Chapter 14

COOPERATION IN 4G NETWORKS

Cooperating in a heterogeneous wireless world

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Abstract: This chapter explores the forthcoming generation of mobile communication systems - the Fourth Generation or 4G - with particular emphasis on motivating the use cooperative techniques within its vast realm. The purpose of this chapter is two-fold, to approach and define 4G from different perspectives, and to identify opportunities for cooperation. A number of key 4G challenges are discussed and some solutions based on cooperative techniques are considered. 4G is usually seen as a convergence platform, where heterogeneous networks coexist. We consider that a tighter interaction among networks is beneficial, leading towards a wider and more ambitious approach to 4G, namely seeing 4G as a cooperating platform where resources are shared and traded by the constituent networks. 4G is in principle a fertile ground for developing and applying cooperative concepts and techniques, offering for the fist time opportunities to apply these ideas in a broad domain, at many different levels and within and across layers.

Keywords: future wireless networks, heterogeneous systems, research challenges

1. Introduction

The ever flourishing mobile and wireless communications scene entered this century with unprecedented momentum, as it is easily perceived by observing

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the unrelenting research and development activities, as well as the increasing levels of acceptance and penetration of such technology on a worldwide scale. Today, at the same time that the deployment of the third generation (3G) of mobile communications systems - also known as IMT-2000 networks - is taking place, the next generation systems are already being conceived and developed. Indeed, at this 3G introductory stage, efforts are being made at a global scale to envision, define and develop the successor mobile communication system. Systems beyond IMT-2000 are commonly referred to as the *Fourth Generation* or *4G* in short. Preliminary exploration tends to show that a great deal of useful and interesting services could be developed under the assumption that a ubiquitous, high-speed wireless access is available. The opposite is also true: future users will be attracted by rich-content based services that pervasively interact with the environment. Thus, it appears that one of the main driving forces for 4G development is the growing demand for higher data throughput in virtually every possible scenario. The key players in the 4G development process are terminal and infrastructure equipment manufacturers, academia, operators, service providers, regulatory bodies and governmental agencies. Considering the complex interaction among the aforementioned players and taking into account that these diverse parties do not necessarily share the same interests, goals and time plans, no one would be surprised to realize that finding a universal definition of 4G has been a very elusive task, even after several years of activities and numerous attempts in the literature. In this chapter we first endeavor to describe and define 4G, highlighting the common views shared by the research and development community. We consider as the main official guideline the ITU-R Framework Recommendation M.1645 [ITU, 2003], which delineates the research goals for system capabilities. The 4G arena is inherently fragmented, as involved parties represent various typically non-aligned sectors. We can see that the worldwide 4G development is following several paths, with target solutions that can be *complementary* (co-existing) as well as *competing* (mutually exclusive).

In this chapter we will initially look at 4G from different perspectives in an attempt to identify its most important characteristics and capabilities. As it will be discussed later, *heterogeneity* and *convergence* are two of the most distinctive features of 4G, and they apply to networks, terminals and services. 4G offers opportunities to the designer to widely adopt several recently developed technologies. One of the most important connotations of 4G is the departure from many conventional solutions used in previous generations. Multi-antenna techniques, justifiably identified as one of the key enabling technologies, mean the departure of relatively simple single-antenna transceivers to systems supporting several parallel receive and transmit branches. Network architectures are expected to be highly diversified in 4G, with a more balanced participation of centralized and distributed network approaches. Interaction among wireless entities is expected to be considerably strengthened in a mutual effort to better use resources and improve performance, leading to cooperation. Cooperating wireless entities include not only concrete or tangible devices like a wireless terminal in the visible domain of the user, but also, and most importantly for designers, layers (of the OSI stack), algorithms, networks, processors, etc. In this chapter we will focus on cooperative techniques, particularly those which appear to have potential to solve many of the technical challenges of 4G. Many of these technical solutions will be first introduced with 4G. Probably in most of the cases we cannot expect that technology will be fully exploited. Initial multi antenna design will favor simple configurations, in particular at the terminal side, where very few antennas will be used, expectedly not more than two in small form factor devices. As far as cooperative techniques are concerned, 4G will be the very first real communication system where these techniques will be implemented, mostly to solve some problems of particular networks, like range extension, enhancement of quality of service (QoS) and others. Rather simple solutions are expected to prevail initially, for instance low-complexity mechanisms implemented at the physical and MAC layers.

2. Defining 4G

During recent years we have witnessed innumerable attempts aiming to define 4G, examples of some recent approaches can be found in [Kim and Prasad, 2006a], [Frattasi et al., 2006], [Bria et al., 2001], [Kupetz and Brown, 2003], [Katz and Fitzek, 2005]. Despite huge efforts by industry and academia a well established and widely accepted definition of 4G has not yet emerged. Moreover, though the term 4G is widely used, it is not endorsed by all involved parties. Other denominations as Beyond 3G (B3G), In particular, the ITU refers to *beyond IMT-2000* in lieu of 4G. A vertical approach to 4G, the *linear vision* tends to see 4G as a linear extension of current 3G systems, basically aiming for higher data rates. This vision is limited to highlight the high speed capabilities of future communication systems. The horizontal approach, or *concurrent vision* of 4G is based on the integrative role of 4G as a convergence platform of several networks, and includes the linear vision as one of its constituent component networks. The latter approach is well in line with the visions of the ITU. Indeed, the ITU-R Recommendation M.1645 [ITU, 2003], states that future wireless communications systems could be realized by functional fusion of existing, enhanced and newly developed elements of current 3G systems, nomadic wireless access systems and other wireless systems with high commonality and seamless inter-working. The ITU approach is generous and flexible, truly allowing legacy systems (2G and 3G), the products of their evolutionary development, and new systems to coexist, each being a component part of a highly heterogeneous network, the 4G network. Backward compatibility and interoperability are key characteristics of 4G. We can expect that the 4G arena will be highly competitive as telecom (mobile) and IT (wireless) communication industry will contend to attain an important share of the business. Note that the words *mobile* and *wireless* are often used to emphasize and differentiate the conventional cellular (wide-area) and local-area approaches, respectively. In the sequel of this section, we will discuss 4G from different perspectives, in an attempt to get a comprehensive insight into what is understood by 4G.

A Multifaceted Approach to 4G

In this section we will approach and describe 4G systems form different perspectives in an attempt to provide a comprehensive overview of the future wireless communication systems.

Brief historical perspective. In a period spanning not more than a quarter of century three mobile communication generations were developed and deployed. The first generation of mobile communication systems, denoted by 1G, provided voice-only services. Users were separated in the frequency domain by implementing Frequency Division Multiple Access (FDMA) in the analog domain. The first generation systems already exploited the basic concepts of mobile communications, namely a centralized cellular architecture. The concept of handover to provide uninterrupted communications across wide area cells as well as roaming across regions or countries. The Second Generation (2G), introduced in the 1990's, made mobile telephony truly popular and widespread, being the reigning mobile technology of today. From the communications perspective, 2G meant the departure from an analog world to the digital one, with all the advantages that this implied. These Time Division Multiple Access (TDMA) based systems offered evident advantages to end users and operators, including high quality voice services, primitive though very popular data services (*i.e.*, Short Message Services), global mobility, increased network capacity, etc. In particular GSM (Global System for Mobile Communications), the most representative 2G system, and its immediate successors represent the most widespread mobile system today. The so called 2.5G extended 2G with data service and packet switching capabilities, bringing Internet into the mobile personal communications. 2G was designed from the beginning as an evolving platform, from which emerged the High Speed Circuit Switched Data (HSCSD), the General Packet Radio System (GPRS) and the Enhanced Data Rates for GSM Evolution (EDGE). 3G, exploiting Code Division Multiple Access (CDMA) techniques, was developed in the late 1990's and is now being deployed globally. Among the key characteristics of 3G, also known as Universal Mobile Telecommunication System (UMTS), we highlight the support of higher data rates (*e.g.*, a few hundred Kbit/s typically) and as well as the provisioning of intersystem handover, *e.g.* 3G-WLAN. Like its predecessor, 3G was conceived as an evolutionary platform, with an evolutionary phase targeting data rates into the 10 Mbit/s range. The enhanced data capability of 3G is the driving force behind mobile multimedia services. As users can now wirelessly and quickly access information databases we are starting to glimpse the birth of person-to-machine communications. The wireless personal communications history is very short but indeed extremely dynamic and rich in accomplishments. The most impressive fact is perhaps to realize that as today (2006) one third of the world population is a mobile phone subscriber, while at the beginning of the 1980's there were virtually none. By year 2010 half of the globe's population is expected to own a mobile handset. At that time, the most optimistic figures already foresee the launching of 4G systems. It is clear that the explosive growth and predicted subscriber base form a very fertile ground for the development of a new communication system. Mobile users are likely to expect a variety of new interactive and on-demand services exploiting high-speed data transfer and location-based capabilities, among others. The upcoming 4G system is projected to solve still-remaining problems of the previous generations and, moreover, to provide a convergence platform that will offer clear advantages in terms of services as well as coverage, bandwidth, spectrum usage, and devices. The terms *convergence platform* specifically refer to the fact that 4G is seen as a wireless ecosystem whose components are different wireless networks interworking in harmony. The world today is comprised of mutually exclusive wireless networks, which are now beginning to work with each other. The needs for better interconnected wireless systems are obvious: better, more reliable and continuous service, wider coverage, and other benefits that mobile users will certainly appreciate. We are witnessing today the beginning of this trend, and this is giving us a clue of what we can expect in the future, the convergence of wireless networks. Thus, we could interpret the future 4G network as a system where heterogeneous networks (3G, WLAN, new very-high speed wireless networks, etc.) would interoperate in a seamless manner. Moreover, from a broader perspective, the overall composite network, a true mosaic of networks, would appear as a single network. Future users will not see the underlying complexity, they will simply be always connected to *the network*.

