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The OFDM-IDMA approach to Multiuser Communication Techniques in Wireless Communication Systems

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Abstract: **This article outlines the basic principles of OFDM-IDMA. Comparisons with other alternative technologies such as OFDM-CDMA and OFDMA are provided. Some attractive features of OFMD-IDMA are explained, including low cost iterative multi-user detection, flexible rate adaptation, frequency diversity, and significant advantages regarding spectral and power efficiency. A number of channel estimation algorithms for iterative receivers are compared for the case of an up-link orthogonal frequency division multiplexing interleave division multiple access (OFDM-IDMA) system. Both pilot based algorithms, used to obtain an initial estimate, as well as semi blind decision-directed algorithms working as a component of the iterative receiver are considered. Algorithms performing either joint minimum mean square error (MMSE) channel estimation, or iterative estimation using space-alternating expectation maximization (SAGE), are evaluated. The considered algorithms differ in terms of complexity, as well as performance. The complexity versus performance tradeoff is at the focal point. There is no single channel estimator providing the best trade-off and the analysis shows how the system load (number of users)and the SNR influence the estimator choice.**

***Index Terms*—Channel estimation, OFDM-IDMA, algorithm complexity, expectation maximization EM), SAGE, discrete prolate spheroidal (DPS) sequences.**

1. INTRODUCTION

IN recent years a new multiple access technique, where the users are separated through their unique interleaving patterns, has generated a large interest in the research community. The technique, referred to as interleave-division multiple access(IDMA) [1], has been shown to mitigate multiple access interference while simultaneously achieving a high spectral efficiency. IDMA shares many properties with code division multiple access (CDMA), where user separation is obtained through user-specific spreading codes, and has shown similar performance but with a reduced receiver complexity [1]–[4]. When the system bandwidth grows in single carrier systems, the equalization process becomes increasingly challenging due to the increase in the number of resolvable paths. Introducing orthogonal frequency division multiplexing (OFDM) simplifies this task by transforming the wideband channel into a set of orthogonal narrow band sub-channels. A simple scalar equalization can then be performed separately for every sub channel. By combining IDMA and OFDM, an efficient multiuser system is formed which efficiently combats ISI and also reaches a high spectral efficiency [5], [6]. For interference cancellation and equalization in such systems, reliable channel estimates are needed. Channel estimates are usually obtained solely based on pilot symbols, which are known to the receiver. With breakthrough of turbo-like receivers, iterative decision-directed approaches to channel estimation have received increasing attention [7].By using decoded symbols as pilots, more reliable estimates are obtained, at the same time as the pilot overhead is reduced. For a multi-user system that performs iterative MUD, such as OFDM-IDMA, iterative channel estimation can be incorporated in a straightforward way into the receiver structure. There has only been limited research conducted on the performance of OFDM-IDMA systems employing channel estimation. For example, in an estimator based on the least mean square algorithm is used, and in a least square (LS) estimate is performed in every iteration. Both methods iteratively perform per-user channel estimation using symbol estimates from the channel decoder. The iterative decision-directed channel estimation algorithms, and an evaluation of different algorithms is performed. The expectation maximization (EM) like algorithm is performing MMSE based estimates on soft interference canceled single-user streams. Furthermore, due to shared properties with OFDM-CDMA, and multiple transmit antenna systems, algorithms available for these technology may be adopted, as will be discussed below. In a discrete Fourier transform (DFT) based estimator for an OFDM system with transmit diversity is developed. The estimator jointly estimates the channels to all antennas. To reduce complexity, a related estimator based on the EM algorithm is proposed, where the channels are estimated per user through indirect interference cancellation. Related to this work, a similar algorithm is proposed for multi-carrier CDMA systems in ,and for multiple antenna systems In a channel estimator that jointly estimates all user channels is developed for OFDM-CDMA, based on a low-rank discrete prolate spheroidal (DPS) sequence approximation of the

