An Interleave-Division Multiple Access Based System Proposal for the 4G Uplink

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***Abstract*— Efficiency and adaptivity play a major role in the design of fourth-generation wireless systems (4G). 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. The systems 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.

In December 2004, NTT DoCoMo announced a lab experiment achieving a data rate of up to 1 Gbps in the downlink employing variable-spreading-factor spread orthogonal frequency division multiplexing (VSF-Spread OFDM) and multiple-input multiple-output (MIMO) technology occupying a bandwidth of 101.5 MHz. Multi-carrier solutions, code division multiple-access schemes, and MIMO-OFDM are considered as key technologies to achieve the high bandwidth efficiencies needed in 4G systems [2]. Furthermore, adaptive transmission schemes are studied to meet the demand for the different quality of service (QoS) levels which are expected for the spectrum of applications to be supported by 4G systems. The increasing importance of packet-based applications implies that 4G networks will at least provide packet-based services, probably using mobile IPv6. High data rates, QoS aspects, and the packet-based services in 4G implies efficient allocation of resources and reduction of overhead between the different layers, and therefore make cross-layer design and optimization inevitable for 4G.

In this paper, we extend the efficient air interface introduced in [3]. Our proposal is based on interleave-division multiple access (IDMA). 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.

The remainder of this paper is organized as follows: In Section II, fundamentals on IDMA are presented. Based on the specific characteristics of this multiple access technology, an IDMA-based system proposal for the 4G uplink is proposed in Section III. Numerical results shown in Section IV demonstrate the feasibility of our proposal, and allow us to predict the power/bandwidth efficiency. Finally, conclusions are drawn in Section V.

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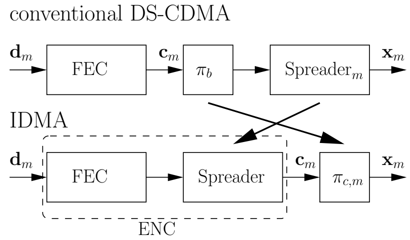

Fig. 1. Comparison of conventional DS-CDMA and IDMA. The data sequence of the m-th layer is denoted as $\mathbf{d}_m$ and the corresponding encoded and interleaved sequence is denoted as $\mathbf{x}_m$.

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-CDMA) systems. Distinct data streams $\mathbf{d}_m$ are distinguished by *different spreading sequences*. In conjunction with channel coding, forward error correction (FEC) coding is typically done before interleaving and spreading, as shown in the upper part of Fig. 1. Conventionally, the same FEC encoder and the same interleaver is used for all data streams $\mathbf{d}_m$.

In the lower part of Fig. 1, a DS-CDMA system is illustrated where the arrangement of interleaving and spreading is reversed. Now, distinct 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. In IDMA, FEC encoding and spreading may be done jointly by a single low-rate encoder, subsequently denoted by ENC. The spreader has no special task. Furthermore, it is important to note that interleaving is done on a chip-by-chip basis. The implications of this fact will be addressed in the following.

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]. 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]. For convenience, each encoded and interleaved sequence $\mathbf{x}_m$ is referred to as a *layer*. Due to interleaving, the layers may be interpreted as *typical sequences* as defined by Shannon [9]. In case of multi-code transmission, a set of typical sequences is superimposed. Accordingly, with IDMA a high bandwidth/power efficiency can be achieved. Shaping [10] is not necessary. Without loss of generality, we assume a superposition of binary (pseudo-)random sequences in the following.

A second alternative is to interpret IDMA as a special form of trellis-coded modulation. For details see [11].

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 ("joint Gaussian detector") and turbo processing in conjunction with the low-rate encoder. Its complexity is 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.

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.

Wireless access	(MC-)IDMA or (MC-)OCDM/IDMA
Total bandwidth	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
Spreading factor SF	$8 - 32 \cdot B/5$ MHz
Code rate (with spreading)	$1/SF$

TABLE I

RADIO AIR INTERFACE PARAMETERS FOR AN IDMA-BASED UPLINK.

III. SYSTEM PROPOSAL

A. IDMA-based Transmission System

For the uplink, an efficient 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. As the interleavers work on the spreaded bit sequence, the requirement of long block lengths is easy to fulfill. We propose a transmitter and receiver structure as published in [3] and shown in Fig. 2. 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 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 I. 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). However, it is also possible to use other parameters than given in Table I.

The numerical results given in Section IV are obtained for a spreading factor (SF) of 10, which corresponds to a code rate of 1/10. For the proposed iterative receiver, in combination with the given block duration, a SF between 8 and $32 \cdot B/5$ MHz should be chosen to achieve good results.