A user-centric approach to 4G. During the development of previous and current mobile communication generations, industry mainly focused on the appropriate technology for providing voice and basic data communications. Services and applications were then developed based on technical capabilities supported by those systems. This approach worked well in 2G, because of the simplicity and novelty of the services offered. In 3G, services were developed in a later phase and despite the enhanced information transfer capabilities, we are finding it difficult to lure users. It is becoming more and more evident that 4G will need to be approached from a different perspective if we want to ensure its commercial success. Technology should be developed to match user's needs, and not the other way around. Indeed, putting the user in the center of the development aims to guarantee a long-lasting, sound and profitable future for 4G. Rather than being attracted by figures like high throughput numbers, users are drawn by useful, convenient and enjoyable services. These services could certainly exploit high data rate capabilities, but it is the services not the data rates that appeal to users. It should be also mentioned that the patterns in mobile user behavior today differ greatly from those prevalent during the development of 2G and 3G. Broadband wired internet is finding its way to every home and users are likely to expect comparable features on the move. The actual trend towards the diversification of terminal capabilities supporting high-quality audio as well as still and video imaging opens up a new world in terms of services and applications. These new terminal capabilities are expected to have an impact not only on the overall data traffic but also on the typically assumed uplink-downlink data traffic imbalance. Indeed, data requirements are expected to increase substantially in the uplink direction. Ultimately, mobile users will become content providers.

A user-centric approach tries to see and understand the user in different contexts aiming to extract some information that will lead to the development of possible scenarios and ultimately, their associated services. The user can be considered as *a*) an isolated individual with personal and (somewhat) unique needs, *b*) a member of a distinctive group with some common characteristic and *c*) an infinitesimal constituent part of the society. These setups will give us some hints on the user needs and expectations, which in turn will be starting point for identifying services likely to appeal the users. Some work has already been done in identifying scenarios and developing services, mostly at the Wireless World Research Forum (WWRF) [WWRF, 2006], in particular in the Book of Visions [BoV, 2001] as well as at the Mobile IT Forum (mITF) [mITF, 2006], in the "Flying Carpet" report [Carpet, 2004]. These fundamental issues are also discussed at the Samsung 4G Forum. We highlight here the following user trends:

- *Mobile user as an information sink/source*: Users are avid consumers of information. Accessing information and knowledge is always valued by users. Information comes in many forms, multimedia formats becoming the de facto presentation style. Mobile users are also becoming avid producers of information, sharing pictures, video, and commentary from wherever they are.

- *Multi-access services*: There are different approaches describing this trend. In general it refers to the delivery of services to multiple devices over multiple networks. It can be also understood as the delivery of service to a terminal equipped with multiple air interfaces in a fashion that more than one air interface are simultaneously exploited. Regardless of the interpretation, multi-access services describes very important emerging areas of research with high potential for developing countless applications. *Pervasive connectivity*: Ubiquity of services drastically increases the value of the information. The wider the coverage and the quicker the retrieval, the better.

- *Personalization of devices and services*: Personal preferences and the uniqueness of each user should be taken into account to allow differentiation of users.

- *Simplicity*: User friendliness is highly valued. Natural, transparent, intuitive and minimal interaction between man and machine will help reduce the gap between people and technology.

- *Predisposition to interact*: Interaction with other mobile users will become more tangible, leading to positive attitude towards cooperation and ultimately paving the way for cooperative communications among users. Users would consent to have their terminals processing signals other than their own provided there is a clear benefit from cooperation (*e.g.*, increased QoS, reduced communication cost, etc.) and provided the interaction is secure (*e.g.*, no possibility for the signal to be tapped by intermediate nodes).

- *User-driven mobile technology*: High data rates alone do not appeal users; useful and attractive services/applications exploiting high data throughputs are likely to please the users.

- *Core life values*: Technological innovations supporting the well-being movement are expected to be widely accepted. Vital user values related to mobile technology include health, closer circles (family, friends), security, environmental values, etc.

Various promising 4G scenarios have been identified. They include typical everyday life situations with the potential to unlock user needs for connectivity and bandwidth. Typical mobile scenarios are: E-commerce, business/work, private life (home/free-time), vehicular, public places, entertainment, education, health-care, travel, etc. Numerous associated services to these scenarios have been identified, trying to match user values and expectations. Examples are personal manager/assistant (finance, health, security, information, etc.), home manager/assistant (control, comfort, security, maintenance, etc.), news/weather report delivery, travel agent/mobile tourist guide, mobile gaming, mobile shopping, positioning-related services (tightly complementing the above mentioned services), and many others. Additional information on 4G scenarios and services can be found in [WWRF, 2006], [mITF, 2006], [Kim and Prasad, 2006b] and [Karlson et al., 2004].

An integrative approach: 4G as a convergence platform. In this section we explore the integrative approach of 4G in particular from the perspective of the aforementioned ITU-R Recommendation M.1645 [ITU, 2003]. We can see that a paradigm shift may be needed to define future wireless communications systems. Indeed, previous and current generations (1G-3G) refer mainly to cellular systems while future systems (4G) are seen to encompass several access approaches, with cellular (wide-access) and nomadic (local-access) being the main component networks. 4G attempts to combine several complementary communications networks into a single network.

Convergence of Heterogeneous Networks in 4G: One of the tenets mostly associated with 4G that is *Being Always Connected, Everywhere, Anytime*. Fulfilling such a simple principle demands unprecedented efforts on the part of the designers of future wireless communication systems. The apparent simplicity and transparency enjoyed by users of future 4G systems has an enormous price to be paid by manufacturers, research community and standardization bodies. Their goal is to make a network of highly eclectic networks appear as a single, simple and everywhere reaching network. In Figure 14.1 the 4G domain is depicted as a conjunction of two well-known mobile (wide-area coverage, cellular) and nomadic (local-area coverage, short-range) developments, corresponding to the upper and lower portions of the figure, respectively. Cellular mobile communications have enjoyed a steady growth in terms of achievable throughput. Every generation of cellular systems (1G, 2G, 3G) offered marked improvements over the preceding one. The same applies with the nomadic (local-area) access, characterized by low-mobility and moderate-to-high data rates. The transitional period between 3G and 4G is sometimes known as Beyond 3G (B3G), where further enhancements are expected. As time goes by, the mobile approach acquires more characteristics of its nomadic counterpart, *e.g.*, supporting higher data throughput, while the same applies for the nomadic systems, which gradually inherit attributes of mobile systems, like higher mobility, seamless coverage, better use and reuse of radio resources and voice/data/multimedia capabilities. Telecommunication manufacturers (the mobile sector) tend to focus on the cellular components of 4G, including both an evolutionary path aiming to further enhance the current mobile systems and an innovative path concentrating on developing new technical solutions. These approaches correspond to the upper right corner of Figure 14.1 (path 1). Equally, IT companies (the wireless sector), with background business in local access systems are more inclined to see 4G as enhanced extensions of current short-range communication systems (lower right corner in Figure 14.1, path 2). In addition to the cellular and WLAN paths there is a third and somewhat more recent development also likely to be incorporated into 4G, namely through enhancements based on wireless Metropolitan Area Network (WMAN), see path 3 in Figure 14.1. In terms of data throughput, mobility and coverage WMANs represent a mid-way point between local- and wide-area approaches. Academia, regulatory bodies and other parties with less economic ties to the wireless business tend to favor a more unified and balanced vision of 4G and its constituent technologies. Summarizing, worldwide 4G development is following several paths with target solutions that can be complementary (co-existing) as well as mutually exclusive (competing). Evolution is an important component of this development, in particular taking into account the integration and further enhancement of legacy systems. In addition, development of novel approaches might be required to cope with some of the stringent requirements.

