Thesis for the Degree of Master of Engineering

Interleave-Division Multiple-Access Schemes for Multi-User Wireless Communications

by

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Pukyong National University

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Interleave-Division Multiple-Access Schemes for Multi-User Wireless Communications

다중 사용자 이동통신을 위한 IDMA 기술

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by

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A Dissertation

by

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요약

본 논문은 사용자 독립성을 보장하기 위하여 최근 다중 접속 기법으로 제시된 IDMA(Interleave-Division Multiple-Access)에 관련된 기법을 제안하였다. IDMA 에 제안된 기법은 CDMA(Code Division Multiple Access)의 다양한 특징과 뛰어난 성능을 가지고 있을 뿐만 아니라 다수의 사용자가 시스템을 이용 가능하도록 데이터 검 파 원리에 기초한 저 비용의 MUD(Multi-User detection)의 실현을 가능하게 하여 고효율의 다중 접속 통신방식이 이루어 질 수 있게 하였다. 본 논문에서 제시된 시뮬레이션 결과는 코딩을 하지 않은 IDMA 의 기법들의 결과를 나타내고 있다.

Interleave-Division Multiple-Access Schemes for Multi-User Wireless Communications

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Abstract

Interleave-division multiple-access (IDMA) is recently proposed multiple access scheme, which employs random interleavers as the only method for user separation. As a particular case of code-division multiple-access (CDMA), IDMA inherits many distinguished features of well-studied CDMA, Moreover, it allows a very low-cost multi-user detection (MUD) based on a chip-by-chip detection principle applicable to the system with a large number of users, which is crucial for high-rate multiple access communications. Simulation results represented in this thesis is completely devote to the investigation of an un-coded IDMA scheme.

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 1Gbps for low mobility or local wireless access are predicted. Systems fulfilling these requirements are usually considered as fourth-generation (4G) systems.

Direct-sequence code-division multiple access (DS-CDMA or simple CDMA) has been adopted in second- and third-generation cellular mobile standards. In a CDMA system, many users share the same transmission media so that signals from different users are superimposed, causing the multiple access interference (MAI) problems. At the receiver side, it is necessary to separate the mixed signals. Multi-user detection (MUD) is a technique to improve performance by jointly processing the signals from all of the users [2, 3]. However, complexity has always been a stringent concern for MUD. Much research effort has been devoted to this issue in pursuit of simpler solution without compromising performance.

Interleave-division multiple access (IDMA) is recently proposed. In this thesis, we describe an interleave-division multiple access (IDMA) scheme in which interleavers are treated as the only way to separate users. In other words, in an IDMA scheme users are distinguished by different chip-level interleaving method instead of by different signatures as in a conventional CDMA system. Being a wideband scheme, IDMA not only inherits many advantages from CDMA, but all have numbers of nice features:

l Rate/power adaptation: The multi-code technique can be used for a rate/power adaptation as propose in [4]. A large variety of data rates can be supported, as opposed to conventional adaptive modulation/channel coding techniques, the modulation scheme is fixed and the same channel code is used for all layers. Power adaptation/savings are particularly useful for uplink.

- (Multiple-input multiple-output) MIMO: Since each layer is assigned a different interleaver, an arbitrary number of transmit antennas can be used [5]. 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 [6].
- 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 [7] derived in [8]. The task of this receive is to cancel any type of

interference jointly. The receiver is based on the Gaussian assumption. Its complexity is linear with respect to the number of layers, number of chips, number of users, number of receive antennas, number of channel taps, and 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 CDMA system.

The remainder of this thesis is organized as follows. Section 2 introduces the development of wireless communication systems. Section 3 is devoted to IDMA system. We discuss IDMA scheme from foundational concepts. Simulation and results are represented in Section 4 and conclusions are drawn in Section 5. Finally, future works that we provide in Section 6.

