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High Spectral Efficient and Flexible Next Generation Mobile Communications

Simon Plass · Stephan Sand · Mikael Sternad · Arne Svensson

Abstract In this article we identify and describe the requirements and challenges of next generation mobile communications systems. The so-called fourth generation (4G) aims at throughput rates of more than 100 MBit/s outdoors with high mobility and 1GBit/s indoors. This requires new advanced techniques in the air interface of such a system. We outline new possible techniques and introduce a future basic physical layer concept. The adaptivity to the channel of all the modules in such a possible concept is highlighted. Since the needed large bandwidth for high data rates is a very valuable resource, future communications systems need a high spectrum flexibility. Furthermore, 4G systems will face severe inter-cell interference scenarios that have to be tackled. Both challenges, i.e., spectrum flexibility and inter-cell interference, are discussed in more detail.

Keywords OFDM · Next generation · 4G · Spectrum flexibility

1 Introduction

Recently, the use of wireless equipments and their standards for mobile communication has steadily increased worldwide. There are still new emerging applications and needs that

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demand higher data rates, e.g., video streaming. Already established standards, such as GSM or UMTS [1] satisfy current market needs, but many actors perceive a latent demand for high-speed wireless access. Therefore, the questions arise:

- What will be the next technical challenges to serve higher data rate?
- How can these technical challenges be solved?

One technical solution can be a simple bandwidths extension. Unfortunately, it is very difficult to find continuous large segments of spectrum. Therefore, the spectral efficiency of future communications is expected to increase significantly compared to today's state-of-the-art. The recent UMTS standard is called the third generation (3G) of mobile communications systems after the deployment of the analog system (1G) and GSM the first digital system (2G).

For flexible usage of spectrum and further increase of data rates, research and development focuses on the definition of standards beyond 3G. Activities in the framework of 3GPP/LTE (3rd Generation Partnership Project/Long Term Evolution) [2] focus on the evolution of the UMTS standard within the available 3G bands as well as new bands designated for cellular systems. Different to that, research and development has already started for the definition of a mobile communications system of the fourth generation (4G).

The focus of a next generation system can be highlighted by the need of high spectral efficiency in combination with high flexibility for packet data traffic to guarantee throughput rates of more than 100MBit/s outdoors and even 1GBit/s for indoors applications [3]. The main requirements can be summarized as follows:

1. A new radio technology shall guarantee the high demands on the efficient use of the valuable spectrum. Therefore, a generalized multi-carrier (GMC) [4] and multi-antenna (MIMO) based access scheme, namely GMC–MIMO, comes in the field of visions.
2. To assure less capital expenditure and less operational expenditure the developed IP architecture has to be flat. This ensures less equipment investments and a possible share or lease of the IP backhaul. Furthermore, this leads to less number of nodes and consequently a decreased delay.
3. New spectrum could be licensed for the next generation air interface. It is likely that parts of the new available spectrum would not exclusively assigned for one operator. Therefore, a flexible spectrum allocation and sharing has to be included.
4. New services have to be integrated in the system that can be based on real time applications, e.g., gaming, or new trends of Web 2.0.

The recent standardization bodies of WiMAX (Worldwide Interoperability for Microwave Access) and 3GPP/LTE already included the first two requirements. Research activities and projects—such as the EU projects WINNER [5], 4MORE [6], and the Swedish project Wireless IP [7]—are taking into account all the four requirements mentioned above for the definition of a 4G mobile radio communications system.

This article tries to give an overview of the emerging technical challenges to achieve a high spectral efficient and flexible communications system based on the aforementioned requirements. First, techniques not yet established in current standards are described that are strong candidates for 4G systems. Furthermore, an overview of a possible physical layer (PHY) within the framework of a next generation system is given. Two of the major technical challenges are highlighted that handle the spectral flexibility and the treatment of emerging inter-cell interference. Finally, an outlook presents the possible time line for a next generation mobile communications system.