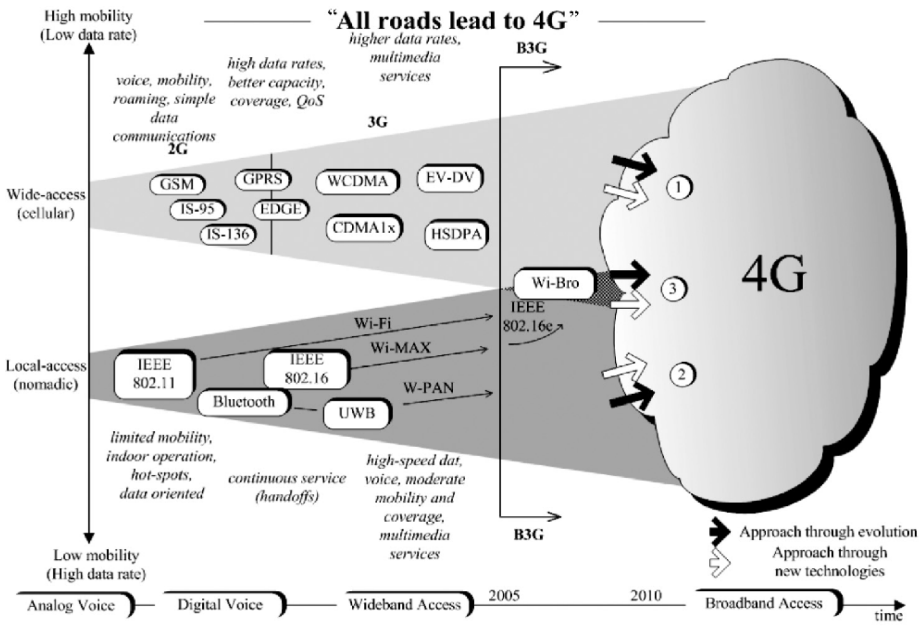

Figure 14.1. Approaching 4G through convergence of cellular, nomadic (WLAN) and metropolitan (WMAN).

4G can be approached from the network coverage standpoint, by looking at how different wireless services are provided at different geographical scales. Figure 14.2 shows the network hierarchy, starting with a distribution layer at the largest scale. This layer provides large geographical coverage with full mobility, though links may convey a chunk of composite information rather than signals from individual subscribers, for instance broadcast services such as DAB and DVB. Next in the hierarchy is the cellular layer, with typical macro-cells of up to a few tens of kilometers. This network also provides full coverage, full mobility but now connections are intended to cater to individual users directly. Global roaming is an essential component of 2G cellular systems, *e.g.*, GSM. Note that the cellular layer encompasses both macro and micro cells. The metropolitan layer or network, of which IEEE 802.16 [802.16, 2004], HyperMAN [HiperMAN, 2005] and Korean WiBro [WiBro, 2004] are typical examples, provides urban coverage with a range of a few kilometers at the most, with moderate mobility and moderate data speed capabilities. In a further smaller scale and moving to the local-area layer, *e.g.*, indoor networks or short-range communications, the network provides here access in a pico-cell, typically not larger than a few hundred meters, to fulfill the high capacity needs of hot-spots. Nomadic (local) mobility is supported as well as global roaming. 3G makes use of the cellular layer (typically micro-cells) in combination with hot-spots (WLAN), through vertical handovers, to provide coverage in dedicated areas. The next in the wireless network hierarchy is reserved for the personal area network (PAN), very-short range communication links (typically 10 m or less) in the immediate vicinity of the user. Within this layer we can also enclose body area networks (BAN), and some other sub-meter wireless short-range access (*e.g.*, RFID, NFC). Wireless sensor networks (WSN) are also one essential constituent part of 4G networks. WSNs are important solutions to the problem of efficiently monitoring, collecting and distributing information in a distributed network made of (typically) a large number of nodes [Cook and Das, 2004]. Going back to the paradigm of a pervasive 4G wireless network, in order to effectively have an unlimited reach while being able to support a variety of data rates, 4G would have to embrace all the described network layers. In other words, 4G could be defined as a convergence platform taking in as well as working along and across WBAN, WPAN, WLAN, WMAN, WSN, cellular and distribution networks.

Convergence of Heterogeneous Terminals in 4G: As 4G is a network of heterogeneous networks, it follows that it needs to support heterogeneous terminals. There is no archetype of a 4G terminal, they will come in different shapes and sizes, and they will have different communication capabilities and additional functions. 4G terminals will fall into a broad range of devices from pen-like to conventionally shaped portable mobile communication devices to PDAs, laptops and other devices, including cars. As 4G involves not only man-to-man but also man-to-machine and machine-to-machine communication, 4G transceivers are expected to be integrated in wide range of devices, *e.g.*, office equipment, home appliances, etc. As far as the user terminal is concerned, the current trend is to have either single-mode or multi-mode terminals. Even though both approaches could easily find considerable market share, the latter

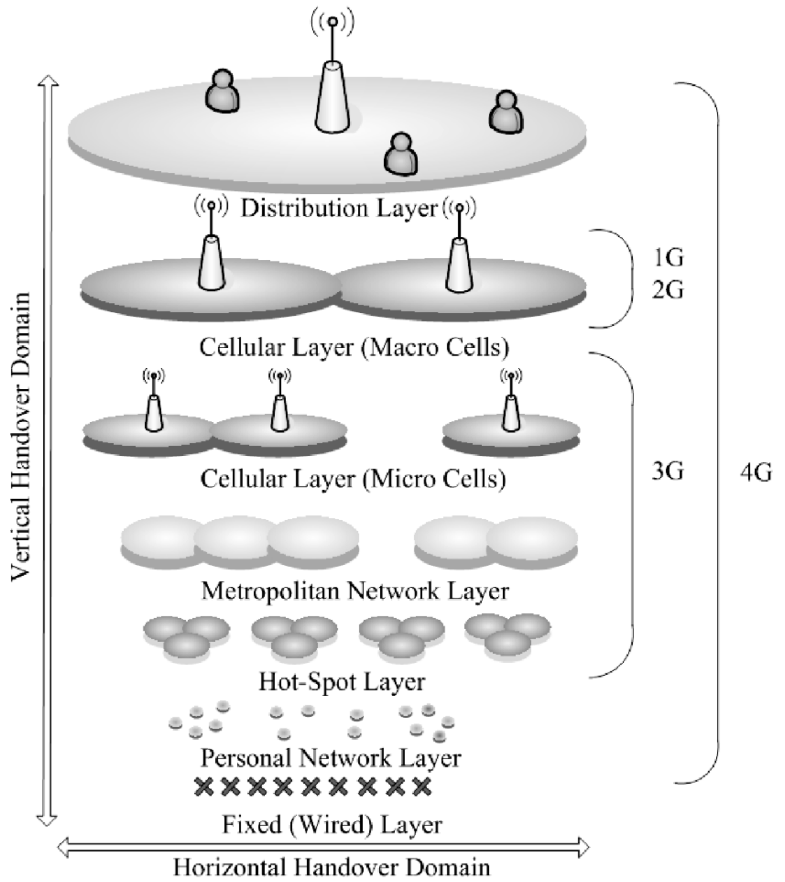

Figure 14.2. Network layers coverage.

will inherently better match the capabilities of 4G networks, namely handling multimedia information of various types supporting advanced services. Multi-functional devices represent the convergence of several technologies. Multi-functionality means several air interfaces on board (*e.g.*, wide-area, local-area, very short range), audio, imaging, positioning and other features. Terminal convergence is possible because there is a 4G network ecosystem supporting pervasive connectivity. This convergence will allow users to have simultaneous or independent access to different networks with a single terminal. 4G will ultimately facilitate and expedite the *three-screen* convergence, bringing together the TV, PC and mobile phone screens into a single portable device.

Convergence of Heterogeneous Services in 4G: Heterogeneous networks and terminals need to be finally complemented by heterogeneous services. In other words, heterogeneous services imply a wide range of services able to operate across different networks and in various types of terminals. In addition, convergence is essential in this context as the concept of multi-access services is becoming a reality.

