A Vision into Medium-Long Term Research in Wireless Communications

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***Abstract*—This paper summarises the 1st NEWCOM++ Vision Book. In it, the community of NEWCOM++ researchers, shaped under the common ground of a mainly academic network of excellence, has tried to distil their scientific wisdom into a number of areas characterised by the common denominator of wireless communications, by identifying the medium-long term research tendencies/problems, describing the tools to face them and providing a relatively large number of references for the interested reader. The identified areas and the researchers involved in their redaction reflect the intersection of the major topics in wireless communications with those that are deeply investigated in NEWCOM++. They are preceded by an original description of the main trends in user/society needs and the degree of fulfilment that ongoing and future wireless communications standards will more likely help achieving.**

***Index Terms*—Wireless Communications. Research trends. Mobile and Ad-Hoc Networks. Telecommunications standards.**

I. INTRODUCTION

VISION books are drafted in several contexts by international research fora (e.g., Wireless World Research Forum), technological platforms (e.g., European e-Mobility), specialised agencies, etc., and serve different purposes. By definition, they need to incorporate some "visionary" germs, and as such deal with medium-long term predictions. Some deal with the scientific/technological evolution, trying to predict the future of key enabling technologies by extrapolating today's characteristics and up-to-date research trends. The authors are typically renowned scientists and industry leaders, and their reports are mainly aimed at influencing the policy makers at large, so as to gain resources in their broad area. Other focus on the societal needs of technology, and try to depict the future needs of prospective customers, so as to offer business hints to equipment manufacturers and service providers. A few envision a more comprehensive view of the future shaped by technological advances and its impact on the large scale societal behaviour, offering matter for sociologists' analysis, and, to a more diffused scale, making human beings dream about the impossible to become possible and available.

In their attempt to predict future trends, vision books typically undertake one of two approaches: either they present easily foreseeable evolution of present technologies and applications, in which case of course the depicted scenario will become real in a short-medium time frame, or they launch themselves in the realm of disruptive technological breakthroughs and "killer" applications, where almost invariably they fail in their visionary scope. There are many examples of this incapacity to capture the great/little potential of scientific/technological advances: fibre optic technology (this year Nobel Prize recognised its pioneer, late as usual), the Internet protocol, Shannon theory, videotelephony, and cellular SMS (Short Message Service), among others.

The reason may be very simple: the great jumps ahead in human history are the result of revolutionary theories/technologies, rather than the evolutionary stretching (and as such, foreseeable) of existing ones. They amount to discontinuities, a kind of "nonlinear" progress that can be predicted by the fantasy of novelists like Jules Verne, rather than by realistic scientists well rooted in their time.

For this, and other reasons related to our particular and somewhat narrower perspective, this paper is not motivated by the ambition to present a future, comprehensive scenario of wireless communications in the decades to come. Rather, a community of researchers, shaped under the common ground of the academic network of excellence NEWCOM++, has tried to distil their scientific wisdom into a number of areas characterised by the common denominator of wireless communications, by identifying the medium-long term research tendencies/problems, describing the tools to face them, and providing a relatively large number of references for the interested reader, which resulted in the 1st NEWCOM++ Vision Book [1][1].

Sections II and III are devoted to networks, with emphasis on features that are likely to characterise their evolution: heterogeneity and opportunism (Section II), and cognition and cooperation (Section III). Section IV stems addresses information-theoretical ultimate limits through mathematical tools like game theory, stochastic geometry, and random graphs, and techniques to approach them, such as decentralised network control, coordination and competition strategies, network coding. In Section V the emphasis is on the maximisation of the throughput per unit of bandwidth through adaptive strategies in the radio access. Section VI refers to processing and reliably delivering of multimedia signals. Section VII is fully devoted to a deep insight into the present and future of "hard" technologies, i.e., silicon technologies, high computing

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[1]A companion paper (G.E. Corazza, A. Vanelli-Coralli, R. Pedone, "Technology as a Need: Trends in the Information Society"), submitted to this same journal, contains an original description of the main trends in user/society needs and the degree of fulfilment that ongoing and future standards will more likely help achieving, so that part will not be treated here. This paper is also extracted from [1], and originated from G.E. Corazza (ed.), Report on Requirements and Constraints in Communication Technologies, ICT-NEWCOM++ Project, Deliverable DI.5.2, European Commission, Brussels, Belgium, Jan. 2010, http://www.newcom-project.eu.

power, great flexibility, and power efficient design. Section VIII deals with "green" communications, a concept drawing from the universally shared concern about sustainable development. Finally, Section IX draws the main conclusions of this paper, highlighting the key aspects.

II. Heterogeneous and Opportunistic Networks

Recent years have witnessed the evolution of a large plethora of wireless technologies with different characteristics, as a response of the operators' and users' needs in terms of an efficient and ubiquitous delivery of advanced multimedia services. The wireless segment of the network infrastructure has penetrated in our lives, and wireless connectivity has now reached a state where it is considered to be an indispensable service as electricity or water supply. Wireless data networks grow increasingly complex as a multiplicity of wireless information terminals with sophisticated capabilities get embedded in the infrastructure.

When looking at the horizon of the next decades, even more significant changes are expected, bringing the wireless world closer and closer to our daily life, which will definitely pose new challenges in the design of future wireless networks. In what follows, a vision is briefly described on some of the envisaged elements that will guide this evolution, and that will definitely impact of the design of the network layers.

A clear trend during the last decade has been a very significant increase in the user demand for wireless communications services, moving from classical voice service towards high bit rate demanding data services, including Internet accessibility everywhere and anytime. From a general point of view, the provision of wireless communication services requires from the operator perspective an appropriate network dimensioning and deployment based on the available technologies and in accordance with the expected traffic demand over a certain geographical area. The target should be to ensure that services are provided under specific constraints in terms of quality observed by the user, related both to accessibility (e.g., coverage area and reduced blocking/dropping probabilities) and to the specific service requirements (e.g., bit rate and delay), while at the same time ensuring that radio resources are used efficiently so that operator can maximise capacity.

The basic ingredients, allowing to successfully face the demand for higher traffic and bit rates, obey the following general principles of increasing:

- spectral efficiency, i.e., the number of bits/s that can be delivered per unit of spectrum.
- the number of base stations to provide a service in a given area, thus, reducing the coverage area of each one.
- the total available bandwidth, i.e., having a larger amount of radio spectrum to deploy the services.

As a consequence, the natural evolution that one can envisage for the next decade resides in the principles of heterogeneity due to the coexistence of multiple technologies with different capabilities and cell ranges, in the need to have smart and efficient strategies to cope with the high demand of broadband services, and also, on a longer term basis, in the introduction of flexibility in the way spectrum is managed.

The introduction of Self-Organising Networks (SON) functionalities, aiming to configure and optimise the network automatically, is seen as one of the promising areas for an operator to save operational expenditures. It is not difficult to envisage that in the next decades different networks will make use of it. Standardisation efforts are needed to define the necessary measurements, procedures and open interfaces to support better operability under multi vendor environment.

