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First Preliminary Report on State-of-the art and Open Problems in Wireless Communications Networks

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Abstract: This report, representing the first deliverable of WPI.5, is a preliminary document summarizing the state of the art and major (research) open problems in Wireless Communications networks (WCNs) as they stem from the work developed in the research WPs of NEWCOM++ in the first year of activity. Each section of the report is devoted to a concise illustration of state-of-the art and open problems in WCNs issues that represent a merging of topics addressed by a subset of NEWCOM++ research WPs. Covered topics include wireless channel modelling, physical layer signal processing algorithms, software defined radio, network layers in WCNs, and information society trends.

Keyword list: Wireless communication networks, wireless channel modelling, iterative processing, network coding, relaying and cooperation, joint source and channel coding, adaptive coding and modulation, software defined radio, cognitive radio networks, radio resource management, opportunistic networks.

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LIST OF ACRONYMS

AMC	Adaptive Modulation and Coding
ARQ	Automatic Repeat request
ASIC	Application-Specific Integrated Circuit
ASIP	Application-Specific Instruction Processor
AWGN	Additive White Gaussian Noise
BEC	Binary Erasure Channel
CPM	Continuous Phase Modulation
CSI	Channel State Information
DF	Digital Fountain
DSAN	Dynamic Spectrum Access Network
EM	Expectation Minimisation
EVM	EValuation Methodology
FEC	Forward Error Correction
FSM	Flexible Spectrum Management
GSCM	Geometric Stochastic Channel Model
JSCC	Joint Source and Channel Coding.
LDPC	Low Density Parity Check
LOS	Line of Sight
LTE	Long Term Evolution
MP-SoC	MultiProcessor-System on Chip
MSK	Minimum Shift Keying
MIMO	Multi-Input Multi-Output
MUD	Multi User Detection
NoC	Network on Chip
NoC	Network on Chip
NOMCM	Non-Orthogonal Multi-Carrier Modulation
OFDMA	Orthogonal Frequency Division Multiple Access
OppNet	Opportunistic Network
QoS	Quality of Service
RAT	Radio Access Technology
RRM	Radio Resource Management
RS	Reed-Solomon
RT	Ray Tracing
SDR	Software Defined Radio
UWB	Ultra Wide Band
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WSN	Wireless sensor Network
WP	Work Package

SECTION 1 – INTRODUCTION

WPI.5 is mainly devoted to the preparation of two Vision Books on Wireless Communications Networks (WCNs), from the angle of NEWCOM++ senior researchers, i.e., with an emphasis on research and medium-long term perspectives and objectives. The two successive editions of the vision book will be prepared by the end of year 2 and 3 of the network life.

This report, representing the first deliverable of WPI.5, is a preliminary document, summarizing the state of the art and major (research) open problems in WCNs as they stem from the work developed in the research WPs of the network in the first year of activity. The document is preliminary and functional to the next redaction of the Vision Books since to make an educated guess on future research issues one needs to:

- Start from a firm background of understood and agreed upon "today" situations (state-of-the art)
- Discuss information and communications technology (ICT) trends in the society, in the form of new services/needs, as they are setting the system constraints/challenges to be investigated by researchers
- Present the main research open problems whose solution could lead to technological breakthroughs in the (r)evolution of WCNs.

Of course, both state-of-the art and open problems description will be limited to those aspects of WCNs that are investigated in the WPs of the network, and in this respect the title of this deliverable is perhaps too comprehensive and ambitious with respect to its actual content, but we feel that this limitation is implicit in the project context and there is no need to make it explicit in the title.

Section 2 to 5 are devoted to a concise illustration of state-of-the art and open problems in WCNs issues that represent a merging of topics addressed by a subset of NEWCOM++ research WPs.

Section 2 deals with wireless channel modelling, an ancillary yet fundamental cornerstone in WCNs analysis and design. Section 3 concentrates on the physical layer of WCNs, one of the key investigation areas in the network. Peculiar topics, investigated in appropriate WPs, are the feedback and resolution of the channel state information, adaptive coding and modulation, iterative algorithms, network coding for the multi-hop wireless channel, and localization and positioning algorithms. The aspects related to flexible radio platforms are discussed in Section 4, with emphasis on computationally intensive computational tasks, the role of parallelism in high-speed receivers, heterogeneous many-processors-systems-on-chip and network-on-chip, and flexibility and multi-standard processing. Section 5 is devoted to the network layers of WCNs. In particular, it touches the aspects of radio resource management, cognitive networks, opportunistic networks, relaying and cooperation in WCNs, network information theory and joint source and channel coding.

Finally, Section 6 represents a contribution from WPI.6 (INTEGRAL), and deals with information society trends, analysis of personal needs and their potential satisfaction through ICT. In the section, ICT trends in Europe are reviewed, with emphasis on future Internet aspects and wireless technologies. It is described how information and learning, environmental fitness, social interactions, working life, transactions, entertainment, security, privacy, and health and wellnessthat could play the role of driving forces for future research issues.

This report draws from many deliverables prepared in the first year of NEWCOM++ research and integration activity. In preparing it, we have carefully avoided all analytical details and developments ("*No equations*" has been a keyword in the instructions to the contributors). All readers interested to delve deeper into some of the topics delineated here are invited to visit NEWCOM++ web site at http://www.newcom-project.eu:8080/Plone and read the corresponding deliverable(s).

SECTION 2 – STATE OF THE ART AND OPEN PROBLEMS IN WIRELESS CHANNEL MODELLING

2.1 Introduction

New challenges in channel modelling for wireless communication systems essentially pass by multi-input multi-output (MIMO) communications. A recent and exhaustive review of existing MIMO channel models was published by NEWCOM++ researchers [2.1]. The state-of-the-art on research on channel modelling foresees the refinement and extension of existing standard models of the radio channel, like the 3GPP (WINNER) Spatial Channel Model [2.2]. The required models should account for all features in the radio channel that affect the behaviour and performance of advanced wireless communication systems, or wireless networks operating in it. Note that the term "model" is used in the general sense, encompassing any type of models, *e.g.* purely stochastic, deterministic, or hybrid deterministic-stochastic.

Within the NEWCOM++ WPR.1, four areas of work representing the state-of-the art in wireless channel modelling were identified:

- *Multi-Dispersive Models*: Development of multi-dispersive models for radio links, which incorporate all dispersion dimensions of the channel, *i.e.*, delay, direction of departure, direction of arrival, Doppler frequency, and polarization. Models describing the long-term temporal fluctuations should also be designed. The frequency-dependent response of scatterers should be included as well in channel models, namely on UWB ones.
- *Multi-Link Models*: Design of multi-link channel models, which account in a realistic manner for the statistical dependence among the responses of the channel links in cooperative or relaying networks.
- *Adaptive Channel Modelling*: Based on the information sensed by the receiver (band, environment), adaptive modelling procedure should be developed taking into account "at best" the information at hand in order for the flexible radio to adapt its power and transmission rate to the channel model.
- *Model Calibration and Validation*: Channel measurement data should be either made available or collected for calibration and validation of the derived models. Due to the costs of collecting a sufficiently large amount of measurement data to achieve significant statistical results, ray tracing simulations should also be performed for the same purpose. Robust, efficient estimators of the channel parameters and metrics characterising the proposed models should be derived and their performance being assessed.

A brief synthesis on the four topics is provided in the following sections. More details are available in NEWCOM++ DR1.1 [2.3].

2.2 Multi-Dispersive Channel Models

The state-of-the-art in multi-dispersive channel modelling is focused on three main scenarios: wireless cellular networks, vehicular networks, and Body Area Networks (BANs). New models and extensions of existing ones are being developed, as well as research on specific issues ranging from prediction and reciprocity to antenna design and classification.
In what concerns wireless cellular networks, quite specific issues on channel modelling are being developed, like:

- Addition of polarisation properties of dispersive components to channel models: Usual maximum entropy characterisation methods are not applicable for describing the component dispersion in two (orthogonal) polarisations at one side of the transmitter (Tx) and receiver

(Rx), or at both sides. Most literature dealing with the dispersion of channel in polarisation focus on the narrow-band case, where the polarisation matrix of channel coefficient is investigated, or on a multipath scenario, studying the polarisation matrix of individual specular paths. However, the full characteristics of the polarisation of dispersive components must be investigated. As examples, the derivation of a parametric model for describing the dispersion of individual components in orthogonal polarisations, or the evaluation of the applicability of the characterisation method and the parameter estimator, or the extension of the above studies to the case where orthogonal polarisations are considered at both sides of the Tx and the Rx.

- Extension of ray tracing (RT) tools: RT tools are used today on a regular basis for MIMO channel modelling [2.4], providing various multi-dimensional channel characteristics as power delay profile, delay spread, angular spread or Doppler spectrum, which can be exploited further at the system level to evaluate diversity system performances. In the last few years, one of the main challenges has been to study and properly include the diffuse scattering into RT tools. Whether for the evaluation of available diversity in a site-specific context, or for being used for fingerprinting in location applications, RT tools have to be complemented in order to access realistically second order parameters of the channel impulse response, especially in NLOS indoor situations. New strategies to complement RT tools for positioning applications increasing channel impulse response realism, while keeping as much spatial coherence as possible, are required. For positioning applications, a combination of RT and pseudo stochastic or semi deterministic methods could be investigated.
- Implementation of the COST 273 model: The COST 273 MIMO channel model [2.5] aims at modelling a large number of different scenarios, by using clusters to model the wideband, time-variant, double-directional, fully-polarimetric radio channel. Its ultimate goal is to provide time series of the MIMO channel for link- and system-level simulations, yielding values of essential characteristics of the MIMO channel (space-time correlations, mutual information, etc.), as a function of environmental and antenna array parameters. To find consistent model parameters, automatic methods identifying the model parameters from measurements are required. To do so, multipath clusters need to be identified in measurement data. Identifying clusters from measurements was automated in the last years, with the difficulty that different kinds of clusters are used to accurately model the radio channel. Extension of the COST 273 channel model, introducing terrain and clutter information into radio channel generation, and an extended parameterisation, should be carried out.

Regarding channel modelling in vehicular networks, deterministic modelling requires intensive computation, which makes it difficult to vary parameters. Stochastic modelling is a potential approach, with the use of a tapped delay-Doppler profile model, which assigns a fixed Doppler spectrum to each single delay tap [2.6]. Also, geometry-based stochastic channel models (GSCMs) have previously been found to be well suited for dynamic environments. Open issues in vehicular-to-vehicular (V2V) communications include the development of a channel model that approximates the V2V channel impulse response by four super-imposed terms: (i) the LOS component, which may contain more than just the true LOS signal, *e.g.*, ground reflections; (ii) discrete components stemming from reflections from mobile scatterers, (iii) discrete components stemming from reflections from stationary scatterers, and (iv) diffuse components.

BAN scenarios will play a key role in future mobile communication systems, being a natural evolution of the increasing demand for anywhere, anytime communications. BANs involve communications ranging from the human body to a distance of 3 m, incorporating a network of sensors located on the human body, or in its close proximity [2.7]. There are various challenges and open issues for the design and study of BANs, most regarding the very particular propagation characteristics of the channel, and most specifically the proximity of the human body. In particular, strategies for an efficient use of the radio channel exploiting various frequencies, or the use of MIMO in BANs. These issues should be deeply analysed, with the design of theoretical models that incorporate the main features of BANs, and allow for their extension to several scenarios. Simulation tools and measurement methods should support this analysis. This task is closely related to multi-link channel aspects.

A general issue to the abovementioned scenarios is the development of channel prediction techniques. Approaches such as adaptive modulation, beam-forming or OFDMA, used to provide reliable services in time-varying environments, need reasonably accurate channel estimates, based on the knowledge of channel evolution. When estimates are only available after a delay (usually due to a feedback link with limited capacity), the process of estimating the current channel is known as prediction. To maintain a good performance, accurate estimates of the temporal correlation behaviour of the channel coefficients should be available. However, this is not the case when the environment changes rapidly. A variety of prediction methods have been studied so far, although none has demonstrated to achieve satisfactory prediction performance when the predicted horizon is greater than the channel coherence time. Parametric model-based methods, focused on the identification of the underlying physical components of the channel, are usually of higher complexity, involving subspace-based estimation algorithms, such as ESPRIT and root-MUSIC, to calculate the parameters, *e.g.*, the orientations and velocities, of moving scatterers in an environment.

Open problems with respect to channel prediction using positioning and tracking algorithms include the design and analysis of the performance of new channel prediction techniques, and the extension of prediction methods to the non-stationary case. Adaptive methods for the blind identification and tracking of the specular components of the spectrum should be investigated, together with the issues associated to non-stationarity.

Another common topic to the above mentioned scenarios is the integration of antenna arrays response in multi-antenna channel models. The inclusion of the electromagnetic effects of antenna arrays into the MIMO channels has been generally studied from the mutual interactions point of view, namely mutual coupling effects. Accurate inclusion of the antenna electromagnetic effects into a developed geometrical channel model is possible. The numerical efficient nature of the technique allows analysing arrays with large number of elements in a short time. It should be noted that, at the moment, the technique is limited to certain antenna types, such as microstrip (or freestanding) patch and dipole elements on planar (or conformal) substrates, since it is capable of analysing dielectric slab and free space Green's functions. In the most recent years, novel array configurations for wireless applications have been frequently encountered in the literature. Examples can be listed as follows: printed planar antennas and wrapped microstrips integrated with laptops for wireless local area network applications, reconfigurable antennas, PIFA (Planar Inverted F Antenna) and multiband PIFA arrays for MIMO, vector antennas, discrete lens arrays, and circular polarised microstrips.

An open problem is the characterisation of very compact multi-antenna topologies, considering different antenna elements with different radiation characteristics and different inter-element spacing. Special consideration should be given to compact orthogonally polarised antennas with very good isolation between adjacent elements over a broad range of frequencies, enabling to closely pack the antenna elements, while maintaining a minimum mutual coupling.
A general requirement for multi-dispersive channel modelling is the set-up of a unitary theoretical framework where the different propagation or channel models can be placed, defining scope, characteristics and common criteria for validation and performance assessment. Some relevant work in the field was been done within the COST 273 framework, defining a set of environments for wireless system simulation (MORANS) [2.5]. Yet, there is still much work to be done. A general study on propagation/channel modelling, with the scope of defining a common background and a common vocabulary for the research activity, is needed. This study should investigate topics like the definition of the concept of model, with reference to propagation and channel models, system

classification (for example, models can be classified in a unitary way by placing them into a 2-dimensional space, whose axis refer to the following couples of adjectives: empirical vs. physical; stochastic vs. deterministic.), the purpose of a model in relation to its classification (channel models and simulators for system design are usually empirical or stochastic models, while propagation models for planning are usually physical or deterministic), or the concept of spatial-scale-level for space-related models (the spatial scale-level refers to the size of the spatial region over which parameters are computed or measured).

2.3 Multi-Link Channel Models

The design of multi-link channel models for cooperative and relaying networks plays a key role in state-of-the-art research on wireless communication systems. Questions like the characterisation of channel correlation in multi-user (MU) and multi-node systems, or the design of beam-forming algorithms for these scenarios, or even the adaptation of acoustic reverberation models to model indoor communications and positioning, are some of the main concerns in this area.

Cooperative networks can be established by using the antennas of multiple users to form a virtual antenna array and by using MIMO transmitting/reception techniques, in order to greatly increase power efficiency, reliability and throughput. The development and realistic performance assessment of such distributed MIMO systems require measurement and characterisation of the different channel links. A few static indoor channel or dynamic outdoor channel measurements of MU-MIMO systems are available, although using single-link MIMO measurements and combine them to form a multi-link scenario. MU-MIMO measurements performed synchronously over multiple users are now being exploited. Open problems in this matter comprise characterisation of the cooperative indoor channels, focusing on virtual multi-antenna (distributed) systems, and exploiting the shadowing correlation between the various channels, as well as the correlation between wideband channel responses. Targeted environments are, *e.g.*, typical indoor offices or apartments, with NLOS between the (indoor) collaborative nodes and the (outdoor) base station.

Characterisation of channel correlations is particularly important in BANs. Path loss for on-body communications is too severe, so that the communication between a sensor and the central recording device might not be achievable, because of prohibitive loss and the reduced transmit power. Hence, an elegant solution consists of using cooperative or relay techniques to ease communication. Yet, such techniques mostly rely on Rayleigh uncorrelated fading between the nodes, which is not necessarily the case for on-body communications. In fact, for BANs, radio propagation takes place via two mechanisms: a surface wave on the body, and multipath arising from obstacles (arms, close objects, ground and walls, etc.). Therefore, the combination of these two mechanisms makes unlikely the channel to be Rayleigh distributed and uncorrelated. The characterisation of channel correlations between multi-sensor links is an open problem in BANs.

The use of beam-forming algorithms for multi-user/multi-cell is another hot topic in multi-link channel modelling. Here, it is important to distinguish between broadcast/multicast and unicast scenarios. Multicast relates to the joint transmission of a number of sources to a number of users, with every source transmitting the same signal and every user interested in the same data. Examples for such a scenario are the nation-wide transmission of video or audio content, using standards like DVB-T or DAB. Upcoming communication standards like WiMAX and LTE boast similar services, with the novelty of providing an uplink for channel state feedback and antenna arrays at the base stations. These two factors enable the use of beam-forming algorithms for the transmission of multicast data. The evaluation of algorithms for beam-forming in multicell/multiuser scenarios requires channel models that mimic not only the important characteristics in a single-link communication but, on top of that, also other characteristics, such as shadowing and users' distribution across space. Finding an optimal trade-off between modelling accuracy and complexity is of paramount importance. In unicast scenarios, modelling the communication of neighbouring cells exactly entails the same high complexity as in the aforementioned case of broadcasting/multicasting, which requires exact, yet low-complex, multilink channel models. Ray launching may be a good solution for channel modelling in a multicell/multiuser scenario, although only a very low number of rays is being traced from any source voxel (volume element) to any sink voxel, prohibiting accurate representation of the power angular density and the power delay profile. Thus, an open issue is the possibility of using a hybrid model, combining the positive characteristics of statistical and ray launching channel modelling. This model may combine ray launching results for path loss and shadowing coefficients, and statistical channel modelling results for fast fading, power angular density and frequency selectivity. It will also be important to study the trade-off between the number of simulated rays per voxel and modelling accuracy.

For indoor scenarios, the adaptation of acoustic reverberation models to characterise communication and positioning has been gaining force. Conventional models implement an exponentially decaying delay power spectrum and impulse response magnitude by including various ad-hoc constraints on the random model parameters. It is important that the models reflect the underlying physical mechanisms that lead to this decaying behaviour. Reverberation modelling exploits the analogy between the acoustical and electromagnetic waves, allowing describing the power-delay profile for indoor electromagnetic wireless channels (*e.g.*, [2.8]). Besides being relevant to indoor communications, this type of models is well-suited for indoor positioning applications, as they relate the power delay profile to the room geometry. Thus, investigation of the statistical properties of reverberant channel impulse responses in indoor wide band and multi-link communications and localisation should be conducted.

2.4 Adaptive Channel Modelling

Flexible radio is currently an object of very active research, providing devices with the capability to change the properties of the air interface in general (carrier frequency, data rate, protocol, etc.) according to their radiofrequency environment (channel quality, interference situation, etc.). Optimisation of radio resources (*e.g.*, through intelligent allocation) is a key factor in many environments. However, the channel and interference models still used for cognitive radio communication systems were mostly ad-hoc. In the field of collaborative communications, the effect of the channel statistics is not yet well understood.

Adaptive channel modelling is concerned with the problem of designing channel representations that can be updated in real time by a device, according to measured quantities. As the knowledge of the environment is hard to acquire and patchy, it is particularly important to design proper representations and methods incorporating sampled data, and use it to make optimal decisions on the adaptive parameters of communication algorithms.

Relatively little work has been done so far in characterising the behaviour of opportunistic or cooperative communication schemes, under imperfect channel knowledge. From an information theoretic point of view, cooperative cognitive transmitters have been shown to approach the capacity of the corresponding MIMO system. However, little is known about the relevant parameters in this context. A first approach may be to focus on already well understood protocols (amplify-and-forward, and decode-and forward), in particular on dynamic protocols where certain parameters (*e.g.*, the duration of the phases) are a function of the ergodic capacity of the channel, as well as of the "distance" of the rate of transmission to the ergodic capacity of the channel. It is important to understand how the performance (in terms of the diversity-multiplexing trade-off) of the different protocols deteriorates in the presence of reduced knowledge of the channel statistics (*i.e.*, in the presence of uncertainty on the ergodic capacity for the different source-to-relay and relay-to-destination paths, or on the multiplexing gain). Efforts should be conducted to identify the needs in terms of channel models and channel representations associated with cognitive and collaborative communication systems, and to develop suitable adaptive models. In the long term, quantifying the relation between imperfection on channel knowledge and error performance can lay the groundwork for introducing similar questions in the setting of cross-layer optimisation.

Up to date, cognitive radio has mostly considered the angle of spectrum sensing, *i.e.*, estimating the presence or the strength of interference in a given part of the available spectrum. A variety of approaches to obtain the spectrum information has been proposed, *e.g.*, cooperative sensing [2.9], where multiple users collaborate in this estimation process. However, the indicator of primary signal absence or presence does not always provide enough information for opportunistic spectrum access decision, since cognitive users should also be aware of "how good" the spectrum opportunities are and make access decision collaboratively to maximise overall network throughput. Efforts in characterising more accurately the interference sources, through their power or their location in beam space, have been made. It is desirable to cast this problem into a probabilistic context, as probabilistic models can incorporate (at least in theory) all sorts of information based on various estimated properties of the channel, and their accuracy (based, *e.g.*, on the knowledge of the estimation error variance, or on data ageing models for cases where only outdated measurements are available) can be dealt with. Bayesian inference promises to be a cornerstone for the development of such models. Adaptive models based on geometric models have also been developed.

Further investigation should be carried out on the design of spectrum sensing methods at the cognitive receiver, including modelling the primary transmission profile combining spectrum occupancy statistics with sensing parameters, *i.e.*, identify the primary transmit power and channel gain between each link in the spatial-temporal dimension according to localisation results. The effects of imperfect sensing errors in channel modelling and adaptive transmission (*e.g.*, joint beam-forming and power allocation) should be further investigated. Furthermore, the Bayesian approach should be exploited, focusing on data fusion problems (integration of prior and field measurements into a probability density function best describing the knowledge about the current channel state) and on the improvement of time correlation modelling. In the same way, the characterisation of geometric models using experimental data should also be investigated.

2.5 Model Calibration and Validation

One of the state-of-the-art problems on multi-link channel measurements deals with the related phase noise issues and their effect on measurements. The symmetry of the electromagnetic propagation channel is often cited in the literature as a convenient way to obtain channel knowledge at the transmitter without feedback. However, this symmetry is in practice disturbed by the characteristics of the radio-frequency circuitry of the transmitter and receiver. In fact, the phase errors between antennas introduced by this phenomenon can be particularly harmful to algorithms relying on reciprocity to provide channel estimates, in particular in systems using antenna arrays where the relative phase of the signals transmitted by various antennas in the array is a critical parameter. Various solutions to this issue have been proposed. One of them is the calibration of each RF circuit involved; another alternative, limited to low-power transmission, is to use a specially crafted transceiver where the same op-amp is used for both transmitting and receiving. A third alternative, named relative calibration [2.10], achieves the same effect than the normal calibration, without the requirement for extra hardware. The extension of the relative calibration method to multi-user scenarios (the channel being alternatively a broadcast and multiple-access channel) is an open issue. Estimators for the calibration parameters are required, as well as the assessment of their performance and robustness (*e.g.* with beam-forming techniques). Those estimators should be able to handle optimally heterogeneous measurements (mobiles might report their calibration information with different periods, with different estimation error variances). Also, design of new protocols and of the scheduling necessary for multi-user reciprocity measurements is required. It is important to recall that when performing multi-channel measurements, all nodes in the channel have to be perfectly synchronised.

MIMO channel sounders and multi-port vector analysers are commonly used in multi-link channels. Another important issue in multi-link measurements is the improvement of these channel sounders. It has been shown recently that concatenated phase noise of the oscillators in the transmitter and the receiver affects the estimation of MIMO channel capacity when using the standard channel matrix estimator to obtain a capacity estimate. It is desirable to study this phase noise effect on standard

parameter estimators, as well as to develop techniques to mitigate it. Methods to alleviate the calibration procedure are also required, namely by using new adaptive waveform techniques.
Recently, characterisation and modelling of time-variant, multi-dimensional dispersive MIMO propagation channels have gained much attention. Parametric characterisation and estimation of time-variant, multi-dimensional propagation channel should be extended to include more dispersion dimensions, such as direction of arrival, direction of departure and polarisations. High-resolution algorithms with low-computational complexity should be used for estimation of the characteristic parameters. Theoretical bounds and suitable metrics are required for evaluation of the performance of the estimators. Measurement data should be used to assess the performance of the estimators. It is required to design estimators for the reciprocity parameters that can handle MIMO multi-user cases, being able to handle optimally heterogeneous measurements. Also, it is necessary that the algorithms take into account near field sources, modelling mismatch, multipath, dispersive sources. Further, self-calibration algorithms are necessary.

Another important issue in channel measurements is the institution of a durable, credible, renewable and publicly available depository of channel measurements. The existing NEWCOM Data Base for Knowledge Networking (DBKN) [2.11], created in November 2005, allows all partners to input and search it for available channel measurements. Gathering of new data into this depository is needed, including multi-user measurements campaigns.

SECTION 3 – STATE OF THE ART AND OPEN PROBLEMS IN THE PHYSICAL LAYER OF WCNS

3.1 Introduction: general drivers for future physical layer research

Investigation of the state-of-the art and main open problems in the physical layer of wireless communication networks (WCNs) is one of the main goals of NEWCOM++, which has devoted to it the research work packages WPR2, 3,4, 5, B, and partly 7.

It is sometimes believed that there is not much left to be done in terms of research on physical layer which would have a large impact on next generation systems. However, just like Multi-Input Multi-Output designs have changed the way we design wireless communication systems, there are other emerging paradigms which could as well be unavoidable in the future. Many times these topics are influenced by the existence of higher layers, but the topics remain at physical layer.