Technology perspective. We see 4G as a continuum of wireless technologies providing ubiquitously a wide range of seamless connectivity options. The most critical technical features of 4G are the pervasive provision of seamless connectivity as well as the support of high data rates in moderate-to-high mobility environments. The integration of eclectic wireless networks needs to be done at the IP networking layer, where the cohesive role of IP is paramount to enable wide seamless connectivity across heterogeneous networks. An all-IP network, embracing the access and core networks, is the most straightforward and effective way to integrate all the possible different networks constituting the 4G network. Horizontal and vertical handovers will assure seamless intra- and inter-network connectivity, respectively. As far as modulation and multiple access schemes for 4G are concerned, it is widely agreed that multicarrier techniques have full potential to attain high data throughput at high mobility. OFDM (Orthogonal Frequency Division Multiplexing) and its multiuser extension OFDMA (Orthogonal Frequency Division Multiple Access) are the main component techniques for 4G. Usually OFDM is combined with other access techniques, typically CDMA and TDMA, to allow, among others, more flexibility in multi-user scenarios. Multicarrier CDMA (MC-CDMA), another technique with great potential, can be seen as a special case of OFDM. OFDM and CDMA are robust against multipath fading, which is a primary requirement for high data rate wireless access techniques. Overlapping orthogonal carriers OFDM results in a spectrally efficient technique. Each carrier conveys lower-data rate bits of a high-rate information stream, hence it can cope better with the intersymbol interference (ISI) problem encountered in multipath channels. The delay-spread tolerance and good utilization of the spectrum has put OFDM techniques in a rather dominant position within future communications. From a technology standpoint, 4G should overcome limitations and solve the problems of the previous generations. The difficulty for CDMA to achieve very high data rates in interference limited multi-user, multi-rate environments puts the mentioned multicarrier techniques in a unique strategic position in 4G. Also, another problem in current wireless systems is the difficulty of providing a full range of multi-rate services with different QoS requirements due to the constraints imposed on the core network by the air interface standard (it is not a fully integrated system). 4G needs to tackle also the lack of end-to-end seamless transport mechanism. Other important constraints of current mobile systems are the limited availability of spectrum and its particular allocation as well as the difficulty of roaming across distinct service environments in different frequency bands.

Number-wise, 4G will favor short–range links, and air interfaces supporting local access are expected to be omnipresent. In addition to conventional narrow and wide band transmission techniques, ultra wide band (UWB) techniques have lately received considerable attention, in particular as a nonintrusive, low power and low cost alternative to other short–range communications methods [Porcino and Hirt, 2003]. In addition, optical wireless communications is also a viable alternative for short–range links. Optical wireless systems can be used not only for point-to-point links, like those standardized through the Infrared Data Association (IrDA) [IrDA, 2006], but also for full-mobility indoor applications based on either infrared or visible light [O'Brien and Katz, 2005a], [O'Brien and Katz, 2005b] and [Tanaka et al., 2003]. Among the main advantages of optical wireless systems, we mention their almost unlimited bandwidth, and inherent security, as the optical signal is confined within the operational scenario. Moreover, in optical systems no RF radiation is generated, consequently no interference pollution nor possible health hazards are produced, thus they are well suited to sensitive environments.

Even though there is not a widespread consensus on the main technical characteristics of 4G systems, several important features are commonly underlined. The main 4G features are shown in Table 14.1.

Geographical perspective. Even though enormous efforts on 4G research and development are global, it is worth noticing that 4G visions, interpretations and emphasis are not identical. Following the paradigm of generational changes, it was originally expected that 4G would follow sequentially after 3G and emerge as an ultra-high speed broadband wireless network [Bohlin et al., 2004]. As Asia pioneered 3G development, it rapidly became involved in 4G developments based on a linear extension of the cellular 3G and focusing chiefly on the high data rate aspects. This linear vision is still the prevalent approach to 4G in Asia, where notably Korea, Japan, China and India are the major players. In North America, emphasis on the high-data rate side of 4G has prevailed,

Table 14.1. Key characteristics of future 4G systems.

Data transfer capability	100 Mbps (wide coverage)
	1 Gbps (local area)
	Design targets representing overall cell throughput.
Networking	All-IP network (access and core networks)
	Plug & Access network architecture
	An equal-opportunity network of networks
Connectivity	Ubiquitous
	Mobile
	Seamless
	Continuous
Network capacity	10-fold that of 3G.
Latency	Connection delay ¡ 500 ms
	Transmission delay ¡ 50 ms
Cost	Cost per bit: 1/10-1/100 that of 3G
	Infrastructure cost: 1/10 that of 3G
Connected entities	Person-to-person
	Person-to-machine
	Machine-to-machine
4G Keywords	Heterogeneity of networks, terminals and services
	Convergence of networks, terminals and services
	Harmonious wireless ecosystem
	Perceptible simplicity, hidden complexity
	Cooperation as one of its underlying principles.

though mainly through the development of wireless local area networks. More recently Asia and America have concentrated on the development and enhancement of metropolitan area networks. On the other hand, the aforementioned concurrent approach is often identified as the European vision of 4G. Indeed, the European Commission (EC) envisions that 4G will ensure seamless service provisioning across a multitude of wireless systems and networks, from private to public, from indoor to wide area, and provide an optimum delivery via the most appropriate (*i.e.*, efficient) network available. This view emphasizes the heterogeneity and integration of networks and new service infrastructures, rather than increased bandwidth *per se*. European research and development activities reflect quite closely such an integrative approach.

3. Cooperation Opportunities in 4G

In this section we will explore different approaches to cooperation in 4G networks, with especial emphasis on solving inherent practical problems of such a communication system. After identifying some technical challenges, we will discuss how cooperative techniques have the potential to tackle many of the identified problems. We mainly underline cooperation taking place among heterogenous networks.

Challenges in 4G

The discussed concept behind 4G is certainly fascinating. However, the research and development community needs to solve many problems to make the 4G vision a reality. Instead of concentrating extensively on the numerous 4G challenges, in this section we would rather focus on some key technical challenges that the designers will be confronting. Then, we will identify cooperative techniques with potential to solve these problems. Many 4G link-network- and system-level setups can be described by models representing cooperative actions between interacting entities. These entities can be in principle either abstract or concrete objects of the wireless communication network, from conceptual OSI layers to actual signal processing or components in the physical world. Cooperation is not only confined to model such a complex wireless system, but most importantly, cooperative techniques can solve or ease many technical problems, as those hinted below. Intra-layer cooperation has probably received most of the attention in the literature, mostly on the MAC and PHY layers. Inter-layer cooperation has recently been the research focus of several studies that consider cross-layer design and optimization in 4G.

Some important technical challenges are a direct consequence of the fundamental nature of 4G: the pervasive provision of a wide range of wireless connectivity over different fixed, nomadic and mobile scenarios and supporting an array of diverse terminal devices. Heterogeneity of networks, terminals and ultimately services poses one of the key challenges as they need to inter-work seamlessly. Seamless connectivity in 4G means temporal and spatial continuity in the service provision within and across networks, as Figure 14.2 suggested. Of the several 4G access components, the most challenging is, without doubt, the design of a new air interface supporting high speed connectivity, with a per user data throughput of one or two orders of magnitude higher than those found in in 2G and 3G, particularly in environments with moderate to high mobility. Spectrum is scarce and this trend will become pronounced as one considers the continued explosive growth of mobile subscribers as well as the emergence of new services exploiting broadband capabilities.

One of the key challenges that we identify is the difficulty to fulfill the foreseeable increase in power demand of future 4G terminals. We particularly consider this challenge as essential, as it has not only crucial technical implications but also affects user acceptance and eventually the success of 4G as a whole. The capability of being wireless of any terminal is ultimately dictated by the battery powering the device. Frequent recharging or replacing of the battery makes terminals and associated services unappealing [TNS, 2005]. Unfortunately we are witnessing already now rather reduced operational times in current devices (*e.g.*, mobile phones, wireless-enabled PDAs). Another illustrative and discouraging example speaks by itself: 3G terminals are typically shipped with two batteries. Figure 14.3 exemplifies the evolution of power demand in past, present and future mobile generations. One of the fundamental challenges in 4G is thus to break conventional design rules targeting advanced services without the need to increase considerably the power requirements. Services are considered as one of the most important factors for the success of 4G systems. In terms of service provision the following paradigm shift is taking place in different generations.

$$Service_{2G} = constant \quad (14.1)$$
$$Service_{3G} \sim f(place) \quad (14.2)$$
$$Service_{4G} \sim f(place, time, terminal, user) \quad (14.3)$$

Breaking the design rules can be interpreted as departing from many conventional technical approaches aiming to a weaker dependence between services and power drain. Cooperative techniques have the potential to break the design rules by sharing or distributing tasks among cooperating entities, for instance by exploiting particular arrangements of these entities, by considering cooperative capabilities already at the design stage of the communication layers and including intra- and inter-layer aspects of cooperation, etc. One of the goals here would be to drastically reduce the dependence between service and power requirements. In 3G systems, as we move to higher data rates (*i.e.*, advanced services) we need to increase considerably the transmitted power, as suggested by Equation 14.1. Under the same cellular network architecture and assuming that multiple antennas are used on the terminal it is difficult to think that things would change in 4G. This trend would pose unacceptable practical constrains in 4G as it will make terminals even more power hungry. New techniques should be sought aiming to make the dependence between service quality and power consumption less dominant, ideally as hinted by Equation 14.4. We believe that cooperative techniques can help us to loosen this dependence, as is shown for instance in Chapter 11.

$$Power_{3G} \sim f(Service_{3G}) \quad (14.4)$$
$$Power_{4G} \sim f(1/Service_{4G}) \quad (14.5)$$

Power consumption in future terminals is undoubtly going to increase considerably due to the following facts:

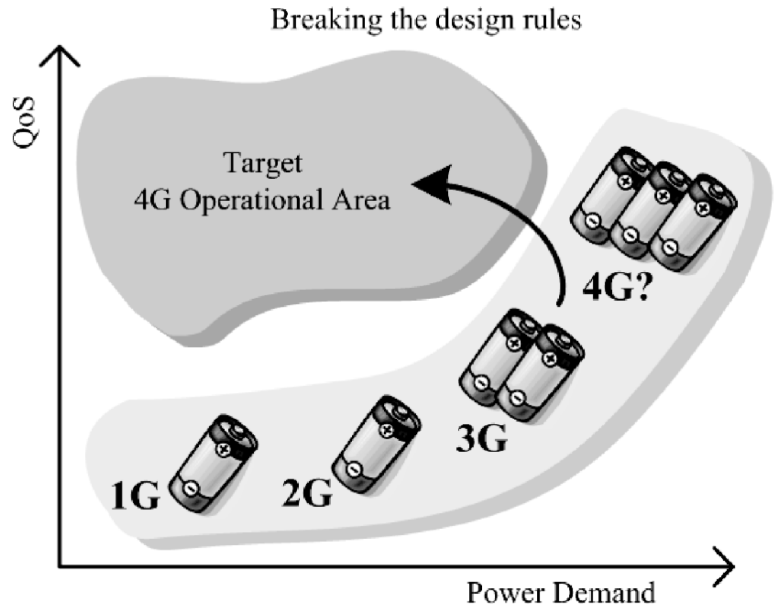

Figure 14.3. Power consumption of past, present and future mobile communication generations.

- Higher data rates: As energy per bit decreases, in order to operate with acceptable signal-to-noise ratios, the transmitted power needs to be increased.

- One of the most mentioned characteristics of 4G is the ability to provide users with a continuous connection, or as it is typically referred to *"always being connected"*. From the battery standpoint, this can also be interpreted as *"always being drained"*.

- 4G favors the emergence of multi-standard, multi-function terminals. Multi-standard particularly means the support of multiple air interfaces which can, in principle, be used simultaneously.

- Multi-antenna techniques are acknowledged as one of the key enabling technologies for enhancing link and network performance in 4G. In particular MIMO-based spatial multiplexing allows increasing data throughput by several folds. Multiple antennas on the terminals mean multiple transceivers on board, consequently boosting power consumption. MIMO techniques can help us to solve many 4G problems (*e.g.*, high throughput, QoS, coverage, etc.) but form the portable terminal implementation point of view, it brings also several challenges.

- Due to current spectrum allocation and high demand of additional bands, it is expected that frequency for future wireless systems will be allocated to less congested higher frequency bands. This means a shift from the 1 to the 2 GHz band to frequencies that could lie within the 3.4 to the 5 GHz band. Attenuation in these higher frequencies in significantly higher. In order to maintain the power budget transmitting ends need to use higher power.

- Increased DSP power is needed to process faster, wider bandwidth data. The power consumption of the processing unit increases as higher clock rates are needed to support greater processing power. Video signal processing is particularly costly in this regards, not only for the high data rate required but also because of the onboard image processing requirements.

- The inherent advanced still and video imaging capabilities of 4G terminals mean displays with higher resolution, higher contrast and higher frame displaying rates. These all having an adverse effect on power consumption.

- Audio capabilities, particularly high-fidelity applications, sometimes incorporating stereo loudspeakers on the handheld device.

- Terminals contain large amounts of mass memory, and one is witnessing that this trend is on the rise. The use of semiconductor memory and particularly the recently introduced hard-disk equipped terminals increase power consumption significantly.

- New services may also unfavorably impact power consumption. For instance, they may exploit user location information obtained by using either a onboard satellite receiver (GPS/Galileo positioning system), or based on processing specific system signaling for that purpose (*e.g.*, time-of arrival, triangularization, etc.)

From the 4G terminal manufacturer perspective the power consumption problem is critical, not only technically but also taking into account the market expectations from a newly introduced technology. The long operational time capability of terminals is both satisfying and vital for users; it gives them a truly wireless experience. This feature has been put at the top of the wish list by consumers as shown recently in [TNS, 2005], and therefore it must be taken seriously by the industry, and indirectly, by the research community. As a concrete example, Figure 14.4 shows the power requirements of different wireless terminal generations, including an approximate power consumption breakdown, [source: Nokia Corp.]. In terms of power consumption we have moved from a relatively low 1-2 Watt range in the first generations to around twice of that in 3G. The prospective for the future does not look encouraging in this aspect, as one could easily expect again another doubling in the power consumption figure. Many of the above listed factors having a direct impact on power consumption are directly related to the basic communications and signal processing capabilities of the terminal and, as shown in Figure 14.4, they account for roughly 50 percent of the power budget. Therefore, any reduction in the power consumption in these functionalities will have a substantial impact of the overall power demand.

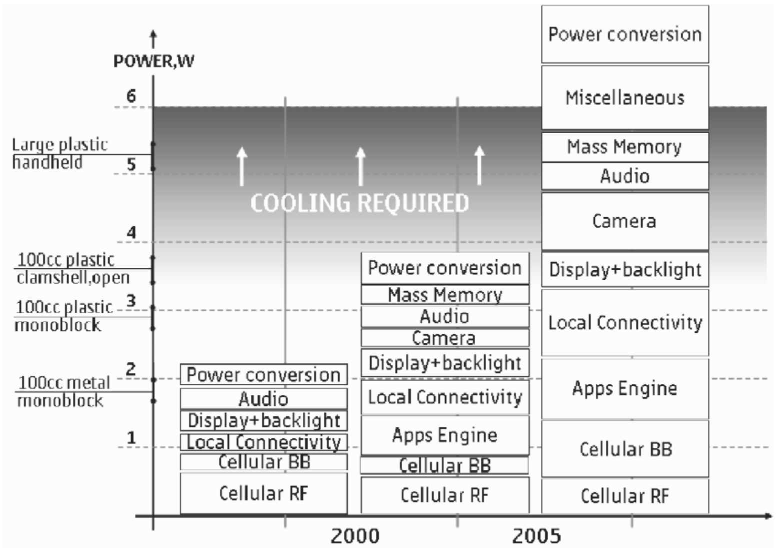

Figure 14.4. Power consumption breakdown of wireless terminals, Figure courtesy of Nokia.

One could wishfully expect that the above mentioned problems will be solved by the use of batteries with high energy density. Fuel cells will provide at the best a ten-fold increase in energy density, as compared to the best batteries today. Fuel cell technology is not yet fully mature, though optimistic predictions foresee the mass introduction of portable cells by the time 4G will be launched. New battery technologies will eventually solve the high power consumption problem by compensating for the power drain. However, high power consumption means also considerable heat dissipation and hence careful terminal design, followed by usually expensive technical solutions, in particular in small form factors. Heat management becomes a need when power levels already exceed a few watts. High power dissipation in terminals means that the temperature of the small handheld devices would rise to unpleasant values for the user, regardless of the effectiveness of the cooling system used. Thus, even though powerful batteries would eventually solve the problem of the high power demand, from a practical point of view it is highly desirable to the reduce effectively the overall power consumption. As Figure 14.3 suggests, we need to find a new operational regime characterized by low power consumption, without sacrificing system capabilities. In the sequel of this chapter we would discuss how cooperative technique could be used to reduce the power consumption as well as solve to some of the mentioned problems.

Cooperative Techniques in 4G: Identifying Research Opportunities

In this section we motivate the use of cooperative techniques in 4G wireless networks. We mostly focus on concepts helping to alleviate the increased power consumption of future terminals, though we strongly believe that cooperative techniques can be used to mitigate most of the challenges identified in the previous section. Two of the most distinctive characteristics of the 4G wireless communication systems were referred to as *heterogeneity* and *convergence*. The former term applies in the network, terminal and service domains, while the latter refers to the integrating platform where different networks, terminals and services operate and coexist. The vision of 4G as a *convergence platform* can be extended to consider it as a *cooperating platform* where heterogeneous networks operate, coexist and interact. As mentioned before, the main components are wide-area cellular networks as well as short-range local access networks. Typically, these two network approaches were considered as competing, though, given the significant support of both concepts by the industry, the current view is to regard these networks as complementing each other. We shall see that moving a step forward and creating synergy through cooperation between wide and local area networks can actually pay off. This will be one of the main 4G cooperative strategies advocated in this chapter. Another major attribute of the fourth generation systems is the availability of a *fine resource granularity*, unseen in previous generations, that can be exploited to design the system. Indeed multi-carrier, multi-antenna techniques, some of the *de facto* 4G assumptions for the physical layer, give to the designer unprecedent degrees of control on the use of time-, frequency- and space-domains. At the same time these extended and more finely partitioned domains make the problem of optimizing the use of resources in a multidimensional space a truly challenging design task.