As a result of the above, SON has received a lot of attention in recent years in 3GPP [2] or in other groups such as the NGMN (Next Generation Mobile Networks) project [3], an initiative undertaken by a group of leading mobile operators to provide a vision of technology evolution beyond 3G for the competitive delivery of broadband wireless services to increase further end-customer benefits. It can be consequently envisioned that SON mechanisms will play relevant role in the mobile networks in the framework of the next decade.

Self-organisation functionalities should be able not only to reduce the manual effort involved in network management, but also to enhance the performance of the wireless network. SON functionalities include [4] self-:

- configuration: the process where newly deployed nodes are configured by automatic installation procedures to get the necessary basic configuration for system operation.
- planning: self-configuration comprising the processes where radio planning parameters are assigned to a newly deployed network node.
- optimisation: the process where different measurements taken by terminals and base stations are used to auto-tune the network targeting an optimal behaviour by changing different operational parameters.
- managing: the automation of Operation and Maintenance tasks and workflows, i.e., shifting them from human operators to the networks and their elements.
- healing: the process intending to automatically detect and to solve/mitigate problems, avoiding impact on users.

Opportunistic networking primarily stems from mobile ad hoc networking, that is, the research area that applies to scenarios where the complete absence of any supporting infrastructure is assumed. Opportunistic networks will spontaneously emerge when users carrying mobile devices, such as PDA (Personal Digital Assistant), laptops, and mobile phones, meet. According to the opportunistic networking paradigm, partitions, network disconnections and nodes mobility are more regarded as challenging chances rather than limiting factors or exceptions.

Mobility, for example, is considered as a way to connect disconnected network portions; partitions or network disconnections are not regarded as limitations since, in a longer temporal scale and by exploiting a store-and-forward approach, the information will finally flow from a source to the final destination. So, in opportunistic networks, delivering can be considered just a matter of time.

Opportunistic networking shares also many aspects with delay-tolerant networking, which is a paradigm exploiting occasional communication opportunities between moving devices. These occasional inter-contacts can be either scheduled or random, although conventional Delay-Tolerant Networks

(DTNs) typically consider the communication opportunities as scheduled in time. Opportunistic networking and delay tolerant networking have been somehow distinguished so far in the literature, although a clear classification does not exist. However, as a common understanding, opportunistic networking could be regarded as a generalisation of delay-tolerant networking with no a-priori consideration of possible network disconnections or partitions.

Vehicular networks, enabling communication between different vehicles in a transportation system have been another topic that has received attention during the last years, driven mainly by the automotive industry, but also by public transport authorities, pursuing the increase of both safety and efficiency in transportation means. Although a lot of effort has been devoted, no solutions are already available to the mass markets allowing the automatic operation of cars and the communications among them. It is thus expected that the evolution of wireless communications in different aspects, such as ad-hoc and sensor networks, distributed systems, and combined operation of infrastructure and infrastructureless networks, can become an important step so that vehicular communications become a reality in the next decades.

From a more general perspective, the term Intelligent Transportation Systems (ITS) has been used referring to the inclusion of communication technologies to transport infrastructure and vehicles targeting a better efficiency and safety of road transport. Vehicular Networks, also known as Vehicular Ad-hoc NETworks (VANETs), are one of the key elements of ITS enabling the one hand the inter-vehicle communication and on the other hand the communication of vehicles with roadside base station.

The evolution of Internet for the next decade has been coined under the term Future Internet, embracing new (r)evolutionary trends in terms of, e.g., security, connectivity and context-aware applications, in which again also wireless technologies will become an important and relevant element for the success of the different initiatives. In particular, one of the envisaged challenging goals for Future Internet is the possibility to interconnect not only people through computer machines (i.e., people connected everywhere and anytime) but also all type of unanimated objects in a communication network (i.e., connecting everything with everything), constituting what has been coined as the Internet of Things [5]. It presents a vision in which the use of electronic tags and sensors will serve to extend the communication and monitoring potential of the network of networks. This concept envisages a world in which billions of objects will report their location, identity, and history over wireless connections, so in order to make it true, this will require dramatic changes in systems, architectures, and communications.

Different wireless technologies and research disciplines can be embraced under the Internet of Things concept. Although Radio Frequency IDentification (RFID) and short-range wireless communications technologies have already laid the foundation for this concept, further research and development is needed to enable such a pervasive networking world, with the necessary levels of flexibility, adaptivity and security. Such technologies are needed as they provide a cost-effective way of object identification and tracking, which becomes crucial when trying to connect the envisaged huge amounts of devices. Also real-time localisation technologies and sensor/actuator networks will become relevant elements of this new vision, since they can be used to detect changes in the physical status of the different things and in their environment. The different things will be enabled with the necessary artificial intelligence mechanisms allowing them to interact with their environment, detecting changes and processing the information to even take appropriate reconfiguration decisions. Similarly, advances in nanotechnology enabling the manipulation of matter at the molecular level, so that smaller and smaller things will have the ability to connect and interact, will also serve to further accelerate these developments.

III. Cognitive and Cooperative Networks

The traditional approach of dealing with spectrum management in wireless communications has been the definition of a licensed user granted with exclusive exploitation rights for a specific frequency. While it is relatively easy in this case to ensure that excessive interference does not occur, this approach is unlikely to achieve the objective to maximise the value of spectrum, and in fact recent spectrum measurements carried out worldwide have revealed a significant spectrum underutilisation, in spite of the fact that spectrum scarcity is claimed when trying to find bands where new systems can be allocated.

One of the current research trends in the spectrum management are the so-called Dynamic Spectrum Access Networks (DSANs), in which unlicensed radios, denoted in this context as Secondary Users (SUs) are allowed to operate in licensed bands provided that no harmful interference is caused to the licensees, denoted in this context as Primary Users (PU). The proposition of the TV band Notice of Proposed Rule Making (NPRM) [6], allowing this secondary operation in the TV broadcast bands if no interference is caused to TV receivers, was a first milestone in this direction. In this approach, SUs will require to properly detecting the existence of PU transmissions and should be able to adapt to the varying spectrum conditions, ensuring that the primary rights are preserved. Based on these developments it is reasonable to think that the trend towards DSANs has just started and that given the requirements for a more efficient spectrum usage, it can become one of the important revolutions in the wireless networks for the next decades, since it breaks the way spectrum has been traditionally managed.

Cognitive Radio (CR) is a paradigm for wireless communications in which either a network or a node change their transmission and/or reception parameters (signal format and bandwidth, frequency band etc.) to communicate efficiently, avoiding interference with licensed or unlicensed users. Most readers are already familiar with this notion, whilst not so many might have heard about the “sister” concept of Cognitive Positioning (CP) [7].

According to our general definition above, cognitive systems strive for optimum spectrum efficiency by allocating capacity as requested in different, possibly disjoint frequency bands.