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. 2. The data stream of one user is parallelized in G_m

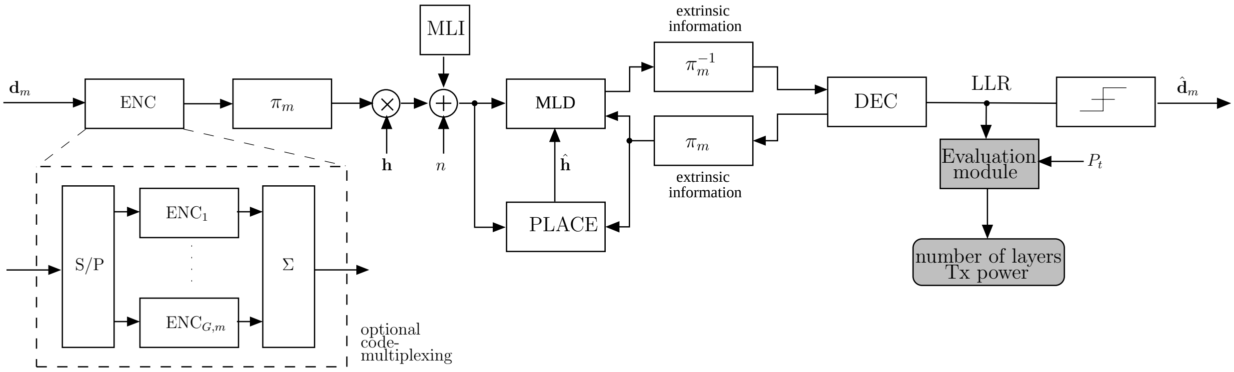

Fig. 2. IDMA-based system proposal.

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 [2], [15].

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. 2 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/Hz can be reached for one transmit antenna. With adaptive power allocation, a spectral efficiency of up to 8 bits/Hz (corresponding to 256QAM) for one transmitter antenna has been reported [17]. With the parameters given in Table I, the maximum theoretic throughput for a single antenna system is 122.95 Mbps for a bit load of 3.75 bits/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 what results in long battery life.

E. Pilot 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 [18] 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 I is four times shorter than in [15].

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 as shown in Fig. 3. Following this proposal, the available frequency bins need not to be contiguous. Even dynamic bandwidth allocation may be considered.

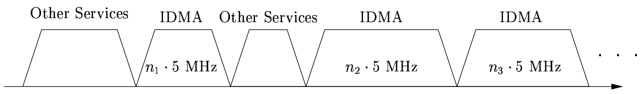

Fig. 3. Possible spectrum allocation for IDMA-based 4G services.

IV. Numerical Results

Our vision of future wireless communications is dominated by two goals: efficiency and adaptivity. In this section, numerical results are presented that confirm IDMA to be an excellent choice for reaching these two goals. All numerical results are obtained by using the low-complexity iterative soft-Rake receiver [14].

The presented results are raw bit error probabilities, i.e., simple spreading codes without coding gain are applied to keep the results comparable. Improved performance results with different channel codes can be found in [4], [6]. While those results are already promising, the design of optimal codes (w.r.t. power efficiency and accuracy of soft outputs) is still an issue for future research. Note that the loads and rates mentioned in this section are not changed by using different channel codes, as for IDMA the code rate is defined by the spreading length (cf. Fig. 1).

Due to the chip-level interleaving, the error performance at high loads is better for IDMA than for conventional CDMA systems, which can be seen in Fig. 4, where Monte-Carlo simulation results are presented for m-OCDMA [19], IDMA, and OCDM/IDMA [16] with a load of $b = 3.75\,\mathrm{bits/Hz}$ on the AWGN channel. In the figure, hard and soft estimates of the bit error probability are shown. Hard estimates are obtained by classical Monte-Carlo simulations, where the number of erroneous bits is divided by the number of transmitted bits. Soft estimates are obtained directly by the soft decoder outputs without any knowledge about the transmitted data [20]. The load of $b = 3.75\,\mathrm{bits/Hz}$ is equivalent to distinctive overspreading in DS-CDMA systems. To allow for a fair comparison, the same spreading code (without coding gain) is used for all three schemes. Although m-OCDMA is especially designed to allow for overspreading, the chosen load is simply too high to obtain a satisfying error performance. For the same load, IDMA performs much better even on the AWGN channel. The hybrid OCDM/IDMA scheme even outperforms IDMA by $2\,\mathrm{dB}$ and reaches the BPSK single-user performance at $\mathrm{E_b/N_0} = 10\,\mathrm{dB}$. We gather from these results that IDMA and OCDM/IDMA are well-suited to overcome the harmful effect of overspreading. Note that the estimates of the bit error probability based on the soft outputs of the (MLD) coincide with the hard estimates. Therefore, the error performance can be accurately estimated at the receiver without the need for an additional code. This property can be used, e.g., for soft link-adaption like proposed in [3].