II.Multiple Access Schemes in Wireless Communication

2.1 The Development of Wireless Communication Systems

Since the beginning of the 20^{th} century, technologies have evolved remarkable to provide new methods and products for wireless communications. Especially in the past two decades, wireless communication services were penetrating into the society with an explosive growth rate.

As this thesis deals with a spread-spectrum multiple-access communication scheme for cellular communication systems, a brief historical review of cellular systems is provides as follows.

2.2 First Generation (1G) Wireless Communication Systems:

The 1 G systems are characterized by the fact that they are all based on the analog technologies. Some representatives of 1G cellular system are the Advanced Mobile Phone System (AMPS) in USA, Nordic Mobile Telephone (NMT) in Scandinavia and the Total Access Communication System (TACS) in UK [9]. They are designed to carry voice transmission only. In these systems, each user has a unique frequency band. This multiple-access technique separates the signal of different users in frequency domain, which is called frequency-division multiple-access (FDMA). With the introduction of 1 G system, the worldwide mobile market experienced annual growth rates of 30% to 50% and there are nearly 20 million subscriber by 1990 [10].

2.3 Second Generation (2G) Wireless Communication Systems:

The 2G cellular systems are all based on the digital technologies. The most popular 2G standards include three time-division multiple-access (TDMA) standards and on code-division multiple-access (CDMA) standard. The Global System for Mobile communication (GSM) is the first operated digital cellular system based on TDMA, whose commercial operation began in 1991 in Europe. The other two TDMA based standards are Interim Standard 54 (IS-45) in North America and Pacific Digital Cellular (PDC) in Japan. The only CDMA based 2G cellular standard is Interim Standard 95 (IS 95). Since the mid 1990s, the cellular communication industry has witnessed explosive growth. There are more than 600 million cellular subscribers worldwide in late 2001 [11]. Most of today's cellular systems belong to 2G.

2.4 Third Generation (3G) Wireless Communication System:

The 3G standards have been developed specially to support high-rate data services such as high-speed Internet access, video stream and high quality image transmission. International Mobile Telecommunication-2000 (IMT-2000) is the global standard for 3G wireless communications defined by a set of interdependent International Telecommunication Union (ITU) recommendations. IMT-2000 provides a framework for worldwide wireless access by linked the diverse systems based networks [12]. The most important 3G standards are the European and Japanese Wideband-CDMA (WCDMA), the American CDMA2000, and the Chinese Time-Division Synchronous CDMA (TD-CDMA). All three standards are based on CDMA and operate around 2GHz. 3G systems have recently been launched or are planned to be launched in many countries and regions. There are four companies CSL limited, Hutchison 3G HK limited, SmarTone 3G Limited and SUNDAY 3G (Hong Kong) Limited who have obtained 3G licenses from office of the telecommunications authority in Hong Kong September 2001 [13].

2.5 Fourth Generation (4G) Wireless Communication Systems:

Even before 3G systems were being deployed, researchers started the investigations on possible techniques for 4G systems. The explicit 4G standard is still not confirmed. In June 2003, ITU approved the recommendation ITU-R m.1645 “Framework and overall objectives of the future development of IMT-2000 and systems beyond IMT-2000 [14]. The document states the capabilities as well as possible technologies for 4G systems. Important features of 4G wireless systems include:

- 4G needs to support data rates of up to 100Mbps for high mobility such as mobile access and up to 1Gbps for low mobility such as local wireless access.
- 4G user of packet-based architectures which will offer increased system security and reliability, intersystem mobility, and interoperability capabilities.
- 4Gsatisgies future requirements for universal wireless network that will provide high data rates and seamless interface with a wire-line backbone network.

The above features impose technical challenges on system design. There are some promising technologies (mainly related to physical layer) for 4G wireless system such as sophisticated forward error correcting (FEC) codes (e.g., [15], [16], [17]), CDMA with improve detection algorithms(e.g., [7], [18], [19]).