Such approach is naturally enabled, by the adoption of flexible MultiCarrier (MC) technologies, in all of its flavours. Most current and forthcoming wideband standards for wireless communications are based on such multicarrier signalling technology, so that the signal allocated to each terminal is formed as the collection of multiple data symbols intentionally scattered across non-contiguous spectral chunks.

On the other hand, modern wireless networks more and more expect availability of location information about the wireless terminals, driven by requirements coming from applications, or just for better network resources allocation. Thus, signal-intrinsic capability for accurate localisation is a goal of 4th Generation (4G) networks. All signal processing techniques that can contribute to the provision of accurate location information are welcome in this respect. Such techniques can pair the ones that a cognitive terminal adopts to establish a reliable, high-capacity link.

The concept of cooperation actually emerged in the late sixties with the work of Van Der Meulen [8]. Interestingly, the capacity of this scheme is still an open problem today. More recently, the concept of relaying or cooperation has gained a lot of interest for several reasons:

- The potential offered by multi-antenna transmission and/or reception is now clearly established, and this technology, known under the generic name of MIMO, has found its way in a number of standards. However, the idea has emerged as whether different non-co-located entities could "form a coalition" to mimic in a distributed manner a multi-antenna system, thereby getting access to the benefits of MIMO in term of bit rate and/or diversity.
- A natural way to exploit this idea is to serve a user by means of two or more base stations (macro-diversity). Assuming a wired backhaul, the base stations know in the best case all the data and the channel state information of all the users in the cell cluster. An issue, to avoid very heavy signalling, is that of distributed solutions based on partial data and/or channel knowledge at the coordinating node.
- While the motivation behind the previous concept is mainly to avoid inter-cell interference, another motivation is associated with the issue of coverage and users that might be out of (good) reach by any base station. An emerging concept is that of a "popping up base station" with wireless backhaul, which would help one or many poor users. The issue of decoding strategy has to be considered.
- Moving to a totally different scenario, like wireless sensor networks, there is also a clear interest for cooperative solutions. The network is of the mesh type, rather than of the star one. The choice of the cooperating nodes may be based on several criteria or utility functions, incorporating not only rate and/or bit/packet error measures, but also penalty depending on the power used and/or the status of the battery of the possibly cooperating nodes.

An important concept that emerged recently and deserves further investigation is that of "network coding", which shows promises, but also needs to properly encode and simultaneously relay the information of several users at the same time. Energy saving has to be considered as well. Transmission power is only one part of the global picture, and associated with any communicating nodes, there are additional power prices, like those associated with computation and security. It would be highly interesting to investigate the potential of relaying or cooperative communications at the light of a holistic analysis of power consumption.

While cognition and learning have received a considerable attention from various communities, the process of knowledge transfer, i.e., teaching, has received fairly little attention to date. A novel framework is introduced, "docitive radios" ("docere" means to teach in Latin), which relates to radios (or general entities) that teach other radios. These radios are not (only) supposed to teach the end-result (e.g., "the spectrum is occupied") but rather elements of the methods to getting there. This concept mimics well our society-driven pupil-teacher paradigm, and is expected to yield significant benefits for cognitive, and thus more efficient, network operation. Important and unprecedented questions arise in this context, such as; "Which information ought to be taught?" and "What is the optimum ratio between docitive and cognitive radios?".

A high-level operational cycle of docitive radios extends the typical cognitive radio cycle [9] through the docitive teaching element, where each of these elements typically pertains to the following high-level issues:

- Acquisition: The acquisition of data is quintessential in obtaining sufficient information of the surrounding environment, which can be obtained by numerous methods.
- (Intelligent) Decision: The core of a cognitive radio is without doubt the intelligent decision engine, which learns and draws decisions based on the provided information from the acquisition unit.
- Action: An important aspect of the cognitive radio is to ensure that the intelligent decisions are actually carried out, which is typically handled by a suitably reconfigurable Software Defined Radio (SDR), and policy enforcement protocols, among others.
- Docition: An extension of the cognitive networking part is realised by means of an entity that facilitates knowledge dissemination and propagation. A significant and non-trivial extension to this docitive paradigm comprises dissemination of information which facilitates learning.

Docitive radios and networks emphasise on the teaching mechanisms and capabilities of cognitive networks, and are understood to be a general framework encompassing prior and emerging mechanisms in this domain. Whilst the exchange of end-results among cooperatively sensing nodes has been explored in the wireless communication domain and the joint learning via exchange of states has been known in the machine learning community, no viable framework is available to date which quantifies the gains of a docitive system operating in a wireless setting. Numerous problems remain, in the areas of Information Theory, Wireless Channel, PHY (Physical) and MAC (Medium Access Control) Layers, and Distributed Learning, among others.

IV. The Ultimate Limits of Wireless Networks

This section discusses the grand challenges associated with the holy grail of understanding and reaching the ultimate performance limits of wireless networks. Specifically, the next goal in the community is to realise the Future Internet.

The challenges associated with max-weight and backpressure type of network control strategies have been shown to be throughput optimal. Grand challenges include the decentralised light-weight implementation of these algorithms, as well as the issue of coping with flow-level and other type of dynamics. Understanding the deep structural properties of these policies and shaping them towards achieving the goals above in the presence of numerous resource and interference limitations would be an important step forward.

A fundamental premise in dynamic queues is that max-weight policies have been initially developed for systems consisting of a fixed set of queues with stationary, ergodic traffic processes. In real life scenarios, the collection of active queues dynamically varies, as sessions eventually end, while new sessions occasionally start. In many situations the assumption of a fixed set of queues is still a reasonable modelling assumption, since scheduling actions and packet-level queue dynamics tend to occur on a very fast time scale, on which the population of active sessions evolves only slowly. In other cases, however, sessions may be relatively short-lived, and the above time scale separation argument does not apply. The impact of flow-level dynamics over longer time scales is particularly relevant in assessing stability properties, as the notion of stability only has strict meaning over infinite time horizons.

Another key feature related to the dynamics and autonomic operation of future networks, is their decentralised architecture. In max-weight policies, the scheduling and resource allocation mechanisms are not amenable to distributed implementation because every node should be aware of all the queue lengths and the topology state variables in order to independently optimise its own strategy. Furthermore, even if the required information is available, the scheduling might become extremely complicated especially for large networks. Hence, it is evident that distributed implementations of optimum throughput techniques will be one of the main challenges of future networks. The maximum matching derivation is the issue that mostly challenges the distributed implementation of max-weight and backpressure routing and scheduling policies. Nevertheless the problem of efficient and fully distributed implementation of max-weight policies is an important open problem the solution of which is highly related to achieving the holy grail of throughput optimal network control.

Game theoretic modelling is a means for understanding and predicting stable network operating points, namely points from which no node has an incentive to deviate. To this end, understanding interaction and convergence to equilibrium points is very important. Furthermore, the community should focus on the notions of competition and cooperation. For the former, non-cooperative interaction would be the best way to model the network, while for the latter, distributed optimisation approaches would be desirable.