From a network topology standpoint, 4G encompasses centralized (a.k.a. infrastructure, cellular) and decentralized (a.k.a distributed, infrastructureless, ad hoc) networks. Cooperation within each particular network is certainly possible. In most of the cases, due to the existence of either a centralized or distributed control strategy, coordinating the cooperative efforts leads to different approaches. Chapters 7 and 8 deal specifically with cooperative techniques for distributed (non-centralized) and centralized networks, respectively. Later in this section we particularly consider cooperative approaches across the two type of networks. At the physical layer, among the most representative cooperative approaches are the basic relaying (or multi-hop) techniques based on amplify-and-forward (AF) [Laneman and Wornell, 2000] and decode-and-forward (DF) [Sendonaris et al., 1998] as well as the concept of coded cooperation [Hunter and Nosratinia, 2002] [A. Nosratinia, 2004]. A unified framework for cooperation, comparing various schemes is proposed in [Herhold et al., 2005]. In general, a two-hop solution appears as a good engineering compromise in cellular networks, while in distributed networks a generic multi-hop approach is usually considered. In the cellular context the second hop need not necessarily be over a wireless link. Several approaches targeting 4G systems consider that the hop between the relaying node and the base station takes place on a fixed link using either a wireline or optical fiber, as in the concepts of Distributed Base Stations (DBS) [Adachi, 2001], [Clark et al., 2001] or Radio Over Fiber (ROF) [Al-Raweshidy and Komaki, 2002], [Way, 1993]. Unlike with the full wireless multi-hop techniques, these hybrid concepts do not exploit diversity provided by the multiple received signals.

A pragmatic approach to cooperation in 4G. Cooperation in 4G can be approached from several angles. We highlight here chiefly those cooperative techniques specifically exploiting some of the basic characteristics of 4G, and/or tackling some of its inherent practical problems. For our purposes we model the interactions taking place in the system with a number of variables. Service (Q) is the ultimate deliverable that the system needs to provide to the user. Such a provision has a cost, measured in resources needed to transfer the required signal to the end user with a given quality. For our purposes we consider power (P), complexity (C) and spectral efficiency (S) as the main contributors in the cost equation. As identified previously, P, C and S represent fundamental challenges in 4G. Figure 14.5 illustrates the interaction of these key practical factors. By cooperating at a given layer (of the OSI protocol stack) or across different layers, we can in principle have some degree of control on how the aforementioned resources are used. Even though cooperation can take place just between two entities (*e.g.*, typically terminals, base stations or functional parts of them), in general the setup for cooperation is understood to include more than the original source and destination nodes. These additional nodes share their resources to help the source node to convey reliably its message to the destination, as in multihop (relaying) networks. One may next ask, what are the incentives for these nodes to cooperate? When a fixed relay node is used, as done typically in cellular networks to increase coverage, the question is irrelevant as the only function of such a node is to help others. However, the situation is different for an autonomous node (*e.g.*, wireless terminal), where sharing resources means in practice letting others use its battery, giving others priority to exchange information, etc. Being selfish has its price and hence *reciprocity* could be seen as the main driving force inducing cooperative behavior. Of course, cooperativeness can be also sparked by other factors, like benefits to cooperative users granted by the network (*e.g.*, access priority), operator (*e.g.*, reduced service price), among others. In some scenarios, like in personal area networks, several wireless nodes in immediate closeness to the user serve him or her, thus, the incentives for cooperation are inherently embedded in the relationship to the user and associated nodes.

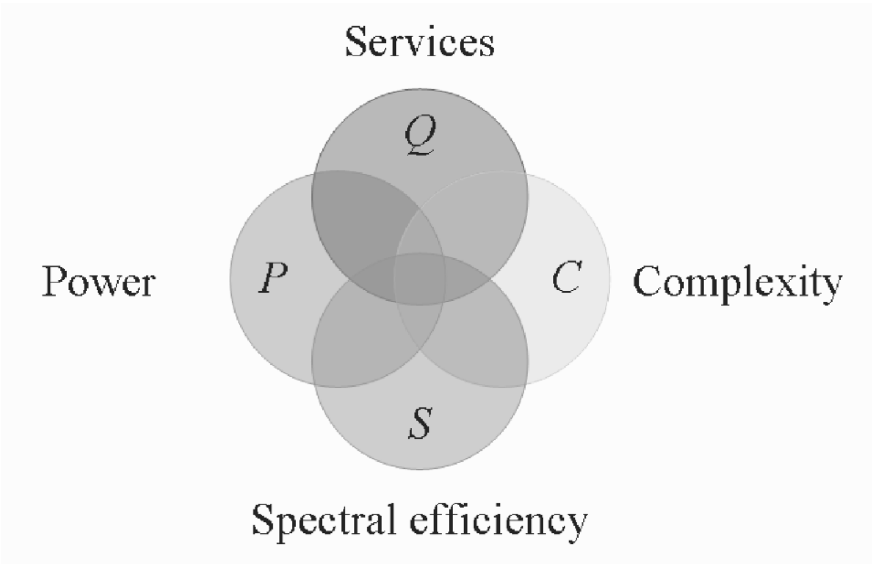

Figure 14.5. Key practical challenges in 4G.

In the following subsections we will explore how cooperative techniques could be used to solve or at least alleviate many important practical problems likely to emerge in 4G.

Cooperation and power efficiency. Let's approach first cooperation form the possible power saving benefits, leading ultimately to an extended operational time of the terminal. Having a number of nodes collaborating by relaying the signal from the source can be seen indirectly as reducing the equivalent average distance (end-to-end) between source and destination. This, together with the diversity gain obtained by the use of multiple signal paths to reach the destination, results in a less stringent power budget for the source, as compared with the direct (non-relaying) case. Of course, the gain comes from the fact that a comparable QoS is attained at destination with reduced power expenditure P at the source. However, one should look carefully to the overall cost of cooperation. The coordinating efforts to bring and keep cooperation among entities consumes valuable resources. The mechanisms for identifying potential cooperating nodes as well as announcing and maintaining the cooperation require exchange of information which in turn consumes power (for transmission, reception and processing), reduces spectral efficiency S (due to the required overhead), and adds in principle complexity C to the system. In some cases the additional power consumption resulting from cooperation may not be an issue, but this cannot be straightforwardly generalized for all types of networks. In typical terminals of cellular systems (*e.g.*, 2G, 3G) up to half of the power consumption comes from communications-related functions like baseband processing, RF and connectivity functions, as depicted in Figure 14.4. In terms of additional power consumption, the cost of cooperation are by no means negligible in such a cellular scenario, though the answer depends on the number of involved nodes, type of protocols used, etc. In wireless sensor networks the energy needed for establishing and maintaining a link could be considerably lower than that required for other onboard functions. Some cooperative techniques exploit the availability at the source transmitter of all channel state information (CSI), an assumption that could result in prohibitive practical implementations in some cases. Certainly, increased latency is another typical consequence of cooperation. Multi-hop techniques are not always energy-efficient, in general their efficiency depends on the type of scenario [Min and Chandrakasan, 2003]. Chapter 18 considers a different approach to achieve better power efficiency, namely task computing by distributing the efforts among a number of cooperative nodes. Power awareness in distributed (ad hoc) wireless networks is a fundamental design issue [Goldsmith and Wicker, 2002], and the problem of attainting energy efficiency is particularly exacerbated in wireless sensors networks, where it is vital for a very large number of nodes to exhibit extremely low power consumption [Min et al., 2002], [Rhee et al., 2004]. Even though an extension of the operative time of the terminal has been recognized as one of the main driving forces for using cooperative strategies, smaller transmitted powers result in less generated heat and reduced radio emissions, which in turn generate less interference to other nodes of the network and less potentially hazardous electromagnetic radiation to the user.

Cooperation and complexity. One of the major challenges of 4G is developing advanced equipment and services at relatively low cost. These targets are sometimes conflicting, as in the case of infrastructure. Providing wide coverage with high-speed connectivity at the high frequency bands likely to be allocated to 4G means that a dense network of base and relaying stations will need to be deployed. In order to guarantee the success of 4G from its launching, terminal prices should be attractively low. Terminal complexity and its associated cost can be traded at the expense of more complex (though expensive) infrastructure. Cooperation can be in principle exploited to bring terminal complexity down by distributing the tasks among several cooperating units. Terminals form a wirelessly connected grid of nodes, each contributing to a shared resource pool with some particular (local) resources, like computational capability, etc. Terminals could then be simple, with plain communicational and processing capabilities, but with enabled cooperative capacity. Under these assumptions, terminals could improve their communicational and processing capabilities proportionally to the number of collaborating units. From a different perspective, an ideal design rule could target relatively simple terminals assuming that a large number of these will cooperate. Figure 14.6 illustrates some of the discussed concepts to reduce terminal complexity (or enhance QoS) in 4G. An example of such a scenario is the use of Multiple Description Coding (MDC) by several wireless terminals, where every intervening terminal acts as the source of one descriptor. The more cooperating units the better the QoS [Fitzek et al., 2005]. In future 4G systems the possible gains (in complexity reduction) would be large if terminals were, by design, enabled with cooperative functions. The cost to support the simplicity of terminals, namely additional power P and overhead, increases with the number of interacting terminals, but still, trading complexity (cost) with power and spectrum is a viable engineering alternative to be considered.