The MIMO impact is not finished yet: A design involving MIMO requires many parameters to be estimated, and one cannot spend too much time estimating them instead of transmitting useful data. Therefore, they will likely be used through reduced accuracy estimates. Open questions are numerous in this direction, such as: what is the best use that can be done of an estimate, given its accuracy ? Or: given some parameter accuracy, what is the ultimate performance that can be attained ? These questions are even more important when allowing (limited) feedback from the receiver to the transmitter. This is addressed in section 3.2. Similarly, an efficient use of adaptive modulation and coding (which allowed the incredible increase in capacity of DSL) is not fully known in the wireless context (section 3.3). Finally, a relatively old (1993!) topic (iterative algorithms) has not yet found its full understanding and applicability, even if many applications are now using similar techniques (section 3.4).

Finally, two topics have the potential for rejuvenating physical layer research as much as MIMO did: In fact, there is a need to improve the performance of existing communication systems without requiring a huge investment in infrastructure, or even designing new hierarchical systems allowing a progressive deployment. With that respect, cooperation between users (techniques named relaying, cooperative communications…) would bring a great help, since they would allow coverage extensions, or throughput improvements without impacting too much the cost of the infrastructure. This topic shares many features with networking, but still concentrates on the physical layer. In particular, coding for multi-hop wireless networks is addressed in section 3.5. Another possibility from an applicative side has been opened by the coexistence of localization and communication possibilities/devices in the same handset. This is a topic of ever increasing interest, since a strong convergence is envisioned between navigation and communication devices, applications, and services (section 3.6).

The first deliverables of those WPs dealt with an extensive presentation of the state-of-the art and the listing of the open problems described above in which they would concentrate the future research activity. While referring the reader to those deliverables for details and extensive bibliography, we summarise in this section the main points.

3.2 Feedback and Resolution of the Channel State

Overview

Reaching the capacity (or closely approaching it) of the wireless channel requires an accurate estimation of the channel parameters at the receiver and, sometimes, transmitter side. However, the number of degrees of freedom to be estimated in the evolution of 3G networks physical layer is increasing quickly, thus making this task more and more difficult. This problem becomes even tougher when the demand in terms of mobility increases, since the channel does not remain constant for long periods of time. When these parameters are made available to the transmitter, it is well known that either a higher capacity can be attained or the way to achieve this capacity is largely simplified. Channel estimation errors, however, limit the accuracy of channel knowledge and lead to performance degradation.

Channel knowledge (channel state information, CSI) at the transmitter side requires a feedback channel for the receiver to the transmitter, over which the channel information is sent after appropriate encoding. This is denoted below as two-way channels.

The two related topics of imperfect channel estimation and two-way channel are covered in WPR.2. A third theme is what is most likely the key practical problem in wireless communications today, namely precoding for the multi-antenna broadcast channel, which can be seen as a practical implementation of the situation above for the downlink in a cellular network. Finally, the precoding techniques are intimately linked with proper scheduling and required feedback information about CSI, which essentially touches also upon network aspects.

Imperfect wireless channel estimation
Techniques for estimating the channel can be considered as "rank reduction" techniques and can be organised in terms of a priori and a posteriori techniques. A priori rank reduction techniques correspond to (time-invariant) re-parameterization of the (in general) Multi-Input Multi-Output (MIMO) channel transfer function in terms of a reduced set of degrees of freedom. The a posteriori rank reduction techniques correspond to statistical parameter modelling techniques with ensuing Bayesian parameter estimation. These techniques may be called a posteriori because they could be applied as a second stage to a deterministic estimate resulting from a first estimation stage.

The end result of many studies is that without the exploitation of the correlation structure in the (MIMO) channel, it is impossible to estimate the channel correctly. However, with the exploitation of time / frequency / spatial correlations, it becomes very well possible to make the channel estimation errors negligibly small. The issue in practice is which correlation to exploit (and in which way) to obtain the proper reduction in channel estimation errors at the smallest computational cost. Many methods were proposed along these directions. However, most of them rely on the knowledge of some additional parameters, namely the noise variance, the delay spread, the Doppler spread, or even the corresponding profiles (power delay profile, Doppler profile) or correlations (time or spatial domain correlations).

Current open problems are mostly linked to the ultimate communication performance (either in terms of capacity, of error rate, or even in terms of outage rates) than can be attained for a given a priori knowledge on the channel (even for the non coherent case) or for a given estimation procedure, the analysis of which can provide some knowledge of the statistics of the true channel given the estimate. As a path leading to practical algorithms, such knowledge would allow to find methods with good complexity/efficiency tradeoffs.

Two-way channels
Feedback-based systems were studied since the early work of Shannon [3.1] who described the notion of zero-error capacity, and laid the foundations of ARQ protocols. Many works also identified the gains that can be attained by feedback, compared to one-way systems [3.2]. Studied systems environments include multi-terminal networks (multiple access channel, broadcast channel, two-way channel, fading channel with CSI feedback) or ARQ-based situations (MIMO-ARQ, and the corresponding coding and signalling).
The MIMO (H)ARQ case has been extensively studied recently, resulting in the definition of asymptotic fundamental limits, and algorithms attaining them. A typical situation is that of a quasi-static Rayleigh fading channel, in which, upon reception, an ACK is passed to the transmitter if the receiver decodes correctly. Upon reception of a NACK, however, the transmitter transmits again the data, and the receiver attempts to decode the message based on the entire received signal. This process is continued until the transmitter receives an ACK. At the last round (L-th round) the transmitter receives an implicit ACK. It has been shown that in this case of quasi-static fading, allowing limited

or even a single bit of CSI feedback at the transmitter can result in substantial diversity gains. For the quasi-static Rayleigh fading channel without feedback, it has been shown that there exists a fundamental error-performance tradeoff between diversity and spatial-multiplexing gains, referred to as the diversity-multiplexing gain tradeoff [3.3]. In the presence of limited noiseless feedback taking the form of an L-round automatic retransmission request protocol, the result has been extended to the diversity multiplexing delay tradeoff as a means of asymptotically approximating (in the high SNR regime) the probability of codeword error, or equivalently the probability of channel outage. Other topics which have retained increasing interest recently are analogue versus quantised feedback [3.4] and the use of feedback in cooperative wireless networks.

Current open problems are extensions towards allowing more mobility in the channels, and especially characterizing the amount of feedback required in such situation, as well as obtaining strategies for minimizing this amount (by exploiting the various time / frequency / space correlations). In the multi-user case, the problem of minimizing the amount of feedback is also challenging, as well as the increasing interference and the problem of user selection or scheduling. Cooperation is also a challenge with respect to feedback, because this feedback has also other purposes, like allowing power control, (distributed) synchronization, or even collaborative resource allocation and distributed channel coding.

Precoding for MIMO broadcast channels

The MIMO broadcast channel (BC) can be understood as a model for the downlink in a cellular network, and as such is of great interest. The design and analysis of this multi-element communication systems under uncertainty conditions have recently attracted considerable attention in both theoretical and engineering aspects. Future communication systems such as the 4G Cellular system and modern wireless LANS will include multiple users and access points using multiple transmit antennas as well as multiple receive antennas. Moreover, these systems will be combined with ad hoc cooperative networks, wireless sensor networks, the newly emerging cognitive radio and other state of the art communication networks (see the recent special issue [3.5] and references within). All of these fit together in the framework of multi-element communications for which a full theoretical framework is still missing. More importantly, one of the main obstacles in practically employing such systems is the lack of perfect knowledge of the environment conditions. There is a vast literature available on the fundamental limits of such channels [3.6]. This may give the impression that we deal here with a mature well-understood subject. Even though massive fruitful research efforts have been invested and much fundamental understanding has been gained, the subject is yet far from being mature. The research objectives are directed towards some of these specific areas in an effort to achieve a deeper information-theoretical understanding and to gain also a better understanding of the practical implications of the theory.

From a more practical side, multiple-antennas (at least 4) will surely be used in evolving standards such as UMTS-LTE and 802.16m combined with feedback channels for channel state information and decoding capacity indicators. Here a capacity boost by a factor equal to the number of antennas at the base station, due to spatial processing, can be attained even without requiring multiple-antennas at the user terminals, which is the case in a MIMO point-to-point scenario. This is only possible, however, with the help of a feedback channel which allows the base station to perform various forms of precoding. Because of this capacity boost, it has become a key technological target for evolving cellular network standards and the search for efficient low complexity techniques is currently ongoing.

In that direction, current open problems range from very theoretical ones to more practical ones.

First, it is very important to characterise bounds on the capacity region of multiuser BC under various uncertainty conditions in both stochastic (in which case the ergodic and outage capacities are of interest) and deterministic (here the compound capacity is of interest) conditions. Moreover, there are still many unsolved issues concerning the practical derivation and evaluation of the optimal transmit schemes. The problem can be addressed by searching for some kind of BC-MAC duality allowing to take into account the uncertainty in the channel state information. On a more practical side, assessing the performance of precoding in MIMO broadcast channels using real channel measurements would also allow a better understanding of the gap between the real performance and the one predicted by mathematical models. Another practical aspect is linked to the quantity and quality of the channel information available during the design. Imperfections in the channel knowledge as well as heterogeneity in the qualities of the information coming from different users must be taken into account. Such a study should result in the design of robust schemes able to control complexity, as well as the increased levels of multi-user interference due to imperfect channel knowledge. Another hot topic is cooperative multi-cell systems under uncertainty, in which the hypothesis of perfect channel state information would be even less realistic than in the standard BC setting.

Other topics of interest are the design of scheduling policies using the available uncertain CSI to optimise the system performance, even with a small amount of feedback. Additionally, the QoS can state further problems in this context : the administrator requirements (such as the maximum number of active users, and fairness among them) are usually set at the higher levels of the communication process, while additional per user QoS requirements are imposed at the physical layer. Solving the problem thus requires some cross layering, which is seen here in a bottom-up approach.

3.3 Adaptive Modulation and Coding for the wireless channel

Overview

The increasing demand for better utilization of owned spectral resources by the operators and ever-increasing QoS demands by the users motivate the design of increasingly more sophisticated communication systems, able to adapt and adjust (in real-time) the transmission parameters on the basis of the currently existing link quality (that is, during real-time operation) for the ultimate goal of approaching, to the degree possible, the inherent capacity of the underlying channel. Collectively referred to as Adaptive Modulation and Coding (AMC), many such techniques have been proposed that target the best use of available resources (system bandwidth, channelization, transmit power, time slots, computational power of executing platform) in order to achieve a pre-specified QoS level. Based on real-time inputs from higher layers (namely, target QoS values pertaining to the physical layer) plus Channel State Information—CSI (or its best estimate), the optimised transmission parameters (in the simplest case, a pair of modulation/coding parameters (such as modulation constellation size , coding block size and code rate) are computed and then deployed in the current transmission. The choice of values for the proper parameters is often not trivial to compute and it depends strongly on the defined cost function (the so-called “adaptation criterion”) underlying the optimisation algorithm. Moreover, the AMC algorithm performance also depends strongly on the accuracy of the CSI, which is in turn affected by the estimation errors and the delay incurred in the feedback channel.

The AMC strategy is broadly defined by the following set: an adaptation criterion or cost function, the target QoS parameters, the CSI (often imperfect, erroneous or obsolete), and the resulting outputs from the AMC algorithm (namely, a set of transmission parameters). A study of possible adaptation strategies can be found in [3.7] with extensive bibliography on the subject, as well as a review on the link-adaptation research history. As far as the adaptation criteria are concerned, there are multiple possibilities and combinations of AMC schemes, in which some particular metrics and quantities may be treated as “inputs” (requirements and constraints) for one strategy or as the criterion or the “output” for another strategy. Some aspects (like data throughput) may be introduced as the metric (objective function), while others (like transmission power limit and delay) may be introduced as constraints. By varying these choices, a large number of adaptation strategies arise. For example, in the throughput-oriented strategy, the AMC algorithm aims at providing the highest bit rate (or spectral efficiency) for a required BER and fixed radiated power limit.

The above considerations are related mostly to the single-link and single-user-pair case. There exist in literature interesting proposals concerning multi-user adaptive schemes. In multi-user systems (for instance, in adaptive FDMA), sub-carriers may be adaptively allocated to users in an optimal (or, alternatively, fair) manner, taking the quality of each one user’s channel into account. Furthermore, in a multi-user scenario, handling the delay-sensitive traffic becomes a major scheduling issue. The most straightforward approach is to prioritise delay-sensitive traffic such that delay constraints are fulfilled. In situations where the channel quality is poor for extended periods of time over the whole bandwidth, more resources such as transmit power or number of sub-carriers must be allocated to delay-sensitive streams in order to guarantee on-time delivery of data.

Research in the AMC area in the last two decades resulted in the successful implementation of optimisation procedures in existing or forthcoming commercial standards/systems. Typical examples are the WiMAX (IEEE 802.16e – 2005) [3.8] standard, IEEE 802.11n Draft Amendment WLAN standard [3.9], 3GPP-HSDPA [3.10]. Other systems exploring AMC to achieve higher spectral efficiency are TETRA Release 2, DVB-S2, and Long Term Evolution (LTE) of UMTS-HSDPA.

Summary of Open problems

1. *Generic modelling for MIMO/OFDMA systems:*
The AMC design problem can be formulated as a constrained optimisation problem, with objective functions and constraints properly defined so as to accommodate specific system scenarios. A simple-to-use (thus, of reduced complexity) yet sufficiently accurate link-performance functional model that accounts for the combination of the transmitted-signal mode choice plus channel and interference conditions is critical for efficient AMC algorithmic design, since it serves as a performance-prediction tool that guides the AMC optimisation sub-routine to reach meaningful decisions. Such a model must be detailed enough to include channel modelling aspects such as, for instance, the effect of multiple antennas at the transmitter and/or the receiver, in combination with the applied MIMO technique (beam-forming or other spatial multiplexing). We note that similar compact-description models are also of great interest in the context of EValuation Methodologies (EVM), which are currently being developed for various systems in the respective standardization bodies (e.g. in WiMax [3.11]). However, these have a different goal in mind, namely to use this type of physical-layer abstraction in order to determine the performance of a given link and thus avoid the need for extensive simulation. This "simulation-shortcut" in turn accelerates the corresponding system-level simulations where a large number of physical-layer-related links need to be taken into account. The abstraction should be accurate, computationally simple, relatively independent of channel models, and easily extendable to various interference models and multi-antenna processing.

For AMC design, the challenge is to derive performance description models capable of supporting emerging standards, based on selected system deficiencies and environment characteristics. The goal is to devise a model description that serves as a compromise between simplicity (thus cost-effective implementation) and accuracy. It must incorporate, among other things, different MIMO options, channel estimation noise, feedback delay and ICI noise (due to phase noise and residual frequency offset) and various forms of interference. Based on this description model, specific AMC algorithms can be devised, based on a number of different optimisation criteria. Another important aspect is the wide applicability of the produced algorithms to a large number of different MIMO-COFDM systems that can be reflected in that model.

2. *Exploration of cross-layer adaptivity:*
In many current applications, only error-free packets are kept by the receiver, while the others are retransmitted through an automatic repeat request (ARQ) retransmission mechanism. In this case, instead of separately dealing with AMC at the physical layer and with ARQ at the data-link layer, a cross-layer design which judiciously combines these layers can and should be pursued in order to improve the actual *overall* system data rate. Therefore, in order to achieve the goal of a good cross-layer link adaptation design, an optimal allocation strategy must maximise the number of transmitted payload bits in the error-free packets per unit of time or, equivalently, the offered layer-3 data rate also known as "goodput". Clearly, depending on the data payload length and the wireless channel conditions, the expected goodput varies with different transmission strategies. The more robust (for example, heavier-coded) the transmission strategy, the more likely the packet will be delivered successfully, although with a resulting lower spectral efficiency. The key idea for an efficient adaptive

cross-layer design is to derive a link adaptation strategy that maximises the expected goodput as a trade-off between the probability that the packet will be delivered successfully on the one hand and the shortest possible transmission time on the other. In particular, in the case of heterogeneous systems, the maximum expected goodput criterion can be used for both multi-user diversity (MUD) scheduling as well as link adaptation.

3. *Sensitivity analysis and robust techniques:*
There are various aspects of provisioning, handling and utilizing the CSI for the purpose of AMC. A first aspect concerns the minimum amount of CSI required for the proper operation of the AMC scheme. This minimum amount may depend, for example, on the duplexing method and the channel reciprocity, on the number of estimated channels (SISO or MIMO), on the properties of the feedback channel, on the applied AMC scheme, and on requirements of how accurate the information should be (quantization levels, etc.). Feedback reduction techniques, yielding acceptable AMC performance deterioration, are thus strongly desirable. A good trade-off between the performance and the required feedback should be identified in order to motivate the broad usage of adaptive schemes.

A second important aspect is the accuracy of the obtained CSI. In the past, a large number of research studies that deal with diversity and MIMO systems in the presence of correlated fading were based on the assumption of perfect CSI at the receiver. However, in realistic scenarios, the assumption of perfect CSI is not valid or even plausible [3.12]. CSI errors have a destructive impact on the performance of the AMC schemes [3.13] and make reliability of adaptive schemes questionable. Thus, it is very important to construct a theoretical framework that is able to capture the sensitivity of AMC schemes to imperfect CSI and then devise schemes that are robust in the presence of such CSI.

4. *AMC design for Non-Orthogonal Multi-carrier Modulations*:
The class of "Non Orthogonal Multi-carrier Modulations" (NOMCM) was first introduced in [3.14] as a novel approach to multi-carrier transmissions over doubly dispersive channels affected by both time-varying and frequency-selective fading phenomena. The underlying idea of NOMCM is to find pulse shapes that yield minimum distortion and performance degradation for a given Doppler-spread and delay-spread profile. It follows that the general problem of AMC design in this two-dimensional signal representation and respective design poses a fresh set of challenges to be addressed, paralleling those identified above.

5. *AMC for Continuous Phase Modulation:*
Continuous-phase modulation (CPM) [3.15] features attractive spectral properties and insensitivity to distortions induced by non-linear amplifiers operating close to saturation. Although various CPM modulations have been studied for several years, their range of applications is rather limited due to the higher complexity of the respective CPM receivers. The classic "success story" is the GSM standard (already in billions of 2G cell phones), where a partial-response Gaussian MSK (GMSK) CPM modulation has been adopted. Current research focuses on versatile coded CPM modulation schemes that facilitate transceiver reconfiguration. Again, the extension of AMC studies here would address the design of versatile CPM coded-modulation with AMC capabilities.

3.4 Iterative Receivers for Wireless Communications

Overview
The "turbo" principle underlies every aspect of modern receiver design, and is now recognised to be a key component for communication systems to achieve an optimal power-throughput-bandwidth balance, especially in wireless communications.

In 1993, the initial turbo coding paper [3.16] demonstrated that it was possible in a simulated communication environment to achieve a rate, power and bit error rate regime within less than 1 dB of the theoretical Shannon limit [3.17]. After the initial shock triggered by this realization, the communications research community set out to understand the theory underlying these results, aiming to reproduce this type of performance for a wide range of channels and in realistic environments. Within 10 years, some of the principles behind the "turbo" effect have become well understood:

- the connection between iterative decoding and graph-based models have been established and explained
- alternative techniques like low-density parity-check codes and repeat-accumulate codes had been (re-)invented that exhibited the same type of performance as Turbo codes
- techniques have been developed to track the convergence of an iterative decoder in the asymptotic regime, i.e., when the code block length tends to infinity, notably density evolution and EXtrinsic Information Transfer (EXIT) charts.

Using these techniques, it became possible to design binary codes that come extremely close to the Shannon limit. However, these designs were limited only to the asymptotic regime of infinite block length, and only to specific channels, notably the Binary Erasure Channel (BEC) and the Additive White Gaussian Noise (AWGN) channel with binary antipodal modulation.
Initial attempts at combining decoding and other receiver components (detection, demapping, demodulation, synchronization) in an iterative fashion have been proposed heuristically and tested by simulation.

In the past five years, some progress has been made towards resolving the remaining issues standing in the way of a successful and complete translation of the "turbo" principle from theory to practice. In particular, LDPC and related codes have been designed and optimised for Multiple-Input Multiple-Output (MIMO) fading channels (e.g., multiple antenna wireless communications); "turbo" designs have been proposed for some multi-user scenarios, in particular multiple access channels; and some design methodologies have been developed for non-binary codes.

Open problems
There are still tremendous challenges in the way of making iterative processing practical for the wide range of scenarios that are relevant for wireless communications. Iterative processing promises to deliver increased data rates, extended reach, and reduced power and bandwidth requirements. These are all crucial contributions towards improving the business case for the deployment of new technologies over the wireless medium, and the difference they make goes beyond the predictive capabilities of most current business analysts in telecommunications. In particular, there is need for:

- new theories to tackle the analysis of the behaviour of iterative systems in general (beyond coding)
- new code designs, for more flexibility
- low complexity designs and implementations
- iterative synchronization.

Iterative algorithms
A better theoretical understanding of the mechanisms underlying iterative algorithms can have a large practical impact, e.g., for a better characterization of their convergence and required number of iterations. Two attempts will be followed within NEWCOM++: the use of information geometry, and divergence minimization approaches.

Concerning a geometrical interpretation of iterative algorithms, some preliminary results were found on the Blahut-Arimoto algorithm. This algorithm is used for computing the capacity of given channels, and has been chosen as a toy example because it is one of the most tractable iterative algorithms. It was shown that it could be interpreted as successive projections in the space of probability densities, and this interpretation allowed to increase its convergence rate by a large factor without losing the optimality of the final result. Bit Interleaved Coded Modulations were chosen as the next example with a complexity which seems to be still tractable. Preliminary results are encouraging.
Iterative divergence minimization approaches address a similar purpose in a different setting. Traditionally, receivers are based on a structure, which consists of three elements: channel estimation,

multi-user interference cancellation and a bank of single-user a-posteriori probability (APP) channel decoders, By applying expectation-minimisation (EM)-like frameworks to the receiver, some optimisation can be performed. However EM/SAGE-like frameworks do not allow the passing of probability distributions for both the parameters of interest and the nuisance parameters, the latter being included in the complete data. For instance, while these frameworks may admit soft symbols from a soft-output decoder as inputs, the channel parameter estimates they return can only be in the form of hard decisions, i.e., they cannot convey any uncertainties in the estimation of the channel parameters back to the decoder. Some modified algorithms were proposed, but they do not fully fit with the underlying framework, making it impossible to incorporate the APP directly as a part of the optimisation. With respect to this aim, there is a need for a unified theoretical framework, with a unique appropriate optimisation criterion, for iterative information processing (or message-passing processing), which integrates currently proposed iterative schemes derived based on intuitive argument or disparate principles. The attribute ”appropriate” means here that optimum information exchange between the different constituents of an iterative system will be identified that maximises the overall convergence and performance behaviours of the iterative solution obtained by using the criterion. Applications of the theoretical framework to concrete problems, should also be investigated and the solutions obtained should be compared to current ones.

Another way of understanding the behaviour of iterative algorithms is the use of graphical models. Such models like Bayesian networks, Markov random fields, junction graphs, and factor graphs have been used in a variety of different fields like coding, signal processing, machine learning, statistics and many others. For example, factor graphs allow to visualise a factorization of a complicated function of many variables into a product of simple functions, each of which depends on a subset of the variables. A generic message-passing algorithm, called the sum-product algorithm, operates on the factor graph and computes various marginal functions associated with the global function. The sum-product algorithm efficiently computes marginal functions by i) exploiting the way in which the global function factors ii) uses the distributive law to simplify the summations, and iii) reuses intermediate values by using partial sums. If the factor graph is cycle free, the sum product algorithm terminates after a finite number of steps and the computed marginal functions are exact. For example, the factor graph describing trellis-like structures is cycle-free and in [3.18] the sum-product algorithm is applied to such a factor graph, thereby (re)obtaining the BCJR algorithm [3.19]. A factor graph modelling a system of state space equations is also cycle-free and the application of the sum-product algorithm leads to the Kalman filter. In case of factor graphs with cycles, the sum-product algorithm no longer terminates after a finite number of steps, but becomes an iterative algorithm, which requires suitable scheduling of the exchanged messages. Furthermore, the computed marginal functions are only approximations. As can be understood from above some extensions are required for a full application of the corresponding framework to iterative algorithms. In particular, there is a need for understanding the behaviour of message-passing algorithms on factor graphs with cycles, deriving guidelines for the approximations of messages passed between the nodes and gaining insight on how the scheduling of the message passing affects performance. Because of the inherent iterative nature of message passing algorithms, close connections between graphical models and information geometry can be expected.

Another field of interest is the extension of iterative algorithms to distributed processing. In particular, a first topic of great practical interest is distributed turbo-processing for relay networks. Preliminary works exist in this context, which is far more difficult than the situations usually studied. Therefore, any progress towards a better understanding of the mechanisms underlying iterative processing should greatly benefit to such situations. This work will be undertaken in close connection with WPR5.

Code design

Under iterative decoding, it is possible to communicate arbitrarily close to the capacity of binary-input output-symmetric memoryless channels for sufficiently large information block lengths by a proper design of the coding scheme using powerful tools such as EXIT charts or density evolution. These tools have been then successfully applied or extended to the design of coding schemes for a wide class of other channels, such as, for example, inter-symbol interference channels or non-binary input channels, etc... Open problems in this field are still numerous:

- New binary coding schemes having low complexity encoding and decoding algorithms would be useful. One such example is polar coding [3.20], which furthermore are explicitly defined by a construction rule. However, full application requires more work (bounds on error probabilities, evaluation of decoding using iterative receivers, combination with turbo-codes, extension to non binary channels, etc…), and searching for other families of codes could also lead to interesting results.
- Non binary codes, defined on the Galois field of order *q*, would also allow overcoming some weaknesses of iterative decoding algorithms, mainly due to the correlation of messages that are passed between nodes. Such correlations arise in the practical situations of short/moderate length codes, and when the modulation has a high number of states (e.g. *M*-QAM). However, the decoding complexity of the receiver increases. Open research problems in this field are: (i) design of irregular non binary LDPC codes, (ii) their optimisation and their decoding in concatenated systems, which could result in symbol-wise iterative systems, in contrast with the classical situation which is mostly bit-wise, (iii) the extension of non binary codes to finite groups rather than finite fields, or varying computational sets, which seem to have the potential for good performance in both the waterfall and the error floor.