In light of emerging future autonomous networks, game theory based analysis and modelling should be enhanced in order to satisfy long cultivated anticipation of research community. First, it is necessary to derive more detailed models that capture all aspects of the novel communication paradigms and therefore result to more stringent conclusions and realisable protocols. In this context, one should expect models which do not preclude the strategy space or the rules of nodes interaction. On the contrary, the possible actions of each player - node, the stages and the repetitions of interactions, the utility functions and other components of the game should be identified dynamically.

Additionally, in future large and decentralised networks each node will operate with limited information about other nodes and the network state. In this setting, it is interesting to study possible equilibrium points and their respective properties such as efficiency loss and computational complexity. In this context, understanding the repercussions of various types of learning algorithms and the way they impact convergence to equilibrium points should be properly addressed.

Moreover, the large number of nodes players yields for the employment of evolutionary game theory where nodes are grouped with respect to their behavioural profile. By observing the results of the repeated interactions, it is possible to identify the dominant strategies and therefore have significant insights to be used in the efficient protocol design.

Network coding has emerged as a revolutionary paradigm for information transfer in uni-cast or multi-cast traffic. Network coding turns out to be particularly effective and robust in environments of intermittent connectivity and continuous volatility. Network coding brings along a number of yet to be resolved challenges in resource efficient network operation, coding (traffic mixing) across the network, security and optimal resource utilisation.

Wireless communications, based on broadcast transmissions, represent the natural background of exploitation for network coding. Nevertheless, it should be taken into account that application of network coding in wireless and sensor networks presents implementation problems different from the wired network setting. The most salient aspect of wireless transmission is the use of broadcast via omnidirectional antennas. Broadcasting may beneficially provide collateral transmission to neighbouring nodes for free, but also causes interference. The use of network coding may significantly alter the nature of the interplay between advantages and drawbacks. Another key example is the communication/computation tradeoff of using network coding within sensor networks. Because communication is relatively expensive compared to computation in sensor networks, network coding may offer substantial advantages in power consumption.

Moreover, network coding will have an emerging role within the context of cooperative networking. The aim of cooperation is that network communications become more reliable and efficient when nodes “support” each other to transmit data. The cooperation can be achieved enabling neighbouring nodes to share their own resources and their power with the hope that such a cooperative approach leads savings for both the overall network resources and power consumption. Network coding must be seen as a form of user cooperation, where the nodes not only share their resources and their power but also their computation capabilities.

Stochastic geometry is a rich branch of applied probability that allows the study of physical phenomena characterised by highly localised events distributed randomly in a continuum, intrinsically related to the theory of point processes [10]. Although stochastic geometry has been used to characterise interference in wireless networks at early 70's, its use for modelling communication networks is relatively new yet rapidly increasing. Stochastic geometry is considered as an enabler for addressing fundamental performance limits of massive and dense wireless networks through network information theory. The main facets of innovation here entail the understanding of modelling certain spatiotemporal node scenarios and protocol interactions with certain stochastic processes and probability distributions and assess their impact on analysing network performance.

Wireless Sensor Networks (WSNs) emerge as a particular class of wireless networks, expected to proliferate in envisioned sensory networks. Central to the reason of deployment of sensor networks lies the estimation of unknown parameters in the area. Key research issues include the sensor network control to fulfil estimation functionalities, realise opportunistic communication and networking under limited spectrum and energy budget. The notion of constrained cooperation is put forward as means for modelling a wide range of wireless network topologies, infrastructure-based or infrastructure-less. A number of challenges associated with sensor networks are:

- Spectrum management: One of the main issues of future WSNs is its operation in a crowded spectrum scenario where multiple WSNs, all of them application-specific, have to coexist.
- Cross-layer designs (MAC/PHY): A cross-layer design encompassing the MAC and PHY layers by adopting realistic multiple access schemes is essential; in these cases, the probability of collision turns out to be directly related to the metric of interest.
- Opportunistic Communications: In a multipoint-to-point network one can exploit the fact that different users act as different antennas obtaining the so-called Multi-User Diversity (MUD).
- Network topologies: Several topologies have to be further considered, like deploying a heterogonous network, composed of sensors with different capabilities.

The massive body of theoretical work exemplifies the advantages of future wireless technologies, which will be based on far reaching processing abilities, harnessing thus the theoretical perspective into practical approaches.

V. Bandwidth And Energy Efficient Radio Access

Through the last two decades, the amount and diversity of services provided by wireless systems has been drastically transformed. Mobile (cellular) communication, for instance, is nowadays offering a wide variety of multimedia-data services, in contrast to the limited voice and very simple data services offered in the past. In Wireless Local Area Networks (WLANs), as another example, the ability to be on-line without needing a wired connection is not sufficient any more, and users expect to experience similar data speeds and QoS as with a wired connection. This has lead to a rapid increase in data-rate requirements within the standards of new and upcoming wireless communication systems.

In order to increase data rates, a simple approach would be to increase the bandwidth allocated to a certain system. However, the proliferation of applications that use the air interface as the transmission medium limits the amount of available bandwidth in the radio-frequency spectrum, making it a very scarce and costly resource. Therefore, research over the last years has been focused towards improving the spectral efficiency of wireless communications, so that higher data rates can be achieved within a given bandwidth. For example, the development of multiple transmit antennas and their stream-multiplexing abilities, along with advanced receiver architectures, has been a critical step in achieving this goal.

This section aims to discuss the current theoretical and practical research topics that address the problem of bandwidth- and energy-efficient radio access, as well as to provide a brief description of unsolved interesting problems for future research in this area. A discussion of coding/decoding techniques, as well as techniques that employ adaptive modulation and coding is performed, after which iterative techniques for receivers are addressed, concluding with cognitive spectrum usage (always for the purpose of advancing spectral utilisation) with a special focus on applied game theory for this goal.

The evaluation of the capacity bounds for various channel models and system scenarios is an active research topic since Shannons pioneer work [11]. The computation of such performance limits defines the framework for the design and development of optimal communication techniques. When the channel fading level is known at the transmitter, then the Shannon capacity is achieved by adapting the transmit power, data rate, and coding scheme relative to this known fading level. In such a fading environment, Adaptive Modulation and Coding (AMC) is a powerful class of techniques for improving the energy efficiency and increasing the data rate over the fading channel. Therefore, trellis and lattice codes designed for Additive White Gaussian Noise (AWGN) channels can be combined with adaptive modulation for fading channels, with the same approximate coding gains.