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channel. The algorithm is extended to multiple-input multiple output(MIMO) OFDM systems in and further developed to utilize time and frequency correlation. The DPS sequences are used to efficiently exploit the frequency correlation. The algorithms all make use of estimates on the transmitted symbols, and the receiver therefore needs to acquire an initial channel estimate. Three pilot based algorithms, based on well known principles, are evaluated for this purpose. The aim is not only to investigate algorithm performance, but also how their implementation complexity relates to performance. Due to limitations in power consumption and chip area, complexity considerations are of high importance when algorithms are implemented in real systems. The main contributions of this paper may be summarized as follows: Three different decision-directed channel• estimation algorithms are evaluated in an OFDM-IDMA system for the first time. One of the algorithms jointly estimates the channels for all users, while the others perform per user estimates based on the space-alternating EM (SAGE)algorithm. Different algorithms for obtaining an initial pilot based channel estimate are also evaluated. The algorithms effect on the overall system performance and convergence is studied, along with their complexity. A complexity versus performance analysis• is performed, where the total number of complex multiplications needed to reach a bit error rate (BER) target is evaluated for the evaluation, the complete receiver complexity incorporating channel estimation, MUD and data decoding is considered

2. IDMA PRINCIPLES

In IDMA [2–4] each user is assigned a unique interleaver, which is used to distinguish it from other users. IDMA can be regarded as a special form of CDMA. An attractive feature of IDMA is that it allows the use of a low-complexity iterative MUD technique that is applicable to systems with a large number of users. The basic principles of IDMA are illustrated in Fig. 1a. At the transmitter side, the information data from user k is first encoded by an FEC encoder labeled by ENC. The resultant signal is then interleaved by its unique interleaver πk before transmission. Let us consider a flat fading channel (i.e., single-path channel). The received signal can be written as

