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White Paper

Broadband Multi-Carrier Based Air Interface

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Abstract – The future success of the mobile communications revolution strongly depends on increasing the data rate and quality of service (QoS) available to the mobile user. This will enable value added services, which are not possible with current state of the art mobile wireless radio systems. While an increase in data rate, and maybe to some extent also QoS, could be achieved by combining techniques in the form of multi mode terminals (e.g. UMTS and wireless LAN), this has the disadvantage that for each new scenario another mode has to be added. The combination may also not be suitable for the mobility requirements of wireless radio systems. This paper proposes using a broadband multi-carrier based air interface. It also includes a discussion of the enabling technologies for multi-carrier mobile systems and the technology trends for future research. The multi-carrier technology offers the desired high data rates for the 4G mobile environments and also has advantages for spectral efficiency and low-cost implementation.

1. Introduction

The main task is to investigate and develop a new broadband air interface which can deal with high data rates in the order of 100 Mbit/s, high mobility, high capacity, and high QoS. Since the available frequency spectrum is limited, high spectral efficiency is the major task of 4G mobile radio systems. The asymmetric nature of traffic in the downlink and the uplink should be considered when designing the new air interface. Also taking into account the nature of the transmitted data (as done today for speech) will lead to considerable higher end to end quality. Another important target of the 4G new air interface is the ability to provide efficient support for applications requiring simultaneous transmission of several bits of streams with possibly different QoS targets.

This research should complement the various approaches relying on the increase of the throughput capitalizing on the higher capacity provided by using a MIMO channel. The goal is to renew the yet becoming classical OFDM transmission scheme and challenge its domination in standards bodies.

2. Multi-Carrier Air Interface Concepts

Orthogonal Frequency Division Multiplexing (OFDM)

Most of the standards developed for wireless high rate data transmission in the recent years have been based on multi-carrier modulation using orthogonal frequency division multiplexing (OFDM) [2] [3]. Among the earliest of these were the digital audio broadcasting standard (DAB) [4] and the terrestrial digital video broadcasting standard (DVB-T) [5]. Work on these started in the 1990s and was followed by the wireless local area network standards (WLANs) IEEE 802.11a/g, ETSI, BRAN, HIPERLAN/2 [6] and MMAC, and the recently developed wireless metropolitan area network (WMAN) standards IEEE 802.16 and ETSI HIPERMAN. The successful deployment of OFDM in various standards and demonstrators is a strong motivation to build on this success in the design of a new broadband air interface for a 4G mobile radio system. The research in OFDM based multiple access was at its beginnings when the important decisions in which direction the 3G mobile radio standards will go has to be decided and, thus, OFDM did not become part of 3G systems. However, this situation has changed and today a lot of research has been carried out on multi-carrier based multiple access schemes. The basic knowledge on these new multiple access concepts is now existing and it is time to apply it for broadband 4G mobile radio systems. There is also a scope for future research to focus on a sophisticated design of the up- and downlink in order to further address the new 4G system requirements of high data rates, high spectral efficiency and low power consumption limits. Figure 1 shows the elementary OFDM based multiple access schemes OFDMA, MC-TDMA and MC-CDMA. Any hybrid combination of these access schemes is also possible.

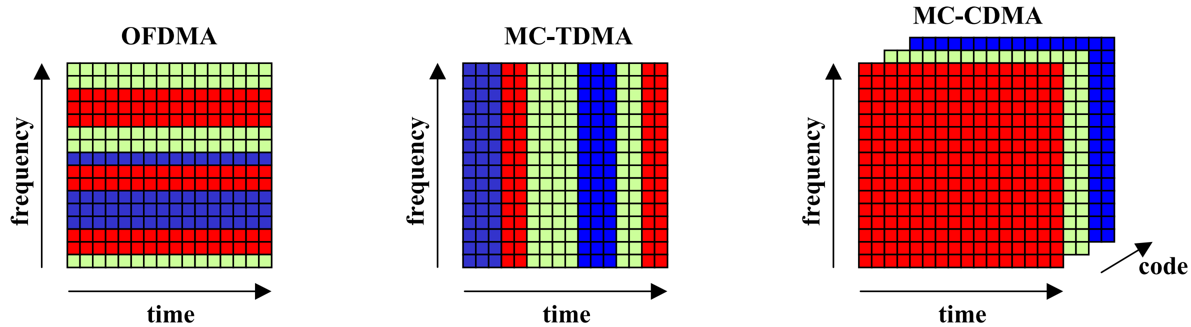

Figure 1: OFDM based multiple access schemes

The advantages of OFDM are:

- high spectral efficiency due to a nearly rectangular frequency spectrum;
- reduced receiver complexity due to simple elimination of inter symbol interference (ISI). This is efficiently achieved by cyclically extending each OFDM symbol and thus enabling very high rate data transmission in multipath channels;
- simple implementation of OFDM by using the Fast Fourier Transform (FFT);
- low complexity multiple access schemes exist like OFDMA, MC-TDMA, MC-CDMA, and TFL-CDMA exist [7] [8] [9] [11] [15] [21] from which some have already been applied in recent wireless standards;
- high flexibility in terms of subcarrier allocation strongly supports data rate, service, and user adaptation;
- very low transmission power and non-bursty transmission modes keeping radiation effects at very low level.