2 Advanced, New Techniques

Recent studies showed that GMC based transmission schemes provide flexible adaptive packet data traffic [4]. Orthogonal frequency division multiplexing (OFDM) [8] as the basic technology for the GMC approach efficiently uses the available spectrum and is very robust to typical mobile radio multi-path environments. With GMC—and in particular orthogonal frequency division multiple access (OFDMA) [9]—it becomes feasible to exploit channel state information (CSI) at the transmitter side, and thus, to apply adaptive bit-interleaved coded modulation (BICM) [10,11], space-time-frequency (STF) precoding, and scheduling [12–14]. In all high speed applications it is difficult to achieve significant system improvements by link adaption techniques due to outdated CSI at the transmitter [15]. In this case, it is beneficial to spread information in one or more of time, frequency, and space to gain diversity through non-adaptive STF precoding. An appropriate technology, which fits into the concept of GMC modulation, is multi-carrier code division multiple access (MC-CDMA) [16]. MC-CDMA combines OFDM and CDMA and benefits from the advantages of both techniques, namely spectral efficiency, flexibility, and frequency diversity.

A survey of link adaptation and adaptive multiuser scheduling for OFDMA-based wireless systems beyond 3G is given in [17]. It is based on recent results from the Wireless IP [7] and WINNER [5] projects and discusses dimensioning of the allocated time-frequency resources, the influence of duplexing schemes, adaptation issues for downlinks and uplinks, and the required performance of channel predictors. This survey complements the survey provided in the present article.

New radio technologies are also seeking for innovative relay based deployment concepts, which are motivated by the limited range of broadband radio interfaces [18]. The range is limited due to high attenuation at carrier frequencies beyond 3.4 GHz, a limited transmission power owing to regulatory constraints, and unfavorable radio propagation conditions, e.g., in urban areas. Relays can be deployed in different usage scenarios in order to increase the coverage range of a base station (BS), to increase the capacity at the cell border, and to cover shadowed areas.

Since the strategy for a new radio technology is based on a high flexible system concept applicable to all kinds of scenarios, the flexibility requires different air interfaces and poses the problem of merging them into one general air interface. For instance, the duplex mode influences the transmitter and receiver architecture. In the time division multiplexing (TDD) mode the available CSI from the received signal can be used for adaptive schemes such as adaptive BICM or STF precoding. On the other side, in the frequency division mode (FDD) the actual CSI is difficult to obtain for the transmitter as independent frequency bands are used for up- and downlink. Thus, the uplink receiver cannot predict the CSI for the downlink transmitter in a different independent frequency band, and then, a feedback scheme must be used.

3 Overview of 4G Physical Layer

Given the above mentioned techniques, we briefly explain in this section the interworking of some of the technologies in the physical layer of base stations (BSs) or mobile terminals (MTs). The basic building blocks of a transmitter and a receiver are displayed in Fig. 1 and 2. In the BS all of the blocks can be implemented, whereas in the MT some may be omitted due to power consumption, cost, and size constraints.

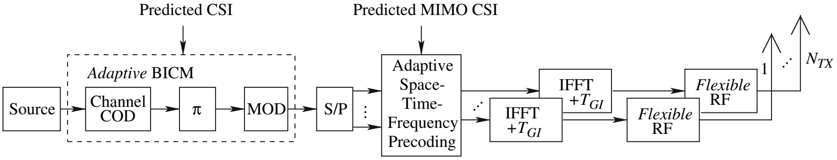

Fig. 1 4G physical layer generalized multi-carrier transmitter

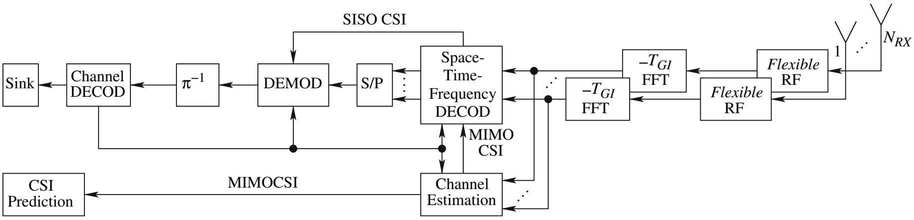

Fig. 2 4G physical layer generalized multi-carrier receiver

At the transmitter (Fig. 1), bits from a binary source are adaptively encoded by the channel coder, interleaved, and modulated (adaptive BICM). For example, the transmitter can adapt the type of channel code, the code rate, or memory [19] and uses adaptive bit- and power-loading algorithms in the modulator [11] to achieve the current quality of service (QoS) requirements.