At the moment there are many research institutions and industrial companies which investigate the appropriateness of different techniques for the 4G air interface. In this thesis, the research work is totally devoted on an IDMA for future wireless communications as introduced in the next section.

III. Interleave-Division Multiple-Access (IDMA) Scheme

In this section, we introduce a comprehensive study of the IDMA scheme. First, we will represent IDMA transmitter and receiver structures. Second, we will provide the function of elementary signal estimator (ESE) and decoder (DEC). Finally, we will derive several low-cost detection algorithms for different channel condition, namely, real-single-path, real-multi-path, and complex multi-path channels. These algorithms are very simple and efficient, as confirmed by simulation results.

3.1 Basic Concept

IDMA is a recently proposed multiple access scheme, in which user-specific interleavers are adopted as the only mechanism for user separation. IDMA can be regarded as a particular case of random waveform CDMA, and the accompanying chip-by-chip (CBC) estimation algorithm [20] is essentially a low-cost iterative soft-cancellation technique [7]. As so, IDMA inherits many advantages of CDMA. Thanks to random interleaving and chip-by-chip (CBC) iterative multi-user detection algorithm, the IDMA scheme is applicable to cancel multiple access interference (MAI) and intersymbol interference (ISI) effectively and support systems with large numbers of users in multi-path fading channel.

3.2 Transmitter and Receiver Structure

The upper part of Fig. 1 shows the transmitter structure of the IDMA scheme with K simultaneous users. Let d_k be the data stream of user-k. This data stream is encoded by a forward error correction (FEC) code, generating a chip sequence c_k. (Here, “chip” is used instead of “bit” as the FEC encoding may include spreading or repetition coding.) then c_k is permutated by a user-specific interleaver-k to produce chip sequence v_k. After binary phase shift keying (BPSK) symbol mapping, the sequence $x_k \equiv \left[x_k(1), \ldots x_k(j), \ldots x_k(J) \right]^T$ is produced, where J is the frame length.

The key principle of IDMA is that the interleavers $\{\pi_k\}$ should be different for different users. We assume that the inter leaver are generated independently and randomly. These interleavers disperse the coded sequences so that the adjacent chips are approximately uncorrelated, which facilitates the simple chip-by-chip detection scheme.