Further Multi-Carrier Modulation Schemes

Multi-carrier systems can also be realized by not exploiting the orthogonality properties of OFDM to typically have a much lower number of subcarriers than traditional OFDM schemes. These schemes can achieve a better PAPR compared to OFDM at the expense of higher receiver complexity. Up to know, these schemes have not become as popular as OFDM. The mobile radio standard cdma2000 [10] employs multi-carrier transmission with three subcarriers and can be considered as one realization of MC-DS-CDMA [11]. The main difference between OFDM and the other multi-carrier modulation schemes is either larger subcarrier spacing or different pulse shaping. The OFDM frequency spectrum and a general multi-carrier frequency spectrum are shown in Figure 2, which illustrates the spectral efficiency of OFDM.

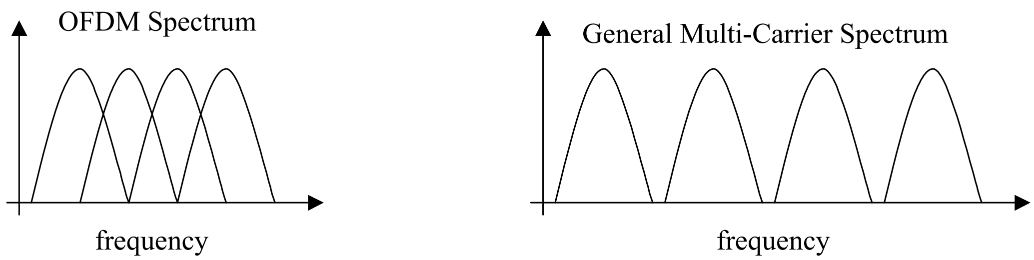

Figure 2: Different multi-carrier frequency spectra

3. Technology Trends and Research Topics in Multi-Carrier Multiple Access

The focus of future research should include general system aspects and technical aspects of the individual access schemes. An overview of the technology trends summarizing important research results is given here together by the identification of future research topics.

Reuse factor

In cellular systems, it is important that the frequency can be reused as often as possible. It is not at all clear which frequency reuse factor can be used with OFDM and more work is needed on this topic. A related issue is the maximum cell size that can be used.

Duplex Method and Multiple Access Method

It is not at all clear which multiple access method or combination of multiple access methods gives the highest spectral efficiency or system efficiency for the uplink and downlink of an OFDM based system. An issue related to this is whether the link should be synchronous or asynchronous. Moreover, it is likely that the traffic in the system will be asymmetric and more work is needed to find an appropriate design solution to efficiently handle this.

Error Correction Coding in Future OFDM Systems

It is well known that current OFDM systems require some forward error correction (FEC) coding in order to achieve excellent performance results in fading channels. FEC coding can be classical convolutional coding as it is used in DAB, DVB-T, IEEE 802.11a/g or HIPERLAN/2 or it can be spreading (repetition coding) or a combination of both. It is of importance to investigate the trade-off between channel code rate, spreading code length, and symbol allocation on the channel for typical 4G mobile radio scenarios. Some new interesting combinations are given in [21] and these need to be further developed.

Adaptive Coding and Modulation in OFDM

With channel state information (channel impulse response, noise levels, interference levels, etc.) available on the transmitting side of the system, completely new designs are possible. Now the transmitted power, the coding rate and the modulation constellation on individual sub carriers can be chosen such that the QoS is fulfilled with maximum spectral efficiency [22] [23]. Diversity (through e.g. channel coding or antennas) becomes less important but may be needed to use also the channel when it is bad. Alternatively, it is possible to exploit the redundancy in the prefix or postfix [18].

Filtered or nonfiltered OFDM

A comparison between filtered OFDM and non filtered OFDM for both spread and non spread OFDM schemes should be done. Although filtered OFDM may lead to higher complexity, it may also lead to higher performances for numerous scenarios.

Advanced ARQ protocols

In some applications ARQ is needed to fulfill the QoS requirements. It may even be needed to have ARQ protocols involved both at the physical layer to make it good enough for upper layer and then another ARQ protocol on the link layer. The protocols need to be designed jointly with coding and modulation on the link layer [23]. The 4G mobile radio system should include optimal error correction with highly flexible dynamic ARQ schemes, especially for the support of future multimedia applications. These algorithms have to evolve from simple repetition to more intelligent redundancy splitting methods which allow for flexible and dynamically increasing error correction capabilities. Hence, retransmissions of data packets can be deployed more efficiently while occupation of radio resources can significantly be reduced.

