Adaptive 4G Uplink Proposal Based on Interleave-Division Multiple Access

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Abstract

Efficiency and adaptivity play a major role in the design of fourth-generation (4G) wireless systems. 4G systems should be bandwidth efficient, power efficient, and allow for low complexity transceivers. The systems should be flexible with respect to data rate (link adaptation), data reliability (QoS), and service provisioning. Moreover, they should operate on frequency-selective and fast-fading channels.

In this paper, a system proposal for the 4G uplink based on Interleave-Division Multiple Access (IDMA) is presented ("KIEL Proposal"), which fulfills the mentioned requirements. Cross-layer issues are addressed.

I. Introduction

The International Telecommunication Union (ITU) recently defined recommendations for mobile communication systems beyond the third-generation (3G) [1]. In these recommendations, data rates of up to 100 Mbps for high mobility and up to 1 Gbps for low mobility or local wireless access are predicted. Systems fulfilling these requirements are usually considered as fourth-generation (4G) systems.

4G systems are expected to achieve the following goals:

- *Quality of service (QoS) provisioning*: Packet-based services (probably using mobile IPv6) will play a major role. Low delays are needed (for example for streaming content), which results in the need for short block sizes. Parallel data streams with different QoS classes should be supported to allow for hierarchical source coding, video streaming, parallel support of different applications, etc.
- *System scalability*: The system should be scalable with respect to data rates (with high peak rates up to 100 Mbps for high mobility and 1 Gbps for low mobility or local wireless acces), bandwidth (about 20 MHz to 100 MHz in 5 MHz slots), and cell sizes (including pico, micro, and macro cells)
- *High efficiency* including bandwidth efficiency (about 4-10 bits/s/Hz) and simultaneously high power efficiency
- High-speed mobility, high velocities, fast adaptation
- Low computational complexity (iterative processing).

Efficient transmission techniques and cross-layer design as well as optimization techniques are required to meet these goals.

Due to many factors, direct-sequence code-division multiple access (DS-CDMA) is currently an attractive candidate particularly for the uplink [2]. DS-CDMA offers well-known features: Dynamic channel sharing, soft capacity, reuse factor of one, low drop-out rate and large coverage (due to soft handover), ease of cellular planning, robustness to channel impairments and immunity against interference, etc. These advantages are due to spreading the information over a large bandwidth ("wideband transmission").

In this paper, we extend the efficient air interface introduced in [3]. It is particularly useful for the uplink of new wireless systems, as well as for an evolution of existing direct-sequence spread spectrum code division multiple access (DS-CDMA) systems. Our proposal is based on interleave-division multiple access (IDMA). IDMA can be considered as a special case of DS-CDMA. In IDMA, each data stream is first encoded by a (very) low-rate encoder. For convenience, each data stream is referred to as layer. The main difference between IDMA and conventional DS-CDMA is that in IDMA each layer is assigned a layer-specific interleaver, whereas in DS-CDMA a layer-specific spreader is applied. As a consequence, in IDMA chip-by-chip interleaving is done and no distinct spreading code is used. The spreading and the forward error correction is done by one and the same code. IDMA is known to outperform DS-CDMA in combination with iterative receiver structures, especially for high bit loads. It has been widely accepted that iterative receiver structures perform better than separated detection and decoding [2].

The remainder of this paper is organized as follows: In the next section we provide more background information about IDMA. Afterwards, we present our system proposal and address the goals mentioned above and point out how they can be realized by our system proposal. Finally, the conclusions are drawn.

II. Interleave-Division Multiple Access

DS-CDMA is a popular transmission technique already applied in 2G (IS-95), 2.5G (cdma-2000), and 3G (UTRA FDD, UTRA TDD, TD-SCDMA) systems. Distinct data streams $\mathbf{d}_m$ are distinguished by *different spreading sequences*. Forward error correction (FEC) coding is typically done before interleaving and spreading. Conventionally, the same FEC encoder and the same interleaver is used for all data streams $\mathbf{d}_m$.

If the the arrangement of interleaving and spreading is reversed, the data streams are distinguished by *different interleavers*. This special case of DS-CDMA is called *code-spread CDMA* [4], *chip-interleaved CDMA (cI-CDMA)* [5], or *interleave-division multiple access (IDMA)* [6] in the literature. We will use "IDMA" throughout this paper.

