – Commissariat à L’ Energie Atomique et aux énergies alternatives (France),
    - IT – Instituto Telecomunicações (Portugal),
    - NICT – National Institute of Information and Communications Technology (Japan),
    - VTT – Valtion Teknillinen Tutkimuskeskus (Finland).
- Universities
    - Technical University of Dresden (Germany),
    - University of Aalborg (Denmark),
    - University of Kent (United Kingdom),
    - University of Patras (Greece).

Thus, the consortium retained a good balance between equipment manufacturers and operators as well as highly respected research institutes and universities in the mobile and optical arenas. Furthermore, the project brought together players with the capacity to assess the impact of FUTON-like concepts in highly differentiated scenarios and business models. The consortium included two European operators, Portugal Telecom and Hellenic Telecommunications, and a Brazilian operator (VIVO) that had more than 70 million subscribers in 2012. The mainly European consortium also incorporated a Japanese research centre (NICT). These links to South American and Japanese regulators and standardization bodies broadened the possibilities of obtaining transcontinental consensus.

The academic partners and research centres also made a strong contribution to the success of FUTON, through their strong experience and know-how in carrying out leading research work. The FUTON consortium brought together expertise from areas of wireless and optical communications, allowing previously untapped synergies between these two areas.

1.3 Overview of this Book

This book consists of 14 chapters covering a broad range of topics related to next-generation wireless communication systems using radio over fiber. It provides a technical background for wireless systems based on distributed antennas and for RoF technology as part of the wireless system architecture.

Chapter 2 gives a historical perspective of wireless communications and presents key recent trends, emphasizing techniques that are likely to be used in future broadband wireless systems. The chapter starts with a brief history. It then discusses principles concerning the signals to be transmitted, the terms ‘quality of service’ (QoS) and ‘quality of experience’ (QoE) and the trade-offs between flexibility and efficiency. Some basic problems in wireless transmission (propagation, attenuation and multiuser interference) are covered, together with some solutions for flexible and efficient use of resources, cell size optimization and handover, dynamic changes and adaptivity, the use of diversity and equalization, multiple-input multiple-output (MIMO) systems, and joint iterative processing. The chapter then covers standardization, briefly presenting a historical perspective, followed by the newest frequency allocations made by the World Radio Conference (WRC) of the ITU-R. The newest standards and their requirements, such as International Mobile Telecommunications – Advanced (IMT-A), Long Term Evolution – Advanced (LTE-A) and Worldwide Interoperability for Microwave Access (WiMAX, IEEE 802.16), are then discussed. Recent trends in the convergence of networks and the Internet are covered, followed by concepts such as location awareness, self-organizing networks, centralized and decentralized control, interaction between protocol layers, competitive and cooperative communications, cognitive radio and distributed learning, frequency reuse and dynamic spectrum allocation, relaying, distributed antenna systems, coordinated multipoint systems and virtual antenna systems, precoding and beamforming. The chapter concludes by summarizing the trend towards increased intelligence in networks and terminals.

Chapter 3 describes the concept of distributed antenna systems relying on a hybrid fiber–radio infrastructure that transparently connects remote antenna units to a central unit where joint processing is performed. Such an architecture will act as an enabler for the development of several wireless technologies to achieve the goals of broadband access, fairness, deployment flexibility and reduced power consumption sought for future wireless systems. Those wireless technologies are virtual MIMO for broadband wireless transmission; intercell interference cancellation for increased system-level capacity; efficient common radio resource management procedures, making uniform the radiation levels in dense urban environments; and smart resource allocation between macro and small cells.

Chapter 4 presents a review of RoF technology, which has received significant research interest over the last two decades and has seen commercial deployment in limited application scenarios, such as the provision of wireless cellular coverage in large indoor spaces, such as shopping malls and airports, and for events requiring flexible coverage, such as Olympic games. The main aim of this chapter is to describe the fundamental concepts of the technology, its varieties and how it is characterized in terms of performance, in order to enable an understanding of the work presented in later chapters (particularly Chapters 5–7).

Chapter 5 presents the design of the RoF distribution links that can meet the requirements for transport of the distributed broadband wireless system proposed in the project. The aim of the design work was to make the fiber-distribution network as transparent as possible to the wireless system being transported. This chapter reviews the objectives of the design and presents the design issues that have to be addressed (such as the radio carrier frequency and bandwidth, the number of channels required, the use of OFDM, the necessary modulation complexity, and the use of MIMO), explaining how each of these issues affect the design requirements.

Chapter 6 lays out the optical network architectures and topologies for the support of future wireless systems. The design of the fiber-optic infrastructure for new wireless concepts, such as proposed in the FUTON project or a similar distributed antenna system (DAS), requires determining the most suitable network topology and combination of multiplexing techniques to cope with the proposed objectives. The coexistence of legacy systems with new DAS systems, which may require additional resources in the optical-fiber infrastructure, is also addressed in Chapter 6.

Chapter 7 focuses on optical transmitters for RoF links. The role of an optical transmitter is to launch a modulated optical signal into an optical-fiber communication network. In most optical communication systems, the components used in the optical transmitter provide the most significant constraints on the capabilities of the system; this is also the case for most radio over fiber (RoF) systems. The aim of this chapter is to describe the design and performance of semiconductor optical-transmitter components developed specifically for the RoF distribution network of the FUTON project.