$$r(n)=\sum_{k=1}^{K} h_k(n)x_k(n)+z(n) \quad (1a)$$

$$=h_k(n)x_k(n)+\xi_k(n), \quad (1b)$$

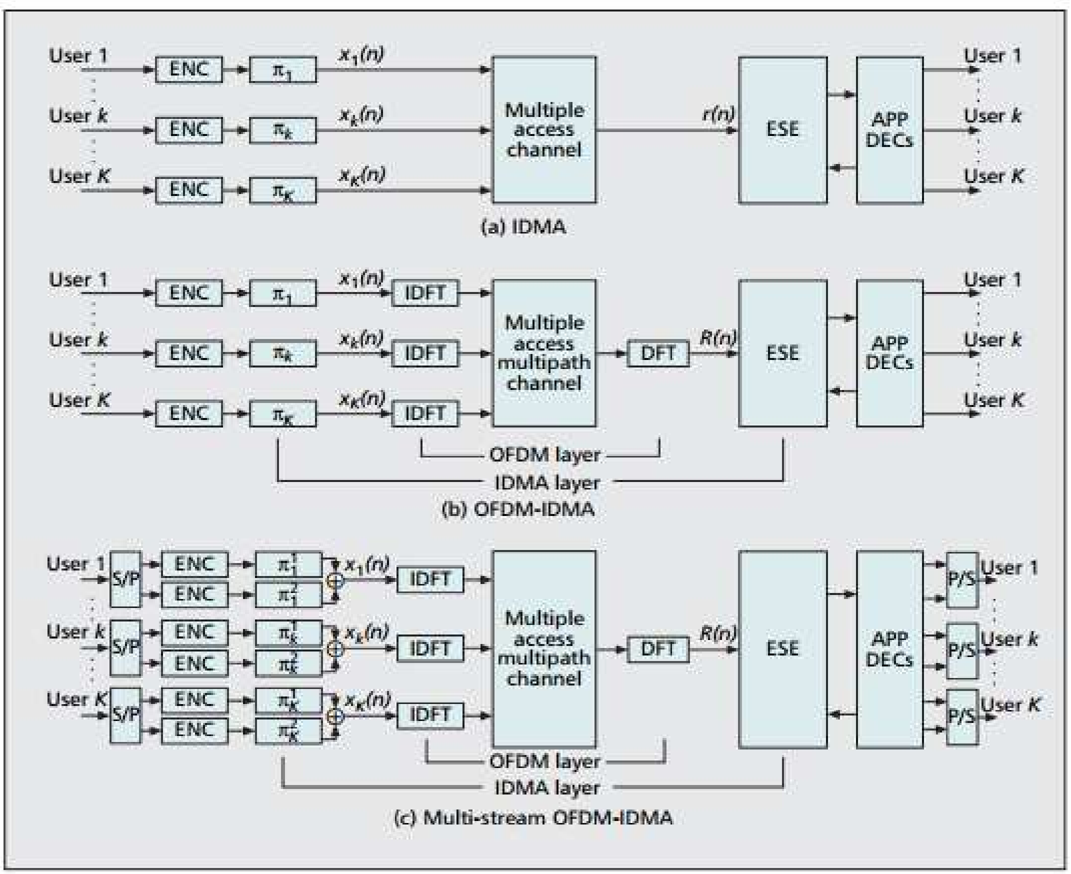

Figure 1. Illustration of various multiple access schemes: a) IDMA; b) OFDM-IDMA; and c) multistream OFDM-IDMA. Cyclic prefix insertion and removal are not explicitly shown in (b) and (c). S/P and P/S stand for serial-to-parallel and parallel-to-serial converters respectively

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where hk(n) is the fading coefficient seen by user k at time n, {z(n)} are samples of additive white Gaussian noise (AWGN), and ξk(n) = Σm≠k hm(n)xm(n) + z(n) represents the interference plus noise component in r(n) with respect to user k at time n. From the central limit theorem, ξk(n) can be approximated by a Gaussian random variable. The core of the IDMA receiver in Fig. 1a consists of the iteration of the following two operations. • Estimate xk(n) based on Eq. 1b. This is a standard signal detection problem since Eq. 1b is in a signal plus noise form. It is carried out by the elementary signal estimator (ESE) shown in Fig. 1a. Under the Gaussian approximation, ξk(n) is completely characterized by its mean E(ξk(n)) and variance Var(ξk(n)). A fast technique is described in [2] to compute E(ξk(n)) and Var(ξk(n)). • Process the outputs of the above operation using the a posteriori probability decoders (APP DECs). The results are used to refine the estimates of the mean and variance of ξk(n) to be used in the next iteration. In MUD for conventional CDMA systems, matrix operations are required to handle the correlation among the spreading sequences of different users [13]. With IDMA (and OFDM-IDMA discussed in the next sub-section), chip-level interleaving ensures that the transmitted sequences from different users are almost un-correlated. Consequently, matrix operations are not necessary and the simple CBC detection outlined above (with cost independent of K) is sufficient to provide near optimal performance. This removes the main obstacle to MUD in applications.

3. OFDM

The use of the orthogonal frequency division multiplexing(OFDM) technique is currently an active field of research in the area of communication and has been used to develop wireless local area network (WLAN) systems, for example the IEEE 802.11a/g standards. New standardization processes already foresee the application of OFDM in future WLAN and ultra- wide-band (UWB) systems . The concept underlying such a system is to modulate a number of mutually orthogonal sub- carriers with the input data. This enables the realization of high-speed transmission systems. However, the entire system performance depends on maintaining the orthogonality of the sub- carriers and failing to maintain this property results in detrimental effects for example inter-carrier interference (ICI) and inter-symbol interference (ISI) during signal reception. In a real system, the orthogonality property of the sub-carriers can be disturbed during the RF up- and down-conversion and by the characteristics of the transmission channel.

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The key challenge faced by future wireless communication systems is to provide high-data-rate wireless access at high quality of service (QoS).Combined with the facts that spectrum is a scarce resource and propagation conditions are hostile due to fading (caused by destructive addition of multipath components) and interference from other users, this requirement calls for means to radically increase spectral efficiency and to improve link reliability. Multiple-input multiple-output (MIMO) wireless technology seems to meet these demands by offering increased spectral efficiency through spatial multiplexing gain, and improved link reliability due to antenna diversity gain. Even though there is still a large number of open research problems in the area of MIMO wireless, both from a theoretical perspective and a hardware implementation perspective, the technology has reached a stage where it can be considered ready for use in practical systems.