As an alternative to the described re-arrangement between interleaving and spreading, IDMA may be interpreted as DS-CDMA without spreading. In effect, for DS-CDMA systems it has been shown by Viterbi that the highest power efficiency can be achieved by low-rate codes [7], and it has been proven by Verdú and Shamai that the highest bandwidth efficiency can be achieved by low-rate codes as well [8].

A second alternative is to interpret IDMA as a special form of trellis-coded modulation. For details see [9].

Due to interleaving, the code is nonlinear. Multiple code words can be linearly superimposed in order to enhance the data rate per user, a concept which is called multi-code technique in UTRA. In conjunction with IDMA, this concept has been proposed in [3]. Due to interleaving, the layers may be interpreted as *typical sequences* as defined by Shannon [10]. In case of multi-code (or multi-layer) transmission, the data streams of different layers of the same user are linearly superimposed (preferably with different phases and amplitudes) before transmission. The data rate can be adapted by superimposing a variable number of layers. The layers can be distinguished at the receiver by means of the common code and the different interleavers. Shaping [11] is not necessary. We assume that the encoder is binary, hence the layers are binary as well which allows for real-valued processing.

Besides being power *and* bandwidth efficient, IDMA offers a number of nice features:

- *Rate/power adaptation*: The multi-code technique can be used for a rate/power adaptation as proposed in [3]. A large variety of data rates can be supported. As opposed to conventional adaptive modulation/channel coding techniques, the modulation scheme is fixed (and even binary) and the same channel code is used for all layers. Power adaptation/savings are particularly useful for the uplink.
- *MIMO*: Since each layer is assigned a different interleaver, an arbitrary number of transmit antennas can be used [6]. No orthogonal or arithmetic space-time code design is necessary. According to Shannon, typical sequences are generated and superimposed.
- *Fast fading*: In conjunction with a superimposed pilot layer, fast fading channels can easily be tracked [12].
- *Frequency-selective fading*: Rake-like reception is straightforward.
- *Complexity*: In conjunction with IDMA, a possible low-complexity receiver is the simplified version of the Wang & Poor receiver [13] derived in [14]. The task of this receiver is to cancel any type of interference (multilayer interference, multiuser interference, multiantenna interference, intersymbol interference, etc.) jointly. The receiver is based on the Gaussian assumption and turbo processing in conjunction with the low-rate encoder. Its complexity is only *linear* with respect to the number of layers, number of chips/layer, number of users, number of receive antennas, number of channel taps, and the number of iterations.
- *Soft-information*: The mentioned receiver inherently delivers reliable soft-output information, which is useful for rate adaptation and cross-layer optimization.
- *Resource allocation*: Resource allocation is greatly simplified since the same interleaver set is used at all times.
- *Low delay*: Due to chip-by-chip interleaving, the block size can optionally be reduced compared to conventional DS-CDMA (which employs symbol-by-symbol interleaving), because the interleaver length is increased by the spreading factor.

In order to cancel the multilayer interference, knowledge of all layers is advantageous. Hence, our system proposal is particularly suitable for the uplink, where base-station processing is done at the receiver side. The common advantages of conventional DS-CDMA (such as immunity against interference, re-use factor of one, large coverage, possibility of soft-handover) are not altered, since IDMA is just a special form of DS-CDMA. As a consequence, existing DS-CDMA systems may be enhanced by IDMA.

III. 4G UPLINK PROPOSAL

A. IDMA-based Transmission System

For the uplink, an efficient yet simple multiple access scheme supporting a high number of active users is needed. Using IDMA, we can handle a large number of users, each of them using a different interleaver. Interleavers are easy to find and for long blocks even random interleavers may be used. We propose a transmitter and receiver structure as published in [3] and shown in Fig. 1. After low-rate encoding, the interleaving is done with a layer specific interleaver π_m. Assuming a linear channel, the impact of the transmission medium can completely be represented by the vector $\mathbf{h} = [h_0, ..., h_L]$, where h_l denotes the l-th coefficient of the equivalent discrete-time intersymbol-interference channel model with memory length L. At the receiver side the individual layers, which are experiencing multilayer interference (MLI), are detected by a low complexity multilayer detector (MLD). An iterative (turbo-like) receiver that exchanges extrinsic information between the MLD and the decoder (DEC) can be applied. This receiver structure is nearly optimal, of low complexity, and provides reliable soft outputs. The MLD uses channel estimates delivered by a channel estimator. We propose a pilot-layer aided channel estimator (PLACE) [12] (see Section III-E). Given the log-likelihood values from the m-th layer passed by the decoder after the last iteration, an evaluation module is used to calculate an estimate of the bit error rate (BER) of the m-th layer. The BER estimate is used for soft link adaptation (Section III-C).