In general, coding techniques for the fading channel should be made by taking into account the distinctive features of the underlying model. There, one relevant question is how code design for the fading channel differs from that for the AWGN channel, assuming a flat, slowly fading channel plus AWGN. The quest for optimal coding schemes in such a fading environment leads to the development of new criteria for code design. If the channel model is not stationary, as it happens in a mobile-radio system, then a code designed for a fixed channel might perform poorly when the channel varies. Therefore, a code optimal for the AWGN channel may actually be suboptimum for a substantial fraction of time. In these conditions, antenna diversity with maximum-gain combining may prove indispensible: in fact, under fairly general conditions, a channel affected by fading can be turned into an effectively AWGN channel by increasing the number of diversity branches. Another robust solution is based on bit interleaving, which yields a large diversity gain due to the choice of powerful convolutional codes coupled with bit interleaving and the use of a suitable bit metric.

The construction of optimal coding techniques is an area of intense scientific interest. Coding and decoding will play a central role in future wireless systems. Apart from improving the theory and practice of Low-Density Parity-Check (LDPC)/Turbo and related families of codes, extended research activity can be found for the improvement of coding and decoding techniques for convolutional codes too. For MIMO systems, space-time block codes can realise full diversity gain and decouple the vector-ML decoding problem into simpler scalar problems, which dramatically reduces receiver complexity. Space-time Trellis codes yield better performance than space-time block codes by achieving higher coding gain at the cost of increased receiver complexity. The area of MIMO communication theory is new and full of challenges. Some promising MIMO research areas are: MIMO in combination with OFDMA (Orthogonal Frequency Division Multiple Access) and CDMA (Code Division Multiple Access), new coding, modulation, and receive algorithms, combinations of space-time coding and spatial multiplexing, MIMO technology for cellular communications and adaptive modulation and link adaptation (AMC) in the context of MIMO.

The recent advances in iterative processing have allowed the design of iterative receivers achieving close-to-optimal performance under the design assumptions. However, many challenges are still left unsolved: the complexity issues of iterative receivers are one of the most important; due to the iterative nature of the receiver, it is clear that the number of operations to perform in these types of receivers will be significantly larger than in the case of a sequential receiver. Furthermore, due to the iteration with the channel decoder, some latency in the detection of the information bits is introduced, which might be unacceptable for certain kind of applications. In order to solve this, future research will have to focus on the development of low-complexity, high performance iterative solutions, which could be derived from the analytical design frameworks by constraining the set of solutions allowed. Also, research on the field of low-complexity decoding will be crucial for the applicability of iterative receivers in practical solutions, as it will significantly alleviate the computational burden of having to perform several successive decoding iterations of the same signal.

Most of the iterative solutions designed so far have only been derived under rather ideal conditions and only address questions such as channel estimation, detection and decoding. In the future, the design of iterative structures should also include considerations such as synchronisation, RF imperfections (e.g. phase noise) or estimation and mitigation of other system's interference. While several analytical frameworks for the design of iterative solutions exist, each fulfilling different optimisation criteria, it is not clear which the best approach for a given problem is. Therefore, much of the research effort in the coming years will be put in the analysis and comparison between the different formal approaches, in order to achieve full understanding of their singularities, advantages and drawbacks. Information geometry might be an interesting tool to be used in this context.

As mentioned, flexible spectrum-access methods will be needed (along with others mentioned above, e.g., adaptivity, MIMO, and advanced coding) in order to increase the efficiency of the utilisation of the scarce spectrum resource. Besides the major objective of maximising spectral efficiency, another goal of modern radio network design is to rationalise the distribution of radio resources and the cost of their usage. This means that some rationalising mechanisms should be employed in order to balance efficiency versus fairness, high QoS versus high Quality of Experience (QoE) for both the licensed as well as unlicensed users of spectrum. Spectrally-efficient modulation techniques and associated waveforms need to be defined which would assure the opportunistic access to fragmented spectrum of dynamically-changing availability. Such techniques and waveform designs should also minimise (or at least limit) interference generated to other nodes and users.

Despite their advantages, the challenges posed by the OFDM-based or NOFDM-based CR still need to be met. Solutions should be found to specific problems such as high Peak-to-Average Power Ratio (PAPR), sensitivity to frequency offsets, and Inter-Carrier Interference (ICI), as well as in conjunction to other CR challenges, such as accurate and agile spectrum sensing, interference avoidance, cross-layer design and complexity, flexible RF front-end, etc.. Multicarrier technologies will probably dominate wireless communication standards in the upcoming 10-15 years. As discussed above, they are also suitable for non-standardised, opportunistic and cognitive access to wireless networks and their spectrum resources. However, there are a number of issues that will be challenges for researchers, engineers and regulatory bodies. One is multi-band MC system design, in which the total bandwidth is divided into smaller parts. The challenges in designing a multiband MC transceiver include flexible broadband RF front-end with broadband antennas and their transmit/receive switches, complex RF circuit design, fast analogue-to-digital and digital-to-analogue converters of high dynamic range, wide-range frequency synthesisers, and so on. Other issues of the MC-based CR are related to the interference reduction between the users, sensing of the radio environment, synchronisation of non-contiguous MC signalling with missing pilots and possibly asynchronous transmissions of multiple users, and detection of the adopted transmission parameters or efficient signalling of these parameters.

VI. Multimedia Signal Processing for Wireless Delivery

Clearly, when one searches to build communication systems to mobiles or between mobile terminals with a very high capacity, one implicitly has in mind that some multimedia (high quality sound, still images, video, and more in the near future) has to be transmitted. Speech by itself would not justify such investments. Even when web surfing is considered, the files by themselves are not very demanding, only the subparts containing images and multimedia are costly in terms of bit-rate. Therefore, it has been recognised that it is useful to tune the communication system globally, taking this fact into account. This approach leads naturally to what is known as cross layer optimisation and "Joint Source and Channel Coding/Decoding" (JSCC/D) approach.

The difficulty is that the layered architecture was designed in order to assign a specific task to each layer, the layers assuming that the previous one was successful in completing its task. Therefore, they are independent of each other, and, as a result, the delivery is independent of the type of signal. This universality of the network should not be put into question, even if some global optimisation is performed. The techniques cited above are relatively short term. While cross layer optimisation is already used, JSC Decoding should be usable soon, due to recent advances, and JSC Coding requires a further global optimisation, which may take some time.

However, the evolution of wireless multimedia will certainly go beyond the mere transmission of speech, sound, images, videos and html files, and such an expansion will require further scientific investment in a number of fields. Obviously, the evolution of wireless multimedia transmission and processing is driven by advances in devices, in the networks, and in the processing. Some of these enabling technologies, which are likely to have an impact in a foreseeable future, include 3D vision and augmented reality, with all the corresponding challenges in signal processing and devices, among others.

It is necessary to develop network coding algorithms tailored to video streaming applications. The algorithms should provide the following set of functionalities.