Extension to more complex situations

Iterative algorithms have been applied to a variety of situations well beyond coding. However, the understanding of the behaviour of decoding in such situations is less advanced than for plain coding. Bit Interleaved Coded Modulations is one of such situations with the simplest structure: the output of a code is interleaved at bit level, before building a high order modulation, using a given bit to symbol mapping. Optimisation of this new ingredient (the mapping) in the error floor region is still an open problem. Other items of interest are the design of the interleaver, and the efficient use of the intrinsic Unequal Error Protection property of QAM symbols which can weight the systematic bits protection versus that of the non systematic ones. A generic tool in that respect would be a precise characterization of the behaviour of the message passing algorithms when the a priori probabilities of the symbols are not uniform.

Another complex situation where iterative algorithms have been extensively studied is synchronization. The complexity of the situation is such that allowing a good synchronization at low SNRs and with a short acquisition time is still a challenge. Iterative algorithms have been used in this context, and bring significant improvements over the standard situation. Here also, the framework of EM algorithms has been applied, and allowed to justify some previously proposed structures. These works have often been obtained in “simple” situations (stationarity, BPSK and QPSK signals). Extensions to more complex transmission schemes (OFDM, time varying carrier phase, etc…) with a reduction of complexity of the receiver would be more than welcome.

Finally, complexity issues are an important aspect for the success and deployment of iterative algorithms. In contrast to the theoretical analysis, practical implementations have strict constraints like numerical stability, quantization of variables, memory requirements and convergence behaviour to mention just a few. Therefore, the research area of low complexity implementation is a broad field with a variety of proposed methods and techniques. Many of them, like quantization issues and approximations of algorithms, are based on heuristic approaches which lead to sub-optimal solutions in general.

(i) Quantised receivers

There is no satisfying theory to motivate the passage from the optimal theoretical real-valued algorithms to their fixed-point finite precision versions. In most communication devices that are implemented, this passage is realised in a heuristic manner, and designed using simulate-and-tune approaches. There is a strong need to fully address the practically significant design of quantised receiver components. Two possible ways were selected: on one hand, develop a theoretical foundation for the design of receiver components directly in the quantised domain; on the other hand, generalise fixed point algorithms that exist in the literature, e.g. Gallager's binary message-passing algorithms "A" and "B" for LDPC decoding, so that they can be implemented with any finite message set rather than use just binary messages.

(ii) Reducing the complexity of the receivers
Another way of reducing the complexity is to introduce approximations in the receiver. A clean mathematical analysis of these approximations and their consequences on the decoding performance is still an area of research with great potential.

(iii) A general problem that is encountered in the design of the physical layer of modern transmission systems is the necessity of building *versatile* encoding/ modulation systems, capable of dealing with different channel conditions and at the same time with different user requirements. A set of channel dependent constraints is, for example, the number of available transmitting and/or receiving antennas, the noise/interference level and its spectrum, and the time and or frequency selectivity of the channel.
On the other side, a set of user dependent constraints could be the desired spectral efficiency, the maximum instantaneous or long term available power, the throughput, and the latency. The joint optimisation of the encoding and signalling part of the physical layer for all possible combinations of channel and user constraints requires an unacceptable complexity of the system on one side, and a very low flexibility of the receiver on the other side. An efficient solution is then to decouple the signalling and encoding part into two separate subparts with sufficient degrees of freedom on both parts to cope with all possible channel and user conditions. Here again, decoupled strategies with performance close to optimal are a necessity.

3.5 Coding for Multi-Hop Wireless Networks

Overview
This research area can be categorised in four thematic topics:

1. Erasure coding on the network layer

When digital information is packetised and sent over a transmission medium, it is common practice to provide protection on the physical layer against transmission errors by using a Forward Error Correcting (FEC) code. Unfortunately, this protection cannot prevent the occasional erasure of packets caused by the presence of noise, fading and/or interference during transmission. Indeed, from time to time conditions on the transmission medium will be such that the code on the physical layer will no longer be able to correct the bit errors within a packet, i.e., the packet will be extensively corrupted. Whenever that happens, the packet is eliminated by the data-link layer, which continuously monitors the integrity of all received packets via the verification of the Cyclic Redundancy Check (CRC) sum of the packet (which serves as a check on the packet's integrity). Evidently, the occasional erasure of packets strongly affects the quality of the information received at the destination (to a degree dependent on the application at hand).

There are different ways to cope with such packet erasures. In the case of delay-insensitive applications where the integrity of the received information is most important (e.g., file transfer), the destination sends to the source a request for re-transmitting erased packets. In the case of delay-sensitive applications that can tolerate a small amount of packet loss (e.g., audio streaming), no measures are taken to recover lost packets. It is assumed that the error protection on the physical layer provides a packet erasure rate that is low enough to yield a sufficient QoS or Quality of Experience (QoE). In the case of delay-sensitive applications that can tolerate only a very low packet loss rate (e.g., video transmission, in particular HDTV), the error protection on the physical layer is typically not sufficient to provide a packet erasure rate that yields a sufficient QoE. In principle this problem could be solved by further enhancing the physical-layer error protection. However, often this physical layer error protection cannot be altered because of standardization. Also, assuming the network provides a mix of applications, it is not efficient to dimension the physical-layer error protection (to be used for all applications) according to the most demanding application. Further, requesting the source to retransmit erased packets is not convenient when the round-trip delays are too large to satisfy the delay constraints of the application. Hence, the only possibility left is the use of erasure coding ([3.21], [3.22], and [3.23]), meaning that the source transmits redundant packets (in addition to the information packets) that allow the recovery of a limited number of erased packets at the destination.

2. Network coding as an enhancement of geographic routing

In traditional networks, coding is used for two different purposes. At source nodes, source coding is applied for data compression and therefore reduction of the required transmission bandwidth. On the other hand, channel coding is used at the link level to ensure reliable communication, thus enabling the modelling of links as essentially error-free channels subject to the channel capacity. Only recently, in the fundamental paper by Ahlswede et al. [3.24], it was shown that it is in general not optimal to restrict coding to these two applications. Even in a scenario where all redundancy at the sources has been removed (i.e., the sources emit independent, unit-entropy bit streams) and channels are error-free, encoding data streams at intermediate nodes in general increases the capacity of the network. Traditionally, intermediate nodes in a network have been restricted to merely routing or replicating (relaying) information. We speak of *network coding* whenever intermediate nodes perform mathematical operations on the incoming data streams to obtain their relaying or routing output.

Ahlswede et al. in [3.24] not only introduced the idea of network coding, but also gave a complete characterization of the capacity of multicast networks. A multicast network consists of one sender transmitting the same information to a set of receivers. For the special case of one receiver, the maximum rate of information flow has long been known to be given by the capacity of the minimum cut separating source and destination [3.25]. Moreover, no encoding at intermediate nodes is necessary to achieve it. The new and surprising result was that, for multiple destinations, the achievable rate is the minimum over all minimal separating cuts between the source and one of the destinations. However, in general this rate cannot be achieved with routing and replicating alone, in general network coding at intermediate nodes is necessary.

3. Information theoretic analysis of network coding

Network communications become more reliable and efficient when nodes support each other to transmit data. By “supporting”, we mean enabling neighbouring nodes to share their resource and their power with the hope that such a cooperative approach leads to savings for the overall network resources and power consumption. Obviously, user cooperation in networks can potentially take place only when the number of communicating nodes exceeds two. Therefore, the three-terminal network, first introduced by van der Meulen in 1968 [3.26], certainly constitutes a fundamental unit in user cooperation and deserves particular attention. A vast portion of the literature, especially in the realm of information theory, has already been devoted to the two-hop and relay channels, seen as special cases. Despite its seeming simplicity, the capacity of the general relay channel is still unknown.

4. Coding for relay networks

Joint channel/network coding was first proposed in [3.27] for the multiple-access relay channel (MARC). The authors considered a cellular-based mobile communication system with two users sharing a common digital relay which performs network coding. Error-free transmission between the sources and the relay was assumed, while errors can occur at the links “user-to-relay” and “user-to-destination”. The authors considered the use of LDPC codes at the transmitter side. Each transmitter encodes its data and broadcasts the coded information to the destination and to the relay. At the receiver side, the destination can exploit the additional redundancy provided by the relay to improve performance. Since the relay provides additional information for both users at the same time, the decoder can use a joint decoding strategy exploiting the turbo principle. In particular, the authors showed that the channel and network codes can be seen as a single LDPC code spatially distributed. Therefore, at the destination, decoding of the channel and network codes can be done jointly on a single Tanner graph. Significant improvements in terms of diversity and coding gain with respect to non-cooperative systems were observed.

Summary of Open Problems

1. Research on Reed-Solomon (RS) and Digital Fountain (DF) codes for erasure coding:
For the RS codes the challenges are (a) to identify the erasure correction capability needed in the case of wireless transmission; (b) to identify the associated decoding complexity of the RS codes; and (c) to compare with a binary code of worse performance but smaller decoding complexity.

Another important topic is the comparison of DF and RS codes. Similarly to other channel codes, DF codes have been developed for generic data. However, the most important practical applications are in the field of multimedia communications, especially video. In this case, it is known that channel coding has to be tailored to the structure of compressed video files, e.g., providing unequal error protection of different layers of scalable video. This can be done with an ad-hoc design of the code or, at the system level, allocating more transmission rate or more retransmission opportunities for the most important layers. However, it is not clear which strategy would provide the best results. Another issue lies in the protocols used for transmitting data using DF codes. The DF code is a flexible tool to generate encoded packets, but in a networked environment some communication between sender and receiver is needed to manage the DF code. Communication protocols are expected to have a significant impact on the performance of a DF code. Such protocols are not yet established and constitute an important topic of current research in this field. Interestingly, such protocols may differ between RS and DF codes, because of the different features of these codes. Unlike RS codes, DF codes require a non-zero overhead to guarantee correct decoding; however, their flexibility in generating the packets may eventually make up for this. The remarks above highlight the need of a comparison between RS and DF codes in a relevant application scenario (e.g., wireless video). A thorough comparison of RS and DF codes is not currently available for practical application case studies.

2. Network coding as an enhancement of geographic routing

While for a single source the multicast capacity of a network is known and also known are practical, capacity-achieving codes, for multiple sources these questions are not answered yet. We still know little about the case of multiple unicast connections sharing a network. This problem is of great practical significance, since most traffic in existing networks, such as the Internet, is point-to-point and not multicast. The multiple-unicast problem significantly differs from the multicast one and is considerably more complicated.

3. Challenges posed in the investigation of the information theoretic aspects behind network coding:

a. Cast practical identified networking scenarios into an information-theoretic setting: rate region characterization for each case; derivation of bounds on outage capacities (proper metric for slow fading); extension of capacity theorems for correlated sources.

b. Evaluation, in terms of capacity gain, of the optimal trade-off between the benefits and limitations of cooperation in wireless communications, and including realistic constraints as delay and coordination requirements.

4. Coding for relay networks

Although previous works are all based on simplistic assumptions (e.g., orthogonal links), they have enlightened the potential benefits of joint network/channel coding for wireless networks and paved the way for further investigations:

a. New powerful network-channel codes on graphs able to approach the theoretically promised rates and diversity gains;

b. Formalization of both the decoding/encoding problems at the relays and the joint decoding problem at the destinations in terms of factor graphs and message-passing algorithms;

c. Derivation of a theoretical framework to solve the critical quantification issue of the intermediate (continuous) propagated messages at the relays;

d. Derivation of new efficient joint source-network-channel coding and decoding strategies for correlated sources;

e. Assessment of the problem of channel uncertainty;

f. Investigation of the relationship between network topology and coding gain. This includes a mathematical characterization of the network coding performance in network models with dynamic topologies (random graph topologies, mobility, and propagation models) and the identification of favourable topologies for network coding (i.e., fundamental characteristics and self-organised mechanisms able to lead the emergence of such topologies in an autonomous and distributed fashion).

3.6 Localization and Positioning Techniques

Overview

From a technological perspective, positioning and navigation systems can be distinguished in satellite and terrestrial systems. One of the main differences between these two systems is the fundamental purpose for which the signal propagating from the transmitter to the receiver has been designed: in the satellite case, the purpose is uniquely localization, whereas in the terrestrial case localization is adjunct to data communication. For this reason, technical challenges are often different in the two cases. This is also why satellite navigation is often viewed as a separate branch of telecommunications, mixed with geographical science and Earth observation. Today, a strong convergence path is envisioned through the integration of navigation and communications devices, applications and services (NAV/COM systems and services).

1. Satellite-based systems

The navigation world is at the cusp of a revolution, namely the advent and full operation of a number of different satellite navigation systems that will compete with the global positioning system (GPS) authority. Europe is deploying its Galileo global satellite system, Russia is radically modernizing its GLONASS, Japan and India have their own regional systems under development (QZSS and IRNSS, respectively), while China is converting its initial regional Beidou system into the global Compass one. USA itself is investing significant resources for GPS modernization. This “plethora in the sky” will deeply affect the market of navigation receivers as well as the consumers’ perspective with new applications, services and new availabilities (e.g., civil safety-of-life applications), inconceivable for the first generation of GPS. However, the unchallenged predominance among satellite-based systems is still GPS. Its functioning principle is the basis of nearly all the other systems, today or in the development/modernization horizon (e.g., GLONASS is going to move towards compatibility with CDMA).

2. Augmentation systems and assisted-GNSS

Augmentation systems try to correct many of the dominant error sources in GPS. This is basically achieved by placing a reference station at a precisely known location in the vicinity of a user, or wherever high-accuracy navigation is required. Equipped with a Global Navigation Satellite System (GNSS) receiver, the reference station measures the range to each of the satellites in view, demodulates the navigation message and, depending on the type of parameter, can compute several types of corrections to be applied to the user’s receiver in order to improve its performance. Such corrections can be, for example, integrity data, ionospheric corrections, ambiguity-resolution information, navigation-message data, etc. Then, the reference station broadcasts its corrections to local users via a data link. Augmentation systems make it possible to achieve position accuracy of several centimeters or less. They are only effective, however, when correcting for a common mode, or for spatially correlated errors such as the ionosphere and troposphere delays. Multipath-induced errors are not common to both the reference station and the users, so they cannot be recovered by means of augmentation systems.

3. Precise indoor positioning

The trend toward personal use of navigation systems requires positioning devices to be able to seamlessly work under various and variable difficult conditions such as inside warehouses, high-rise buildings, underground stores and parking, indoor commercial and office campuses, and so on. Examples of such applications are location identification of products stored in a warehouse, or of medical personnel or equipment in a hospital, or of firemen in a building on fire, or of police dogs trained to find explosives in a building, or of tagged maintenance tools and equipment scattered all over a plant [3.28]. Unfortunately, GNSS signal indoor reception is dramatically impaired by strong attenuation due to walls and slabs, and by multipath. Therefore, indoor environments create challenging issues in the GNSS signal processing and receiver design, to which new modulations (such as those foreseen for Galileo) and new navigation approaches (mainly, assisted-GNSS services) provide an answer. Pioneering work on indoor positioning dates back to more than 10 years ago, but a lot of work is still currently under development to refine and extend these pioneering ideas, both in academia and industry. The most promising technology seems today to be offered by wireless ad-hoc networks that support an UWB transmission layer.

4. Terrestrial network-based systems

The phrase “terrestrial network-based positioning and navigation systems” refers to location systems that use wireless technologies strictly deployed on the ground. Therefore, they do not use any satellite infrastructure as the GPS system. The most used wireless technologies are: cellular networks, WLAN’s, wireless systems based on UWB technology, and WSN’s.

Much research has been focused on the use of terrestrial wireless technology for developing positioning and navigation systems that work wherever satellite systems fail: for instance, in indoor environments or where satellite signals are corrupted by severe multi-path, which is typical of urban areas. In addition, lots of new applications have emerged in the last years such as emergency services, monitoring and tracking for security reasons, location-sensitive billing, fraud protection, asset tracking, fleet management, intelligent transportation systems, mobile yellow pages, and even cellular-system design and management. Furthermore, these applications require a certain level of location accuracy to be met by the corresponding positioning systems which have to deal with propagation problems typical of wireless communication, such as channel fading, low signal-to-noise ratios (SNRs), multiuser interference, and multipath conditions.

Summary of Open Problems

Positioning and navigation technology is seeking novel solutions to improve precision, reduce cost and size, increase possibilities of use, include new services and globally enhance its performance and appeal. Some of the main directions are:

a. Versatility of system deployment and optimisation of resource management, both obtainable with ad-hoc networks and/or wireless sensor networks (WSN’s) where distributed and cooperative approaches are implemented;

b. The integration among different technologies, aimed at overcoming the limitations of each single technology by exploiting in a common positioning/navigation problem different and independent portions of information made available from different kinds of sensors;

c. The definition of a novel implementation technology able to keep pace with the R&D trends, allowing a fast technology evolution at affordable development costs and helping to fill the gap between R&D achievement and commercial exploitation.

The following topics offer a view of the "cutting-edge" scientific and technological achievements in the above directions:

1. Cooperative positioning and localization - Positioning with MIMO sensors

Large networks with large numbers of nodes may have a great potential advantage from the use of an extended number of measurements, possibly in a distributed way; ad-hoc wireless networks with no or a few fixed nodes need cooperation for computing all the nodes' coordinates; the integration of nodes with different technological platforms (e.g., heterogeneous networks with WiMAX/4G systems, GNSS – Global Navigation Satellite System and WPAN solutions) may have a substantial benefit from a cooperative approach.

In general, cooperative techniques may rely on the extension of the conventional approaches to the cooperative one. The problem formulation is similar to that of the non-cooperative approaches. It is based on the definition of cost functions involving the estimated distances/angles among nodes. Considerable work has been done in this area (see [3.29] and references cited therein). In network-based positioning (e.g., for 2G-3G networks) or large ad-hoc networks the location of either fixed or moving nodes can be estimated by algorithm processed in reference stations or locally in all the nodes [3.29].

In an environment characterised by rich multipath the presence of multiple antennas in both transmitter and receiver (MIMO) allows the exploitation of the spatial diversity in the channel and it has a twofold impact on the network link: transmission performance can have a considerable improvement with a consequent positive impact on the noisy measured parameters (or reduction of the transmitted power) and multiple hybrid parameters (time of arrival, angles of arrival and departure of the strongest paths) can be estimated simultaneously at the same node [3.30]. An interesting extension of the MIMO concept is the case of different nodes in a sub-network that cooperate in order to form improved nodes with multiple antennas: this form of cooperation, often referred as virtual MIMO, is realised at the physical layer without involving the positioning algorithm itself but it can improve channel quality and the number of measured parameters [3.31].

Various application requirements (such as scalability, energy efficiency, and accuracy) can influence the design of cooperative localization systems. An open direction for research is the design of cooperative distributed algorithms that take into account energy, complexity and/or rate constraints, especially for low-complexity wireless sensor networks. Promising solutions for practical applications are the received signal strength (RSS) methods (which are relatively inexpensive and simple to be carried out) and the high-resolution time-of-arrival (TOA)-based methods (e.g., in UWB systems).

2. Signal processing to extract positioning information

Systems primary designed for other applications (cellular networks, metropolitan area networks, local area networks, personal area networks, wireless sensor networks) can provide worthy information for positioning: each transmitter can be considered as a beacon. Furthermore, the mobile device could include a low-cost inertial measurement unit (for instance, redundant accelerometer sets based on MEMS technology), providing complementary information. The way in which information can be extracted will depend on the nature and technical features of the given technology. For instance, wireless systems can be observed in the time domain, providing information about the length of the propagation path. They can also be taken into account in terms of received signal strength, evaluating the distance to the transmitter according to a propagation loss model. Other domains can be exploited: the frequency shift provides information about the radial velocity (the Doppler effect), an antenna array at the receiver could provide information about the direction of arrival, or the identification number of a base station could be related to its geographical location. The choice of the parameter to observe mainly depends upon accessibility.

The simplest way to perform a combination of the above mentioned parameters could consist of the position computation for each different system, and then averaging the results using weights for each technology according to its expected accuracy. However, problems arising from new data of different nature arriving sequentially in time find a natural framework in Statistics. More concretely, Bayesian models allow including prior knowledge about the phenomenon being modelled, handle sequential arrival of data and provide on-line inference, thus becoming a very well-suited mathematical foundation for positioning purposes.

3. Channel-model-based ranging and localization

Commonly radio based ranging and localization methods rely on a mathematical model of the propagation of an electromagnetic wave emitted from a transmitter and observed at another position by a receiver. Theoretically, working in the non-relativistic domain, the propagation can be described using Maxwell's equations. In the simplest cases this is indeed possible: the far-field propagation in free space can be described in closed form from Maxwell's equations leading to a constant propagation speed together with an inverse squared distance power law. In most other cases, however, such an approach is not feasible either due to the excessive amount of computations needed to approximate a solution for the field equations or because of a lack of knowledge of the propagation medium. Thus, practically, useful mathematical models of the received signal in complex propagation environment are necessary. Of special interest with respect to ranging and localization are propagation models including a relation between geometrical parameters of the environments (such as the distance between the transmitter and receiver) and the received signal. Most state-of-the art position methods use a combination of path-loss models and time-of-arrival models.

Examples of possible uses of advanced channel modelling for positioning purposes are:

- Modelling of channel variability for finger printing techniques: In positioning techniques the position is determined on the basis of prior knowledge of the channel characteristics. This prior knowledge may be obtained via pre-recorded channel measurements. By matching observed features (finger prints) to the database, position estimates can be obtained. A fundamental assumption for this method to work is the ability to match—at least approximately—an observed feature to the database and thereby obtain a meaningful position estimate. This ability, however, depends on which channel features are stored in the database and on how they vary with position and over time. Furthermore, it is relevant how the finger prints vary with respect to system parameters such as carrier frequency and antenna patterns. Consequently, to design and test reliable positioning algorithms using a finger-printing technique, it is of much importance to have suitable models of the profiles that accounts for these types of variability.
- Error Models: For the purpose of designing, testing, and applying positioning systems, it is beneficial to be able to model the position error. For this purpose models of the errors of, e.g., time-of-arrival estimators are important. These error models may rely on channel models [3.32] or on measurements [3.33]. Thus it is of interest to develop error models that are close-to-reality, yet flexible enough to be used for different systems.

SECTION 4 – STATE OF THE ART AND OPEN PROBLEMS IN FLEXIBLE RADIO PLATFORMS

4.1. Introduction

Recent advances in wireless communications introduced the employment of powerful concatenated codes and iterative processing of soft information together with the transmission over Multiple-Input, Multiple-Output (MIMO) channels as a very efficient but also a very computational intensive way to achieve throughput increase and to approach the theoretical capacity limits [4.1]. These approaches, jointly or independently, together with the employment of OFDM-based systems, paved the way towards efficient transmission in terms of channel utilization. They have attracted the interest of the currently emerging standards and have been included in IEEE802.16 family, IEEE802.11 family and 3GPP/3GPP-LTE and now IMT-advanced. However, the current practical implementations of radio platforms (flexible or not) able to support these methods are still far from the theoretical performance limits. It has been proved difficult for the system designers to manage the complexity and to meet the latency and energy consumption requirements of systems incorporating those advanced concepts, considering that most of the time, these transceivers are aimed to be embedded in mobile battery operated devices.

Flexibility in modern radio networks is another important field of research which has been proposed to serve different goals. First, along the design steps and due to the high pressure of time to market constraints the chipset and equipment manufacturers have adopted over the past few years a platform approach for the design of a new release. This methodology, by its flexibility and modular approach enable to consider the evolution between standards in an incremental efficient fashion in which a new chipset is considered as an evolution of its predecessor rather than a brand new design. Such a methodology, though using a flexible approach at the design stage, does not necessarily lead to a flexible instantiation eventually. A second interest of flexible platform, which is radically different from the first one, is to consider that a transceiver needs to handle flexibility in operation. This interest has been increasing over the past years and is often referred to as Software Defined Radio (SDR) [4.2].

The emergence of a considerable number of digital radio standards has pulled this concept from the world of academia to military and now civil applications [4.3, 4.4]. In fact, two levels of flexibility can be considered. The first one captures the ability of a transceiver to support a variety of different "modes" incorporating different modulation schemes (i.e., QAM constellations), different coding schemes (including the computationally intensive Turbo and Low-Density Parity Check (LDPC)) and code rates to enable adaptive modulation scheme support, or even MIMO methods as well as channelisation scalability to reassure spectrum harmonization in the long term. The second one relates to the fact that a modern transceiver has to handle different standards that are switched from depending on availability and user needs. However, current solutions still exhibit low performance either in terms or flexibility or in terms of power consumption. New research trends which are addressed in this section are expected to provide better performance tradeoffs.

Concurrently with these advances in the communication theory and its methods, which force to more computationally intensive algorithmic realizations, the silicon implementation barriers prevented the proportional development of the platforms. Considering both the International Technology Roadmap for Semiconductors (ITRS) [4.5] and the evolution of wireless communication standards, is a good way to understand that the evolution of the wireless world cannot be caught up by the Moore's law alone and that new architectural concepts have to be found to fill the gap. This moved the centre of attention to the exploitation of parallelism and, unavoidably, opened new and questions about how to capitalise the different levels of parallelism and how to develop consistent interconnection patterns. These open questions are significant in Many-Processor-System on Chip (MP-SoC) research. These systems try to exploit *independent-task* or *functional* parallelism by mapping them to a large number of processors, interconnected via a proper communication structure (e.g., Network on Chip (NoC)). It

is worthwhile to note that in these modern approaches, all the parallelism exploitations depicted in [4.6] are considered and exploited.
In Subsection 4.2 the silicon barriers which lead to the adoption of parallel processing are discussed, where in subsection 4.3 some open issues are sketched which are either raised to the adoption of the parallel paradigm (i.e., Parallelizability Identification and Description, etc.) or have to be revisited (i.e., efficient mapping onto hardware, corresponding tools, programming models, etc.) due to adoption of the new paradigm. In Subsection 4.4, the potential role of the heterogeneous Multi Processor Systems on Chip (MP-SoCs) in flexible wireless flexible platforms is presented, while state of the art and open problems about flexible MP-SoC design, multi-standard and computationally intensive processing are briefly discussed in Subsections 4.5-4.7. It is noted that the focus of this Section is on the base-band part of the platform, and doesn't consider the equally important RF portion of it.