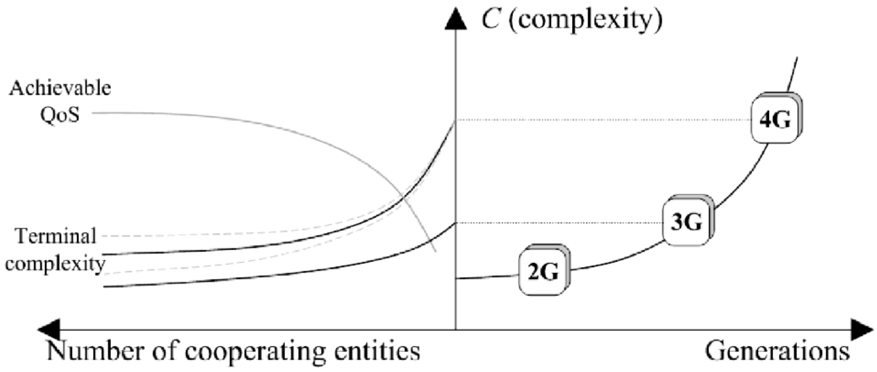

Figure 14.6. Can cooperation help us to reduce terminal complexity in 4G?.

Cooperation and spectral efficiency. Spectrum has always been a very limited radio resource and it is expected that 4G will dramatically accentuate this trend. We can also resort to cooperation to efficiently use the spectrum. This is not necessarily a straightforward task, as overhead needed to support cooperative techniques also tend to consume that valuable resource. *Cognitive Radio* techniques aim to better usage of the spectrum by sensing the environment over a wide bandwidth and dynamically allocating users to temporarily unused bands, thus boosting spectral efficiency [Weiss and Jondral, 2004], [Cabric et al., 2005]. To be effective, the cognitive behavior needs to be complemented with flexible and cooperative systems. Knowledge of the spectrum is not a necessary condition to increase spectral efficiency. In the next section we will consider some examples (though not based on cognitive principles) where cooperation between networks is exploited to increase spectral efficiency. Cooperation between heterogeneous networks has the potential to improve spectral efficiency, particularly when the interacting networks make use of licensed and unlicensed spectra.

Exploring cooperation in heterogeneous networks. The fact that 4G is fundamentally a platform embracing different networks makes certainly 4G the ideal setting for exploring inter-network cooperation. It is interesting first to consider the relationship between the two prevailing networks in the 4G context, namely cellular networks for wide area access and ad hoc networks for local access. Already a legacy feature from 3G networks, we highlight the importance of network convergence leading to *coexisting networks*, an approach that can be also interpreted to mean *competing networks*. More recent visions tend to see these networks in a slightly amicable manner, namely as *complementary networks*, though interactions between networks take place mostly for (vertical) handover purposes. We advocate a closer and synergetic interaction, leading to *cooperating networks*. These evolving visions are illustrated in Figure 14.7, where the typical contending network solutions are seen in a different light, namely within the framework of *cooperating heterogeneous networks*. Cooperation between networks is a rapidly emerging research area. A summary of the research activities being carried our at the Cooperative Network Working Group of the WWRF can be found in [Politis et al., 2004], where network cooperation is mostly approached from the transport and network layers. The Ambient Networks project [Network, 2006] addresses the problem of cooperation in heterogeneous networks, particularly where networks belong to different providers or exploit different access technologies [Niebert et al., 2004], [Ahlgren et al., 2005]. The ultimate goal of these projects is to ensure seamless operation between heterogeneous networks, a fundamental requirement in 4G. Cooperation in this context refers to the mechanisms and architecture required to support the automatic and simple (to the user) provision of end-to-end connectivity regardless of the interacting networks and access technology involved. Many fundamental challenges related to interworking between different networks are being tackled by these projects.

It is interesting to investigate the potential of cooperation between heterogeneous networks beyond the goal of achieving inter-operativity, aiming to a more synergetic and dynamic interaction. To get a better insight on these potentials, an example of a possible 4G specific cooperation approach is discussed next, aiming, among others, to enhance spectral efficiency. Let's assume a multicast

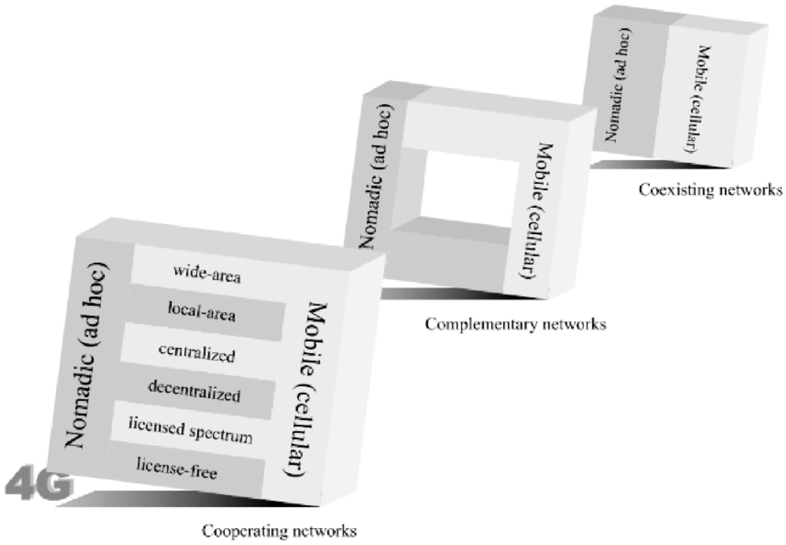

Figure 14.7. Recent views on the role of heterogeneous networks in 4G: Getting mobile and nomadic networks to cooperate.

service being provided by a base station. A number of terminals using the same multicast service and being in relatively close proximity form a given *local group*. Figure 14.8 depicts the considered scenario. Due to the channel fluctuations, there will be situations in which the signal cannot be successfully decoded by particular terminals. In such cases, the cellular network would need to resend a given packet, consuming additional resources, namely, spectrum and power. However, a *local retransmission* by any of the group members would do the same, with no additional spectral cost as license-exempt frequency bands are used for the ad hoc communication. In terms of energy, the local retransmission is carried our at low-level power using a short-range link, instead of a global retransmission from the base station, involving much higher power levels, and generating more interference. In a small-size group, cellular retransmissions would be needed occasionally, but spectral efficiency increases with group size.

We briefly discussed the concept of cooperation in heterogeneous networks, and highlighted the possible benefits of the interaction between a wide-access (cellular) and a short-range network. As exemplified in Figure 14.2, the constituent 4G elements range from distribution (*e.g.*, broadcast) networks down to personal networks, and thus, the possibilities for inter-network cooperation are in principle numerous. Note that fruitful cooperation strategies between more than one network can be devised around a single user, assuming that his terminal is equipped with multiple air interfaces. In principle cooperation between

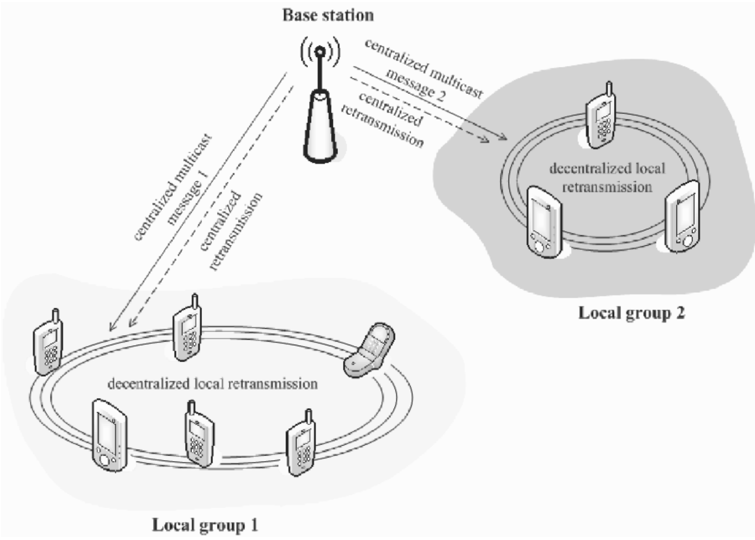

Figure 14.8. Network cooperation: Bringing together mobile and nomadic networks.

networks can take place at any of the OSI layers. Next, and to motivate further exploration, we mention a few promising concepts and scenarios:

- **Exploiting *air interface diversity* at the terminal**: Cellular (wide-area) links support typically less data throughput than their counterpart links for local-access. At the destination the data rate or QoS can be improved by combining multiple signals jointly provided by the cellular and ad hoc networks. Multiple description coding could be used for this purpose, for instance for video streaming, as suggested in [Frattasi et al., 2005a]. Multiuser diversity exploits the fact that in a multiuser environment a base station is likely to find at least one user with good channel conditions, making possible high-data throughput transmissions to such destinations. However, at a given time, multiuser diversity may not necessarily favor a particular high-data rate user, a fact that would become an issue in low mobility scenarios. Extending the centralized network with a locally distributed one, formed by an ad hoc group surrounding the target user, will help to convey more efficiently the high-data rate information to the destination. The larger the ad hoc group, the better are the chances to find a good overall multihop path to the destination. Thus, through cooperation between a cellular and ad hoc network we can in principle fulfil very well the request of the destination while the source is efficiently used.