The key challenge faced by future wireless communication systems is to produce high-data-rate wireless access at high quality of service (QoS).Combined with the facts that spectrum may be a scarce resource and propagation conditions square measure hostile owing to attenuation (caused by harmful addition of multipath components) and interference from different users, this demand imply suggests that to radically increase spectral potency and to enhance link responsibility. Multiple-input multiple-output (MIMO) wireless technology appears to fulfill these demands by givingredoubled spectral potency through abstraction multi plexing gain, and improved link responsibility owing to antenna diversity gain. albeit there's still an oversized range of open analysis issues within the space of MIMO wireless, each from a theoretical perspective and a hardware implementation perspective, the technology has reached a stage wherever it will be thought-about prepared to be used in sensible systems.

Interleave division multiple access is one of the most suitable candidate for future wireless communications because of its power efficiency and low decoding complexity. We will discuss the complexity issues of IDMA in this work. In multiple access techniques multiple access interference (MAI) introduced by other users poses a serious problem and

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complex multi user detectors (MUD) that jointly decode all user's data are used at the receiver.

But, the use of MUD increases the complexity of the decoding, for example as in the case of CDMA. Previous work has suggested that by using turbo-type MUD to remove the MAI, the decoding complexity of IDMA is independent of the number of users, whereas in other types of codes the decoding complexity is dependent on the number of users. Also, mutipath fading increases the decoding complexity.

In such cases, OFDM along with IDMA solves the problem decoding complexity with multipath fading. This is called as OFDM-IDMA. But, still when the number of users is more the computational complexity at the receiver is more. We observe that decoding complexity of OFDM-IDMA is linear in the number of users sharing a particular subcarrier rather than the number of users of the system. Here, the key idea is each idea is every user is assigned a a channel only on a prescribed subcarrier called Grouped-OFDM IDMA.

In G-OFDM IDMA, users and subcarriers are divided into a number of groups and each user group's data is only transmitted on the corresponding group of subcarriers. The work also shows that this design is capable of reducing the complexity but still preserves the bit error probability (BEP) and bandwidth efficiency of conventional OFDM IDMA.

4. OFDM-IDMA PRINCIPLES

The IDMA receiver complexity over multi-path channels is related to the channel length. Recently, OFDM-IDMA was proposed [5, 6] as an alternative to plain IDMA over multi-path channels. OFDM-IDMA inherits most of the merits of OFDM and IDMA. The key advantage of OFDM-IDMA is that MUD can be realized efficiently with complexity per user independent of the channel length and the number of users, which is significantly lower than that of other alternatives. Figure 1b shows the transmitter/receiver structure of an OFDM-IDMA system with K users. The coded signals are first interleaved by user-specific interleavers {πk}. Then the resultant signals, again denoted by {xk(n)}, are modulated onto subcarriers by using IDFT. Each subcarrier can be occupied by several users, so users are solely distinguished by their interleavers. The received signal after DFT can be represented by