After adaptive BICM, the symbols from one or several sources, e.g., different users, are adaptive STF precoded when predicted MIMO CSI is available. Within the adaptive STF precoder, linear and non-linear techniques [13] can be applied for STF resource allocation to avoid interference for different users (linear or non-linear pre-equalization [13], beam forming [12]), increase data rate (spatial multiplexing [20]), or gain diversity (code division multiplexing, STF coding [21]).

For each of the N_{TX} antennas in the GMC transmitter, the time discrete transmit signal is calculated by an inverse fast Fourier transform (IFFT) to the set of complex valued modulated symbols. Each generalized OFDM symbol is cyclically extended by the guard interval T_{GI} to avoid inter-symbol interference from multipath propagation [8]. A flexible radio frequency (RF) front-end [22] digital to analog converts the signal and up-converts it to the appropriate frequency bands.

At the receiver (Fig. 2), the flexible RF front-end first down-converts the received signal into the base band, samples it, and converts it from analog to digital format. Then, the guard interval is removed and the signal is transformed via an FFT into the frequency domain. The channel estimation now computes from the received signal MIMO CSI by exploiting special properties of the transmit signal, e.g., known pilot symbols [23,24]. The CSI prediction uses the MIMO CSI to predict CSI for the next transmission period of the GMC transmitter [15] whereas the STF decoder uses the MIMO CSI to separate different source signals. These signals are then soft demodulated, deinterleaved, and soft decoded. The decoder can feedback the soft bits to the demodulator, STF decoder, and channel estimator to improve the estimates of these components [24,25]. If the QoS requirements are met or the estimates do not further improve, the iterations are stopped and the decoder outputs hard decided estimates of the originally transmitted bits. In case the QoS requirements are not met, the receiver can request some modified retransmission via an hybrid automatic repeat-request (HARQ) protocol [26].

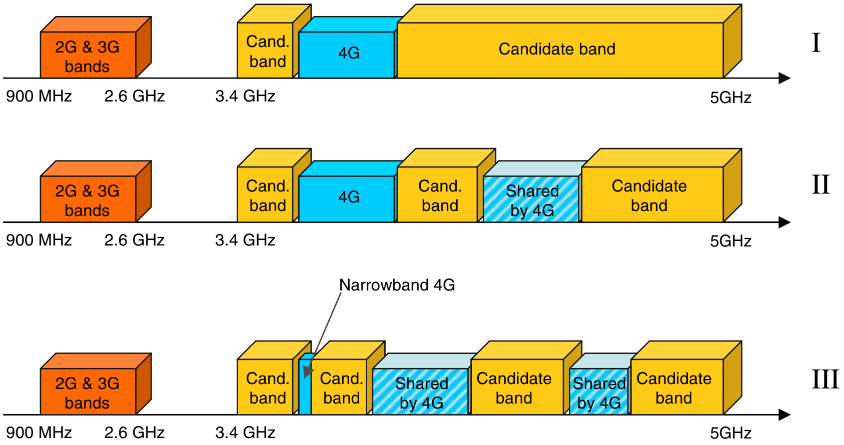

Fig. 3 Spectrum deployment scenario examples for dedicated bands within the candidate band

4 Technical Highlights

A new generation of mobile communications systems will include many advanced techniques to handle the challenges of the system requirements. In the following, two of the major technical challenges are described in more detail, namely the required spectrum flexibility and concepts to cope with inter-cell interference.

4.1 Spectrum Flexibility

Even if the spectral efficiency is expected to increase significantly compared to today's state-of-the-art, 4G systems require a bandwidth up to 100 MHz. Unfortunately, it is very difficult to find continuous large segments of spectrum. Figure 3 [27] shows the current spectrum situation and 4G candidate bands together with possible 4G spectrum deployment scenarios, according to the state of the discussions and surveys of this topic in 2007. The 4G candidate bands are ranging from 3.4GHz up to 5GHz.

In Scenario I a whole wideband spectrum band is available for a 4G system. This guarantees the exploitation of the complete 4G potential. Scenario II provides a further piece of wideband spectrum, which has to be shared with another radio access network. Scenario III assumes that only a narrowband spectrum is exclusively licensed for a 4G system. This ensures a safe mode operation for basic operations. The residual operations have to be made cooperatively with other radio access networks in shared spectrum bands. Since bandwidth is a valuable resource and frequency bands most probably won't be owned by one operator exclusively, the emerging 4G system has to provide enabling technologies for spectrum sharing and cooperation between operators.