Scheduling of Resources

In order to increase spectral efficiency in a multi-user system, channel resources have to be efficiently scheduled between users in such a way that spectral efficiency is maximized given the requirements on QoS (BER, delay, etc.) [23]. In this way, resources are given to those that can best use them, e.g. a user that can transmit at high rate with low power is allowed to transmit instead of a user that cannot transmit or only can transmit with high power and low rate. New MAC protocols and efficient signaling between the physical and MAC layers will have to be developed and carefully engineered to accomplish this. In such a scheme, the overall generated interference and thus the radio exposition of humans is reduced, increasing the conformance to tighter future emission regulations and the public acceptance of a system.

Single- and Multi-user Detection in MC-CDMA and MC-DS-CDMA

Investigations have shown that the most promising single user detection technique is MMSE equalization. It can be implemented in a suboptimum version with very low performance degradation and with similar complexity to zero forcing or equal gain combining.

Multi-user detection techniques can significantly improve the system performance at the expense in complexity. Various interference cancellation schemes and block linear equalizers with and without feedback have been investigated and proposals have been made, how the optimum maximum likelihood detector can be realized with reasonable complexity in MC-CDMA systems. Results for the up- and downlink have been presented. In future research, it is important to compare all these techniques in a fair way, to consider their imperfections and to investigate their robustness against different kinds of interference like inter cell interference and near-far resistance.

Iterative Detection and Decoding Strategies

The iterative combination of detection and decoding has gained increasing interest recently resulting in novel detection schemes like soft-interference cancellation [12]. These schemes exploit reliability information about the coded bits from the outer decoder and feed this back to the detector and possibly to the channel estimator. The results indicate that a better performance can be obtained with soft interference cancellation than with separated maximum likelihood detection followed by classical convolutional decoding. These promising schemes have to be adapted to the requirements on 4G systems. The benefits of these schemes have to be proven also for system imperfections such as imperfect power control, imperfect channel estimation and interference from neighboring cells.

Moreover, in order to improve the multi-carrier detection scheme iterative demodulation algorithms (turbo demodulation) of bit interleaved higher order coded modulation enables significant performance enhancement over standard bit metric derivations.

Channel Estimation

Pure OFDM systems can easily apply differential modulation (as used in DAB). In the case of multiple access schemes like MC-CDMA, the coherent detection with pilot symbol assisted channel estimation has gained more interest due to its higher user capacity. Efficient two-dimensional channel estimation concepts have been developed [13], which can significantly reduce the overhead due to pilot symbols by exploiting the correlations of the mobile radio channel in both the time and frequency dimension. These schemes are especially of interest for downlink systems. For the 4G system, concepts have to be developed for an efficient MC-CDMA uplink channel estimation that can cope with high numbers of active users. Alternatives or extensions of pilot symbol aided channel estimation schemes including blind or semi-blind estimation algorithms [14] [19] that reduce the overhead due to pilot symbols have gained high interest in the past years. The suitability of these schemes for 4G broadband systems should also be investigated in detail.

Channel prediction

Large spectrum and system efficiency improvements are possible by making channel state information available to the system and the transmitters [22] [23] [24]. This however requires that channel prediction algorithms that can predict the channel impulse response well into the future can be designed and that these have reasonable good performance [25]. Furthermore, adaptive coding/modulation schemes, fast scheduling algorithms, and multiple access schemes that can use the information (predicted channel impulse response and the accuracy of it) provided by the channel prediction algorithm must be developed. A feedback channel is needed in the system and this needs to be designed such that it does not consume too much of the bandwidth resources.

Synchronization

OFDM inherently offers the possibility to use the guard interval for synchronization [16] and thus can reduce or even completely avoid additional overhead for reference symbols required for synchronization. Investigations are necessary to show whether these algorithms are sufficient to perform acquisition and tracking in a 4G system or whether additional measures are necessary [17].

PAPR Reduction

Multi-carrier signals have a non constant envelope which reduces the efficiency of the power amplifiers in the transmitter and due to the nonlinear amplifier characteristics distorts the transmitted signal and enhances the out-of-band power. A multitude of measures have been proposed to reduce the peak-to-average power ratio (PAPR) or to apply predistortion to increase the power efficiency of the transmitter. It is important to study the PAPR techniques to conclude which methods best fit the requirements in the uplink and in the downlink.

Thus, deriving digital strategies either in the frequency or time domain to reduce the peak to average power allows a significant decrease of the backoff for the power amplifier [20]. This would impact the battery life of the wireless terminals a lot. More generally, the study of digital means for reducing the OFDM constraints on the RF front-end and transceiver architectures that targets lower power operation will be important for reaching high data rate and preserving true wireless operation.