- Unequal error protection: The algorithms shall provide differentiated packet treatment, enabling a more reliable delivery of the most important video packets, through their identification and involvement into more coding operations, and the provision of smooth video quality.
- Multiple description coding: Decoding for video applications should provide incremental quality as more packets are received, e.g., by applying multiple description coding techniques.
- Fully distributed versus centralised network coding: Fully distributed algorithms are extremely simple, but suboptimal, while a centralised network code optimises the end-user probability of correct decoding based on full or partial knowledge of the packets they have already received; partially distributed algorithms should also be considered in order to limit the communication overhead.
- Low-complexity decoding: Although it has been shown that complexity is manageable, especially the wireless applications could benefit from simpler algorithms, therefore, it is foreseen to develop such algorithms using techniques borrowed from sparse random coding theory and digital fountain codes.

Research in application-layer QoS and error control techniques for network coding can be expected to focus on the following aspects:

- Forward Error Correction (FEC) coding: As a network coding environment behaves similarly to a broadcast channel, even for point-to-point communications, it is not clear whether retransmission or FEC codes, or a hybrid thereof, will provide the best performance, and which FEC strategy should be used.
- Joint source/network coding: All elements of the video compression chain need to be rethought in light of the new communication environment, including the design of scalable optimised video coding and/or multiple description coding schemes, which can provide the desired QoS.
- Packet scheduling: Another important element of QoS control is packet scheduling, as the selection of which packets must be combined and forwarded is expected to have a significant impact on the end-to-end performance, hence, tailored algorithms should be designed taking rate-distortion information and deadlines of video packets into account.

In many situations, when several mobile users are asking for a given media at the same time, they will not have the same link capacity, and some of them can have a very small one. Since the delay must remain small, retransmissions must remain limited (if not forbidden); moreover, each terminal may need a different signal quality. This is the motivation for the use of scalable signals (the bitstream contains the various qualities needed) and multiple descriptions (the more descriptions you get, the better the signal quality) on the source side. This has a number of consequences on the whole communication system, since all layers must be adapted to this point to multipoint situation.

Moreover, there is much to be gained in terms of bandwidth savings and performance improvement when considering a multicast situation: a number of registered users are requiring the same signal, may be with different qualities. Most known techniques for robust transmission of multimedia have to be adapted to this situation. Layered coding is known to be the theoretical solution from an information theory point of view, but a lot of work has to be undertaken in order to be able to build a full, practical system making optimal use of this property all along the protocol layers.

One should make the best use of any redundancy found in the bitstream, either left by the source encoder, or introduced by the protocol (headers, cyclic redundancy check, and checksums), the network (network coding), and the physical layer (channel coding and modulation). However, in this JSCD approach, even when protocol layers are involved, it is easily seen that one level of optimisation is not used: due to backward compatibility, the allocation of the redundancy along the whole system is not performed. This is the next step in this direction, which would result in a true joint source/protocol/network/channel optimisation.

One should also realise that, even if the research has concentrated mostly on video, other types of multimedia signals should be considered, such as audio, html files, and even Stereo TV and 3-D objects, as argued previously.

Finally, the global trend can be seen to be a more global optimisation of the wireless network, including properties of the source into account. This should be done ideally without losing the universality of the network (which should still be able to carry various applications and signals). The tendency towards a variety of application and service (more than plain transmission) can also be seen in the recent years. Therefore, it seems that on top of the integration of the various aspects: source, channel, protocol, network, the service should also be integrated (more than just the source). In this sense, one will then be able to have true multimedia available, rather than simple video transmission. Such applications could be augmented reality (see above), machine to machine communication, content retrieval, and many situations that are currently studied in the multimedia setting.

VII. Enabling "Hard" Technologies

Wireless technology has been benefiting from the advances the silicon technology has offered in the 90s and 00s. The whole telecommunication mutation from the analogue domain to the digital realm has in fact been made possible by the miniaturisation of transistors, leading to higher density though with low power efficient Integrated Circuits (ICs). In turn, this move to digital communication has created the boom or the digital ICT at all layers, from broadband communications to multimedia services. With this in mind, it would not make sense to foresee what telecommunication will offer in the future without considering the trends in silicon technology research and industry.

The key factor behind the digital revolution has been the CMOS (Complementary MetalOxideSemiconductor) technology down-scaling following the so-called Moores Law, which coined in the early 70s that the number of transistors would double every year. Although this rule has been validated over the 40 last years by the silicon industry and by the International Technology Roadmap for Semiconductors (ITRS) [12], it is agreed that we are coming to a new era where this rule is no longer valid. Several reasons can be identified:

- the physics of silicon introduces side effects in deep submicron technology;
- predictability of transistors behaviour is getting less accurate, leading to lower yield or less optimal usage of silicon;
- power density is going to levels beyond what cooling can offer;
- static power increases, which makes the assumption that the overall power consumption decreases as transistors shrink no longer valid;
- investments needed for new deep submicron CMOS are being so huge that only less than an handful of application justifies it.

For all these reasons, it is likely that we are on the verge of significant changes in the silicon capability roadmap, which make the analysis of future trends useful. Indeed, it is foreseen that the roadmap has to move from a pure down-scaling to new functionalities and combined technology-system innovation in order to manage future power, variability and complexity issues. However, there is no accepted candidate today to replace CMOS devices in terms of the four essential metrics needed for successful applications: dimension (scalability), switching speed, energy consumption and throughput [13]. Moreover, when other metrics such as reliability, designability, and mixed-signal capability are added, the dominance of CMOS is even more obvious. It is then realistic to think that other micro- or nano-technologies should be seen in the future as an add-on to CMOS and not as a substitute for it. This transition between the "business as usual" era and the entry to the post 2015 period, where new alternative or complementary solutions need to be found, needs to be addressed.

Bearing in mind this disruptive future and rather than extending the technology evaluation proposed by the ITSR, technology analysis carried out in Europe by MEDEA experts [14] suggests considering 3 major paradigms:

- More Moore: corresponding to ultimate CMOS scaling. This will be essential to supply the massive computing power and communication capability needed for the realisation of applications at an affordable cost and a power efficiency exceeding 200 GOPS/Watt (Giga Operations per Second/Watt) for programmable and/or reconfigurable architectures [15].
- More than Moore: corresponding to the use of heterogeneous technologies, such as MEMSs (Micro Electro-Mechanical Systems) or MEOMSs (Micro Electro-Opto-Mechanical Systems). This approach intends to address parallel routes to classical CMOS by tackling applications for which CMOS is not optimal, which can be classified in three major categories: interfacing to the real world, enhancing electronics with non-pure electrical devices, and embedding power sources into electronics.
- Beyond CMOS: corresponding to nanotechnology alternatives to CMOS. This paradigm intends to identify technologies that could replace CMOS, either in a disruptive or evolutionary way after CMOS will reach its ultimate limits.

The context of coexistence and convergence is driving demand for flexible and future-proof hardware architectures offering substantial cost and power savings. Manufacturers have already started activities towards the provision of multi-mode handsets featuring the advancements of the recent radio access technologies (e.g., 3GPP LTE, WiMAX IEEE 802.16m, and DVB-T2/H). However a large gap is growing in the field of flexible radio between advances in communication algorithms, methods, system architectures on one side, and efficient implementation platforms. Despite the large amount of available results in the system level technologies related to multi-mode, multi-standard interoperability and smart use of available radio resources (e.g., AMC and cross layer optimisation), a very limited number of hardware solutions have been proposed to really support this flexibility and convergence by means of power efficient, low cost reconfigurable platforms. In most cases, chipset vendors offer different solutions for each combination of standards and applications to be supported.