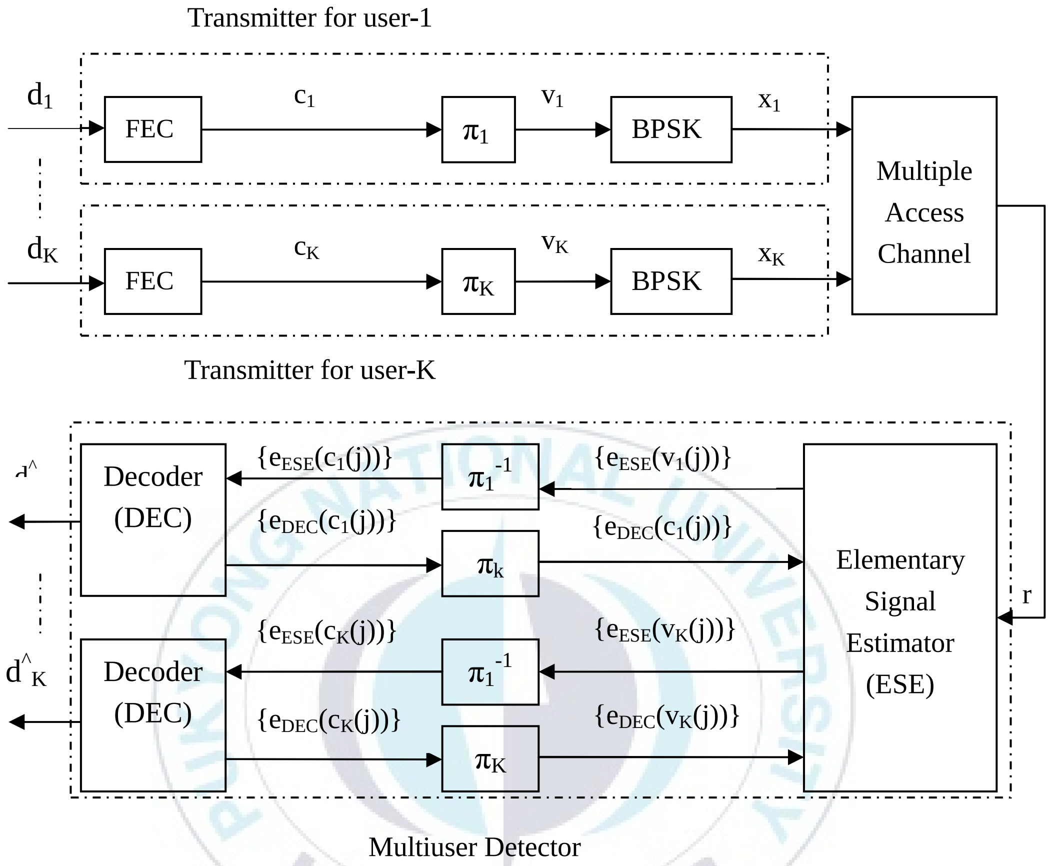

Figure 1: Transmitter and receiver structures of an IDMA scheme with K simultaneous users.

As illustrated in lower part of Fig. 1, and iterative sub-optimal receiver structure is adopted, which consists of an elementary signal estimator (ESE) and K single-user decoders (DECs). In the iterative detection process, the ESE and DECs exchange extrinsic information in a turbo-type manner [15].

The outputs of the ESE and DECs are extrinsic log-likelihood ratios (LLRs) about

$\{x_k(j)\}$ defined below [5][8][21] :

$$e(x_k(j)) \equiv \log\left(\frac{\Pr(y|x_k(j)=+1)}{\Pr(y|x_k(j)=-1)}\right), \forall k, j \qquad (1)$$

These LLRs are further distinguished by subscripts, i.e., $e_{ESE}(x_k(j))$ and $e_{DEC}(x_k(j))$, depending on whether they are generated by the ESE or DECs. For the DECs, y in (1) is the deinterleaved version of the outputs of the ESE. A global turbo-type iterative process is applied to exchange the LLRs generated by the ESE and DECs [5][22], as detailed below. We focus on detecting $x_k(j)$ after receiving r. The CBC detection algorithm includes two parts: ESE part and DECs part.

3.3 CBC Detection Algorithm

3.3.1 ESE Function

3.3.1.1 The Basic ESE Function

We first assume that the channel has no memory. After chip-matched filtering, the received signal from K users can be written as

$$r(j) = \sum_{k=1}^{K} h_k x_k(j) + n(j) \qquad \text{j=1, 2,}\cdots\text{, J} \qquad (2)$$

where h_k in the channel coefficient for user-k and $\{n(j)\}$ are samples of an white Gaussian noise (AWGN) process with variance $\sigma^2 = N_0/2$. We assume that the channel coefficients $\{h_k\}$ are known a priori at the receiver. Due to he use of random interleavers $\{\pi_k\}$, the chip-by-chip interleavers allow us to adopt a chip-by-chip (CBC) estimation technique [23] in the ESE, with only on sample $r(j)$ used at a time. Rewrite (2) as

$$r(j) = h_k x_k(j) + \xi_k(j) \qquad (3a)$$

where

$$\zeta_k(j) \equiv r(j) - h_k x_k(j) = \sum_{k' \neq k} h_{k'} x_{k'}(j) + n(j) \qquad (3b)$$

is the distortion (including interference-plus-noise) in $r(j)$ with respect to user-k. From the central limit theorem, $\zeta_k(j)$ can be approximated as a Gaussian variable, and $r(j)$ can be characterized by a conditional Gaussian probability density function

$$p\left(r(j)\middle|x_k(j)=\pm 1\right)=\frac{1}{\sqrt{2\pi Var\left(\zeta_k(j)\right)}}\exp\left(-\frac{\left(r(j)-\left(\pm h_k+E\left(\zeta_k(j)\right)\right)\right)^2}{2Var\left(\zeta_k(j)\right)}\right) \quad (4)$$

where $E(\cdot)$ and $Var(\cdot)$ are the mean and variance functions, respectively.