For the radio air interface we are considering the parameters shown in Table III-A. These parameters are suitable for the proposed system and make it comparable to the uplink proposal in [15], which uses the same bandwidth, chip duration, and is also based on code-spreading [4]. Therefore, the proposal in [15] is combinable with our proposal (Section III-B).

B. Extensions of Pure IDMA

In [16] it is shown how to improve the error performance of IDMA by means of a hybrid scheme with orthogonal code multiplexing and IDMA (OCDM/IDMA). An optional extension of IDMA based on this approach is depicted in Fig. 1. The data stream of one user is parallelized in multiple layers. Different encoders are used for the single layers. All layers of one user share one interleaver.

It is also possible to perform the spreading over multiple sub-carriers to obtain an MC-IDMA system. This is an interesting alternative to IDMA for systems with a huge number of sub-carriers, or an extension of existing or planned MC-CDMA systems [17], [15].

Table III-A: Radio air interface parameters for an IDMA-based uplink.

Wireless access	(MC-)IDMA or (MC-)OCDM/IDMA
Total bandwidth	e.g. 40 MHz
Roll-off factor	0.22
Frequency bin width B	Multiples of 5 MHz
Chip duration T_c	244 ns $\cdot$ 5 MHz $/B$
Block duration T_B	156.25 μs
Chips per block	T_B/T_c
Data modulation	BPSK with layer-specific phase offsets
Spreading factor SF	$8 - 32 \cdot B/5$ MHz
Code rate (with spreading)	$1/SF$

C. Soft Link Adaptation

One enormous advantage of the low-cost IDMA-receiver considered in [14] is the inherent reliability of soft output information. In [3] an adaptation strategy based on the soft outputs is described. Besides of delivering hard decisions after the final iteration, the receiver in Fig. 1 calculates estimates of the BER in an evaluation module. The evaluation module compares the estimated BER with the predefined target BER P_t. Since the BER degrades with increasing number of layers because of increased MLI, the number of layers transmitted in the next block is decreased at the transmitter side if the estimated BER is higher than the target BER. If the estimated BER is below the target BER, the transmission power can be reduced. It was shown in [16] that the proposed iterative receiver is appropriate for the suggested adaption strategy.

D. High Bandwidth and Power Efficiency

In Section IV, it is shown that without adaptive power allocation a spectral efficiency of about 3.75 bits/s/Hz can be reached for one transmit antenna. With adaptive power allocation, a spectral efficiency of up to 8 bits/s/Hz (corresponding to 256QAM) for one transmitter antenna has been reported [18]. With the parameters given in Table III-A, the maximum theoretic throughput for a single antenna system is 122.95 Mbps for a bit load of 3.75 bits/s/Hz, which is higher than the results presented for the uplink in [15].

In conjunction with the proposed adaptation strategy, a continuous operation near the theoretical limit can be achieved. However, due to soft link power adaptation the mobile device always uses minimum power for transmission which results in long battery life.

E. Pilot-Layer Aided Channel Estimation

The receiver under investigation needs reliable channel estimates. In IDMA it is suitable to use pilot-layer aided channel estimation [12], where one layer for every user carries training symbols for channel estimation. This is especially useful for the uplink as the channel for every mobile station is different at a base station. An allocation of a pilot layer has been shown to achieve good estimates for the whole block length even for rapidly changing frequency-selective fading channels.

F. Multiple Antenna Systems

Multiple antenna systems are a key technology for 4G. In [19] IDMA has been extended to multiple antennas with good results. The extension of IDMA to MIMO systems is easy because the superposition of the different layers at the transmitter side and their separation at the receiver side is done anyway. Therefore, neither special design is needed nor further increase in complexity is caused.