To enable a single modem to service multiple different wireless systems, highly flexible solutions are needed. In practice, currently implemented flexible hardware modems are focused on the receiver segment placed between the RF (Radio Frequency) front end and the channel decoder. In this part of the modem, several digital signal processing algorithms, such as equalisation, interference cancellation multipath correlation (rake receiver), synchronisation, quadrature amplitude mapping/demapping and FFT (Fast Fourier Transform) can be run on vector processors, which allow for GOPS rates resorting to very high level of parallelism. However, other functional components of a modern modem (such as channel decoding) are not efficiently supported by vector processors and alternatives to software programmable architectures are not considered solid solutions: cost of hardwired dedicated building blocks becomes rapidly unacceptable with the number of standards to be supported, while reconfigurable hardware, such as FPGAs (Field Programmable Gate Arrays), are too expensive in terms of silicon area and standby energy consumption (which is due to leakage current, proportional to area).

SDRs, with cognitive capabilities, are getting prominence as potential candidates to meet the future requirements of mobile devices. Compared to the pragmatic design approach for flexibility motioned above, the SDR approach aims at providing a comprehensive design framework encompassing platforms, architectures, software, methodology and design tools. The paradigm of SDR poses new challenges or makes current design challenges more stringent. The most relevant ones are:

- Portability, which can be defined as the inverse of porting effort, represents the ease with which one waveform can be moved to another hardware platform, requiring a platform independent waveform description.
- Efficiency with respect to area and energy is essential, in order to decrease the power/energy consumption and extend the battery life, requiring high efficiency in waveform implementation.
- Interoperability denotes the ability that a waveform implemented on two different hardware platforms interoperates with each other.
- Loadability illustrates the ease with which a waveform can be loaded, over-the-air, into a hardware platform, programmed, configured and run, which can be increased by well defined and known interfaces in waveform implementation.
- Trade-offs between flexibility and efficiency becomes challenging in the wake of their contradictory nature, making heterogeneous Multi-Processor System-on-Chips (MPSoCs) an inevitable candidate as the hardware platform for implementing a waveform.
- Cross layer design and optimisation techniques are getting popular, if not mandatory, in order to cope with the increasing need for spectrum and energy efficiency, leading to very tight dependencies, interactions between physical and MAC, higher layers that have cognition, requiring flexibility in implementation and algorithms.

The complexity of modern, flexible implementation structures would hardly be manageable and their development is a tedious and error-prone task. What is needed is a description method that can lead to a (semi-)automatic generation of a waveform implementation directly from the specification. Therefore, a methodology is required, that raises the abstraction level of receiver design to make it manageable.

The digital communication research on multi-standard radio has started based on the assumption of SDR, which extrapolated that RF stages of a radio would be transparent for the baseband processing either thanks to highly flexible RF components or to very high speed converters. Both have shown limitations and further research is needed to achieve highly flexible SDR. In fact, too major approaches emerge for designing a flexible RF: the first considers very large band RF that can therefore accommodate several systems, which suffers from bad sensitivity level though; the second relies on tuneable components with which parameters can be adapted to match the system requirements. These rules often contradict the guidelines RF designer are used to consider when defining an RF architecture, which is usually optimised for sensitivity, power consumption, and IC integration.

VIII. Green Communications

Since the United Nations General Assembly in December 1987, and its Resolution 42/187, sustainable development has become an issue and an aspiration of our civilisation. The most often-quoted definition of sustainable development has been formulated by the Brundtland Commission [16] as the development that “meets the needs of the present without compromising the ability of future generations to meet their own need”. European Union in particular is continuously making efforts in legislation, regulations and recommendations to all sectors of the industry and agriculture, as well as in promoting ecology, and ecological life-style to address anticipated future climate issue and sustainable development in general. Surprising as it may seem, the ICT domain should be particularly concerned: currently, 3% of the world-wide energy is consumed by the ICT infrastructure, which causes about 2% of the world-wide CO_2 emissions. As the transmitted data volume increases approximately by a factor of 10 every 5 years, this corresponds to an increase of the associated energy consumption by approximately 20% per year, i.e., energy consumption is doubled every 5 years, which may cause serious problems in terms of sustainable development.

A holistic approach to the wireless communication eco-sustainability is based on the idea that all wireless system and network components, as well as all infrastructure components, should contribute to the overall sustainable development of the considered ICT sector, and that the properties of that sector related to the impact on the eco-system cannot be determined only by its component parts alone. In other words, the eco-sustainability of the wireless network is not only about just the network elements, rather being about the whole network development, which would take all the relations and interactions between the network components to achieve the wireless communication sector sustainable development. Thus, a great attention has to be given to multiple network components and their dependencies to come out with noticeable power savings of the communication network.

Two major axes are to be distinguished within Green Communications:

- Infrastructure: this includes the transmission over the wired core network, switching, network management and maintenance, and is mostly concerned with the energy-savings matters.

- Radio access: energy consumption is still of importance for wireless devices, their users and their environment, and one should distinguish between on the one hand signal processing, RF front-end processing and amplification, and HW power supply (which has an impact on the global energy-consumption) and on the other energy radiation (which may have an impact on human health and the so-called electromagnetic pollution).

As mentioned above, the concept of Green Communications results from the emerging global consciousness concerning the ecosystem. It is noticeable that notions such as consciousness, intelligence, cognition, sensing, so far closely related to the human nature, are being used for the description of artificial intelligence and for the functionalities of various decision-making and learning devices, including designs for modern wireless communication. CR is such an emerging concept of an intelligent communication design that can orient itself in the radio environment, create plans, decide and take actions. One believes that consciousness is still related to a human being only, and it is an umbrella above the notion of cognition. It seems however that cognition alone of the CR devices can be used for making the Green Communications the reality at the radio access level. In fact, many researchers look at CR as an enabling technology for reasonable utilisation of radio resources, namely power consumption and available frequency band. Moreover, in this context, the "classical" understanding of green communications (i.e., power consumption) can be extended towards many other aspects of radio communications.

In order to achieve these expectations, research work has to be done into the following domains:

- Signal processing techniques in order to sense the environment, and apply energy-optimised signal processing and transmission procedures.
- Computer science encompassing decision making, learning, and prediction, in order to make the adequate decisions.
- Hardware and software reconfigurability capabilities to modify and adapt the equipment behaviour and its power consumption.

The concept of a smart grid to deliver electricity from suppliers to consumers using digital technology is relatively new, and aims at controlling appliances at consumers' homes and premises to save energy. Additionally, it is supposed to reduce cost and increase reliability and transparency of both the suppliers and the consumers. For the idea of smart power grids to happen, the need of robust, scalable and reliable communications infrastructure has been identified. It is supposed to be based on cooperative communications in home-area networks connected through wide-area networks. The privacy and safety of this communication is also a major issue.