The following is a list of the ESE detection algorithm based on $(2)\sim(4)$ [8], assuming that the a priori statistics $\{E(x_k(j))\}$ and $\{Var(x_k(j))\}$ are available

Algorithm 1. Chip-by-Chip Detection in a Single-Path Channel

Step (i): Estimation of Interference Mean and Variance

$$E(r(j))=\sum_k h_k\left(x_k(j)\right) \quad (5a)$$

$$Var(r(j))=\sum_k |h_k|^2 Var\left(x_k(j)\right)+\sigma^2 \quad (5b)$$

$$E\left(\zeta_k(j)\right)=E(r(j))-h_k E\left(x_k(j)\right) \quad (5c)$$

$$Var\left(\zeta_k(j)\right)=Var(r(j))-|h_k|^2 Var\left(x_k(j)\right) \quad (5d)$$

This approximation is used by ESE to generate LLR for $x_k(j)$. The phase shift due to h_k is cancelled out in $(3a)$, which means that $r(j)$ is not a function of $x_k(j)$. Therefore we get

$$e_{ESE}(x_k(j)) = \log\left(\frac{\Pr(x_k(j)=+1)}{\Pr(x_k(j)=-1)}\right)$$

$$= \log \frac{\exp\left(-\frac{r(j)-E(\zeta_k(j)-h_k)^2}{Var(\zeta_k(j))}\right)}{\exp\left(-\frac{r(j)-E(\zeta_k(j)+h_k)^2}{Var(\zeta_k(j))}\right)}$$

$$= 2h_k \frac{r(j)-E(\zeta_k(j))}{Var(\zeta_k(j))}$$

Step(ii): LLR Generation

$$e_{ESE}(x_k(j)) = 2h_k \frac{r(j)-E(\zeta_k(j))}{Var(\zeta_k(j))} \tag{6}$$

Comments:

- Assuming independent $\{x_k(j)\}$, (5) is a straightforward consequence of (2) and $(3b)$.

- Step (ii) is obtained by evaluating (1) based on (4).
- Algorithm 1 is an extremely simplified form of that derived in [20] when the spreading sequences are all of length-1.
- The cost in $(5a)$ and $(5b)$, i.e., generating $E(r(j))$ and $Var(r(j))$, are shared by all users, costing only three multiplications and two additions per coded bit per user, overall, the ESE operation in $(5) \sim (6)$ cost only seven multiplications and five additions per coded bit per user, which is very modest. Interestingly, the cost per information bit per user is independent of number of users K. this is considerably lover than that of other alternatives.

3.3.1.2 The ESE Function for Multi-path Channels

We now consider the ESE function in a quasi-static multi-path fading channel with memory L-1. Let $\{h_{k,0},...h_{k,L-1}\}$ be the fading coefficients related to user-k. After chip-matched filtering, the received signal can be represented by

$$r(j) = \sum_{k=1}^{K} \sum_{l=0}^{L-1} h_{k,l} x_k (j-1) + n(j) \qquad j = 1, ..., J+L-1 \qquad (7)$$

where $h_{k,l}$ is the l^{th} channel coefficient for user k (corresponding to a delay of l chip durations)

We write

$$r(j+l) = h_{k,l}x_k(j) + \zeta_{k,l}(j) \tag{8a}$$

where

$$\zeta_{k,l}(j) = r(j+l) - h_{k,l}x_k(j) \tag{8b}$$

where $\zeta_{k,l}(j)$ is the distortion (including additive noise, interference from other users as well as intersymbol interference (ISI) from the same user) contained in $r(j)$ with respect to $x_k(j-l)$.