$$R(n) = \sum_{k=1}^{K} H_k(n) x_k(n) + Z(n) \qquad (2a)$$

$$= H_k(n) x_k(n) + \Xi_k(n), \qquad (2b)$$

where Hk(n) is referred to as the channel gain of the nth subcarrier for user k, Z(n) denotes AWGN at subcarrier n, and Ξk(n) = Σm≠k Hm(n)xm(n) + Z(n) represents the interference plus noise component in R(n) with respect to user k at subcarrier n. From the central limit theorem, Ξk(n) can again be approximated by a Gaussian random variable. The similarity between Eqs. 1 and 2 indicates that the receiver principles outlined for IDMA earlier can be directly applied to OFDM-IDMA. Suppose that the aggregate rate R in Fig. 1b is fixed and each user has a single-user rate R/K. When K is large, the single-user rate R/K will be low. A simple and convenient way to realize a low-rate code is concatenating a common FEC code (such as a rate-1/2 convolutional or turbo or LDPC code) with a repetition code. In this case, the repetition coding acts similarly as the spreading operation for CDMA. The outputs of a repetition encoder are dispersed over different subcarriers after IDFT. At the receiver, the inputs to a repetition decoder are collected from different subcarriers and combined. As a result, the frequency selective part of fading (i.e., the difference among the gains of different subcarriers) is averaged out when the rate of repetition coding is sufficiently low (e.g., ≤ 1/8), and the average channel gains of subcarriers become the dominating factor, hence achieving frequency diversity. The above also implies a fast technique to predict the performance of OFDM-IDMA based on knowledge of the average channel gains. Figure 2 shows the simulated and predicted performance of OFDM-IDMA using a rate-1/2 convolutional code (with generator (23, 35)8) followed by a repetition code with different length S. QPSK modulation is used. The average channel gains are used for prediction.3 The number of users K = 2S, so the system throughput is kept constant (R = 2). We can see from Fig. 2 that the predicted and simulated performance curves are quite close when S ≥ 8. The availability of a fast performance prediction technique is crucial for search-based system optimization. In particular, it has been shown in [2] that the spectral and power efficiency of IDMA can be greatly enhanced by using an unequal power allocation strategy. The same principle also applies to OFDM-IDMA and the optimization techniques developed in [2] can be used. The optimized OFDM-IDMA scheme possesses several attractive properties, including • Very high spectral efficiency • Flexibility in multi-user as well as single-user mode transmission, • Multi-user gain in fading channels

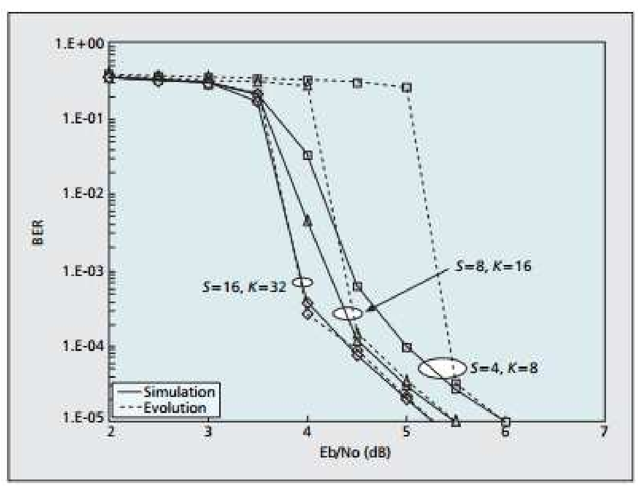

Figure 2. The predicted and simulated performance curves for OFDMIDMA. In this example, we assume that {Hk(n), ∀k, ∀n} are uncorrelated and identically Gaussian distributed [10], and each user has unit average channel (power) gain. Information bit length = 512, and iteration number = 15.

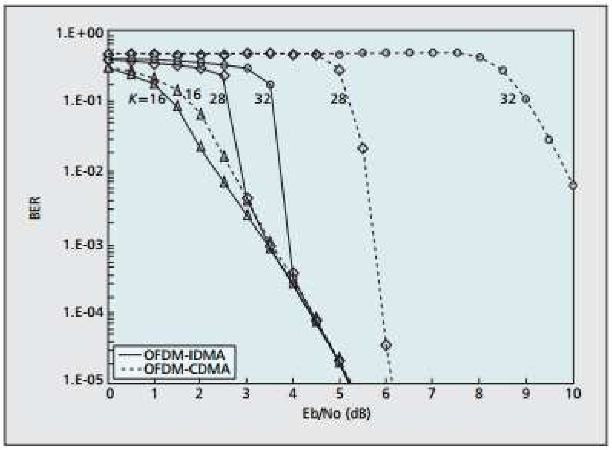

Figure 3. Performance comparison between OFDM-IDMA and OFDMCDMA. In both schemes, information bit length = 512, iteration number = 5 when K = 16, and iteration number = 15 when K = 28 and 32.