One of the challenges of the future wireless radio systems is to globally reduce the electromagnetic radiation levels to obtain a better coexistence of wireless systems and lower interference. Thus, any signal processing study investigating ways to increase the wireless networks capacity are contributing to Green Communications. A few examples of the trendy topics include: MIMO processing, near-Shannon limit channel-coding schemes, and cooperative communications and relying. Thus, all the signal processing research lead in this sense in the next 20 years will be contributing to the Green Communication field.

Moreover, new adaptive spectrum sharing models should be designed, and cooperative communication techniques at all layers can be applied to increase the spectral and power efficiency, to enhance network coverage, and to reduce the outage probability in wireless networks. a result, one may expect better spectrum usage in available bands, release of some other bands that should be reserved for other purposes, e.g., radiation detection of various natures, lower transmission power, thus, lower interference. Cognitive and cooperative communications with all their aspects of the radio environmental awareness and flexible and efficient usage of resources are long term objectives.

In the sense of sustainable development, not only the energy consumption is considered, but also the spectrum pollution with the increase of radiation related to communication systems should be addressed. Spectrum may be considered as a natural and public resource, which should be carefully used, shared world-wide, and economised. Spectrum indeed only exists if there is sufficient energy to generate the electromagnetic waves, thus, spectrum savings is a question of capacity versus power spectral density of radio transmission.

Another challenge of future wireless radio systems is to globally reduce the electromagnetic radiation levels in order to reduce human exposure to radiation.

The power-efficiency of the radio hardware equipment cannot be overestimated as its contribution to the mobile-terminal, base-station and overall-network power consumption is noticeable. The silicon components optimisation towards lower power consumption in Watts per Gigabit of the data processing is recognised as the continuously hot research topic. Moreover, handset system design is a continuing area of innovation (examples include hardware design to improve music playback time). Nevertheless, it has been recognised, that not enough attention is paid to the behaviour of software taking into account an increasing number of applications relying on web services.

IX. Conclusions

This paper identifies medium-long term research challenges in wireless communications, based on the 1st NEWCOM++ Vision Book [1]. Section II addresses wireless networks, with emphasis on heterogeneity and opportunism. The basic ingredients allowing to successfully coping with the increasing demand of traffic and bit are addressed, via the increase of the spectral efficiency, increase of the number of base stations to provide a service in a given area; and increase of the total available bandwidth. Trends towards decentralisation and flat architectures, and perspectives on flexible spectrum management are shown as well. Self-organising networks are included in the analysis, since it is expected that many mechanisms will be established to allow the self-configuration of a network with minimum human intervention. The features to be included in such an approach include: self-configuration, self-planning, self-optimisation, self-managing, and self-healing. Opportunistic networks are also addressed, linking with Delay Tolerant Networks (among others), vehicular communication networks are analysed, linking with Intelligent Transportation Systems, and the Future Internet is viewed from the Internet of Things and RFID perspectives.

Section III also addresses wireless networks, but focusing on cognition and cooperation, and providing a view on efficient ways of setting networks. When addressing Cognitive Radio Networks, several aspects of spectrum usage and management are discussed. A number of techniques to be developed for the implementation of efficient spectrum usage through cognitive radio networks are dealt with: spectrum sensing, spectrum management, spectrum mobility, and spectrum sharing mechanisms. Cognitive Positioning is then addressed, in relation with cognitive radio, Multi Carrier systems being taken as an example. Finally, the concept of Docitive Radios & Networks is introduced, i.e., a novel framework on radios & networks that teach other radios & networks. These radios & networks are not (only) supposed to teach them the end-result, but rather elements of the methods to getting there.

Section IV presents the main facets of research challenges that lie ahead towards the goal of understanding the ultimate performance limits of networks, and of designing innovative techniques to approximate and even achieve them. Various optimisation- and control theory driven techniques where put forward such as distributed optimisation and the max-weight control principle. Novel and disruptive approaches are described, such as network coding, and their potential is analysed. Furthermore, mathematical tools such as cooperative and non-cooperative game theory, learning theory and stochastic geometry will be needed in order to model and understand the spontaneous interactions of massively dense autonomic networks. Clearly, the way ahead is promising. Novel and disruptive approaches will need to be undertaken, oftentimes relying on cross-disciplinary techniques migrating from a wide range of disciplines and thrusts as described above.

Section V discusses theoretical and practical problems on bandwidth- and energy-efficient radio access. The first part of the section discusses on approaching the fundamental communication limits, by addressing them, and then, by showing some techniques that enable this approach, namely coding/decoding techniques, as well as adaptive modulation and coding. Afterwards, iterative techniques in wireless receivers are presented, including the framework for iterative processing, applications on iterative receiver design, and low complexity decoding. Finally, cognitive spectrum usage (always for the purpose of advancing spectral utilisation) with a special focus on applied game theory is discussed, including multicarrier techniques and distributed spectrum usage.

Section VI addresses on multimedia signal processing for wireless delivery, encompassing a discussion on the current situation, a review of enabling technologies, and a view into the global optimisation problem. A discussion on the general trend is presented, including some of the current technologies, presenting some of the driving forces, and extracting general consequences for future work. The review on the enabling technologies addresses 3-D representation (based on stereo vision and signal processing), screens and cameras, the network (e.g., mobile ad hoc networks and network coding, and possible research direction). The global optimisation issue includes cross-layer optimisation, joint source-channel-network-protocol coding, and services and usage from a wireless multimedia processing viewpoint.

Section VII fits within recent trends in silicon technology and communication system demands, which exhibit a growing gap between application needs and what the technology can deliver. A key driver for the telecom industry is the mobile business. Mobility, which relies on battery operated hand-held devices, provide stringent requirements on equipments in terms of processing power, power consumption and flexibility. At the same time the battery and silicon technology does not progress at the same pace. The emergence of new standards implementing ever more efficient air interfaces also put stringent constraints on the design time. Thus, the reuse of hardware building blocks and a proper methodology and tools are needed to evaluate hardware performance tradeoffs at the earliest stage. Flexible radio is a promising approach in this regard. However, a unified framework is still to be found to enable the co-design of communication functions and hardware platforms.

Section VIII deals with "green" communications, a concept drawing from the universally shared concern about climate changes and aspiration toward a sustainable development guided by ecological considerations. European Union is taking efforts to address the climate issues including the ICT related issues and footprints on the environment. It is of major importance for the sake of radio domain in the 21st century to bring progress to people and to their confidence, and not to make them fear of the radio evolution. Green Communications developments should provide this confidence as an ICT approach for finding solutions to the issues of CO_2 emission, energy consumption, resources utilisation, electromagnetic pollution and heath issues. Undoubtedly, this can be considered as a challenge for the next 20 years.

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