4.2. Architectural Barriers for Computationally Intensive Tasks

Traditionally, technology scaling has been one of the driving forces for computational performance increase and energy efficiency. It made the implementation of today's fairly complex transceiver algorithms possible and has paved the way for the development of highly complex algorithms and schemes, for example, iterative schemes putting higher demands on the computational complexity. However, with technology scaling below 65nm, this trend of supporting complexity while being more energy efficient slows down dramatically as the proportion of leakage current increases. Random dopant fluctuations and sub-wavelength lithography lead to process variations that cause decreasing yields especially as the design size increases and also impacts predictability at design time. Reduced supply voltage results in reduced noise margins making the circuits more susceptible to energetic radiation, electromagnetic interference and capacitive coupling. These issues together lead to reliability degradation when simply scaling down architectures to smaller technology nodes, thus causing diminishing gains from technology scaling. Besides, the emergence of new complex algorithms and also of an always increasing number of wireless standards leads to a significantly different paradigm from the one of the computer world which evolves in a more incremental way. Another specific aspect of the wireless world is the extremely stringent requirements in terms of power consumption and form factor.

In order to still cope with the increasing computational demands of future flexible radio platforms, it becomes mandatory to fully exploit ways of parallelism for architecture development. However, parallelism approaches that maintain full flexibility – like massive pipelining, multi-issue processing (e.g. superscalar, VLIW etc.) – get very costly in terms of area and energy consumption. Especially the limited energy budget for mobile telecommunication devices creates a huge barrier for these approaches. Recent approaches face this challenge by sacrificing architectural flexibility and making it application specific. Application specific optimisations that increase the parallelism of an architecture can increase the energy efficiency and the computational performance at the same time. One way of maintaining the desired flexibility is to target programmable architectures. [4.7] gives an example of such an architecture gaining in computational performance and energy consumption while maintaining a high degree of flexibility.

Increasing parallel computing often results in high data rates and throughput demands within the architecture. This causes traditional memory architectures to reach their limits. Simple load store architectures limit the overall performance dramatically due to the additional latency for transferring the data to the computational units creating a memory barrier. Even cache hierarchies or scratchpad memories cannot cope with the throughput demands of a highly optimised data path which is common in application specific architectures. Therefore, special memory architectures are required to target this performance bottleneck. These dedicated memory architectures in addition to application specific pipelining can improve the performance extensively as demonstrated in [4.8].

In summary, the specialization of architectures comes at the cost of flexibility. However, with careful design optimisations, a flexible architecture that is energy efficient can still be delivered.

Nevertheless, such an architecture is neither suitable for all different tasks, nor a single architecture could deliver the computational performance required for a whole flexible radio system. Like mentioned in the Introduction section, future flexible radio platforms are most likely to host different specialised architectures in a single system leading to a heterogeneous MPSoC. These MPSoCs involve another level of parallelism, *Task Level Parallelism*, which again increases the computational performance. Such a system tend to fulfil the architectural objective of reducing the energy per correctly decoded bit or alternatively more MOPS/Watt and MOPS/mm^2 in battery driven applications like radio platforms. However, it also comes with some open issues, which are outlined in the following Sections.

4.3. The Role of Parallelism and the Open Issues

As already noticed, the exploitation of parallelism has not only been proposed to reduce the execution time, but also to achieve energy efficiency. This paradigm change from sequential processing to parallelism not only raised new questions, about how one can efficiently exploit it, in each of its different versions (e.g., *Data level, Instruction Level,* and *Independent Task Parallelism)* but also forced to revisit issues already present in sequential systems (an introduction to parallel architectures can be found in [4.9]).

One of the open issues is *Parallelizability Identification.* In principle, telecommunication systems consist of functionalities/building blocks which are loosely coupled. In wireless communication systems many of the tasks are sequential (i.e., synchronization, channel estimation, decoding, exchange of soft information between soft de-mapper and a MAP decoder. etc.). This sequential (and iterative) nature seemingly prevents these systems from extensive exploitation of *task level parallelism* via MPSoC architecture. However, this can be achieved by splitting (in an exact, or even approximate manner) the computationally intensive tasks in parallel or loosely coupled sub-tasks, emphasizing to the need for *algorithmic and hardware co-design*.

Another difficult and multi-dimensional problem is *Parallelizability Capitalization*, namely the transformation of the concepts of parallelism into architectural gains. Efficient realization of the tasks/functionalities has to take place by *mapping* them onto processing and memory elements and by defining proper inter-connection-networks. At this time, the interdisciplinary task of identifying a set of management principles which will allow the efficient exploitation of parallelizability and flexibility has to follow. For this reason, it will be of great value to employ and extend design methodologies that make use of high-level *tools* which allow the exploration of the different decisions in an early stage [4.10].

Finally, one significant issue is the efficient *Description and Management of Parallelizability*. This can be, likely, achieved by indentifying commonly used computation and communication patterns which also abstract key elements of the underlying hardware (e.g., in line with the "Nuclei" concept [4.11]). Such a description could be used not only for the efficient mapping of the corresponding nuclei onto platforms and the development of corresponding tools, but also to develop efficient programming models able to efficiently run on these platforms.

4.4. Heterogeneous MPSoC as the Way to Go Forward

In the wireless communication domain, the requirement of computational performance will lie at tens or even thousands of computational power in the foreseeable future [4.5], which cannot be met anymore by single processors in embedded systems due to the architectural barriers. One turnaround to cope with this situation is to handle the most computational intensive tasks by hardware accelerators [4.12]. These hardware accelerators can exploit parallelism at a low level in an efficient way and even local reconfigurability [4.13]. At a higher level, MPSoCs, which exploit parallelism by executing multiple tasks on several processing elements in parallel, have shown the ability to confront this performance challenge. In [4.14] a multi-core chip with 188 processors is presented, which produces an aggregate 50 billion instructions per second at a 250 MHz clock frequency.

However, as stated in the previous sections, high performance requirement is not the only challenge in the wireless communication domain. Power/energy efficiency and flexibility are dominating issues as well. Even worse is that these are in principle contradictory demands. Hence, trade-offs between them become more and more stringent and important. Generally MPSoCs can be divided into two groups: homogeneous and heterogeneous MPSoCs. In comparison to homogeneous MPSoCs, where all processing elements are of the same type, heterogeneous MPSoCs are of special interest to play the trade-offs between power/energy efficiency, computational performance and flexibility, by employing different types and granularity of processing elements.

Depending on the design requirement, the selection of processing elements can range from General Purpose Processors (GPPs), which offer the highest flexibility but very low power/energy efficiency, to Application Specific Integrated Circuits (ASICs) or even physically optimised ICs, which provide very high performance and power/energy efficiency but limited flexibility. Among the different types of processing elements, Application Specific Instruction-set Processors (ASIPs) are of special importance to play the trade-off. As introduced in Section 2, they can provide high computational performance and power/energy efficiency with specialised architectures and instruction-sets, while keeping certain programmability at the same time.

The employment of different types of processing elements provides the opportunity to optimise the workload of the system in an efficient way. The tasks which require high computation power, e.g. for intensive data processing, can be run on the special processing elements such as ASIPs or ASICs to guarantee the high performance, while the tasks which are not computationally intensive but require flexibility such as control flows can be executed on the GPPs. As an example, in 384kbps UMTS receiver the most computationally intensive components are the pulse matched filter and path searcher, which require more than one thousand MOPS [4.12, 13]. Consequentially, they should be implemented as ASICs since high computational power is demanded on the one side, and power/energy consumption should be kept low on the other side. The components such as correlator and channel estimator, which require less computational performance, typically at tens or hundreds of MOPS, the best choice of the hardware architecture would be ASIPs, which can still provide quite high performance and have the programmability meanwhile. For the components such as SIR estimation, which requires low computational performance, the computation can be performed on DSPs or GPPs.

In addition to the use of power/energy efficient processing elements such as ASICs or ASIPs in terms of reducing the power/energy consumption, the high performance gained from the parallel processing of the tasks makes it possible to scale down the clock frequency of the system. In this way, the power/energy efficiency can also be greatly improved. Another efficient way to reduce the power/energy consumption is dynamic downscaling of the voltage supply of the processing elements or even switching-off [4.15].

The advantages of heterogeneous MPSoCs are drawing more and more attention in the recent years. At the same time, this new paradigm poses new challenges for both hardware and software architects, when designing MPSoCs. As mentioned in the previous sections, these challenges include communication architecture exploration, task separation and mapping and programming models of MPSoCs, which will be addressed in the following sections.

4.5. State of the Art and Open Problems in NoCs and MP-SoCs

The implementation of complex (iterative) wireless communication systems became essential to reach the performances now required in term of quality of transmission. Dedicated hardware architectures (i.e. ASIC) implementing parts of these systems are already tackled in several academic and industrial research teams. However, the requirements of: fast low design time and increased flexibility of the implementation, make the resort to adequate multiprocessor architectures inevitable. In this context, Multi-Processor System-on-Chip architectures are being widely investigated these last years in order to accommodate the increasing throughput and flexibility requirements of emerging wireless communication standards.

Considering this approach implies typically diverse skills and tasks:

- parallelism exploration of the considered algorithms (leading to parallel or loosely coupled sub-tasks)
- computational resource design (already available cores to be embedded in the SoC, or ASIPs specifically tailored around the class of applications to be supported)
- on-chip communication resource design (ranges from simple bus architectures up to sophisticated Network-on-Chip solutions).

Defining architecture and instruction set of the processing elements and designing, the communication structure involves the exploration of several alternatives that need to be investigated, functionally validated, characterised and compared in terms of cost and performance.

Besides application parallelism exploration and application-specific processor design (Subsections 3.2 and 3.3), the on-chip communication network connecting the multiple on-chip cores constitutes a major issue. Conventional on-chip busses become inefficient in large systems and the nanotechnology integration issues (propagation delay, crosstalk, etc.) make their use no more practical. In this context, Network-on-Chip has recently emerged as a new paradigm allowing to cope with these major design issues, and more particularly with the on-chip interconnection issues, and to accommodate future on-chip integration of several hundreds of components. The concept of network on chip aims at adapting the models, the techniques and the tools from the field of computer and telecommunication networks to the context of silicon integration. This is on the way to become crucial for the design of the future embedded systems.

In this context, we can cite the FAUST chip (Flexible Architecture of Unified Systems for Telecom) [4.16]; a 2D mesh-based NoC architecture which targets 4G terminal MP-SoC implementations. For this kind of platforms, the computation nodes consist of the heterogeneous building blocks of the wireless communication system (i.e., synchronization, channel estimation, channel decoding, etc.). A survey of the existing NoC based architecture can be found in [4.17]

On the other hand, several research activities are currently targeting fine-grain NoC-based MP-SoC architectures for each of these building blocks. Channel decoding is one of the most explored blocks due to the underlying extensive computation and communication of iterative decoding techniques (Turbo decoding and LDPC) and the severe requirements in terms of throughput and flexibility. In parallel turbo decoding, extrinsic information is iteratively and concurrently exchanged between two component decoders. Furthermore, these exchanges become more and more massive with decoder level parallelism and the number of iterations. Since turbo code interleaving rule varies from one standard to another and/or one mode to another; the requirement of a fully flexible on-chip communication network interconnecting the two component decoders implies its ability to support the intensive interleaved memory accesses induced by parallel turbo decoders and to convey any permutation from the network input ports to its output ports. To that purpose, several application-specific on-chip communication networks were recently introduced. Topologies based on Benes, Butterfly, 2D Mesh, chordal ring, and de Bruijn [4.18] were explored, designed, and integrated for an MP-SoC decoder implementation.

Regarding LDPC parallel decoders, same approach is investigated. In [4.19], application of the permutation network scheme of Tarable with a modified version of the belief propagation algorithm is proposed. Moreover, a Benes network replaces the two original crossbars used for the permutation network. Another solution is proposed based on a heterogeneous network (MDN) whose topology is a randomly generated graph with non-regular node degrees.

Recent research activities in this direction target the design of MP-SoC platforms for flexible Turbo/LDPC decoders and first results start appearing in this year [4.20].

Indeed, for future massively multi-core architectures, the problem will not be any more to design powerful components but mainly to assemble them efficiently. The principal difficulties relate thus to the heterogeneity of the interfaces of the components and their interconnection. In these systems, the communication architecture relies mainly on a set of hierarchical buses. Although they present an attractive solution from the point of view of their simple implementation and their low cost, they become the bottleneck when the number of components to be connected increases. Indeed, the buses cannot manage anymore the bandwidth required by the processors, memories and IP blocks of heterogeneous architectures. The interconnection and the communication between the various components to be integrated on the same chip become, thus, the critical part of the system.

While multiprocessor architectures have been studied for several years, the on-chip implementation of MP-SoC architectures brings a number of new problems. Compared to a typical communication networks, an MP-SoC is highly resource limited in terms of routing cost and power budget. Moreover, in the case of MP-SoC, a huge level of complexity has to be managed both in terms of distributed processing capability and inter-processor exchange of information

The choice of the on-chip communication architecture is a complex optimisation problem, implying the exploration of a large design space, with several dimensions and parameters. Cooperation among hardware designers and network experts must be encouraged to take full advantage and adapt the already known results to the specific domains of NoCs, where latency and cost constraints make impossible the simple reusing topologies and routing protocols commonly adopted in traditional communication networks.

Another critical aspect in the study and implementation of MP-SoC is the need for efficient design and simulation tools. Defining architecture and instruction set of the processing elements and designing the communication structure involve the exploration of several alternatives that need to be explored, functionally validated, characterised and compared in terms of cost and performance. Accurate models and efficient co-simulation environments are thus required to validate hardware and software components.

In addition, a low-complexity run-time management layer is an important feature of an MP-SoC platform, to map applications on the platform and to optimise performance, energy consumption, memory usage and bandwidth according to available resources and current processing conditions.

4.6 State of the Art and Open Problems in multi-standard processing

Wireless equipments are integrating more and more radio standards. First step consisted in merging in the same terminal several radio access technologies of the same nature as two 2G standards such as IS-95 and GSM in the US. Then a third mode was implied also, in order to add a second frequency band for GSM, so that roaming between US and Europe becomes possible. This has been pursued with the introduction of 3G [4.12]. In addition, other standards than cellular are now used in a terminal, such as Bluetooth for PAN purposes, but also GPS for positioning, and we may expect soon broadcast TV (DVB-H, DVB-SH, etc.) and radio (DAB, DRM), as well as WLAN as WiFi and soon WiMax. Intelligent transport systems (ITS) and remote paying or identifying means are also foreseen. Terminals are turning to PDA or smart phones including five and soon maybe ten wireless standards. This imposes a new paradigm for radio equipments design for these devices of limited form factor and energy.

Till now, the “Velcro” approach dominated. It consists in adding fully pre-built standards in the form of one, two, or more chips. These chips can not be used for another standard and are switched off when their related standard is not running. It is obvious here that the majority of the available processing power is not used at each instant. This solution has been economically viable and the best one till now as not so many standards were integrated together. But it is not infinite. Thanks to the improvement of digital processing units in terms of processing power and power consumption, alternative solutions may be envisaged for a bigger number of standards, based on flexible radio principles. Flexible radio is indeed a key enabler for answering multi-standard equipments design issue.

One key issue of flexible design is the processing granularity to be considered. Velcro is at the coarsest grain level (it is not only a hardware matter, but may also be considered in software). In a fine granularity approach, generic processing-based approaches may combine or privilege on of:

- software (SW) programmable processing (typically DSP),
- hardware (HW) flexible processing (typically FPGA).

Intermediate opportunities between coarse and fine granularity may be foreseen for SoC and NoC design. But which level of granularity should be the best then? Anyway, except in the “velcro” context, all other approaches require some kind of multi-granularity exploration. In other words, the solution consists in identifying the set of operators necessary to provide a trade-off between flexibility and efficiency. Efficiency means here both computational and power consumption efficiency.
In a FPGA the flexibility level has been chosen at the gate level and can be reused for multi-purposes by changing the gates connections. In a DSP flexibility has been chosen at the ALU level and can be re-used for multi-purposes just by changing the programming code. In a Soc or NoC approach flexibility has been chosen at level of parameters. Flexibility at the Velcro level is a single switch. Except for the latter case, there are many ways in each situation to dimension the atomic structures, depending on each design and designer objectives. For instance [4.21] and [4.22] considers multi-standard radio design at different levels of granularity. It permits to identify the set of operators that can be factored to perform all the processing needs of a given multi-standard equipment. It can adapt also the exploration in function of the granularity requirements of the designer so that it may consider any kind of coarser or finer granularity.

Anyway, we may consider that any flexible multi-standard radio platform will be composed of a plurality of processing units probably combining DSPs, FPGAs, and ASICs inside a SoC or NoC or in a distributed manner. The real-time management of flexibility inside such a heterogeneous equipment is very challenging if the goal is to take full benefit of each processing element nature advantage. [4.23] for instance proposes a distributed reconfiguration management architecture in 3 levels of hierarchy. The provision of a Hardware Abstraction Layer (HAL) is of utmost importance to upgrade the transceivers’ functionality using an abstract level language that can be handled by designers who have not necessarily involved in the design of the chipset itself. [4.24] integrates the reconfiguration management in a global design methodology. These solutions go further than the DoD SCA (Software Communication Architecture) [4.3] that provides an abstraction of HW for the deployment of SW radio applications, more than a real-time reconfiguration management [4.25].

In the longer term, real-time management of reconfiguration of multi-standard equipments is of major importance if you consider scenarios such as inter-standard vertical handovers. All the more so as the only realistic solution today would be based on a Velcro approach. Considered at its extreme point, multi-standard handover opens the way towards cognitive radio (CR) in order to better use resources (spectrum, battery, etc.). This opens an entirely new research area. This implies to integrate somehow the cognitive cycle inside the multi-standard equipments. This means providing terminals with sensing and decision taking means in addition to reconfiguration means. The depth of the embedded smartness will depend on the chosen approach: terminal-centric or network-centric. But probably a mix of both is to expect. A generic framework to support that features inside equipment is a challenge. A first attempt of proposal is made in [4.26]: HDCRAM for Hierarchical and Distributed Cognitive Radio Architecture Management.

4.7 State of the Art and Open Problems in Flexible Architectures for Computationally Intensive Processing

In the last years, great advances have been achieved in the implementation of MP-SOC platforms efficiently supporting several base-band processing functions and MP-SOC technology is the key enabling vehicle for Tier-2 Software Defined Radio. However, some of the main processing tasks in a wireless transceiver are computationally intensive and their implementation usually resorts to the design of dedicated hardware accelerators.

Current implementations of decoders for modern Forward Error Correction (FEC) are in the form of accelerators optimised for specific standards, but do not take into account flexibility and scalability issues. Particularly current design approach implies the allocation of multiple separated HW accelerators to realise multi-standard systems in a “Velcro” fashion, which often result in poor HW efficiency and long design times. So a key research challenge is the design of HW accelerators for channel decoding incorporating some elements of flexibility.

A first objective is the search for efficient FEC architectures handling several codes of the same family [4.27]. Very recently, a significant case of study is represented by LDPC codes. Codes of this family are usually decoded by means of a “message passing” algorithm that implements the iterative exchange of messages generated by processing nodes. The communication structure to support this message exchange is critical: fully parallel architectures result in excessive cost and serial architectures are too slow, while partially parallel architectures allow for proper cost-performance trade-offs. Unfortunately parallelism introduces the collision problem in memory access, a well–known problem already addressed in parallel turbo decoders. Two main approaches have been proposed to deal with collisions: (i) designing collision free codes, specifically conceived with the purpose of handle their decoding in parallel forms [4.28], (ii) designing decoder architectures able to avoid or mitigate collision effects [4.29]. Even if the first approach has proven to be effective, it significantly limits the supported code classes, spoiling the flexibility of the obtained solution. The second approach, on the other hand, is well suited for flexible and general architectures.

Another challenging task is the design of LDPC decoders that are flexible in terms of supported block sizes and code rates. The need for decoders able to dynamically adapt to different transmission conditions is well known in practical communication systems. This problem has been faced in the past again introducing suitable constraints in the code design. With the approach introduced in [4.30], it is possible to design a fully flexible decoder able to support any LDPC code. The underlying architecture is based on a scalable, partially parallel topology and a reorganised message-passing algorithm, known as LT-BPA (Low Traffic Belief Propagation Algorithm).

An even more ambitious objective is the exploration of FEC architectures dedicated to both LDPC and turbo codes. Results on this side have been published only very recently and they are all based on the MP-SOC approach. An alternative solution can be searched in the direction of flexible hardware accelerators, which exploit the commonalities between the LDPC and turbo-decoding algorithms in order to come to a versatile architecture, covering both code families with the same hardware support. In both cases, exploiting the inherent parallelism of the iterative decoding algorithm and enabling the efficient partitioning of the decoding task among several communicating processing elements, the throughput can be efficiently multiplied. A communication network has to support the communication demands of the different processing elements without degrading the throughput of the overall system. Either a general purpose NOC (Network-on-Chip) or a less flexible but more efficient dedicated network can be used to support the communication needs: the second approach leads to low cost permutation structures such as Benes and Clos networks or de Brujin graphs, while the bi-dimensional mesh and other regular topologies can be considered for the implementation of an NOC.

The design of a versatile processing element can move from the idea of simply sharing internal memories required by turbo and LDPC decoding, with separate processing units, independently optimised for the two cases. More efficient solutions can be achieved by design proper processing components that can be maximally reused when handling both turbo and LDPC codes. This approach is facilitated by the adoption of Turbo Decoding Message Passing (TDMP), which is an alternative algorithm proposed for decoding LDPC codes.

Another significant case of study in the design of flexible architectures dedicated to computationally intensive processing tasks is MIMO detection. In comparison to SISO systems, a wireless MIMO system provides higher throughput at no additional cost of bandwidth, but the high complexity of the detection algorithms poses a major challenge to the hardware implementation: as a consequence, algorithms and architecture need to be carefully considered and optimised in order to limit implementation cost and energy consumption.

Maximum Likelihood (ML) MIMO detection guarantees optimal performance but implies huge processing complexity, which makes acceptable this approach only when the number of transmitting antenna is low and the adopted modulation scheme has a small cardinality. Sphere decoding (SD) is an efficient method that significantly reduces the average processing complexity with no performance penalty. Hardware components have already been realised to implement SD [4.31], although its non-deterministic data rate is a heavy limitation for VLSI design.
The main research directions for the implementation of future MIMO detectors can be organised according to the following points:

1. Realization of flexible MIMO detection architectures supporting different modulation schemes and number of antenna.
2. Efficient implementation of more sophisticated algorithms that get close to the optimum BER performance with a processing complexity much lower than ML and a constant throughput (List Sphere Decoding and k-Best algorithm are two important examples).
3. Design of soft detection architectures, capable to output the reliability associated with each hard output bit. This kind of detector has to implement a much more complicated algorithm than the hard version, but it allows serial concatenation with a channel decoder in a unique iterative system. Several concatenated schemes have been studied and performance results are already available in terms of analytical bounds and simulations, however few implementations of soft output detectors have been reported till now and a clear picture of possible advantages that can be provided by this approach is missing.

4.8. Conclusions

In this section, several trends on hardware design related to digital transceiver design have been described. Although some concepts can be derived from classical computing hardware design, wireless communication systems have their own constraints that lead the designer to reconsider some of the trade-offs to be done. Low power consumption, small form factor are key constraints. On the other hand the emergence of new wireless standard at a fast pace imply the development of flexible approaches, both at design and run time. In a very near future, the transceiver architectures will evolve to handle more modes and more standards. This is caused by the emergence of new standards and also of a new challenge referred to as the cognitive radio which heavily relies on reconfigurable transceivers. This wireless market is also hardly pulled by an increasing demand in throughput which in turn translates into highly computational operations. This section has shown that there is not a single answer to these antagonist demands and that research is carried out at various levels (management, system, operator, management, communication, memory, and technology) to fulfil these requirements.

SECTION 5 - STATE-OF-THE ART AND OPEN PROBLEMS IN NETWORK LAYERS OF WCNS

5.1 Introduction: general drivers for future wireless 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 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 the following some of the envisaged drivers that will guide this evolution, and that will definitely impact of the design of the network layers of wireless networks, are briefly described:

- Heterogeneity in networks and devices:
Following the current trend in which multiple technologies are being deployed one on top of the other, such as the cellular evolution GSM-UMTS-HSPA-LTE or the profusion of WLANs and short-range technologies (e.g. Bluetooth, RF-ID), the future wireless arena is expected to be heterogeneous in nature, with a multiplicity of cellular, local area, metropolitan area and personal area technologies coexisting in the same geographical region. In addition even for a given cellular technology also different deployments will be envisaged particularly in urban areas, where macro, micro, pico and femtocell deployments will be coexisting as the means to achieve the desired large capacities. Heterogeneity will not only be present from the network perspective but also very different types of wireless devices will exist. In addition to classical phones, also PDAs, navigators, sensors or more simple RF-ID devices will constitute different ways of having access to the wireless services.

- Multiplicity of services:
Recent years are starting to witness the (from some time ago) expected explosion of wireless data services, mainly thanks to the deployment of wideband technologies (e.g. HSPA) that allow a user experience closer to the one that can be achieved in wired networks. In future years, it is expected that this trend continues and even other services achieve more significant market-shares, such as mobile TV, multimedia, games, etc., and also some other specific services dealing with healthcare (e.g. through biosensors) or location-based services thanks to the proliferation of navigators.

- "Internet of things": everything connected to everything
The next logical step in the technological revolution to connect people anytime and anywhere is to connect inanimate objects in a communication network. This is the vision underlying the "Internet of things" concept [5.1]. The use of electronic tags and sensors will serve to extend the communication and monitoring potential of the network of networks, as will the introduction of computing power in everyday items. Advances in nanotechnology (i.e. manipulation of matter at the molecular level) will serve to further accelerate these developments.