Although flexible spectrum use has recently received wide attention, only a few pragmatic solutions for the required radio resource management (RRM) functionalities have been proposed. Here, we outline solutions and designs that are at present studied within the EU WINNER project [5].

The WINNER project considers both solutions, an FDD mode, which requires paired spectral bands and a TDD mode, which requires a single band. Both system proposals use the GMC modulation technique. From today's technological point of view a powerful A/D converter in combination with a single FFT processor are to process the transmit and receive signals inside a bandwidth of up to 100 MHz.

Two spectrum sharing mechanisms are distinguished, *sharing and co-existence* and *flexible spectrum usage*. The first is implemented by a function called *(inter-system) spectrum sharing* and deals with spectrum sharing between WINNER radio access networks (RANs) and RANs from other radio systems. The latter is implemented by a function called *spectrum assignment* and deals with spectrum sharing between WINNER RANs.

4.1.1 Spectrum Sharing

Many of the candidate bands indicated by Fig. 3 are currently occupied by satellite-to-ground links of fixed satellite systems (FSS). In most countries, there are at present relatively few FSS ground stations that use these bands. Spectrum sharing with FSS ground stations is therefore of primary concern within the WINNER project. Two methods are investigated in this respect:

- The use of geographical "exclusion zones" around FSS ground stations. Within which transmission by 4G systems is precluded. Here, services have to be provided within other bands. Preliminary evaluations that use conservative assumptions on interference propagation models indicate that such exclusion zones would have to be rather large, with 20–40 km radius.
- Use of directional antennas and beamforming to avoid line-of-sight transmission from base stations towards FSS ground station sites. Such methods promise to be able to reduce the exclusion zone radii by a factor of 10.

4.1.2 Spectrum Assignment

If all systems that share a spectrum use the same radio technology, this simplifies interference avoidance and packet collision avoidance. Furthermore, if these systems synchronize their transmission, the use of guard-bands in-between them can be avoided, further boosting the spectral efficiency. The WINNER project studies solutions that enable several WINNER operators/RANs to share a common spectral resource. These RANs may or may not synchronize their transmission.

As outlined in [28], the solution is based on decentralized coordination within geographical regions. The only central entity is a central data base, maintained by a regulator or some other authorized party. The basic parameters in the data base can be used to execute a high-level control on the spectrum assignments through spectrum priorities and fairness/cost metrics.

The spectrum assignment is executed on three different time-scales:

- *Long-term Spectrum Assignment* coordinates and negotiates the spectrum assignments between multiple networks for large geographical areas. The assignments are updated at a slow rate, on the order of tens of minutes. The required signaling between RANs is carried out via the IP based backbone (non-WINNER) network.
- *Short-term Spectrum Assignment.* This function controls short-term and local, i.e., cell-specific deviations from the large-scale spectrum assignments. It enables adaptation to local load variations. The time-scale is on the order of several seconds to minutes. Short-term spectrum assignment may be extended to handle also vertical sharing in a hierarchical cell structure, i.e., between a macro-cell and several micro-cells/hotspots.

– *Resource Partitioning.* Within cells, the assigned spectrum is distributed for use by a base station and also by optional relay nodes. This is done by the medium access control (MAC) layer implemented in each base station logical node [29]. First, the constraints on allowed use from the spectrum assignment are combined with other constraints, from e.g., inter-cell interference avoidance schemes. This is done by a constraint processor function. A resource partitioning function then assigns inter-RAN guard-bands, inter-cell interference avoidance guard-bands, bands for use by relay nodes and bands for use by base stations. These assignments are performed on a super-frame time-scale (5–10 ms), which is much faster than the time-scale of the short term spectrum assignment. As seen by the resource partitioning, the spectrum assignment is simply a fixed constraint.

The spectrum assignment could work with time, frequency, and spatial resources. Frequency division would complicate adaptive signaling and channel prediction and is therefore unattractive. The use of a spatial component, i.e., granting the use of certain frequency resources only for transmission in specific directions, is of interest. Note that the scattering environment complicates the fulfillment of such spatial constraints. Frequency resources shared between two operators, could be provided as large contiguous bands, or as many interlaced bands. The use of many interlaced bands would maximize the offered frequency selectivity for each operator, but it would essentially require synchronized systems. The overhead due to spectral guardbands would otherwise become too large. The current main assumption for research within WINNER is the use of large contiguous bands.