The similarity between $(8a)$ and $(3a)$ is clearly seen, assume again BPSK signaling and real channel coefficients. Algorithm 2 below is a straightforward extension of Algorithm1.

Algorithm 2. Chip-by-Chip Detection In a Multi-Path Channel

Step(i): Estimation of Interference Mean and Variance

$$E(r(j)) = \sum_{k,l} h_{k,l} E(x_k(j-l)) \tag{9a}$$

$$Var(r(j)) = \sum_{k,l} |h_{k,l}|^2 Var(x_k(j-l)) + \sigma \tag{9b}$$

$$E\left(\zeta_{k,l}(j)\right)=E\left(r(j+l)\right)-h_{k,l}E\left(x_k(j)\right) \qquad (9c)$$

$$Var\left(\zeta_{k,l}(j)\right)=Var\left(r(j+l)\right)-\left|h_{k,l}\right|^2 Var\left(x_k(j)\right) \qquad (9d)$$

This approximation is used by ESE to generate LLR for $x_k(j)$. The phase shift due to $h_{k,l}$ is cancelled out in $(8a)$, which means that $r(j+l)$ is not a function of $x_k(j)$. Therefore we get

$$\begin{aligned}
e_{ESE}\left(x_k(j)\right) &= \log\left(\frac{\Pr\left(x_k(j)=+1\right)}{\Pr\left(x_k(j)=-1\right)}\right) \\
&= \log\frac{\exp\left(-\dfrac{r(j+l)-E\left(\zeta_{k,l}(j)-h_{k,l}\right)^2}{Var\left(\zeta_{k,l}(j)\right)}\right)}{\exp\left(-\dfrac{r(j+l)-E\left(\zeta_{k,l}(j)+h_{k,l}\right)^2}{Var\left(\zeta_{k,l}(j)\right)}\right)} \\
&= 2h_{k,l}\frac{r(j+l)-E\left(\zeta_{k,l}(j)\right)}{Var\left(\zeta_{k,l}(j)\right)}
\end{aligned}$$

Step(ii): LLR Generation and Combining

$$e_{ESE}\left(x_k(j)\right)_l = 2h_{k,l}\frac{r(j+l)-E\left(\zeta_{k,l}(j)\right)}{Var\left(\zeta_{k,l}(j)\right)} \qquad (10a)$$

$$e_{ESE}\left(x_k(j)\right)=\sum_{l=0}^{L-1}e_{ESE}\left(x_k(j)\right)_l \qquad (10b)$$

Comments:

- It is easy to see the connection between (9) and (5).
- From (7), each $x_k(j)$ is observed on L successive samples $\{r(j), r(j+1), ..., r(j+L-1)\}$. Assume that the distortion terms with respect to $x_k(j)$ in these L samples, i.e., $\{\zeta_{k,0}(j), \zeta_{k,1}(j), ..., \zeta_{k,L-1}(j)\}$, are un-correlated. Then the overall a posteriori probabilities for $x_k(j)=\pm 1$ are the products of the individual *a posteriori* probabilities generated from $\{r(j), r(j+1), ..., r(j+L-1)\}$. Hence the LLR s for $x_k(j)$ can be directly summed as in (10b). This LLR combining (LLRC) technique is similar to the rake operation used in CDMA.
- The overall complexity is approximately L times of that of Algorithm 1.

The un-correlation assumption mentioned above is only approximate, but it greatly simplifies the matter. The complexity (per coded bit per user) for Algorithm 2 is $O(L)$. There are other alternative treatments for channels with memory. One is the joint Gaussian (JG) technique [24] that takes into consideration the correlation among $\{\zeta_{k,0}(j), \zeta_{k,1}(j), \ldots, \zeta_{k,L-1}(j)\}$. This technique leads to improved performance but also increased cost $\left(O\left(L^2\right)\right)$. Another alternative is the maximum ratio combining (MRC) technique [31], in which $r \equiv \{r_j\}$ is passed through K MRC filters, each matched to the L tap-coefficients for a particular user. An MMSE detection is then applied to generate $\{e_{ESE}(x_k(j))\}$. The related complexity is O(KL) [25].