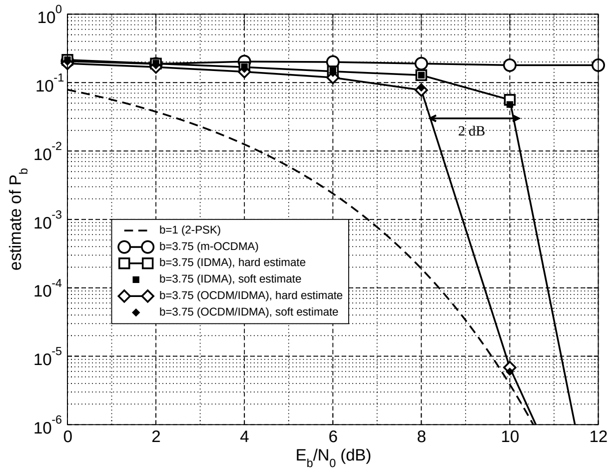

Fig. 4. Soft and hard estimates of P_b for the proposed IDMA system with a bit load of $b = 3.75\,\mathrm{bits/Hz}$ on AWGN channel.

Frequency-selective fading channels form an obstacle for reliable communications in conventional CDMA systems due to orthogonality loss. In Fig. 5, Monte-Carlo simulation results are presented for uplink transmissions via Rayleigh fading channels. The maximum Doppler frequency is normalized to the chip rate. As can be seen, the mentioned drawback of orthogonality loss does not arise for IDMA. In contrast, the IDMA system permits to constructively make use of the inherent channel diversity in time, delay, and across the data layers and therefore improves the error performance compared to the single-user case in frequency-flat block-fading.

Fig. 6 shows the error performance for different loads on a six-tap Rayleigh channel with power decay profile like used in [15]. The error performance does not degrade up to a load

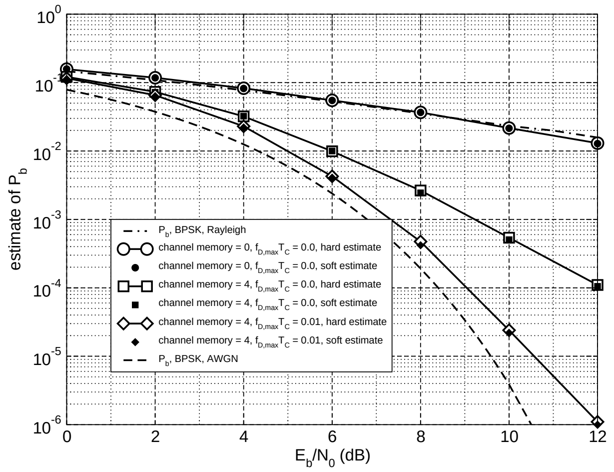

Fig. 5. Soft and hard estimates of P_b for the proposed IDMA system with a bit load of $b = 1$ on independent Rayleigh channels (uplink, one layer per user).

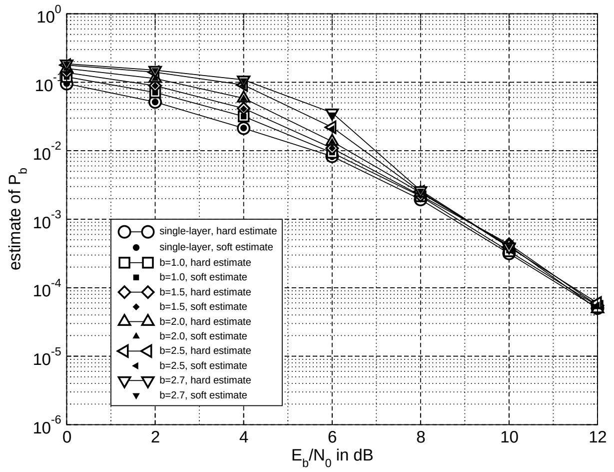

Fig. 6. Soft and hard estimates of P_b for the proposed IDMA system with different bit loads on independent Rayleigh channels (uplink, one layer per user) with power decay profile and six taps. The normalized maximum Doppler frequency is $f_{D,max}T_C = 1.22e^{-6}$.

of $b = 2.7$ for $\mathrm{E_b/N_0} = 8\,\mathrm{dB}$ or higher. Note that with the parameters given in Table I, a load of $b = 2.7$ corresponds to a data rate of $88.5\,\mathrm{Mbps}$ in the uplink. Even higher loads are expected when using more sophisticated detectors (e.g., with joint Gaussian assumption [14]) or power allocation [21].

V. 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], [2] and [15].

Numerical results demonstrate the good performance of IDMA on fading channels and the feasibility of high bit loads. Further research is needed in the area of channel code optimization and interleaver design.

Although focus is on 4G, the proposed techniques are also applicable to enhance the UMTS system (3.5G). Another potential application are ad-hoc networks.

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