- Self-management operation:
With the increasing complexity in the network deployments, networks have to be optimised by tuning a multiplicity of parameters that have a relevant impact over system performance. In addition, there is a current trend to reduce the cell range with e.g. pico and femtocell deployments, with the corresponding increase in the number of access points. These aspects will impose very important challenges in the network management field, and automated mechanisms to provide the networks with cognitive capabilities enabling its self-configuration without the need of human intervention will be the key for the success of future networks.

- Distributed systems:
Decentralisation at different degrees has also been one of the trends that have been observed in the current network evolution, since this contributes to reducing signalling and impacts on service performance in terms of improved latencies. This is the case of e.g. the implementation of some functions at the edge nodes of the network (e.g. the scheduling carried out at the base stations of the HSPA systems, instead of doing executing them in centralised nodes). The next natural step in this trend is to bring decentralisation towards the terminals, which will have to be able to autonomously take decisions affecting their connectivity.

Based on the above trends, in the following sub-sections a summary of the state-of-the-art and open problems in different fields of the wireless networks are identified. They are mainly based on the work currently being carried out in the framework of the networking work packages of NEWCOM++. The presented topics constitute a summary of research aspects that will be needed by future networks to deal with the drivers presented previously. For more details in the state-of-the-art of all the presented topics, the reader is referred to NEWCOM++ deliverables DR6.1 [5.2], DR7.1 [5.3], DR8.1 [5.4], DR9.1 [5.5], DR10.1 [5.6] and DR11.1 [5.7].

5.2 Radio Resource Management techniques

Motivation for RRM functions

The convergence between mobile and data access internet-based services posed specific challenges to wireless networks designers about how to exploit the set of resources available as efficiently as possible. In the first wireless networks, since the only application supported was voice, main requirements were to keep a good subjective voice quality and a bounded blocking probability to ensure accessibility in the coverage area. These two aspects were easily handled by means of an adequate network planning that ensured the SINR constraints in the coverage area and that a sufficient number of channels were available. However, with the evolution of wireless networks to support the provision of different types of services with different requirements (e.g. mixing both real time and non-real-time applications with different degrees of user profiles) and the development of more sophisticated and flexible radio access technologies (e.g. based on CDMA or OFDMA), QoS provision cannot be achieved only through a static planning procedure, but it is dynamically pursued by a set of functionalities grouped under the term "Radio Resource Management" (RRM). RRM functions can be defined as the set of functionalities whose aim is to provide services according to the QoS negotiated for each application over the area covered by the system, and to optimise the system capacity through the choice of the best resource sharing among users [5.8][5.9]. RRM functions can be implemented in many different algorithms, this impacting on the overall system efficiency and on the infrastructure cost. Additionally, RRM strategies are typically not subject of standardisation, so that they can be a differentiation issue among manufacturers and operators.

In accordance with the constraints imposed by a given radio interface technology, RRM functions are responsible for taking decisions concerning the setting of different parameters influencing on the radio interface behaviour. This includes aspects such as the number of simultaneous users transmitting with their corresponding powers, transmission bit rates, the corresponding code sequences or sub-carriers assigned to them, the number of users that can be admitted in a given cell, etc. Since the different RRM functions will target to track different radio interface elements and effects, they can be classified according to the time scales they use to be activated and executed. In that sense, RRM functions such as power control, scheduling or link adaptation mechanisms tend to operate in short term time scales (typically in the order of milliseconds) while other functions such as admission control, congestion control or handover tend to operate in longer term time scales (typically in the order of seconds).

RRM in heterogeneous networks

Heterogeneity is already present in current wireless networks, where multiple radio access networks coexist in a given area and can thus be seen as different candidates to provide a certain service to a given user. This is the case of current 3G networks that in many cases were deployed on top of existing 2G networks and that also coexist with other non-cellular technologies such as WLANs. With the advent of future 4G networks and the introduction of other broadband technologies such as WiMAX network heterogeneity is still to be reinforced. However, this trend must indeed be regarded as a new challenge to offer services to the users over an efficient and ubiquitous radio access thanks to coordinating the available Radio Access Technologies (RATs), which on the other hand exhibit some degree of complementariness. In this way, not only the user can be served through the RAT that fits better to the terminal capabilities and service requirements, but also a more efficient use of the available radio resources can be achieved. This calls for the introduction of new RRM algorithms operating from a common perspective that take into account the overall amount of resources available in the existing RATs, and therefore are referred to as Common RRM (CRRM) or Joint RRM (Joint RRM). In the literature different approaches have been proposed [5.10][5.11].

Scheduling techniques

Focusing on the RRM strategies operating in the short term, scheduling mechanisms try to assign the resources to users in order to fulfil user QoS requirements while maximizing system usage and, thus, the aggregated throughput, while trying to guarantee some fairness among differently located users. One of the first ideas explored by researchers was the exploitation of the channel variability through the so called "opportunistic scheduling" [5.12]. The aim of such algorithm is the maximization of system throughput by serving always the user(s) with the best channel conditions. This technique has the advantage of maximizing throughput and spectral efficiency, which is crucial in wireless systems due to spectrum scarcity, but has an important drawback in its unfairness, since users affected by poor channel conditions may starve for long time.

In order to provide fairness among users, in [5.13] it was shown that it can be at least partially restored by modifying the scheduling criteria in one of several possible manners. Many new algorithms were proposed, which can be grouped into two categories. The main algorithms in the first category which could be recognised are: the Proportional Fair (PF) scheduling [5.14], whose aim is maximizing throughput provided that long-term fairness is guaranteed; strategies like Max – Min Fairness, Weighted Max – Min Fairness, Purely Fair Scheduling, Wireless Adapted Fair (WAF) scheduling, could be considered as enhanced versions of PF scheduling. The second category is based on the concept of leading and lagging flows, where lead is defined as the amount of service that a flow, having experienced good channel quality until the current instant, should release in favour of "unlucky" users, whereas lag is the amount of service a flow should receive due to the fact that it has experienced bad channel quality until the current instant. Obviously, a flow could be either leading or lagging, not both simultaneously. The main strategies based on this approach are the following: Wireless Fair Service (WFS), Idealised Wireless Fair Queuing (IWFQ), Channel condition Independent Fair Queuing (CIF – Q), Server Based Fairness Approach (SBFA). However, also these strategies suffer from some important limitations: in particular, they do not support short-term fairness since transmission is always subjected to good channel conditions, they are based on very simplified channel quality evaluations such as only "good" and "bad", leading users may be affected by ungraceful service degradation since they can be excluded from transmission for long time, which is critical in case RT applications should be supported.

The above scheduling strategies were initially applied to TDMA air interfaces. However, with the evolution towards 4G systems and the consolidation of OFDMA as multiple access technique in systems such as WiMAX or UMTS LTE, new dimensions are open in the scheduling problem, thanks to some interesting properties of this technique such as the flexibility in allocation and supportable bit rates, robustness against interference and frequency selective fading, high spectral efficiency, ease of implementation and, especially for scheduling, possibility to easily benefit from multiuser diversity. Then, the focus is to develop algorithms to determine which users to schedule, how to allocate subcarriers to them, and how to determine the appropriate power levels for each user on each subcarrier.

Following the path opened by the seminal article by Wong et al. [5.15], many resource allocation algorithms have been proposed to take advantage of both the frequency selective nature of the channel and the multi-user diversity in OFDMA systems. Most of the works in the literature follow either the *margin adaptive* approach, with the goal of minimizing the transmitted power with a rate constraint for each user, or the *rate adaptive* approach aiming at maximizing the overall rate with a power constraint. In this latter case, the optimal solution for resource allocation in the downlink is often found as an application of the well-known waterfilling algorithm. However, all these works only consider allocation in a single cell. Because of its complexity, resource allocation in multi-cellular systems has not been fully studied yet and only few works tackle the problem [5.16][5.17].

Automated optimisation of RRM parameters

Recent trends in joint radio access network optimisation research include the concept of autonomous or self-managing systems and the application of artificial intelligence techniques to support self-management tasks such as optimisation, monitoring and fault diagnosis. Specifically, current networks include a set of parameters controlling the (J)RRM functions that need to be accurately tuned, normally at cell level, in order to achieve an optimised network performance (in terms of network capacity, QoS level and network coverage). Traditionally, this tuning was done manually or semi-automatically during initial network deployment phase, leading to static parameter settings. However, being wireless networks inherently dynamic and very sensitive to traffic and interference variations, which is particularly more relevant with the CDMA and OFDMA-based radio interfaces, a current natural challenge is to provide the network with intelligent techniques to make the automated tuning of (J) RRM parameters. [5.18] presents an extensive literature survey in the area of automated radio resource management parameter optimisation and in particular presents admission control related theory and references.

Decentralised RRM

Finally, another relevant aspect to mention is the current trend in the decentralisation of (J)RRM functions. Traditionally, these functions have been implemented in a centralised way, i.e. in central network nodes that can have a more complete picture of the radio access status than a particular node, so that decisions can be made with more inputs. However, centralised implementations have some drawbacks in terms of increased signalling load or transfer delay of the algorithm's inputs to the central node, which prevents an efficient implementation of short-term (J)RRM functions such as packet scheduling and explains why wireless cellular technology evolution (e.g. HSDPA) exhibits the trend towards implementing (J)RRM functions on the radio access network edge nodes (e.g. base stations).

Going one step further in this decentralisation direction leads to the implementation of distributed (J)RRM functions at the terminal side, where relevant information for making smarter decisions is kept. This approach has claimed to be inefficient in the past because of the limited information available at the terminal side (e.g. the terminal does not know what is the cell load). Nevertheless, this can be overcome if the network is able to provide some information or guidelines to the terminal assisting its decisions, in addition to the valuable information that is already kept by the terminal (e.g. knowledge of the propagation conditions to surrounding cells). In this way, while a mobile-assisted centralised decision making process requires the inputs from many terminals to a single node, the network-assisted decentralised decision making process requires the input from a single node to the terminals, which can be significantly more efficient from a signalling point of view. An example of this trend is the IEEE P1900.4 protocol, currently under standardization.

Summary of open problems

Based on the above discussions, many open problems still remain to be solved in the context of RRM techniques for future wireless networks. In the following a list of the main identified problems is provided, being some of them investigated in NEWCOM++ WPR8 and WPR9:

- Development of efficient scheduling techniques for multi-cell OFDMA systems, with different possible levels of coordination between cells (i.e. centralised, distributed or hierarchical schemes).
- Development of efficient scheduling techniques for multi-carrier and space division systems
- Development of scheduling techniques for self-organising and distributed networks

- Study the potentialities of interaction between network coding and scheduling
- Development of automated optimisation techniques for heterogeneous networks
- Development of efficient (J)RRM algorithms in heterogeneous networks, including the forthcoming new air interfaces based on WiMAX and LTE technologies.
- Development of decentralised solutions for (J)RRM.

5.3 New paradigms in spectrum management

Flexible spectrum management

Together with the evolution of wireless technologies to allow delivering more advanced multimedia services, the regulatory perspective on how the spectrum should be allocated and utilised in a complex and composite technology scenario is evolving as well. The evolution is towards a cautious introduction of more flexibility in spectrum management together with economic considerations on spectrum trading. This new spectrum management paradigm is driven by the growing competition for spectrum and the requirement that the spectrum is used more efficiently [5.19]. Then, instead of the classical fixed spectrum allocation to licensed systems and services, which may become too rigid and inefficient, it is being recently considered the possibility to use Flexible Spectrum Management (FSM) strategies that dynamically assign spectrum bands in accordance with the specific traffic needs in each area [5.20]. There are different FSM scenarios presenting different characteristics in terms of technical, regulatory and business feasibility. While a fully enabled FSM scenario can be envisaged at a rather long-term perspective, there are already some basic FSM scenarios that are becoming a reality. Spectrum refarming, providing the possibility to set-up communication on a specific RAT in different frequency bands (e.g. refarming of GSM spectrum for UMTS/HSxPA communications), is a first example. Another case for FSM arises from the so-called digital dividend, which corresponds to the frequencies in the UHF band that will be cleared by the transition of analog to digital television. The cleared spectrum could be utilised by mobile TV or cellular technologies like UMTS, LTE, WiMAX, etc. and also for flexibly sharing spectrum between smart radio technologies. The exploitation of the so-called TV White Space, which refer to portions of spectrum that are unused either because there is currently no license holder for them, or because they are deliberately left unused as guard bands between the different TV channels, is another opportunity for FSM mechanisms.

As a result of the above trend, future wireless terminals will have to be reconfigurable in nature and will have to face the challenge of having to identify which is the spectrum band that can be used for each specific service. In turn, networks will have to adapt themselves to the varying conditions by being able to change the spectrum bands that they are operating with. Consequently, future wireless systems will have to be designed under the principles of cognition, reconfigurability and adaptability. Several works in the literature have recently dealt with flexible spectrum management strategies. In [5.21] the DIMSUMNet architecture is presented for coordinated, real-time dynamic spectrum access based on a centralised entity called Spectrum Broker as opposite to other opportunistic, uncoordinated methods. In particular, this architecture introduces the concepts of coordinated access band and statistically multiplexed access to spectrum. Further work on this topic has considered different formulations for solving the spectrum allocation problem based on linear programming techniques.

One of the open points to enable the efficient operation of mobile terminals in FSM scenarios is to devise mechanisms to assist them with the procedure of discovering which are the available access technologies and the frequencies in which they are operating. In that sense, different proposals exist such as the Common Spectrum Coordination Channel (CSCC) in [5.22] or the Cognitive Pilot Channel (CPC) in [5.23]. It consists in a channel that carries the information corresponding to the operators, RATs and frequencies available in a given area, so that cognitive terminals do not require scanning the entire spectrum in order to find out which these available systems are and which frequencies are they using.

Secondary spectrum usage

The traditional approach in spectrum management 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 have revealed a significant spectrum underutilization, in spite of the fact that spectrum scarcity is claimed when trying to find bands for new systems. From an economical point of view, economists have long argued that market mechanisms should be applied to radio spectrum. From the technology point of view, advances in recent years such as ultra-wideband (UWB) and cognitive radios enable other forms of spectrum access. Cognitive radios, as devices with the capabilities to be aware of actual transmissions across a wide bandwidth and to adapt their own transmissions to the characteristics of the spectrum, offer great potential of developing more advanced spectrum management approaches.

As a result of the above, one of the current 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) [5.24], 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 have to sense the spectrum to detect PU or SU transmissions and should be able to adapt to the varying spectrum conditions, ensuring that the primary rights are preserved. These events culminated in the creation of the IEEE 802.22, developing a cognitive radio-based physical and medium access control layer for use by license-exempt devices on a non-interfering basis in spectrum that is allocated to the TV broadcast service.

The primary-secondary (P-S) spectrum sharing can take the form of cooperation or coexistence. Cooperation means there is explicit communication and coordination between primary and secondary systems, and coexistence means there is none. When sharing is based on coexistence, secondary devices are essentially invisible to the primary. Thus, all of the complexity of sharing is borne by the secondary and no changes to the primary system are needed. There can be different forms of coexistence, such as spectrum underlay (e.g. UWB) or spectrum overlay (e.g. opportunistic exploitation of white spaces in spatial-temporal domain sustained on spectrum sensing, coordination with peers and fast spectrum handover). As for cooperation, again different forms of P-S interactions are possible. For example, spatial-temporal white spaces that can be exploited by SUs can be signalled through appropriate channels. In addition, the interaction between PUs and SUs provides an opportunity for the license-holder to demand payment according to the different quality of service grades offered to SUs.

One of the key enabling technologies for DSAN development is the cognitive radio, which allows the terminals determining which portions of the spectrum are available, selecting the most appropriate channel for transmission, and vacating the channel whenever a licensed user is detected. In this respect, there are a number of techniques to be developed for an efficient secondary spectrum usage and can be categorised as [5.25]: spectrum sensing techniques (i.e. detecting unused spectrum and sharing it without harmful interference with other users), spectrum management techniques (i.e. selecting the best available spectrum to meet user communication requirements), spectrum mobility techniques (i.e. maintaining seamless secondary communication requirements during the transition to a better spectrum portion) and spectrum sharing techniques (i.e. providing the fair spectrum scheduling method among coexisting secondary users).

Summary of open problems

Based on the above discussions there are a number of identified open problems in the area of spectrum management, some of them being listed in the following, and being under investigation in WPR9:

- Development of efficient dynamic spectrum management strategies to assign portions of spectrum to cells in wireless network
- Development of efficient mechanisms to provide the terminals with the necessary spectrum awareness information in flexible spectrum management scenarios
- Development of spectrum sensing techniques to detect unused spectrum bands in which secondary transmission can be allowed without causing interference to primary users
- Development of spectrum mobility (spectrum handoff) techniques for secondary spectrum usage
- Development of spectrum scheduling techniques to organise secondary transmissions over a licensed band

5.4 Cognitive networks

Cognitive networks concept

The word 'cognitive' has recently been used in different contexts related to computing, communications and networking technologies, including the cognitive radio terminology coined by. J. Mitola III [5.26] and the cognitive network concept. Several definitions of cognitive networks have been proposed up to date, but all of them have one thing in common: they present a vision of a network which has the ability to think, learn and remember in order to adapt in response to conditions or events based on the reasoning and prior acquired knowledge, with the objective of achieving some end-to-end goals [5.27].

The central mechanism of the cognitive network is the cognitive process, which can perceive current network conditions, and then plan, decide and act on those conditions. Then, this is the process that does the learning and decides on the appropriate response to observed network behaviour [5.28]. The cognitive process acts following a feedback loop in which past interactions with the environment guide current and future interactions. This is commonly called the OODA (Observe, Orient, Decide and Act) loop, which has been used in very different applications ranging from business management to artificial intelligence, and which is analogous to the cognition cycle described by Mitola in the context of cognitive radios.

In the cognitive behaviour, the perception of the stimulus is the means to react to the environment and to learn the rules that permit to adapt to this environment. This is directly related with the observation phase of the cognition cycle, which tries to capture the network status. This involves a large number of measurements and metrics that can be obtained at different network elements. It is important to identify which are the most relevant ones for each phase of the cognition cycle, since measurements relevant for a particular function need to reach the network element where the corresponding function is implemented. Measurements and metrics of interest may be at connection level (e.g. path loss from terminal to cell site, average bit rate achieved over a certain period of time, etc.) or at system level (e.g. cell load, average cell throughput achieved over a certain period of time, etc.). It is worth mentioning here that the observation function may bring the "sensing concept" to all the layers of the protocol stack, depending on which are the aspects to be observed (e.g. not only the measurement of radio electrical signals at the physical layer should be addressed but also the configuration of different applications or network protocols can be also considered). Any means that permits to analyze the environment, and that may be helpful for the adaptation of the communication system to the constraints imposed by the environment, is worth being taken into account.

Being the learning one the most relevant aspects for a cognitive network, many strategies have been envisaged in the literature as learning procedures with the ultimate goal of acquiring knowledge. In particular, machine learning has been widely considered as a particularly suited framework, with multiple possible approaches. The choice of the proper machine learning algorithm depends on the desired network goals. In any case, one of the main challenges here is that the process needs to be able to learn or converge to a solution faster than the network status changes, and then re-learn and re-converge to new solutions when the status changes again, so that convergence issues are of particular importance. Machine learning algorithms can also be organised in different categories (supervised learning, unsupervised learning, semi-supervised learning, and reinforcement learning being the most common ones) depending on how their desired outcome is obtained. Some of the identified machine learning strategies studied in the literature are neural networks, genetic algorithms, expert systems, case-based reasoning, Bayesian statistics, Q-learning, etc.

From the above considerations, it is clear that the term cognitive network is not limited to wireless networks but can be applied to any type of network. In any case, in the particular wireless context and the complexity associated with future wireless networks, cognitive networks can have wide ranges of applications thanks to the capability of building self-managing or autonomic networks, able to reconfigure automatically without human intervention. Specifically, some of the applications can be the development of automated tuning of (J)RRM parameters in wireless networks, or the design of flexible spectrum management techniques, not only from the terminal perspective (e.g. the possibility that a secondary spectrum usage is carried out when terminals are able to detect some unused spectrum bands) but also from the network side (e.g. the possibility to automatically decide the amount of spectrum to be assigned to a set of cells in a wireless network).

Summary of open problems

When trying to identify some research challenges related with cognitive networks, they are mainly related with each specific application of the cognitive network concept. In any case, focusing on the wireless world, some of the general open issues that deserve further investigation are outlined in the following. For a detailed overview of the different approaches and mechanisms in this field the reader is referred to [5.27][5.29].

- Development of the appropriate sensing mechanisms to observe the environment. In this line, some activities such as the sensorial radio bubble or the standard recognition sensor are already being investigated in NEWCOM WPR9.
- Development of cooperative communication mechanisms so that different nodes in a network can share their observation measurements to take appropriate decisions (i.e. combination of the complementarities offered by cooperative and cognitive techniques).
- Development of learning strategies fitted to the particular problem and leading towards the autonomous networking.

5.5 Opportunistic networks

The emerging paradigm of opportunistic communication enables nodes and user devices to self-configure and exploit resources in extremely dynamic networks. It encompasses features and methods that are especially suitable in both disconnected environments, in which islands of connected devices suddenly appear, disappear and reconfigure dynamically, and pervasive networking scenarios, where epidemic data exchanges occur among mobile devices in temporary proximity.

Opportunistic networks can be seen as an evolution of mobile ad-hoc networks in which mobile nodes are enabled to communicate with each other even if a route connecting them never exists [5.30]. They provide a way to communicate source and destination nodes that might never be connected to the same network, at the same time. Routes between source and destination are built dynamically, and any possible node can opportunistically be used as next hop. In this way, resources of different networks can be exploited in accordance with the needs of specific application tasks. Usually this capability of communicating not connected nodes comes at the price of additional delay in messages delivery, since messages are often buffered in the network waiting for a path towards the destination to be available.

Opportunism in wireless networks is a very recent concept getting a growing attention in the latest literature even though it is used by different authors with slightly different meanings. In particular, two main research trends appear to be the most relevant, namely the Delay Tolerant Networks (DTNs) and the oppnets, as discussed in the following.

Delay Tolerant Networks

A Delay Tolerant Network (DTN) is defined as a network of regional networks, where a regional network relies on its own protocol stack. All the nodes of the regional network use the same type of communication mechanism [5.30]. Then, a DTN is an overlay which supports the interoperability of regional networks which may be characterised by one or more of the following characteristics: intermittent connectivity, long or variable delay, asymmetric data rate and high error rate.

DTNs have applicability in different situations:

a) Terrestrial Mobile Networks. Some of these networks may become unexpectedly partitioned due to node mobility or changes in signal strength, while others may be partitioned in a predictable manner.
b) Non-conventional Media Networks. They include near-Earth satellite communications, deep space communications and acoustic links in air or water. These systems may be subject to high latencies with predictable interruptions.
c) Tactical Ad Hoc Networks. These systems can operate in hostile environment where different factors may be cause for disconnections.
d) Sensor/Actuator Networks. Here the intermittent behaviour is given by the periodic active/sleep state of nodes, rather than by their mobility.

The overlay network which characterises the DTN architecture has the task to act as a Gateway to allow the communication between different types of networks. In particular, a DTN may support different wireless technologies including radio frequency (RF), ultra-wide band (UWB), free-space optical and acoustic (sonar and ultrasonar) technologies.

The characteristics of DTNs are clearly different from the common networks where we assume that there is a continuous and bidirectional path between the source and destinations with reliable and fast symmetric links. Instead, in a DTN a mechanism is needed which allows to move a message from a storage place to another storage place, along a path that we suppose reaches the destination. This mechanism is called the store-carry-forward mechanism because if a message cannot be delivered immediately, each node in the network holds it and waits for future contact opportunities with other devices to forward it. Obviously, the best carriers are those having the highest chance of successful delivery.

The most representative opportunistic networking applications, which fall under the research trend of Delay Tolerant Networks, are the Pocket Switched Networks (PSNs), Autonomic Networks and Socio-Aware Community Networks (see [5.7] for details).

Oppnets

Oppnets constitute the category of ad hoc networks where diverse systems, not originally employed as nodes of an oppnet, join it dynamically in order to perform certain tasks in which they have been called to participate [5.31]. Oppnets differ from traditional networks, in which the nodes of a single network are all deployed together, with the size of the network and locations of its nodes pre-designed. In oppnets, the initial seed oppnet grows into an expanded oppnet by taking in foreign nodes. In other words, diverse devices join the original set of seed nodes to help the oppnet realise its goals and are so called helpers. In fact, it might happen that the resources available in the seed oppnet are not sufficient to accomplish a given task; in such situation, the network can try to scan the radio environment, detect the presence of other networks deployed for different tasks (e.g. WiFi hot spots, or computer networks in an office environment, or GSM/UMTS public networks) and address such helper networks trying to exploit their available resources.

Oppnets might be perceived as networks that lie within the intersection of ad hoc networks, P2P systems, and sensor networks. They can be used for emergency situations and homeland security. In predictable disasters (e.g. hurricanes), seed nodes can be put into action before the disaster when it is much easier to locate and invite other nodes. For example, the first invited helpers could be the sensor nodes deployed for monitoring buildings, roads, etc. In emergency situations, entities with any sensing capabilities (whether members of sensornets or not), such as cell phones with GPS or desktops equipped with surveillance cameras, can be especially valuable for the oppnet.

Properties and requirements of opportunistic networks

In an opportunistic network, nodes are typically mobile (e.g., pedestrian users or vehicles), although some fixed nodes may be present as well. Nodes can discover each other and communicate by using all kinds of communication media, including Bluetooth, WiFi, RFID, cellular-based technologies, etc. Also, some of them may act as point of access toward the fixed Internet or a satellite link.

As it has been mentioned, an end-to-end path between the source and the destination may never exist, and, due to link variability, even if it exists, it may last only for a brief and unpredictable period of time. To solve this issue, node mobility and local forwarding can be exploited for data transferring: the network nodes can store and carry data around while they are moving, and then forward the data during opportunistic contacts. During these opportunistic contacts, entire chunks of a message can be transferred from one storage place to a storage place in another node. Then, it follows that nodes may transfer data to the destination either through single-hop transmissions or using the multihop paradigm (i.e., along a path that is expected to reach the destination).