4.2 Inter-cell Interference

Another major challenge to reach the envisaged data rates is the required efficient use of the available spectrum in all areas of the mobile radio system cells. Current system designs tend to apply a frequency reuse factor of one. By using the same frequency in neighboring cells will results in large inter-cell interference, especially in the cell border area [30]. This causes severe performance degradations or even connection loss. Current mobile communications systems approach the problem of potential inter-cell interference in different ways, which is often an inflexible compromise between inter-cell interference occurrence and efficient usage of the available spectrum. The GSM system avoids the reuse of a carrier frequency directly in all neighboring cells by a cell planning procedure. This results in an inefficient allocation of available frequency resources. In the third generation a frequency reuse of one is employed. Due to the nature of wideband CDMA (WCDMA), the so-called processing gain provides the robustness against interference [31]. In contrast, the challenge for future 4G technologies is to develop and to assess concepts both at the base station and at the mobile terminal to handle inter-cell interference. Only this will provide a reliable and acceptable system performance throughout the whole cell/sector site. These techniques can be based on new resource management mechanisms, e.g, scheduling, inter-cell interference averaging, avoidance and mitigation schemes. There is also the possibility of inter-cell interference canceling techniques at the mobile terminal.

Theoretically, gains from using inter-cell interference avoidance schemes are large [32], but maximal gains would require fast and tight inter-cell coordination. Frequency partitioning in cellular networks on a slower time-scale has for a long period received interest [33], using power control [34], dynamic channel assignment, and channel borrowing. Note that the packet-switched channel-aware scheduled transmissions that will take place in 4G systems complicates the use of many of the previously suggested schemes for inter-cell interference avoidance. For example, it is not, without additional side information, possible to conclude that the interference power in a set of subcarriers is likely to be higher/lower than average just because it is measured as high/low at present. This is a major challenge for dynamic measurement-based resource assignment schemes.

The highest gain, both in terms of spectral efficiency and in terms of a satisfied user criterion, is obtained by concentrating the efforts on links that would have low SINRs at reuse 1 (typically close to the cell edge) while allowing frequency reuse 1 for good links. A simple scheme is allocating low-SINR users to a separate frequency pool with e.g., frequency reuse 3 [35]. This simple scheme is hard to beat at high cell loads [33]. At lower loads that are unevenly distributed among cells, a lower fraction of unsatisfied users can be attained by dynamic frequency assignment and/or coordinated beamforming.

5 Conclusions & Outlook

The challenges, requirements, and possible new techniques for a next generation mobile communications system are investigated in this article. A high spectral efficient and flexible air interface has to be designed to achieve the proposed demands of very high data rates. The flexibility of the air interface highly depends on the availability of the channel state information. With this information most of the processes on the physical layer can be optimized at the transmitter and receiver side. Thus, the future challenge is an efficient design of the adaptive process blocks such as the modulation, space-time-frequency precoding and scheduling, and corresponding reverse operations.

An overview over possible spectrum flexibility concepts is also given and discussed in the article. Two different mechanisms are identified, namely spectrum sharing and spectrum assignment. Finally, the severe problem of emerging inter-cell interference can be overcome by new resource management mechanisms in the transmitter, e.g., adaptive varying frequency reuses or inter-cell interference mitigation.

The World Radiocommunication Conference (WRC) in October/November 2007 has been given the task of handling the spectrum assignment for new mobile broadband systems, that have a significantly higher capacity compared to 3G (IMT 2000) systems. These new systems are denoted IMT-Advanced, or IMT-A. This clears the way forward for defining technologies and standards. The road map of the ITU-R (International Telecommunication Union Radiocommunication Sector) [36] targets the availability of IMT-A-based standard proposals for the year 2012. As soon as frequency bands for IMT-A are defined, 4G standardization activities are expected to start.

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Mikael Sternad is professor in control theory at Uppsala University since 2001. He is actively involved in the design of techniques for adaptive transmission in beyond-3G systems, by leading the Swedish national Wireless IP project and leading the development of the MAC layer of the system concept developed within the WINNER project. He also has an interest in audio signal processing, being founder and chairman of the board (2001–2005) of the company Dirac Research.

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