Spectral Efficiency

OFDM modulation is well known for its robustness to multi-path time varying propagation channels. This is mainly due to the insertion of a guard interval (cyclic prefix), a very efficient and simple way to combat multi-path effects. However, guard interval is pure redundancy, which decreases the spectral efficiency (sometimes 25% loss). It is interesting to study alternative OFDM modulation schemes, which can provide the same robustness without requiring a guard interval, i.e. offering a better spectral efficiency. For this purpose, the prototype function modulating each sub-carrier must be very well localized in the time domain, to limit the inter-symbol interference. Moreover, it can be chosen very well localized in the frequency domain, to limit the inter-carrier interferences (due to Doppler effects, phase noise etc.). This function must also guarantee orthogonality between sub-carriers. Functions having these characteristics exist, but the optimally localized ones only guarantee orthogonality on real values [26]. The corresponding multi-carrier modulation is OFDM/OffsetQAM [27]. Among these functions, the localization is optimal with the IOTA (Isotropic Orthogonal Transform Algorithm) function [26] [28]. It would be interesting to investigate on the potential of the OFDM/OQAM modulation for the new OFDM-based air interfaces addressed, as it has already been done in the 3G context in e.g. [29].

MIMO-OFDM and Smart Antennas

The recent developments for space-time coding and smart antennas should also be taken into account in the design of the 4G mobile radio system and air interface. The combination of MIMO with OFDM is an enabling technology to fundamentally improve the spectral efficiency of the 4G mobile radio system. OFDM is well suited for the implementation of MIMO technology. The advantage of OFDM over CDMA to implement MIMO technology is significant. The effects of MIMO schemes on the system capacity of an OFDM based air interface are of high importance for the design of the detection and decoding scheme. It is important to study techniques to combine MIMO and smart antenna schemes to allow the antenna technology to be optimized and closely integrated into the 4G air interface. The MIMO techniques may lead to many significant increases in throughput, robustness and number of simultaneous transmitters.

MAC Layer

The new air interface should be designed to carry different types of traffic including real time traffic and non-real time traffic. This will require the design of an efficient MAC that maximizes the system throughput and minimizes the overhead. The MAC design must take into account that, in addition to data, control information is transmitted that requires high robustness against errors. With the vision that a future 4G system will have different types of physical layer concepts, the MAC should be generic to support the different physical layers and adaptable to different environmental conditions like interference, mobility, available spectrum etc.

Spatially Differentiated Air Interface Access

With the application of multiple element antennas as linear or two-dimensional arrays with flexible on-demand beam forming in 4G networks, radio access protocols should take into account the spatial separation of users which are simultaneously requesting service in a certain area. The ability of directing multiple antenna beams to specific sectors and mapping spatial differentiated data streams to them increases the spectral efficiency of the radio air interface while also reducing the interference emitted from the network. The MAC should be aware of the individual locations of other communicating stations by making use of positioning techniques such as measured angle of arrival statistics from the uplink direction. With this information, a multi-dimensional access with respect to temporal, frequency, sub-carrier and spatial domain could be established with self-organizing dynamically re-use of radio resources in hierarchical network topologies.

4. Conclusions

The future demands on data rate, mobility, and QoS require the design of completely new air interfaces for the next generation of mobile radio systems. The multi-carrier technology has shown its suitability for very high rate systems in many digital broadcasting and wireless LAN standards and seems to be an excellent candidate to fulfill the requirements on 4G mobile radio systems. Future research is expected to show that multi-carrier will be a superior technology for 4G. We see great potential e.g. in diversity schemes and iterative receiver algorithms which consider the interaction between components which operated in an isolated mode today.

An extensive cooperation between research groups is also very important encompassing but not limited to Smart Antennas, Spectrum Issues, Channel Modeling and Propagation Measurements.

We intend to shape the next generation mobile radio systems by contributing to European research and development of future wireless systems, standards bodies and research forums.

Following institutions declared their intention for research in Broadband Multi-Carrier Based Air Interfaces (alphabetical):

Aachen University (Germany), Carleton University (Canada), CEA-LETI (France), Chalmers University of Technology (Sweden), DoCoMo Eurolabs (Germany), France Telecom R&D (France), Fujitsu Laboratories of Europe Ltd (UK), German Aerospace Center (DLR) (Germany), Mitsubishi Electric ITE (France), Motorola Labs (France), Nortel Networks (UK), Royal Institute of Technology (KTH) (Sweden), Telefónica (Spain), Technical University of Ilmenau (Germany), THALES Communications (France), University of Linz (Austria), Uppsala University (Sweden) and VTT Electronics (Finland).

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