The intermediate nodes between a source and a destination implement the store-carry-forward message switching mechanism, by overlaying a new protocol layer, called the bundle layer, on top of heterogeneous region-specific lower layers. Thus, in an opportunistic network, each node is an entity with a bundle layer which can act as a host, a router (i.e. carrying messages between nodes in the same region) or a gateway (i.e. forwarding messages between two or more regions).

In an opportunistic network, whenever nodes move away or turn off their power to conserve energy, links may be disrupted or shut down periodically. These events result in intermittent connectivity. In such a context, the following aspects are of particular importance:

- Contact opportunity: Due to the node mobility or the dynamics of the wireless channel, a node might make contact with other nodes at an unpredicted time. Since contacts between nodes are hardly predictable, they must be exploited opportunistically for exchanging messages between some nodes that can move between remote fragments of the network. In addition, the contact capacity needs to be considered, i.e., in other words, how much data can be transferred between two nodes when they are in contact with each other.

- Storage constraints: As described above, to avoid dropping packets, the intermediate nodes are required to have enough capacity to store all messages for an unpredictable period of time until next contact occurs. In other words, the required storage space increases as a function of the number of messages in the network. Therefore, the routing and replication strategies must take the storage constraint into consideration. If the node storage capabilities are limited, a buffer-management (i.e., data drop) strategy must be implemented.

- Cooperation level: In many cases, in opportunistic networks nodes may be required to provide their own resources (e.g., memory, bandwidth, battery power) for others to use, without getting any direct benefit from that. A strategy based on reciprocal altruism (also said Tit-for-Tat) may not be sufficient to guarantee cooperation, especially in a mobile environment, where also observations on the node behaviour may be affected by errors.
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Summary of open problems

Based on the above discussions, the main research challenges in the field of opportunistic networking depend on the two types of opportunistic networks considered. In particular, in DTNs the main issue to be investigated is the routing and forwarding approach, while in oppnets the main research challenge corresponds to the resource discovery.

Focusing on the routing/forwarding techniques the main problem arises due to the intermittent connectivity between nodes. Consequently, it is important to characterise how long are the transmission opportunities (contact duration) and how long are the time gaps between transmission opportunities (inter-contact time), because they impact on the storage period of the information at the different nodes. In the literature there are two categorizations of routing protocols, being the first one based on the type of network [5.32] (i.e. without infrastructure and with infrastructure) and the second one based on the evolution of the network [5.33] (i.e. the future topology of the network is either deterministic or stochastic). The reader is referred to NEWCOM++ deliverable DR11.1 [5.7] and references therein for an exhaustive list of the corresponding protocols in each case.

On the other hand, concerning the resource discovery algorithms, of interest in the case of oppnets, it is necessary to develop methods to detect helpers with useful resources and facilities, as well as methods to invite candidate helpers and to control helpers. Similarly, methods for deciding which tasks should be "offloaded" by oppnet to its helpers, and techniques for coordinating helper tasks by oppnets need also to be developed. In this context, also the analysis of spatial mobility allows developing enhanced mobility models, improve location and mobility management, and making mobility predictions, which can facilitate the task of resource discovery.

Finally, another relevant aspect in oppnets is the impact on the scheduling and resource allocation mechanisms. Being the network composed of nodes accessing the radio channel via different air interfaces, the scheduling and resource allocation units need to be unified and consider all users jointly in the optimisation process. In this case, however, since a fully optimised scheduling could require an infeasible complexity, it may be useful to split it in some steps, even though it leads to a suboptimal solution. It is worth mentioning that DTNs, on the contrary, do not present relevant MAC and scheduling issues because, due to sparseness, network communications reduce to communications between pairs, thus not needing resource allocation among a multiplicity of users.

5.6 Relaying and cooperation

Cooperative communications

In the mid 1990s, the use of the spatial dimension of the wireless channel by the use of multiple antennas at the transmitter and/or receiver was identified as a means to achieve huge performance gains with the so-called multiple-input multiple-output (MIMO) communications. They can be designed to provide either a diversity or a multiplexing gain by using appropriate space-time pre-coding techniques. In cases where the devices cannot support multiple antennas, the spatial dimension of the channel can still be exploited by using cooperation. Roughly speaking, this means that several terminals, each with one or more antennas, form a kind of coalition to cooperatively act as a large transmit or receive array. This approach conveys to the channel some characteristics of the MIMO transmission and provides a cooperative diversity gain. In contrast to the more conventional form of space diversity built upon physical arrays, creating and exploiting space diversity using a collection of distributed antennas belonging to multiple terminals, each with its own information to transmit, makes the terminals share their resources to form a virtual array through distributed transmission and signal processing. Earlier works on cooperative communications can be found in [5.34] and [5.35]. Cooperative diversity has been studied in [5.36][5.37] for cellular networks and in [5.38] for ad hoc networks. Cooperative transmission might occur, for example, in a multihop wireless network or a sensor network. These networks consist of a group of nodes that communicate with each other over a wireless channel without the assistance of any centralised control. Examples of applications include networking mobile computer users on a campus, coordinating an emergency rescue, Bluetooth and automated transportation systems. A more involved application is that of communication systems that incorporate relaying and user cooperation to achieve higher throughput.

The simplest form of cooperative diversity is the one with one transmitter-receiver pair and a relay node, commonly known as the relay channel (RC) [5.39]. The study of the RC is of fundamental importance to cooperation in wireless networks since it captures the fundamental ability of a user to assist in transferring information from a source to its destination– a situation which is prevalent in wireless networks due to the sharing of wireless medium among all users. More complicated relay networks have also been studied including relay networks with multiple relay nodes simultaneously relaying information to destination, relay networks with multiple levels of relay nodes forwarding information from one level to the next and relay networks with multiple cooperative sources or destinations. More involved scenarios have the relay nodes also decoding (and/or sending) dedicated messages.

Cooperative network models

A general cooperative network model considers a situation in which two source-destination pairs communicate through a multiplicity of nodes. Each node can communicate with any other node as all intermediate nodes act not only as relays but also as receivers. In this general model, the following types of cooperative networks exist:

a) Relay network:

This corresponds to the particular case in which the intermediate nodes only act as relays (i.e., they receive no dedicated information or stated otherwise they are just there to help the different transmitter-receiver pairs). From an information theoretical point-of-view, the capacity of this multiple node relay channel is unknown. Although the corresponding building block, the three-terminal RC, was introduced a long time ago, its capacity is known only under some restrictive conditions for the channel. The most thorough analysis to date of the T-node RC was provided most notably by Xie et al. [5.40] and also by Gupta [5.41], Kramer et al. [5.42] and Reznik et al. [5.43]. These information-theoretic studies of relay networks have motivated practical relaying protocols and code designs to achieve user cooperation diversity.

b) Relay broadcast network:

The relay broadcast network is a particular case for the downlink of a centralised network. The impact of relaying and user cooperation in this case has been investigated recently. The building block for this cooperation is the relay broadcast channel (RBC), which has potential use in rate demanding downlink transmissions, because relaying increases capacity. In a RBC, the relay node also receives a dedicated message from the transmitter. Depending on the degree of cooperation between nodes fully-cooperative and partially-cooperative relay broadcast networks can exist.

c) Multiple access relay network:

This corresponds to the particularization of the general model for the uplink in a centralised network. It is basically a multiple access channel exploiting the technique of relaying to improve the system throughput. These cooperative schemes have been explored in a number of recent works (see, e.g., [5.36][5.37][5.38][5.42]).

Network coding

Another form of cooperation that is emerging in the last years is the so-called network coding, which assumes the communication between source and destination is done through a multiplicity of relaying nodes. Network coding comprises the joint design of routing and coding in this multi-node scenario, under the idea that a node will not simply retransmit its received information but it will combine the information received from many nodes to then forward that joint information to other nodes. Then, the core notion of network coding is to allow mixing of data at intermediate network nodes so that the receiver can see these data packets and deduce from them the messages that were originally intended for that data sink [5.44].

Summary of open problems

Under the above framework, research in NEWCOM++ WPR6 addresses the potential of cooperative behaviour in the view of obtaining significant capacity and multiplexing gain in wireless communications. This encompasses strategies and codes (including error correcting codes, linear precoders or both) which exploit relaying diversity in order to realise seamless communication and reduce complexity of routing in highly volatile/mobile networks. Specifically, some of the identified open problems in this type of networks are listed in the following:

- Development of proper distributed space-time-frequency codes to better exploit the diversity in relay networks.
- Development of proper resource allocation strategies (power/bit rate allocation) for relayed OFDM systems.
- Development of MIMO relays (i.e. the combination of MIMO and cooperation to further increase the capacity and/or diversity of the system)
- Development of new linear receiver structures for Virtual MIMO Systems with a reasonable trade-off between complexity and performance
- Development of efficient cooperation protocols that efficiently allow relay nodes transmitting also their own information.
- Development of strategies to efficiently select the most adequate nodes that should cooperate in a mobile ad-hoc network

5.7 Network Theory

Network theory concepts

Wireless networks have several distinct characteristics that render the understanding, analysis, design methods developed for wired networks either invalid or inefficient. Specifically, wireless networks are signified by scarce bandwidth resources that need to be allocated carefully in order to achieve adequate user performance and efficient utilization of the wireless channel. Wireless channels are error-prone, wireless links are volatile and link quality in terms of error probability and available bandwidth is time-varying. Wireless devices are often mobile, implying that network topology changes over time. In addition, mobile devices use batteries as energy resources and this poses further constraints on how transmissions will be controlled and energy will be managed. More importantly, due to the broadcast nature of wireless transmissions, cross-channel interference becomes an important factor that needs to be judiciously taken into account when controlling the network.

Communication over a single wireless link has now reached a mature state of understanding, whose roots can be identified in the ground-breaking work of Claude Shannon. This work essentially founded the thrust of Information Theory. Information theory among others seeks to characterise the performance limits of communication over a single link. Wireless networks consist of a multitude of wireless links and numerous devices interconnected in a complicated manner. Wireless nodes come in the vicinity and engage in spontaneous interaction in order to carry out network specific tasks. While performance links over a single wireless link have been fully characterised, the corresponding goal in wireless networks is far from being achieved. The non-trivial way in which the network needs to be engineered so that flows traverse the network and the complex ways in which nodes interact with each other, together with the multi-faceted constraints in terms of spectrum, battery and delay set up very challenging problems and objectives [5.6].

In this respect, the main objective of network theory is to understand fundamental performance limits of wireless networks, together with the development of tools and techniques for approximating or even achieving these bounds. In the last few years a wave of research was focused on the need to characterise network transport capabilities of a large number of wireless nodes. This emerged from the need to characterize massively large network topologies that are expected to proliferate as the sensory extension of wireless internet. Specifically, in their seminal paper [5.45], Gupta and Kumar introduced the notion of transport capacity, which extends the Shannon capacity to account for the distance travelled by the data. They computed bounds on this transport capacity for both the protocol model, which is defined in geometrical terms by a spatial footprint taken by each transmission, and the physical model, which is defined in terms of the Signal to Interference and Noise Ratio (SINR). Starting from this work, this line of research has addressed the issue of how network capacity and user throughput scale with the number of nodes in a completely wireless network.

The work of Gupta and Kumar accepts several extensions towards different directions, particularly when wireless networks with infrastructure support are considered. The basic result derived in this works is that, in order for the infrastructure to have an effect on the capacity of the network, the investment in it must exceed a given threshold. Below that threshold, the infrastructure is useless, since employing the infrastructure will result in bottlenecks, and the nodes are better off using the wireless network they form. On the contrary, when operating above that threshold, the network should make extensive use of it without using any multi-hop wireless routing at all.

The work of Gupta and Kumar assumes that the nodes are static, or at least that they are moving on time scales that are much greater than the allowable delays. The first work to consider networks with mobile nodes was from Grossglauser and Tse [5.46]. There, the authors assume a number of nodes moving within a unit disk, according to an ergodic process that covers the disk uniformly and independently of each other. The authors prove that it is possible for each node to communicate directly its destination, with a rate that does not decrease as the number of nodes goes to infinity. Therefore, the aggregate throughput increases linearly with the number of nodes.

Another aspect of network theory is the characterisation of connectivity of wireless networks. Works in this area are mainly based on the percolation theory on lattices. In the particular case of wireless sensor networks as well as ad-hoc and mesh networks, connectivity aspects have been also intensively studied recently, with emphasis on the impact of connectivity on node isolation and network end-to-end information transfer capability.

Focusing on combined scheduling, routing and flow control, the back-pressure network control policy [5.47] has been shown to achieve the maximum end-to-end network throughput. More specifically, if the traffic loads are such that the network as a system is stabilisable, then the back-pressure policy will transfer the traffic loads to their destinations while maintaining bounded node buffers. This strategy has inspired different scheduling and routing algorithms in wireless networks with time-varying connectivity. Similarly, distributed implementations of the back-pressure network control algorithm are currently being analysed.

A defining characteristic of envisioned wireless networks is the requirement that they should operate in an autonomous fashion, in the absence of a central monitoring entity. In this setting, nodes will have motive to deviate from legitimate protocol operation in an effort to obtain more share of resources and satisfy their needs. It is therefore necessary to devise mechanisms for ensuring proper autonomous operation of wireless networks. In this framework, game theory results in an appropriate tool and there exist different forms of games that model selfish behaviour and the evolution of selfish node interactions.

When considering large wireless networks it is important to study the tradeoffs between the most important performance metrics characterizing the wireless network: such as the throughput, delay and energy consumption, or lifetime. In this framework, there exist some results and laws between achievable throughput and packet delay in wireless networks and different associated throughput-delay scaling laws. These laws can be extended for the case of energy constrained wireless networks by bringing into stage known results about scaling laws of energy versus delay and by using previous results for the case of unconstrained energy.

Summary of open problems

The main open problems addressed by network theory, currently under investigation in NEWCOM++ WPR10, can be summarised as follows:

- Determine and characterise the fundamental performance limits of wireless networks in terms of throughput, delay and energy efficiency, and to identify fundamental tradeoffs among these parameters. Specifically, it is important to address fundamental theoretical aspects which are essential for wireless networks, including scaling laws and asymptotic behaviour of wireless systems when

users and nodes dramatically increase, theoretical bounds to such metrics as capacity and network lifetime.
- Develop a network information theory for understanding the theoretical foundations necessary for quantifying fundamental performance limits of wireless networks in capacity, throughput, and delay and devise techniques to closely approximate and even achieve them.
- Understand fundamental tradeoffs and interdependencies in wireless networks, including the interplay between capacity, energy consumption, stability and delay. To this end, information theory will be combined with non-classical constraints such as finite battery life, traffic characteristics, topology and mobility.
- Devise distributed optimisation and game-theoretic methods for distributed self-regulating wireless network paradigms, ranging from wireless sensory ones to wireless overlays and autonomous computing. The focus should be on decentralization of network operations and its impact of wireless networks fundamental performance limits.

5.8 Joint Source and Channel Coding/Decoding (JSCC/D)

JSCC/D concept

Due to bandwidth constraints, efficient transmission of multimedia contents requires the use of some source coding scheme. However, compressed data are very sensitive to transmission errors. A single corrupted bit may lead to a loss of a large amount of multimedia data at the receiver. Consequently, the bit stream entering the source decoder has to be almost error-free. This constraint is hardly satisfied when considering transmission over wireless channels. The data stream at receiver side may be heavily corrupted and not directly usable by the source decoder. A first solution to this problem consists in grouping data into packets protected by an error-detection code (CRC or checksum). Packets which have not been correctly received are identified, and can then be retransmitted. Nevertheless, retransmissions may become difficult in scenarios with strong delay constraints, e.g., for visiophony, or may even become impossible when broadcasting data, e.g., in satellite television. In such situations, the standard solutions make use of very strong error-correcting codes at Physical layer combined with packet-erasure codes at intermediate protocol layers. The redundancy introduced by these codes may however be oversized when the channel is good, reducing the bandwidth allocated for the data. In bad channel conditions, some corrupted packets still cannot be recovered, and are assumed lost. Error-concealment techniques may then be used by the source decoders at Application (APL) layer. They exploit the redundancy (temporal and/or spatial) found in the multimedia data for estimating the missing information.

In the recent years, joint source-channel coding/decoding (JSCC/D) techniques have been proposed as cross-layer techniques to correct damaged packets (see e.g. [5.48][5.49]). These methods involve robust source decoders, which exploit the inherent redundancy in the received packets for correcting errors. Several sources of redundancy have been identified. Constraints in the syntax of variable-length source codes have been used first. Redundancy due to the semantic of the source coders improves significantly the performance of robust decoders. Altogether, the various redundancies can attain an unexpected amount. Furthermore, redundancy introduced by channel codes at PHY layer can also be used in combination with residual redundancy to build iterative decoders.

Joint decoding schemes provide improved performance when compared to classical schemes, and could be of great use in many applications. However, they are not compliant with the standard protocol stacks in several aspects. First, they require exchange of soft information between the channel decoders at PHY layer and the robust source decoders at APL layer. Consequently, this poses a number of research challenges to make this approach feasible. The main compatibility problem is that standard protocol stacks do not even allow damaged packets to reach the APL layer, the main reason being that the errors may impact some essential information contained in the headers, which is necessary even for the robust APL decoders.

Joint source-channel decoding techniques allow at APL layer the correction of many errors based on soft information provided by lower protocol layers. As an example, the recently introduced UDP-Lite mechanism, combined with lower permeable protocol layers [5.50], allows packets with binary errors to be fed to the APL layer. With UDP-Lite, a checksum protects a limited number of bytes (generally including the UDP-Lite, RTP, and APL header fields). Thus, packets with erroneous headers are still discarded, even if their payloads contain only few erroneous bits. This constitutes the bottleneck of this permeable transmission scheme.

With the permeable protocol stack the idea is that the various source of redundancy in the protocol stack can be used to recover headers, increasing the amount of packets that can be used for robust decoding at APL layer. As a result, the efficiency of joint source-channel decoding techniques at APL layer may be improved.

Complexity is a very important issue for JSCC/D techniques. In that respect, some solutions have been proposed using simplified stack-based decoding algorithms for Huffmann Variable Length Codes (VLC). In this case, the complexity is mainly reduced for good channel conditions, while it may remain intractable in poor channel conditions. In contrast, trellis-based techniques keep a constant but high complexity when varying channel conditions. The M-algorithm and its soft-output variant allow building reduced but constant complexity estimation algorithms for variable-length codes. The price to be paid in this case is a suboptimality of the decoder when the noise level increases.

Another trend in the JSCC/D field is the use of distributed source coding in multi-terminal networks, which finds its foundation in the seminal Slepian-Wolf (SW) [5.51] and Wyner-Ziv (WZ) [5.52] theorems.

Summary of open problems

Based on the above considerations, some of the open problems in the field of JSCC/D are listed in the following, being under research in NEWCOM++ WPR7. The reader is referred to the corresponding deliverable DR7.1 [5.3] for more details on each of these concepts:

- Development of optimal JSCC/D algorithms with reduced complexity
- Cross-layer optimisation by selecting the best allocation of redundancy in the different protocol layers.
- Development of joint source channel coding mechanisms for fading channels
- Development of joint source coding and network coding mechanisms
- Merging successive refinement and broadcast channel coding
- Multiple descriptions with side information at the decoder
- Development of distributed source coding mechanisms.

SECTION 6 - INFORMATION SOCIETY TRENDS IN WCNS

6.1 Personal Needs and the ICT European Context

A good starting point to describe the overall picture of the ICT European context is to consider the society conditions in which the ICT evolution and innovation are taking place. Thus the focus is firstly put on the individual, in line with the approaches undertaken in parallel by other policy programmes in Europe, among which it is worth citing the AAL (Ambient Assisted Living) programme as the champion for focused attention on the human being [6.3].

Indeed, the individual person is always at the centre of any societal development, because any transformation translates necessarily into modifications of personal habits, and often is actually resting upon their intrinsic nature. Re-interpreting in a more modern key the classical approach by Maslow [6.4] who modeled the personal necessities through a universally famous pyramid, needs can be grouped into 8 major categories as described in the map in Figure 1.

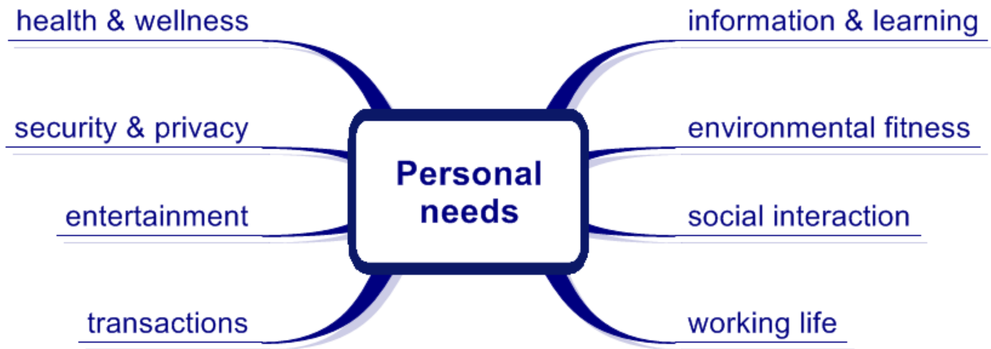

Figure 1 – The map of personal needs

It is interesting to note that each of these 8 categories of needs can be linked to a series of clear trends in the current ICT European arena. Accordingly, insight into this classification is a useful starting point to guide us towards the identification of the ICT trend roadmap:

1. **INFORMATION AND LEARNING** is the natural need for knowing, being up-to-date and informed anytime and anywhere, which has assumed a particularly compelling connotation in recent years with the rapid and capillary diffusion of Internet applications. In the digital era, the person is more and more eager to reach rapidly and efficiently all contents he/she needs in a precise moment, at home, at work, on the move. This trend is confirmed by the interest towards the creation of *digital libraries* in the current European research framework programme, and by the advent of new applications aiming at satisfying the user thirst for receiving information and learning in remote areas, in the form of e-learning. As broadband becomes a necessity of daily life (*broadband for all*), the impact of information exclusion for citizens that do not have broadband access or who cannot afford it will be dramatic. Today's digital divide may become tomorrow's social-exclusion.

2. **ENVIRONMENTAL FITNESS** is a broad interpretation of the necessity for any human being to adapt the surrounding ambient to its habits in order to allow comfortable living. This need is mapped onto a series of ICT trends that can be identified in the current picture. First of all, *mobility* reflects the possibility for the user to communicate, work, be entertained, and more generically reach the outside world while being on-the-move, a very popular and wide-spread tendency among users of all kinds (from consumer to professional and institutional). Ubiquitous multimedia communications have been the key to third generation cellular standards, and foreseen to become even more attractive in the next future. The current trend towards *info-mobility* is a specification of the wider mobility concept, consisting in the distribution of information to passengers of various transport means. The most relevant

example is that of car passengers, which opens the way to more sophisticated applications such as Automatic Vehicle Monitoring or *intelligent cars* (the Intelligent Cars Initiative, i2010 [6.5]). *Ambient awareness* is another form of environmental fitness, integrating aspects of ambient intelligence into context awareness systems. A key role is played by navigation systems, such as GPS or the European Galileo, which enable location-based services. The process of adaptation of the surrounding environment to the user ICT experience should avoid to forget the environmental footprint, identifying solutions to exploit resources efficiently and favour sustainability, in line with the *Green IT* and *energy efficiency* requirements.

3. **SOCIAL INTERACTION** is the natural need of humans to belong to some form of society, from a small scale (a family, a group) to a larger scale (a community, a Country), in response to the continuous search for support, discussion, comparison and opinion exchange with other persons. This need takes a completely new connotation with the recent technology advances. In particular, it is worth mentioning here the tendency for *social networking*, so highly popular nowadays amongst younger generations, and the trend towards virtual interactions in *cyber-realities* where all aspects of life can be artificially re-constructed, through the creation of virtual identities or avatars (Second Life). The web is now used in a participative mode, as testified by the success of a number of applications such as Wikipedia, blogs, MySpace, Facebook, YouTube, GoogleMaps, etcetera. In this framework, other foreseen trends are *enhanced reality* (with brain electrochemical stimulation), and *augmented reality* (combination of real and digitally modified identities and environment).

4. **WORKING LIFE**, is the need for self-fulfillment and self achievement realised through working activities, which enables to exploit talents and education, contributing fundamentally to self-esteem. The need for a satisfactory working life is reflected in an important ICT trend, that we can identify as *e-Business*, comprising home-based or mobile-based teleworking, broadband connection between different enterprise premises, remote training, videoconferencing, etcetera. The nomadic use of ICT will challenge the meaning of 'being at work'.

5. **TRANSACTIONS** is the need of humans to be supplied with services and goods in order to satisfy material/immaterial desires. ICT can be of help here with the supply of a host of *e-commerce* tools, that can be used in business, private, or consumer contexts. Home banking is but one example.

6. **ENTERTAINMENT** is the need for amusement and hobbies, to aliment the innate human tendencies towards recreation. In partial overlap with the social interaction need when applied to the personal sphere, the necessity for entertainment is one of the most typical goals of ICT services, taking on various forms such as on-line gaming, portable consoles, mobile TV, P2P downloads, MP3 players, social networking (YouTube, Facebook, SecondLife), etcetera. Indeed, social networking is a direct response to the entertainment need.

7. **SECURITY AND PRIVACY** are primary needs of any person to feel protected during any aspect of life. In particular, this translates into the need for preserved secrecy on private data, which becomes a real social challenge in an era where communication of personal digital data is at the center of many applications, especially web-based Internet applications. In the digital economy, public authorities have the responsibility to make sure that citizens can trust the use of the Internet, combating cybercrime, avoiding episodes of personal identity theft and of malware (malicious software) dissemination via spam and website attacks, and improving at the same time the authentication, validation and *digital identity management* for high level transactions (Internet banking).

8. **HEALTH AND WELLNESS** is the last but fundamental need of humans for truly satisfactory livelihood, which should be provided anywhere and anytime thanks to the ICT enablers. As a prominent example, *e-health* applications remotely assist patients, for example exploiting

body area networks capable of monitoring vital parameters. E-heath ICT is the response to critical social challenges such as *home care* (or domiciliary care), i.e. health care or supportive care provided in the patient home by healthcare professionals, and *independent living*, i.e. supporting assistance to disabled people. All of this at a significantly reduced social cost.