Chapter 8 describes algorithms for coordinated multipoint techniques. With the ever-increasing demand for high-data-rate wireless services on the one hand and the scarcity of radio spectrum on the other hand, we have seen the advent of cellular wireless systems with full frequency reuse. While these systems generally promise a higher overall spectral efficiency than legacy systems with frequency planning, they suffer severely from intercell interference, which limits high-quality services to a small percentage of users located at the cell centre. To overcome the obstacle of interference to achieving significantly enhanced spectral efficiency, the coordination of base stations is seen as a very promising technique for cellular systems. Thus, coordinated multipoint (CoMP) techniques are considered as promising candidates for LTE-Advanced. However, there are still many challenges that need to be addressed before CoMP can be put into practice. Amongst these challenges is the backhaul infrastructure that needs to be available to exchange large amounts of information between the base stations. In this chapter, some of the most common CoMP techniques are reviewed with a clear focus on linear algorithms that can be implemented with reasonable complexity. Algorithms for both up- and downlink transmission are discussed. The benefits of CoMP algorithms and their use in conjunction with the FUTON architecture are underlined by numerical simulation results. Furthermore, their practicability is discussed and the implementation of a downlink CoMP scheme with a RoF network is presented with laboratory measurements from this prototype system.

In Chapter 9, we discuss the design of cross-layer algorithms, taking into account the trade-offs between data rate and quality of service. We present cross-layer resource allocation and scheduling algorithms and concepts that have been developed for the FUTON system. First, we describe a downlink power and antenna allocation algorithm that takes advantage of the fact that, in a DAS system such as FUTON, a mobile terminal may be connected to more than one multiple-antenna RAU. Moreover, in order to maintain reasonable complexity, the algorithm allocates resources in chunks of subcarriers. A downlink scheduling and resource allocation algorithm is presented for scenarios where feedback is limited. Finally, careful pilot design for channel estimation can improve the FUTON system capacity where multiple antenna units are needed. Use of multiplexed and superimposed pilots is considered here.

Chapter 10 discusses the main impairments in the RoF infrastructure and methods of dealing with the less-than-ideal nature of such an infrastructure. Two general problems and their solutions are addressed: first, the nonlinear behaviour of the RoF links, dealt with through baseband compensation; second, the fiber delay that affects symbol and frame synchronization and can be compensated by timing advance mechanisms. An overview of possible compensation techniques applicable to RoF links in a distributed antenna system (DAS), such as the FUTON architecture, is presented with a literature review of optical–electrical compensation, pre- and post-distortion, and adaptive compensation. We describe a system model for baseband predistortion and discuss algorithms applicable for the compensation of the RoF links and their implementation. For performance degradations due to delay introduced in the signal transmission links, we study the degradation that can be expected from misaligned OFDM reception in the DAS, where mobile terminals can be served by multiple non-co-located RAUs. In this case, the signals originating from multiple RAUs arrive at the mobile terminals with different delays, depending on the position of the users within the service area. We discuss the performance trade-off between the orthogonality of the OFDM subcarriers and the length of the cyclic prefix. Furthermore, we review simple methods to significantly improve the timing alignment.

Chapter 11 describes the importance of RoF network management, specifically addressing the FUTON environment with its requirements for heterogeneous network operation and different applications and services. The relationship of the network management functionality to network and physical layer transport and its operation in a signal control plane are described, as well as its general requirements for monitoring of network elements from the central unit (CU) to the remote antennas at the RAUs. We describe the principles on which a RoF manager would be based, including the general principles of interaction with middleware at the CU. The architecture of a RoF management system is then described. Configuration management is defined and shown to have responsibility for configuring network elements and maintaining their status and parameter configurations. It is also concerned with low-level network configurations that enable the deployment of particular services. Fault management is defined and discussed in the context of the definition of fault parameters, alarm thresholds and fault detection, and the treatment of faults.

Chapter 12 addresses the system-level evaluation of the new DAS (such as the FUTON architecture) and, in particular, the distributed broadband wireless system (DBWS). The aim of this chapter is twofold: to present the design of a system-level simulator for the FUTON architecture and to discuss system-level simulation results obtained after implementing relevant algorithms from different layers (physical, medium access control and radio resource management). Emphasis is put on the methodology used to provide an appropriate abstraction model for these algorithms at the simulator and hence guarantee the accuracy of the final results.

Chapter 13 discusses the business evaluation of the FUTON architecture by considering different profiles, in terms of morphology and typical user characteristics, for major cities in Greece and Portugal. It is based on a model that combines different types of deployment area (dense urban, urban, suburban and rural) and, hence, various types of network configuration in terms of number of cells, coverage areas, and customer base. Differing initial scenarios, greenfield and migration (where only partial investment is necessary on top of an existing infrastructure), are also considered.

Chapter 14 concludes by summarizing the technical and economic benefits of a wireless communication system based on a distributed antenna system (DAS) with centralized signal processing supported by radio over fiber (RoF) optical links. The main achievements of the FUTON research project are presented.

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