- **Security**: Peer-to-peer communications over a short-range link is certainly a very feasible approach to exchange information. However, such a direct communication could be seen sometimes as risky, from the point of view of interacting with an untrusted (or unknown) counterpart. Thus, through *cellular-controlled short-range communication* the base station could take the role of verifying, authenticating and making secure a given transaction. If service is requested over a short-range link to a machine (*e.g.*, printing, vending machines, content retrieval) the infrastructure network could intervene providing initial secure configurations for the transaction (including distribution of keys) and billing services [Frattasi et al., 2005b]. In another example, both collaborating networks could also boost security by spatially and temporally spreading the signal targeting the destination. In other words, the composite signal arriving to the destination will come, time-multiplexed, from different nodes, some of them in different networks. In order to be able to decode the target signal the destination will need all the signal components to be present. Assuming that some of the components are provided by a wireless local-area network, reconstructing the signal is impossible for a node not in close proximity to the destination.

- **Local retransmission**: As discussed before, the interaction between centralized and decentralized networks can be exploited to improve, among others, spectral and power efficiency. Typically, centralized approaches (*e.g.*, cellular networks) consume spectrum and require more power, while decentralized approaches (*e.g.*, WLAN) operate in unlicensed frequency bands and require lower power levels. Cooperation between these two networks will aim to use as much as possible short-range links, bringing advantages to users (in the ad hoc networks) as well as to the operators.

- **Synchronization**: For some purposes local synchronization may be required, leading to a common reference time among a number of nodes. This common timing could be defined at different layers, *e.g.*, physical and application layers. In the former, a distributed process may need a precise common temporal reference, which may not be straightforwardly distributed by a central entity. By combining master-slave and mutual synchronization approaches provided by the cellular and ad hoc networks respectively, local synchronization can be obtained. At the application layer, some services shared by a group may need to have a common timing reference, *e.g.* aligning video and audio signals on the group users, as suggested in [Frattasi et al., 2005b].

We have mostly considered the interaction between centralized and decentralized networks, represented in this section mostly by cellular and WLAN and WPAN systems. 4G will consist of several other network technologies and associated air interfaces with high potential for cooperation, also comprising WMAN, sensor networks, near-field communications, RFID and other wireless networks.

4. Discussions and Conclusions

In this chapter, we have explored 4G from various perspectives, aiming to identify opportunities for applying cooperative techniques, and taking into account some practical issues. Global efforts to find a universal and well accepted definition of 4G are slowly paying off. A consensus on the 4G vision is hard to come by, because the perceptible departure from a cellular-oriented mobile communications generation paradigm towards an extended "all-encompassing network" approach. Even though a great deal of players in the 4G R&D arena tend to approach 4G from different and seemingly conflicting business interests, a number of common visions have recently emerged. The role of WWRF as a global consensus making organization on future wireless communications is significantly helping to create common understanding on 4G. We highlight here the integrative role of 4G, serving as a converging platform where a heterogeneous wireless networks will operate, coexist and cooperate. Virtually every imaginable wireless network will be integrated to the 4G network, from broadcasting networks down to wireless personal area networks, including wireless wide and local networks, sensor networks, etc. As a whole, 4G would be seen as a single, monolithic and simple network where a myriad of different terminals with different capabilities can be connected. Heterogeneity and convergence are the words that best describe 4G in terms of networks, terminals and services. It seems convenient to extend the rather established notion of 4G as a convergence platform to consider cooperative aspects, in particular those pertaining to the beneficial interaction between heterogeneous networks. In short, we extend the concept of coexistence and complementarity of networks in 4G to also embrace cooperativity.

We briefly discussed several technical challenges of 4G, mostly taking into consideration implementation aspects of terminals. In addition to improving basic performance measures like data throughput, coverage, QoS, etc., a number of practical but critical issues needs to be properly addressed by the research community to guarantee a successful 4G, including effective solutions to reduce power consumption and complexity in the terminal while boosting spectral efficiency. Power, complexity and spectral efficiency are key resources that can be traded in different ways to achieve a desired level of performance, and *cooperation is a promising resource-trading framework* for future wireless networks. We emphasized that cooperation has the potential to solve many of the challenges of 4G. There is already a vast and rapidly growing body of literature showing numerous advantages of cooperation in wireless networks. However, additional efforts are needed to better understand limitations and practical aspects of cooperative techniques in wireless systems. Undeniably, cooperation in wireless networks brings advantages, but its overall impact on system design, performance and practical implementation needs to be studied in more detail. Initially cooperation was confined to particular layers, typically physical and MAC layers, though, through cross-layer design, 4G is extending it to the inter-layer domain. Moreover, 4G opens up new possibilities, specifically cooperation among different component networks. Figure 14.9 illustrates, layer- and network-wise, the realm for cooperation in different communication generations. We note that the possibilities for cooperation are open but we cannot take for granted that this will happen. More research efforts are needed to better position these techniques within the developing course of 4G. A few motivating examples of inter-network cooperation were briefly discussed in this chapter, to unearth the potential of cooperation. Cooperative techniques should be considered as one of the fundamental enabling technologies for 4G.

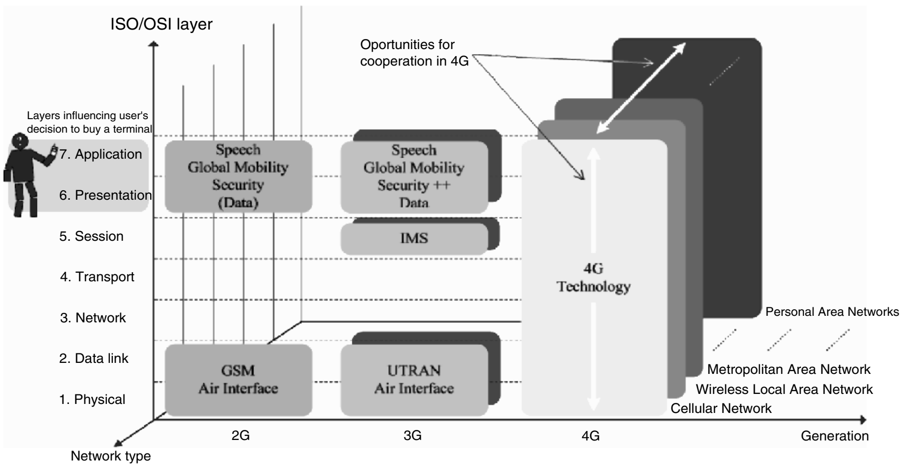

Figure 14.9. Domains for cooperation in 4G mobile and wireless networks.

Where will the user stand in a cooperative wireless world? Cooperation decisions can be inside or outside the realm of user choice. Many techniques can inherently exploit cooperation, the user is not part of the process. However, in some cases a given user can take an important role by deciding to share or not share with others the resources of his or her terminal. If clear and appealing incentives for cooperation are provided, like improvement and/or cost reduction of services, cooperation-enabled terminals costing less than non-cooperating ones, etc., users will be motivated to cooperate by sharing their resources. Thus, in a cooperation-enabled wireless world incentives would encourage users to cooperate. In such a scenario noncooperative behavior will be discouraged by the implicit punishment of missing the benefits. Supporting cooperation, security issues need to be solved to ensure that users of cooperating nodes cannot obtain other users' signals being processed by their terminals. In Figure 14.9 we show that the decisions made by an user when buying a terminal are influenced basically by features defined in upper layers, typically presentation and application layers. In the future the "cooperation-capability" feature could be a strong selling point for terminals, where ultimately users, manufacturers and operators would benefit.

In this chapter, inter-network cooperation was identified as a potentially promising area of research that can help us to solve several important practical challenges of 4G. We need to exploit the synergetic effects of combining centralized and distributed networks, taking advantages of the interaction between licensed and unlicensed frequency bands, wide and local area coverage, public and private, as well as high and low mobility networks. In order to *enhance* performance by cooperation, we need to both *enable* cooperation by design and *encourage* cooperation by clear incentives.

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