ICT can indubitably be considered as an enabler for satisfying these user needs via different forms of response, as outlined above. Europe is investing considerably in research activities in these fields, to devise novel and efficient applications in response to the user primary needs and to solve the social challenges posed by continuous evolution and innovation.

However, scientific research is not the only measure. For the first time, a conspicuous effort is being directed towards investing on ICT infrastructures, via the so called European structural funds. Indeed, 20% of the overall budget for 2007-2013 must be devoted to the introduction of ICT innovation. This European cohesion policy aims at ensuring that less developed regions, and regions confronted with serious structural change, can improve and contribute to European competitiveness. This fact will be essential to support the major investments needed to create the basic ICT backbone able to sustain the entire ICT evolution in the next future, i.e. the high-speed Internet architecture and telecom infrastructure. Founding the Internet of the future is one of the main challenges of the European i2010 strategy that will contribute in accelerating the pace of change. Indeed, the sheer scale and complexity of nomadic computing and the new forms of the future Internet, will place the existing Internet architecture under strain, requiring quantum leap progress in terms of scalability, mobility, flexibility, security, trust and robustness. Considering the 8 personal needs described above, we can observe that the concept of *future Internet* can be seen as a *common denominator* for their satisfaction, since:

- it provides the platform for applications and data storage for information and learning,
- it provides the most part of the contents that the user may want to receive while on-the-move and the reference structure for environmental fitness
- it is the central stage for ICT social interaction via the social web
- it is a new unavoidable platform for professional telework
- it is the new digital enabler for e-commerce transactions
- it provides new means to entertain, such as IPTV, communities, chats, on-line gaming
- it embodies the need for security and privacy
- it provides the platform and enabling data storage for remote health and wellness applications.

It is very interesting to note that this technological evolution is very much felt also at the highest political levels, as testified for example by the recent communication of the Commissioner for Information Society and Media, [6.2]: "*The Internet of the future will radically change our society" [6.…] providing "seamless 'anytime, anywhere' business, entertainment and social networking over fast, reliable and secure networks. It means the end of the divide between mobile and fixed lines.*"

Of course, the definition for the "Internet of the Future" is far from being obvious, and certainly not unique. Instead of attempting at this exercise, we can at least describe some of the most significant aspects that find broad support as important elements of this future network of networks [6.6], [6.7]:

- *participative web*, i.e. transformation of the Web from a network of separate applications and content repositories to a seamless and interoperable whole, with Social Network Sites at its basis;
- *semantic web*, whereby data is enriched by meta-information to allow efficient content search and filtering, in a common framework that allows data to be shared and reused across application, enterprise, and community boundaries, with semantic application platforms and statement-based data-storage (distributed semantic databases);
- *intelligent applications*, consisting in natural language processing, machine learning, machine reasoning, and autonomous agents that process meaning to enable the semantic web;

- *open technologies*, i.e. open APIs (Application Programming Interfaces) and protocols, widgets (portable code that any user can install and execute on its webpage), open data formats, open-source software platforms, and open data;
- *network computing*, i.e. Software-as-a-Service (SaaS) or cloud computing, the shared use of distributed computing resources as an alternative to in-house IT applications using local servers and personal devices (offering scale flexibility and cost-efficiency), which translates into Web services and distributed computing (for example, grid computing is a form of distributed computing whereby a "super and virtual computer" is composed of a cluster of networked, loosely-coupled computers, acting in concert to perform very large tasks);
- *portable identity* (to allow Internet users to log on to many different web sites using a single digital identity) and roaming of portable identity and personal data;
- *ubiquitous connectivity*, i.e. broadband adoption and mobile Internet access via mobile and portable devices.

It is worthwhile noting that also in the business arena social networking tools, collaboration, together with the emergence of the SaaS concept, will lead to a new generation of computer services available on demand and with much reduced overheads. Internet-based enterprise software is expected to grow worldwide at a rate of about 15% in 2006-2011.

It is evident that these expected developments of future Internet applications and services will generate unprecedented volumes of IP traffic, requiring significant strengthening of transport capacity both in the core and at the edges of the network. To fix ideas with numbers, it is useful to quote a recent Cisco white paper [6.9], focusing on estimates of IP traffic in 2012.

- *Annual global IP Traffic will exceed half a zettabyte (10^{21} bytes) in four years***.** At just under 44 exabytes per month, the annual run rate of traffic in late 2012 will be 522 exabytes per year. A zettabyte, or 1,000 exabytes, will be the new milestone to look for beyond 2012. IP traffic includes both Internet traffic and traditional telecom/broadcast traffic transported over IP. The Internet itself in 2012 will be 75 times larger than it was in 2002. Internet traffic will generate 28 exabytes per month in 2012, the equivalent of seven billion DVDs each month.
- *Global IP traffic will nearly double every two years through 2012***.** Total IP traffic in 2012 will be four times larger than it is in 2008. Growth will be driven by high definition video and high-speed broadband penetration, at a compound annual growth rate (CAGR) of 46 percent.
- *P2P is growing in volume, but declining as a percentage***.** Peer-to-peer (P2P) file sharing networks in June 2008 are carrying 600 petabytes per month more than they did in June 2007, which means there is the equivalent of an additional 150 million DVDs (1 DVD contains approx 4 Gbytes) crossing the network each month, for a total monthly volume of over 500 million DVD equivalents, or two exabytes. Despite this growth, P2P as a percentage of consumer Internet traffic dropped to 51 percent at the end of 2007, down from 60 percent in 2006, and is estimated to drop to 44 percent by the end of 2008. The decline in traffic-share is due primarily to the increasing share of video traffic. A secondary factor in the decline is a trend toward web-based file sharing in place of P2P file sharing in some regions.
- *Internet video is now approximately one-quarter of all consumer Internet traffic***,** not including the amount of video exchanged through P2P file sharing. Internet video was 22 percent at the end of 2007, and will reach 32 percent by the end of 2008.
- *The sum of all forms of video (TV, VoD, Internet, and P2P) will account for close to 90 percent of consumer traffic by 2012***.** Internet video alone will account for nearly 50 percent of all consumer Internet traffic in 2012.
- *YouTube is just the beginning. Online video will experience three waves of growth***.** Even with a six-fold increase between 2007 and 2012, current Internet video growth is in its initial stages. Internet video to the PC screen will soon be exceeded by a second wave arising from the delivery of Internet video to the TV screen. Beyond 2015, a third wave of video traffic will result from video communications.
- *Video communications and dynamic video content will ultimately test the Internet more than pre-recorded video content.* Service providers have a host of options available to help ease the

burden of on-demand video traffic. Real-time video communications, on the other hand, will be a bandwidth burden with few remedies.

- *Mobile data traffic will double each year from now through 2012.* Mobile broadband-enabled laptops are creating sharp increases in mobile traffic. Mobile operators in many parts of the world are offering mobile broadband services at prices and speeds comparable to fixed broadband. Though there are often data caps on mobile broadband services that are far lower than those of fixed, some consumers are opting to forgo their fixed lines in favor of mobile. This has a familiar ring to it from the mobile voice substitution effect that began in the late nineties and is continuing today. As a result of the mobile broadband substitution effect, mobile data traffic in 2012 will be over twenty times what it is today.
- *Business IP traffic will grow at a CAGR of 35 percent from 2007 to 2012.* Increased broadband penetration in the small business segment and the increased adoption of advanced video communications in the enterprise segment will result in a CAGR of 35 percent for business IP traffic from 2007 to 2012.
- *TelePresence will start to be a significant driver of enterprise IP network traffic by 2012.* In 2012, the amount of TelePresence traffic on enterprise WANs will be more than five times the volume of the entire U.S. Internet backbone in 2000.

But this is not the end of the story. In fact, all of the above can be considered as an **Internet of Humans** (**IoH**), where the presence of the human element is always very close to the network and to the application. A whole new picture opens up when the main objective becomes the interconnections of objects, in a so-called **Internet of Things** (**IoT**). IoT entails seamless and self-configuring connection of devices, sensors, objects, rooms, machines, vehicles, etc. through fixed and wireless networks, based on *machine-to-machine* communications and RFID smart tags. The use of electronic tags and sensors will serve to extend the communication and monitoring potential of the network of networks, as will contribute to the introduction of computing power in everyday items. Advances in *nanotechnology* (i.e. manipulation of matter at the molecular level) will serve to further accelerate these developments [6.8]. The IoT concept finds particular relevance in a host of applications, such as for example:

- transportation through intelligent cars, logistics and traffic systems
- environmental fitness through smart buildings
- security systems
- health monitoring

IoT will represent an unprecedented challenge in terms of scalability, connectivity, security of the network.

We conclude this Section by a quick overview of the available **technologies** that must be leveraged upon to realise the practical implementation of the described ICT evolution in the pursuit of user needs satisfaction.

- *Broadband core network technologies.* Here, the undisputed queen will be the optical communication technology, the only capable to sustain the immense traffic offer that the future Internet will generate. Advances in optical fiber process, laser characteristics, dense wavelength division multiplexing techniques, optical switching and signal processing will bring enormous benefits in handling Tera-bps flows with sustainable power consumption.
- *Access technologies.* This will be the arena for fierce competition among several technologies, such as xDSL, fiber-to-the-home, wireless, and satellite, with broadband data rate that will range from 30Mbps up to 10Gbps. Wireless technology, the focus of the Newcom++ NoE, may be seen as the more flexible and economic of all the alternatives. The network of the future will be prevalently constituted by an optical core network terminated at the edges by broadband wireless access.
- *Media and broadcasting* of digital content via satellite (DVB-S2, DVB-RCS with mobile extension, DVB-SH), cable (DVB-C2), and terrestrial networks (DVB-T2, DVB-H), along with the advent of high definition and 3D standards, and IPTV delivery via the Internet.

- *Software technology*, through the already discussed concepts of network computing, SaaS, Web Services, Service Oriented Architecture (SOA), Semantic Web, Distributed databases, open source.
- *Embedded systems* and *sensor networks,* to embed sensing and intelligence in materials and environment, in line with the IoT and ambient intelligence trends. An example is provided by the deployment of passive RFID tags. Miniature wireless chips are being embedded in objects, such as security passes or medical devices, to provide broad access to digital content in the physical world (e-health). Ultra wideband (UWB) technology is also worth to be mentioned, often used in conjunction with RFID technology for high precision e-health applications.
- *Nano-technologies*, providing the necessary electronics and miniaturization to enable a myriad of new applications, including the embedded utilization of tags and sensors. Indeed, advances in nano-technologies will imply that smaller and smaller objects will have the necessity to interact and connect to the network, from local area networks to homes and offices, further down to personal and body area networks, and conceivably down to networks of nano-systems.
- *Location and positioning technologies*, exploiting a combination of satellite-based navigation systems (GPS, Galileo, Glonass, etcetera) and of terrestrial positioning methods, exploiting cellular and wireless networks.

6.2 Major trends in the ICT world

We must now take on an original point of view and try to give a fresh reading of the above discussion on the European ICT context, identifying what we believe are the underlying and unifying major trends. We have seen that there exist many trends, in response to various personal needs, and it is difficult or even unnecessary to give a ranking, but it is possible and useful to try to classify them in order to make the discussion more interesting and organised. It is clear that from the point of view of Newcom++, we will always have to specify clearly where and how each specific trend has a bearing onto wireless systems.

We elect to say that the two main forces which are governing the revolution brought in by ICT technologies are *personalization* and *distribution*. Using a biological metaphor, we can think of *personalization* and *distribution* as the two strands, the two filaments, in a DNA structure, upon which and through which other trends are formed. This is what we call *The DNA of ICT evolution*, represented pictorially in Figure 2. The two filaments generate and are linked by the bases, each one corresponding to a major ICT trend. Therefore, in the following we will identify *personalization* and *distribution* as meta-trends, or “trends of trends”.

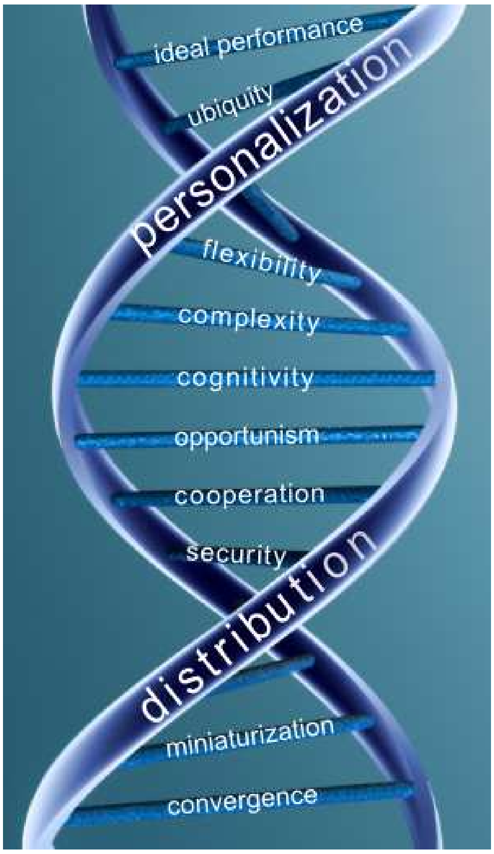

Figure 2. The DNA of ICT evolution

Before we get into the more specific elements of the DNA of ICT evolution, let's dwell on *personalization* and *distribution* to give a rationale to our statement on their importance.

Personalization
The success of the industrial society was based on the mass production of goods at low cost, to be sold to a consumer market with homogenised tastes and desires. This paradigm today is completely reversed. The strategy is to go to the person, produce for the individual, satisfy specific needs, and segment the market into small niches each tailored to a particular group of persons. This is all made possible by the fact that today it is feasible to produce at low cost with flexibility and modularity. Now, this trend is clearly reflected in the world of communications. Since the advent of mobile telephony, also identified as *personal* communications, we do not call a location, but an individual. We are now used to see the number that is calling us, associated to a person in our phonebook, and we decide whether to take the call or not. We select a specific tariff structure, suited to our calling profile, and we may even have lower tariffs when we call specific groups of people. In terms of accessing the Internet, we start from our preferred home page, we can browse over portals shaped according to our own profile, we can select our favored content from a huge offering, we can even become content producers by uploading pictures and movie clips. The individual has become a source of information, and not only a sink to be filled with advertisement. Even when watching TV, we now have at our disposal a growing number of on-demand offerings, from which we can freely select. The individual is more important, enjoys more freedom, and is much more active than it was in the past.

Distribution
Another fundamental ingredient of the industrial society was the concentration of resources and intelligence into a few centers. This made interactions and investments more efficient, while also increasing the risk associated to losing a center, and caused large movements of people (the first of which was the move out of the country into cities). The structure of companies was based on rather rigid pyramids, with very specific work functions and descriptions, and linear work flow procedures. Again, also this paradigm is reversed in the information society. Today, there is a clear trend towards

the distribution of resources. In the world of manufacturing, it is customary to have parts produced in geographically distant premises. This reduces costs and creates a global economy where effects propagate unboundedly. Intelligence is distributed and decisions are obtained through a network of interactions. This adds greatly to the responsibility of each person in the organization, and the work functions become ever more flexible. This also creates a need for continual education, for it is not possible to adapt to the fast dynamics of the current societal evolution if one considers that his/her training ended in school. Companies' structures evolve from pyramids into networks of intelligent nodes, and the structure may evolve on a per product basis. The more futuristic version being the virtual company, where different entities join into specific ventures which only have the lifetime of a product life cycle. It can be stated, without the minimal shade of doubt, that all of this is resting upon ICT technologies. The network of people relies on the telecommunication network, and in the future, the same will happen for the network of *things*, also known as machine-to-machine communications. A distributed society, a distributed company, needs to find the necessary information anywhere they might reside. This is only possible thanks to the Internet and the associated search engines which allow having nearly all the information in the world at one's fingertips. Intelligence is pushed to the edges, which reduces the risk associated to the loss of any network node, but at the same time requires a new ethical code, as well as security in communications. Networks evolve from heavy infrastructures to lightweight ad-hoc self-organizing topologies, where the role of operators needs to be defined anew.

As in the DNA structure, the two fundamental strands of *personalization* and *distribution* are actually running into opposite directions, i.e. they are the anti-parallel support of the ICT DNA double helix. In fact, while personalization implies a local view, distribution naturally translates into a global reality. Therefore, ICT is imposing on society a complex organization, whereby the global truth is formed through belief propagation from individual nodes which intelligently work within their local boundaries. As we will see later, this has much to do with the concepts underpinning iterative processing algorithms.

The two meta-trends of personalization and distribution can be combined in various ways to form the *trends of ICT evolution*, which in our DNA metaphor correspond to the bases, the sequence of which identifies the genetic code. The following is our elected list of ten trends: Ideal performance, Ubiquity, Flexibility, Complexity, Cognitivity, Opportunism, Cooperation, Security, Miniaturization, Convergence. Let's dwell on each in turn.

1. Ideal performance

The search for the ultimate ideal performance is the major force behind the evolution of any technical or technological system. It appears to be in the nature of the human kind to strive for the extraction of the maximum possible output, the optimal exploitation of resources, with the largest possible efficiency. This requires knowledge of the ultimate performance boundaries. In the case of communications, the boundaries are the object of Information and Communication theories, which in many instances do indicate where these limits are. The trend is therefore towards achieving the performance limits set by Information Theory. How does this link to the two meta-trends? The optimisation of performance requires perfect fit to the specific communication conditions (propagation channel, interference, transmission format, etcetera), which can be interpreted as matching the individual user needs and constraints. This is part of *personalization*. On the other hand, the limits set by Information Theory are not restricted to a single link, but can and should be extended to the more complex case of networks. In this case, achieving the optimal limits requires global optimisation, to balance fairness and overall throughput, with distributed intelligence. This is evidently part of the distribution meta-trend.

2. Ubiquity

The trend towards ubiquitous communications, the overused "Anywhere, anytime" motto, has been the driver for the evolution of cellular communications since the 70's. Coverage is today extremely good in most urban areas, and surprisingly good in unexpected locations, even though obviously gaps remain in developing parts of the world. What is yet necessary is to sharply increase the geographic spectral efficiency (in bit/s/Hz/km^2), to provide ubiquitous *broadband* wireless access. Associated to ubiquity, we find mobility and pervasiveness. Mobility is the trend towards communication systems which can interconnect terminals moving at any speed, including all types of vehicles, trains, airplanes, ships. Pervasiveness is the trends towards finding connectivity all around us, in a truly *wireless ambient*. This concept has many important social implications, as already discussed in Section 2. Essentially, by living into a collaborative wireless ambient, the individual can benefit from optimised environmental fitness, which satisfies a basic human need. This is clearly a specification of the *personalization* meta-trend. At the same time, this personal fitness can be carried along in any location, becoming ubiquitous fitness, an evident derivation from the *distribution* meta-trend. Even though ubiquity and distribution may seem very similar concepts, we separate them by limiting the interpretation of ubiquity to the pervasiveness of wireless networks, and by attributing to distribution this and all other implications related to social aspects, work organization, global economy, etcetera.

3. Flexibility

Along with the search for Ideal Performance, this is also a major trend in the evolution of any technical system. All engineering systems start as rather simple and rigid, performing but a few functions, with limited scope for modifications in response to user needs. In the course of its development, the system acquires more and more functions, more and more options, which can be selected flexibly depending on instantaneous necessities. This is a very strong trend in wireless communications. Transmission systems, protocols, and terminals, are being designed as reconfigurable entities, with capabilities that can be flexibly adapted to the conditions set by the propagation channels, the transmission buffers, the spectrum availability, the interference environment, the desired quality of service, etcetera. Dynamic spectrum assignment strategies are being devised and starting to find their way into regulatory policies. Digital electronics capabilities are exploited to design software radios and flexible radios. Even analog electronics is now being bent to the requirements of designing flexible RF front-ends, with reconfigurable filters over large bandwidths. It is an easy task to map the trend towards *flexibility* as a direct son of the *personalization* meta-trend. In fact, it is obvious that flexibility is only useful if it is used to accommodate individual conditions and needs. On the other hand, it may be harder to describe the connection with the distribution meta-trend. However, *flexibility* at system level requires knowledge of all local conditions, in order to find a global optimum satisfying the requirements of the entire user population. Therefore, we can say that *global flexibility* is related to the trends towards *distribution* of intelligence, where as a minimum each user must sense its own environment and feed back this information to peers or to base stations. Also, the trend towards flexible network topologies is clearly out-spinning from the *distribution* meta-trend.

4. Complexity

Technical systems always evolve towards increasing levels of complexity, as functionalities increase and performance improves. On the other hand, technological complexity can become a major hurdle in its usability. Therefore, while internal complexity increases monotonously, there is a contextual trend towards the simplification of the human-to-machine interface. Complexity and simplicity must live together in harmony. As complexity grows, we must face the danger of increasing energy consumption, which could make entire systems unsustainable. A clear trend towards the design of "green" technical systems is growing powerfully nowadays. We could say that energy consumption is to complexity as energy saving is to simplicity. Mapped onto the world of wireless communications, complexity is visible in systems, protocols, terminals, network equipment, essentially in every element. The need to simplify is stringent for user terminals, but also for network management. And we can say that "green" communications are emerging as very hot area of research and development. The relationship between complexity and the *personalization* meta-trend is inherent in the fact that we do not accept standard and rigid solutions, but rather we always look for configurations which are adapted to individual needs. A personalised solution is always more complex than a standard item. The key enabler for the realization of complex systems is the fact that today we are able to produce personalised objects in a very cost effective manner. It is also true that, in many instances, personalization is perceived by the final user, but it is in reality a specific combination of a few standard objects. In view of the *distribution* meta-trend, it should be apparent that distributing intelligence, responsibilities, management functions, all translate into a more complex system. In this case, complexity also brings in the concept of *emergence*: the arising of novel and coherent structures, patterns and properties during the process of self-organization in complex distributed systems. Emergence can be weak when it can be reduced to its elemental parts, or strong when irreducible. Irreducible emergence can be thought of as an independent system, living a life of its own.

5. Cognitivity, self-organization and bio-inspiration
As complexity of systems grows larger, control becomes more and more difficult. At a first inspection, it would be desirable to be able to set rigid rules to which all system elements should abide. This has worked in the past and still does today. However, this can only be pushed to a limit, when exceptions to the rules become frequently necessary, but difficult to handle, and the overall efficiency is severely degraded. Also the system may become extremely large, and scalability of control becomes a major issue. Or, finally, flexibility demands may pose tremendous challenges to setting correct and efficient rules. In front of all of these difficulties, we are turning our observations to nature, where incredibly complex beings live apparently without any form of rigid control. This is the source for bio-inspired algorithms, techniques, and protocols. We see that life in nature is self-organised, and we can try to apply self-organization into devices, networks, and systems. And clearly, the most beautiful and powerful example of self-organised system is the human brain, with its capability of cognition. Therefore, the extreme finalization of this trend is to endow devices, networks and systems with cognitivity, i.e. the cognition capability. Hence the example of cognitive radio, where radio spectrum is not assigned a priori, but is cognitively selected based upon observations of the wireless environment. Seen through the light of the *personalization* meta-trend, we can see that we are actually turning our network nodes and devices into primitive forms of "persons", with a certain amount of artificial intelligence that allows them to "think" and make decisions with a certain degree of autonomy. In the Internet of Things, the human element largely disappears, and the network is completely populated by artificial beings, or agents, which carry out functions to achieve specific objectives. The *distribution* meta-trend is related very closely to the concept of self-organization, where local realities and decisions contribute, through message passing, to the global behaviour. This can be brought to the extreme where the overall objective functions, such as for example the estimation of a parameter, are elaborated only in a distributed manner, and the final result is not necessarily collected at a fusion center, but can itself be distributed into the network.

6. Opportunism
With increasing degrees of distributed intelligence, flexibility, and complexity, it becomes crucial to execute operations not at any generic time instant, but when and only when the conditions are optimal.
In other words, it becomes necessary to catch the opportunity for performing a specified task in the most efficient manner, and with the largest associated benefit. Indeed, all systems are dynamically varying in several dimensions (as a minimum, time), which means that conditions will fluctuate and opportunities will be created. To use a dimension or another, depending on the underlying conditions, can be interpreted as a form of diversity. Therefore, opportunism is a way to exploit diversity, choosing from time to time the path which offers the minimum resistance to our action, and thus optimizing the use of resources. In a sense, opportunism can be seen as the opposite of the brute-force approach, where exploitation of resources is total and completely independent of the ensuing conditions. The beauty of this is the fact that, in a network (be it technical or social) the total amount of resources is limited, so if each one use the minimum necessary to achieve its own purposes, then the overall efficiency is maximised. In other words, the use of brute force from any single individual hurts the entire network. In wireless systems and networks, and particularly in the family of Beyond 3G cellular networks, opportunism has become a major flagship for resource assignment, scheduling, and multiple access. Resources are given dynamically to those terminals which are at a particular instant enjoying the best channel conditions, which will allow serving them with the minimum effort and maximal efficiency. In order to avoid that some terminals are always left out of the game, opportunism should always go along with fairness, implemented in one of its several possible embodiments. In this specific case, the *personalization* meta-trend materialises in the fact that we go after the opportunity which is occurring for a specific individual, knowing that it will only last for a

limited window of time. On the other hand, we want to be fair to all users, and as such protocols and strategies are ready to consider also the needs of those for which opportunities do not seem to happen, at least not with sufficient frequency. In terms of the *distribution* meta-trend, we observe that opportunities may also be visible at a local level. This is because, to enable scalability, it is not conceivable that all information be collected in a single decision making node. Therefore, decisions to seize specific opportunities should be taken locally, with feedback on instantaneous conditions transmitted only when and where necessary, possibly on short legs to minimise latency and thus maximise network reactivity. Hence, opportunism must go along with distribution.