G. Quality of Service

The quality of service (QoS) is mainly defined by a maximum bit error rate, a minimum data rate, and a maximum delay (especially for packet based services). These parameters are highly dependent on the application, e.g. text message, voice transmission or video transmission. IDMA-based systems can be made highly adaptive in order to guarantee a certain QoS level. Hence, we do not seek quasi error-free transmission, but apply the mentioned soft link adaption strategy to guarantee a certain bit error rate for a layer or group of layers allocated to a user or application. On the other hand, we keep the transmission power as low as possible for longer battery life and less emitted radiation.

- The bit error rate that can be tolerated is application-dependent, e.g. voice transmission allows higher bit error rates than data transmission. Instead of using adaptive modulation and/or channel coding, in IDMA the number of layers and the transmission power are modified to meet this requirement. The number of layers used for transmission can be reduced if the data rate is higher than needed or, if the data rate cannot be reduced for QoS reasons, the transmit power can be increased until the target BER is achieved.
- The data rate is an essential QoS parameter, for example text messaging services need much lower data rates than video transmission. The data rate is adapted in a similar way as the target BER is. With a higher number of layers assigned to a user, its data rate is higher. To ensure a certain BER the power can be adapted as well.
- In some applications, e.g. real-time speech transmission, a large delay is very inconvenient, in other applications even critical, e.g. packet loss in TCP based networks. To achieve small delays, the block length for IDMA transmission can be chosen to be quite small. This is possible because the chip-by-chip interleaving is done. Note that the block length given in Table III-A is four times shorter than in [15].

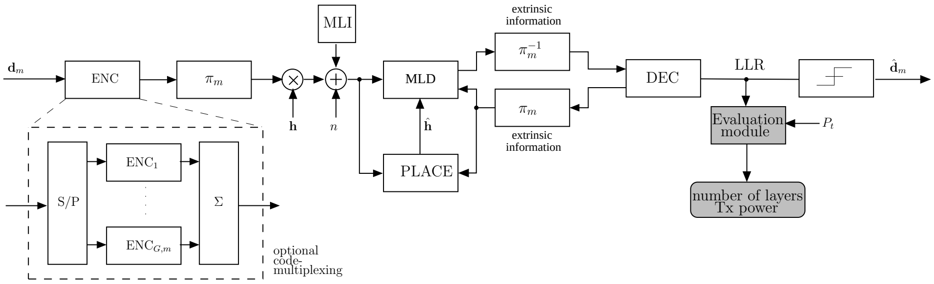

Fig. 1. IDMA-based system proposal (m-th layer).

H. Cross-layer Design

To achieve high data rates in 4G, the overhead between the different layers (e.g. physical layer and data link control (DLC) layer) should be minimized by an optimized cross-layer design. Medium access can be managed quite easily for IDMA systems as it can be done mainly by allocating layers. The use of different layers for the transmission of different information from the same user can be combined with ARQ protocols at the link or transport layer for intelligent retransmission of data in an extra layer. That could be the retransmission of a whole block, retransmission of unreliable bits, or additional code bits for hybrid type-II ARQ schemes without interrupting the data flow on other layers, which again helps to fulfill QoS parameters. The soft outputs provided on the physical layer may be used up to the transport layer, e.g. to avoid unreasonable decrease of the TCP congestion window because of fading conditions.

I. Scalable Bandwidth

For reasons of scalability and ease of implementation we propose to divide the available bandwidth. Since the frequency bins allocated to 4G systems are not known yet, we suppose to divide the 40 MHz suggested in [15] into multiples of 5 MHz. That could be 2×20 MHz as considered in [15], but also an inhomogeneous allocation. Following this proposal, the available frequency bins need not to be contiguous. Even dynamic bandwidth allocation may be considered.

IV. CONCLUSIONS

In this paper, an IDMA-based system proposal for the 4G uplink is presented. We addressed some of the requirements and possible characteristics of the 4G uplink and explained how IDMA might be used to meet them. The main advantages of IDMA are its low complexity, high bandwidth and power efficiency, and excellent adaptivity. Besides soft link adaptation, the reliable soft outputs generated by the receiver described in this paper enables a wide range of possible applications like soft channel decoding, iterative schemes and other information combining technologies. Further improvements are expected from the straight forward extension to key technologies like MIMO and MC technologies, which are currently considered for 4G systems [1], [17] and [15].

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