5. MULTICARRIER INTERLEAVE DIVISION MULTIPLE ACCESS

MC-CDMA is robust to multipath propagation but its performance degrades rapidly as the number of users increase due to multiple access interference. Various multiuser detection techniques have been proposed to combat MAI but their computational complexity is prohibitive for practical implementations [74]. MC-IDMA is proposed to encounter the problems faced by IDMA and MC-CDMA systems [75, 76]. Soon after [75, 76], several papers appeared on MC-IDMA [77–80]. In [75–79], uncoded MC-IDMA is considered and simple repetition code is used for spreading each user's signal, however as described in [55,56], IDMA and hence MC-IDMA systems are spectrally efficient and outperform the CDMA and MC-CDMA systems only if low rate turbo codes are used for bandwidth expansion. In [80], authors compared the performance of a basic MC-IDMA system with other OFDM based multiple access techniques such as MC-CDMA, OFDMA etc. While comparing MC-IDMA and MC-CDMA, they used rate 1 2 convolutional codes in conjunction with repetition codes of length 16 in MC-IDMA and in MC-CDMA, they used Walsh Hadamard codes of length 16 for number of users up to 16. For number of users greater than 16, they used randomly generated codes. As far as the number of users is less than or equal to 16, performance of both systems is same but as the number of users increase the performance of MC-CDMA degrades rapidly due to non-orthogonality of random codes. In fact MC-CDMA doesn't support users more than 16 due to its capacity limit. In [82], an MC-IDMA is considered with low rate Concatenated Zigzag Hadamard (CZH) codes and its performance is compared with MC-CDMA system which is considered as a reference. A simplified iterative detection algorithm is developed taking into account the complex nature of channel gains. An MC-IDMA system like IDMA inherently uses BPSK or QPSK. In [84], implementations of higher modulation schemes are suggested to enhance data rate. An MC-IDMA system with adaptive subchannel allocation is presented in [83] which uses only those subcarriers in the transmission which have largest fading amplitudes among all the subcarriers. In this chapter, we consider an MC-IDMA system and combine the work presented in [75,76,82–84]. We analyze the iterative CBC detection scheme with multicarrier communication in frequency selective multipath fading channels. It is shown that MC-IDMA can combine all the energy scattered in frequency domain and reduces the complexity J times as compared to IDMA where J is the number of multipaths. We exploit the iterative CBC detection scheme with multicarrier communication in multipath fading channels for uplink transmission. It is shown that MC-IDMA can combine all the energy scattered in frequency domain and reduces the complexity approximately J times as compared to IDMA, where J is the number of multipaths. We also compare the performance of MC-IDMA and MC-CDMA with different coding schemes.

6. DISCUSSIONS AND CONCLUSIONS

We have outlined the basic principles of OFDMIDMA and compared it with other alternatives, including OFDM-CDMA and OFDMA. We have shown that OFDM-IDMA has significant advantages regarding spectral and power efficiency, flexibility for adaptive transmission, and receiver complexity. As a relatively new concept, there remain many outstanding issues in OFDM-IDMA, including pilot signal design, channel estimation, close-loop power control, adaptive transmission, and resource allocation. The possibility of lowcost MUD creates quite different dimensions to these issues compared to the situation in traditional systems as many functions can now be conducted jointly and iteratively. Our discussion here relates mainly to the uplink. Theoretically, multi-user gain also applies to the downlink [15], but the related MUD cost can be a serious concern. From Fig. 5, a large portion of the potential multi-user gain can be achieved by supporting only a small number of active users (e.g., K = 4). Although this observation is made for the uplink in Fig. 5, it is also true for the downlink following the uplink/downlink duality principle [15]. The available gain can outweigh the cost concern (since MUD for a small K is less demanding) and further research on this issue is desirable. In conclusion, OFDM-IDMA appears a competitive candidate for future wireless communication systems.

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