7. Cooperation

Cooperation can be seen as the virtuous consequence of awareness. If an individual, or an entity, is isolated, it can only work for its own specific goals. On the other hand, even if the entity is not isolated, but is unaware of the needs, or even the sole presence, of other entities around it, it will behave exactly as it did in isolation, working undividedly towards the achievement of its objectives. Only when an entity becomes aware of the presence, requirements, and needs of other entities around it, it can realise that working in isolation may not be the most efficient way. Even the objectives are modified, at least because one sees not only its own objectives but also those of others, thus creating the notion of global objectives. Awareness generates a change of perspective, which can lead to various forms of cooperation amongst the individuals. Cooperation requires trust, fairness, and regulation, in order to ensure that all individuals benefit from the process. Cooperation in wireless communications can, for example, take the form of relaying the information sent by another user, in order to help it reach the final destination. In this way, the cooperating node is spending part of its resources not to achieve its own objectives, but rather to help another node do so. In return, it will trust that the situation will reverse when its own opportunity comes along. It is clear then that cooperation and opportunism go together, as the mechanism for cooperation will adapt itself to the underlying conditions which will vary dynamically over time. Other interesting forms of cooperation can be envisaged for virtual beamforming, virtual MIMO, collaborative positioning, etcetera. Cooperation is an act between individuals, and as such it possesses intrinsically the character of the *personalization* meta-trend. The personalised network entity is aware of the other entities, cognitively decides that it is useful to cooperate, trusts the other entities, and expects to receive mutual benefits and to achieve its own goals while contributing to the global goals. This comes very close to the description of the behaviour of a person in a social network. On the other hand, the exploitation of cooperation means, once more, that the operations in the network do not belong to a single terminal and a single central control entity, but rather require the involvement of a multitude of actors, distributed of the area of service, whereby decisions and operation occur as the result of the overall interaction. This is clearly in line with the distribution meta-trend, and we can say that cooperation without distribution is impossible, and distribution without cooperation is less effective and not exploited to its fullest.

8. Security

We must also recognise that, in front of all the positive aspects brought in by the personalization and distribution meta-trends, there is also an associated increase in the risk of misuse of ICT technologies. Centralised control may be bulky and in some cases unfair, but it can also serve as a guarantee for secure transactions, which can be protected more easily by various kinds of threats. On the other hand, when organizations become distributed, when decision making is the result of consensus, when resource management requires information from the edges, then it is clear that there are so many more possibilities for an alien to come in and disturb or deviate the process far from its intended objectives. And since there is a trend for personalization, any individual or any entity is up front with all of its features, which can be stolen or misused in many ways. Therefore, the meta-trends of *personalization* and *distribution* require that much attention is paid to ensure security, guarantee privacy, defy malicious attacks, and propagate trust. This applies to society in general, and certainly it does also to wireless communications, which traditionally have been the weak side of network security. One special word for trust: it is not just a matter of making sure that content is encrypted, that access is conditional to authentication, that sensitive data is not exchanged (or at least not frequently). It also a matter to make sure that the final user *perceives* that using ICT technologies is secure. In other words, there must be trust in ICT technologies, or else the uptake will always be below expectations, and the impact much more limited than the potential.

9. Miniaturization

In the evolution of technology, we always see a trend towards miniaturization, as the results of improvements in the processes and in the understanding of the underlying physics. This has held marvelously in the case of digital electronics, where the scale of integration of ICs (Integrated Circuits) has grown exponentially through the years. Digital ICs are horizontal enablers for the progress in wireless communications, not only from the technical point of view, but also from the economic side, given that the cost of ICs has also decreased steadily through the years. And the end is not in sight: with the rush for nanoscale devices, unprecedented improvements are yet on their way. Also, circuits built on organic materials promise to change forever the notion of "hardware", as we will be seeing and use devices in plastic and even softer materials. Nanotechnologies will produce entire nanosystems, which can be distributed as smart dust for a multitude of distributed sensing applications. Here comes the relationship with the distribution meta-trend. On the other hand, the trend towards miniaturization can also be seen in a more general way. In terms of cellular mobile networks, there is a clear trend towards the miniaturization of cells, which went from macro to micro, pico, and now femto-cells. The femto-cell is intended to be installed by and individual in a home or a small office, and as such we can see the connection with the *personalization* meta-trend. We can also see the miniaturization of networks, as for the case of the body area network, interconnecting different parts of the body for various applications for the benefit of the individual, such as e-health.

10. Convergence

Last but not least, convergence. It is placed at the end because in a way it connects all previous trends. In a general sense, convergence can be seen as that process according to which concepts which used to be separated come together to form new meaning. The process eliminates barriers and distinctions, and creates larger classes. Since we use classification as an instrument for clarification, it is indeed true that convergence always causes a certain amount of confusion, as previous certainties are questioned and new approaches must come in. In economic terms, convergence is an earthquake that shakes market shares and inevitably increases both opportunities and threats. From the point of view of scientific research, convergence can be seen as the uprising of interdisciplinary research, where competences from different areas are merged. The major benefit is that different frames of mind coming together have the potential to produce breakthrough innovation. From the point of view of wireless communications, convergence plays a major role in at least two ways. First of all, the distinction between mobile and fixed telephony is vanishing, with operators offering bundles which include also Internet access and TV (the so-called quadruple play). Considering also the fact that IP (Internet Protocol) is rising as the common network protocol for all services, we can see clearly the incredible force of service convergence. Secondly, there is also convergence in the world of wireless terminals, which more and more become phones, computers, cameras, organisers, etcetera. Let's interpret the trend for convergence in view of the *personalization* meta-trend. No matter where the person is, we want to provide the same access conditions and the same service profile as if the person was virtually at home. Convergence of networks and terminals can enable this concept. On the other hand, this can also be seen as the famous "anywhere, anytime" motto, i.e. the fact that we are always surrounded by a converged (albeit heterogeneous) network infrastructure, of which we don't want to know the details, as long as we can use it for our purposes. Therefore, convergence can be seen as an enabler for the *distribution* meta-trend, because without it we would not see a seamless wireless ambient but rather a jigsaw puzzle of technologies.

6.3 Newcom++ research: Impact on ICT trends

It is interesting to note that the scenario described in Subsection 6.2 is reflected, in a significant part, by the research activities currently on-going within the NEWCOM++ project.

In a completely dual approach, we can map the 10 ICT trends onto the activities initiated or planned within NEWCOM++, or we can associate each activity to one or more ICT trends.

In the following, we select the first approach and accordingly we list the 10 ICT trends with a different objective: to outline the degree of involvement that the NEWCOM++ research work packages present in their respective, trying to provide practical example of concrete actions taken by the consortium towards these trends. The content of this section is in part the result of the post-processing of the responses received by WPR leaders to a survey issued by WPI.6, aimed at identify the goals of the WP, i.e. the activities also called **innovative ICT concepts** (**IICs**), and the associated users, requirements, constraints, estimated impact and foreseen risk. The complete survey result is listed in Appendix for the sake of completeness.

6.3.1 NEWCOM++ towards the Ideal Performance trend

The match between the Ideal Performance trend and the activities carried out within **WPR1** on "Modelling, calibration, and validation of multi-dispersive, multi-link channels" is very clear. In fact, *channel models are the instrument to describe the ultimate limits on performance,* essential means for quantify the reference boundaries that cutting edge research is trying to approach. The first IIC of WPR1 is to design radio channel models (considering broadband, mobile-to-mobile, and body area), which incorporate all relevant features and *impairments affecting performance*, such as multi-channel correlation, multi-dimensional dispersion, polarization, fast time-variance, localization, near-field conditions, etcetera. Moreover, the focus is on the design of *efficient and robust channel estimators*, which is of primary importance to avoid that all effort spent in the design of efficient air interfaces and protocols become fruitless due to inefficient channel estimation.

This consideration suits perfectly also to **WPR2** on "Feedback and Resolution of Channel State", the work-package with the objective to explore the *role of feedback* to optimise performance in wireless communication networks and its relation to the resolution of the time-varying channel state. In particular, WPR2 aims at assessing the effect of imperfect channel knowledge at the receiving end due to the time-varying nature of the wireless channel and methods to encode it for the return channel as a function of the allocated bandwidth for feedback.

While **WPR3** is more oriented towards unifying paradigms and descriptions, in order to design flexible receivers with limited complexity, we can say that it also contributes to the Ideal Performance trend through its strife for *adaptively reconfiguring the air interface* to optimise performance under all propagation conditions.

The push towards the Ideal Performance trends is clear for **WPR4** on "Iterative Receivers for Wireless Communications", where *iterative processing* is investigated to optimise performance (often with the price of complexity), with a look on practical design, from imperfect channel knowledge to fixed point implementations and down to synchronization problems and joint receiver design. All WPR4 IICs (see Appendix) are oriented towards the Ideal Performance trend.

WPR5 on "Coding for Multi-Hop Wireless Networks" pursues the Ideal Performance trend by designing coding at network and physical layers for multi-hop wireless networks, aiming at providing *better throughput*, energy efficiency and resource utilization both in unicast and multicast communications.

One of the IIC reported by **WPR6** on "Relaying and cooperation in networks" aims at setting the reference *bounds for performance in the case of cooperative networks*.

Similarly, the activities within **WPR7** (on "Joint Source and Channel Coding/Decoding") are also explicitly in the direction of *reaching ideal performance*.

WPR10 on "Network Theory" is inherently involved in the Ideal Performance trend, being devoted to the analysis on the fundamental theoretical aspects and ultimate performance limits at network level, in terms of *capacity, throughput, and delay*, with the aim of devising techniques to closely approximate and even achieve them.

Finally, the last WP we feel to mention under the Ideal Performance trend is **WPRA** on “Security in Wireless Networks”. In this case, the accent on performance is testified by the attention given to the *equivocation concept,* i.e. on the measure of secrecy, and by the activities aiming at the definition of its theoretical limits in fading channels.

6.3.2 NEWCOM++ towards the Ubiquity trend

All 2 NEWCOM++ work-packages are in some way linked to the Ubiquity trend, with a special mention for WPs related to network aspects. In particular, in these WPs the ubiquity requirement is achieved through distributing the intelligence centers and easing the mobility, portability, and pervasivity aspects. In addition, we find a clear synergy between the ubiquity and cooperation trends, since cooperation is often instrumental to achieve ubiquity.

Accordingly, **WPR5** approaches ubiquity through the study of *distributed channel and network coding*, and *geographic routing*.

WPR6 exploits the concept of ubiquity through *distributing synchronization, localization, interference mitigation. Cooperation* itself is a concept that has a clear connotation of ubiquity since collaboration arises to allow connectivity anywhere anytime.

WPR8 on “Scheduling and adaptive radio resource assignment” *distributes scheduling capabilities* to optimise efficiency for distributed wireless networks, which is a rather new concept since typically in distributed environments random access is implemented. The approach followed for distributed scheduling is game-theory based.

WPR9 on “Joint RRM and Flexible use of radio spectrum” optimises the *radio resource distribution* strategy to improve network efficiency.

WPR10 on “Network Theory” is towards Ubiquity through *the distributed implementation of the back pressure* resource allocation algorithm. Back pressure is a routing, scheduling and resource allocation policy that is based on the simple principle of performing resource allocation decisions based on queue backlog differentials. It is named after the corresponding natural property of fluid flows. The decentralised architecture of wireless ad hoc networks and the lack of central controller in some cases limit the applicability of centralised algorithms such as the back-pressure policy. Accordingly WPR10 is investigating its extension in a distributed context.

WPR11 on “Opportunistic networks” focuses on *wireless sensor networks*, marrying the Internet of Things trend towards environmental fitness, and introducing algorithms and design solutions to cope with nodes and user equipments on-the-move. This paradigm encompasses features and methods that are especially suitable in both disconnected environments, in which islands of connected devices suddenly appear, disappear and reconfigure dynamically, and pervasive networking scenarios, where epidemic data exchanges occur among mobile devices in temporary proximity. Further, WPR11 is devoted to the mobility concept through the *Pocket Switched Networks* (PSNs) as a communication paradigm that relies on both occasional transmission opportunities and user mobility to carry the data to the destination, with the purpose to reflect the reality faced by the mobile users.

In addition, **WPRB** on “Localization and Positioning Techniques” reflects the Ubiquity trends in focusing on *location-based services and cooperative positioning strategies*.

Finally, considering that cognitivity relies on the ability of devices to adapt their behaviour to decisions based on environment changes, we can state that there’s a strong synergy between the Ubiquity trend (in the sense of environmental fitness) and the *cognitivity* trend.

6.3.3 NEWCOM++ towards the Flexibility trend

The Flexibility trend is also present in a massive way within the research activities of 2 NEWCOM++.

WPR3 on "Adaptive coding/modulation for the wireless channel" implements flexibility in terms of transmission format, through *adaptive selection of modulation and coding* scheme in a dynamic fashion, according to the channel conditions. In particular, this trend towards adaptation is investigated within 2 NEWCOM++ via the IIC on OFDM systems.

Focused on cooperative networks, **WPR6** is naturally linked with flexibility because *cooperative networks* are the opposite of rigid networks, with an inherent flexible, dynamic, and reconfigurable topology and protocols. In particular, WPR6 investigates on *adaptive relays*.

WPR8 is also inherently flexible, being devoted to the design of scheduling techniques with *adaptivity at resource management level.* In particular, we mention here the IIC on Scheduling Techniques for Heterogeneous Networks, where the heterogeneousness further stresses the degree of flexibility object of research.

Similarly to WPR8, **WPR9** has the concept of flexibility already in its name: "*Flexible use of radio spectrum*", with several IIC on this topic: joint radio resource management (JRRM) for heterogeneous networks. Adaptivity is also selected for algorithmic computation of the optimal parameters to be adopted by RRM.

WPR10 follows the flexibility trends through IICs such as the *back pressure* based resource allocation, the main objective of which is to push the capacity limits of wireless through decentralized network control with minimum overhead.

WPR11 is focused on the emerging paradigm of opportunistic communications to enable nodes and user devices to *self-configure and exploit resources in extremely dynamic networks*, such as Wireless Sensor Networks, Underwater Sensor Networks, Pocket Switched Networks, Delay-Tolerant Networks, and Autonomic Networks.

Finally, **WPRC** achieves flexibility through the "*Flexible Radio Platforms*" it is based upon. In the view of WPRC, flexibility is expected to be a must in transceivers that will have to cope with an ever increasing multitude of air interfaces and radio technologies in the future. In this sense, flexibility is a means to achieve real-time processing in various radio environments with limited transceiver complexity and reasonable power consumption. Another aspect of flexibility is its ability to provide easy maintenance or upgrade of transceivers by adjusting through adequate parameters or software updates. A specific IIC of WPRC is on "Define flexible radios able to implement several modes and/or standards with limited overhead in terms of reconfiguration time, computing overhead and power consumption".

6.3.4 NEWCOM++ towards the Complexity trend

The Complexity trend is a central topic with its wide interpretation. Almost all WPR activities and IICs proposed have set requirements and forecast risk often linked with the complexity issue.

WPR3 is focusing on the design of new algorithms for specific challenging system scenarios, such as Coded-OFDM, Non-orthogonal multicarrier, CPM, and Coherent QAM systems. This IIC has the specific requirement to offer a wide range of choices in terms of the *performance/complexity trade-offs*.

Similarly, for all IICs set by **WPR8**, the main *requirement and, at the same time, constraint is set by the complexity of implementation*. Indeed the approaches to be used often require application of complex design procedures, accounting for many separate aspects (channel model, physical layer issues, the type of radio resources, network topology, application level requirements, buffer management strategies, etc). Such complexity in many cases prevents from using mathematical approaches and requires heavy simulations which are time and effort consuming.

Interpreting the current Energy saving tendency under the Complexity trend, we can cite here **WPR10** because *energy consumption* is a central topic in wireless sensor networks, with the constraints provided by finite battery life, traffic characteristics, topology and mobility. In this sense goes also **WPR11**, with a specific IIC dedicated to design and develop new *forwarding/routing algorithms that match the energy-saving requirements* of emerging networks where opportunistic techniques are expected to be exploited.

WPR4 on coding is for nature careful towards the complexity theme being the need for *low complexity receivers* the basic requirement, with *reduced power consumption of handsets and extended battery life*. Some explicit examples are the IICs on Quantised Design for Iterative Receiver Components and on Low-Complexity Components in Iterative Decoding. Also **WPR6** has strong attention towards the requirements of power decrease and length of battery life and for reduced complexity of routing in highly volatile/mobile networks.

Complexity is also a central requirement for all RRM activities carried out within **WPR9**.

Further, because all cooperation systems can be seen as complex systems, we can signal under the Complexity trend all those WPRs that are related to *cooperation*.

Finally, a special mention towards the trend to minimise complexity must be done for **WPRC**, which handles with *computationally intensive communication tasks* and aims at defining flexible radios able to implement several modes and/or standards with limited overhead in terms of reconfiguration time, *computing overhead and power consumption*.

6.3.5 NEWCOM++ towards the Cognitivity trend

The Cognitivity trend is present in **WPR3** through *adaptive coding and modulation*, i.e. proper real-time adjustment of transceiver parameters, based on the environmental and operational conditions for better spectral utilization.

A cognitivity influence can also be found in all network related WPs. In particular, **WPR6** through the self-configurability, related to the surrounding environment, that is characteristics of the relay and cooperative networks it tackles.

WPR8 has set a specific IIC on this direction on the design of *scheduling in Cognitive Radio Networks*, with the objective of optimizing performance with contained complexity.

WPR9 introduces the interesting IIC on the "*Sensorial Radio Bubble*" concept for Cognitive Radio Equipment. In a cognitive behaviour, the perception of the stimulus is the means to react to the environment and to learn the rules that permit to adapt to this environment. WPR9 proposes to define a volume around the equipment, called the "sensorial radio bubble", the diameter of which is at the scale of the sensing possibility of the equipment. It will be the responsibility of a cognitive radio equipment to be aware and interact with all the pertinent information available in the area that can help the equipment to match its functionality to the global state of its environment.

WPR11 exploits cognitivity through the *dynamism associated with the networks* characterizing opportunistic communications, dynamism related to the surrounding environment where several groups and islands of connected devices suddenly appear, disappear and reconfigure dynamically.

Finally, **WPRC** exploits cognitivity since the main concept on which it is based, i.e. *flexibility*, is a must whenever cognitive radio is considered, since cognition relies on the ability of the transceiver to adapt its behaviour to decisions based on environment changes.

6.3.6 NEWCOM++ towards the Opportunism trend

The Opportunism trend is the essential entity of **WPR11** on *Opportunistic communications*. The main IICs in this context are to devise and develop new models and tools for user and node mobility that really fit the characteristics of Opportunistic Networking environments; to design and develop new forwarding/routing algorithms that match the energy-saving requirements of emerging networks where opportunistic techniques are expected to be exploited; to design and develop a transport layer protocol that supports and fully exploits the potential of Opportunistic Networking; to design and develop a middleware system that facilitates application development within Opportunistic Wireless Sensor Networks (WSNs); to develop radio resource management algorithms for management of heterogeneous wireless mesh networks; to design topological structures that are not only based on the relative distance between nodes, but also on their intrinsic properties and to allow the existence of several of these topological structures simultaneously; to devise new technology-agnostic schemes to describe resources within the node and the (wireless) network, so they can be managed more easily.

WPR2 investigates *opportunistic beamforming* strategies which have proved that the sum rate due to complete CSI can be asymptotically achieved using only partial CSI. In particular, with Multibeam Opportunistic Beamforming (MOB) only the channel modulus information is sent through the feedback channel from each user so decreasing the feedback load in comparison with the full CSI (phase and modulo with respect to each antenna) by a factor higher than 2, depending on the feedback strategy. The MOB scheme benefits from the partial CSI that is available from all the users, to extract the system multiuser gain, as an implicit users' selection is included in its performance.

WPR7 and **WPR8**, among other techniques, put some focus on *opportunistic scheduling*. The aim of this algorithm is the maximization of system throughput by serving always the user(s) with the best channel conditions, realizing the so called multiuser diversity, i.e., the independence of random channel fluctuations experienced by each user in the system. However, it is worth noting that this gain can be realised only if link adaptation techniques are available to take advantage of the improvement in channel conditions. This technique has the advantage of maximizing throughput and spectral efficiency, which is crucial in wireless systems due to spectrum scarcity, but it has an important drawback in its unfairness, since users affected by poor channel conditions may starve for long time.

WPR8 is also focused on *Opportunistic Spectrum Access techniques*. An opportunistic frequency channel skipping protocol is proposed for search of better quality channel, where the channel decision scheme is based on Signal-to-Noise Ratio (SNR). The key mechanism is that if the SNR is not favorable, mobile nodes can opportunistically schedule better quality frequency channels enabling data transmission at higher rates.

WPR9 has also some reference to opportunism, through algorithms such as *Opportunism Sub-Carrier Allocation* and opportunistic spectrum usage.

WPR10 focuses on opportunistic transmission and multi-user diversity (traditionally used for providing high throughput efficiency and fairness) to provide high quality estimation by appropriately coordinating sensor node transmissions towards the fusion center.

6.3.7 NEWCOM++ towards the Cooperation trend

The Cooperation trend is widely present in Newcom WPRs.

WPR6 is of course centered on Cooperation, as its title immediately reveals, in the view of obtaining significant capacity and multiplexing gain in wireless communications. This encompasses strategies and codes (including error correcting codes, linear precoders or both), which exploit relaying diversity in order to realise seamless communication and reduce complexity of routing in highly volatile/mobile networks. In particular, the focus is on *cooperative techniques at both physical and network level*, considering algorithms, protocols and electronic device, and on the definition of bounds on the performance achievable with cooperation.

WPR5 can also be seen under the Cooperation trend, because it is linked with *P2P that can be seen actually as a cooperative application*.

Game theoretic modelling of node interactions in autonomous systems is the response of **WPR10** to the Cooperation trend, in particular with *the cooperative games*. Game theory represents a useful tool to model and try to counterfeit misbehaviour at wireless network nodes, and cooperative games are those games where some synchronization and collaboration among network nodes is allowed and, thus, more interaction between users is needed.

WPR11 is in line with the Cooperation trend via its opportunistic networks, where in many cases nodes may be required to provide their own resources (e.g., memory, bandwidth, battery power) for others to use, without getting any direct benefit from that, on a cooperation level.

WPRB follows Cooperation via its *cooperative positioning*, which arises fro the observation that all positioning system must be energy-efficient and robust to imperfections in hardware, varying multi-path and fading propagation conditions, NLOS channels and possibly also strong interference. However, with the wide diffusion of WSN only few nodes are placed in known positions in order to reduce the installation costs, thus leaving several unknown-location devices out of the range of any reference node (due to the short transmission range). This is the case of ad-hoc network scenarios as well. Thereby, conventional positioning techniques employed in cellular mobile systems or WLAN are not appropriate and localization needs to be carried out cooperatively by the nodes, i.e. by allowing nodes in unknown locations to exchange measurements on a peer-peer basis.

6.3.8 NEWCOM++ towards the Security trend

The trend of Security is embodied by **WPRA** on "*Security in Wireless Networks*", the transversal WPR specifically addicted to the privacy and security topics. Basically the goal of this WPR is to further formalise secrecy concepts for fading channels. A particularly intriguing opportunity is the security that is provided by the random channel. The random channel naturally provides a level of protection against wiretapping and similar attacks

6.3.9 NEWCOM++ towards the Miniaturization trend

The Miniaturization trend is reflected by **WPR1** through the *body area network* concept, exploiting the concept of miniaturization in the sense of "*network cells miniaturization*".

In addition **WPR6** benefits greatly from the *miniaturization of devices*, which allows the design and fabrication of extremely powerful and complex ICs, FPGAs, and DSPs.

6.3.10 NEWCOM++ towards the Convergence trend

The Convergence trend belongs to **WPR11** through the concept of *oppnet*, where it assumes in particular the meaning of *network convergence*. Oppnet can be seen as hoc networks where diverse systems, not originally employed as nodes of an oppnet, join it dynamically in order to perform certain tasks they have been called to participate in. They are used for emergency applications.

WPR7 implements the convergence trend through joining source coding with channel coding to optimise performance, implementing the *coding convergence*.

WPR9 realises the *convergence of resource exploitation*, by joint RRM and flexible spectrum utilization.

Finally, by discussing on cross-layer techniques, **WPR7** is towards a *layer convergence*. Cross-layer optimisation offers many opportunities to improve end-to-end distortion without the need to redesign all components of the communication chain, but rather by exploiting information from one layer in existing optimisation mechanisms in another layer. An instance of this is the use of feedback mechanisms provided by mobile communications standards in order to optimise the perceived quality of mobile video streaming, applied to *cross-layer scheduling*.

7. CONCLUSIONS

This Report has summarised the state of the art and major (research) open problems in Wireless Communications networks (WCNs) as they stemmed from the work developed in the research WPs of NEWCOM++ in the first year of activity. Each section of the report has been devoted to a concise illustration of state-of-the art and open problems in WCNs issues that represent a merging of topics addressed by a subset of NEWCOM++ research WPs. Covered topics include wireless channel modelling, physical layer signal processing algorithms, software defined radio, network layers in WCNs, and information society trends.

Section 2 to 5 have been devoted to a concise illustration of state-of-the art and open problems in WCNs issues that represent a merging of topics addressed by a subset of NEWCOM++ research WPs. In particular, Section 2 dealt with wireless channel modelling, an ancillary yet fundamental cornerstone in WCNs analysis and design. Section 3 concentrated on the physical layer of WCNs, one of the key investigation areas in the network. Peculiar topics, investigated in appropriate WPs, are the feedback and resolution of the channel state information, adaptive coding and modulation, iterative algorithms, network coding for the multi-hop wireless channel, and localization and positioning algorithms. The aspects related to flexible radio platforms have been discussed in Section 4, with emphasis on computationally intensive computational tasks, the role of parallelism in high-speed receivers, heterogeneous many-processors-systems-on-chip and network-on-chip, and flexibility and multi-standard processing. Section 5 has been devoted to the network layers of WCNs. In particular, it touched the aspects of radio resource management, cognitive networks, opportunistic networks, relaying and cooperation in WCNs, network information theory and joint source and channel coding.

Finally, Section 6 represented a contribution from WPI.6 (INTEGRAL), and dealt with information society trends, analysis of personal needs and their potential satisfaction through ICT. In the section, ICT trends in Europe were reviewed, with emphasis on future Internet aspects and wireless technologies. It was described how information and learning, environmental fitness, social interactions, working life, transactions, entertainment, security, privacy, and health and wellnessthat could play the role of driving forces for future research issues.

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