Generally speaking, the JG technique demonstrates better performance but this becomes noticeable only when the number of users is very large or when the rate of C is high. Overall, the LLRC method is a good compromise between complexity and performance. See [25] for a detailed discussion.

3.3.1.3 The ESE Function for More Complex Channels

We now extend our discussion to more complex situations. We will use either superscripts "Re" and "Im" or function notations $\mathrm{Re}(\cdot)$ and $\mathrm{Im}(\cdot)$ to indicate real and imaginary parts, respectively. Consider quadrature-phase-shift-keying (QPSK) signaling,

$$x_k(j) = x_k^{\mathrm{Re}}(j) + i x_k^{\mathrm{Im}}(j) \tag{11}$$

where $i=\sqrt{-1}$, $x_k^{\mathrm{Re}}(j)$ and $x_k^{\mathrm{Im}}(j)$ are two coded bit from c_k. For convenience, we still call the elements in x_k "chip". Note that in this case, each chip contains two coded bits. We adopt channel mode (7) and expand it using complex channel coefficients $\{h_{k,l}=h_{k,l}^{\mathrm{Re}}+ih_{k,l}^{\mathrm{Im}}\}$ as

$$r(j)=\sum_{k,l}\left(h_{k,l}^{\mathrm{Re}}x_k^{\mathrm{Re}}(j-l)-h_{k,l}^{\mathrm{Im}}x_k^{\mathrm{Im}}(j-l)\right)+i\sum_{k,l}\left(h_{k,l}^{\mathrm{Re}}x_k^{\mathrm{Re}}(j-l)-h_{k,l}^{\mathrm{Im}}x_k^{\mathrm{Im}}(j-l)\right)+n(j) \qquad (12)$$

where $\{n(j)\}$ are samples of a complex AWGN process with variance σ^2 per dimension. Denote by $\overline{h_{k,l}}$ the conjugate of $h_{k,l}$. Recall (8): $r(j+l)=h_{k,l}x_k(j)+\zeta_{k,l}(j)$. The phase shift due to $h_{k,l}$ is cancelled out in $\overline{h_{k,l}}r(j+l)$, which means that $\mathrm{Im}\overline{h_{k,l}}r(j+l)$ is not a function of $x_k^{\mathrm{Re}}(j)$. Therefore the detection of $x_k^{\mathrm{Re}}(j)$ only requires

$$\mathrm{Re}\left(\overline{h_{k,l}}r(j+l)\right)=\left|h_{k,l}\right|^2 x_k^{\mathrm{Re}}(j)=\mathrm{Re}\left(\overline{h_{k,l}}\zeta_{k,l}(j)\right) \qquad (13)$$

Algorithm 3 below outlines the procedure to estimate $x_k^{\mathrm{Re}}(j)$ based on (13).

Algorithm 2. Chip-by-Chip Detection In a Complex multi-Path Channel

Step(i): Estimation of Interference Mean and Variance

$$E\left(r^{\mathrm{Re}}(j)\right)=\sum_{k,l}\left(h_{k,l}^{\mathrm{Re}}E\left(x_k^{\mathrm{Re}}(j-l)\right)-h_{k.l}^{\mathrm{Im}}E\left(x_k^{\mathrm{Im}}(j-l)\right)\right) \qquad (14a)$$

$$E\left(r^{\mathrm{Im}}(j)\right)=\sum_{k,l}\left(h_{k,l}^{\mathrm{Re}}E\left(x_k^{\mathrm{Im}}(j-l)\right)+h_{k.l}^{\mathrm{Im}}E\left(x_k^{\mathrm{Re}}(j-l)\right)\right) \qquad (14b)$$

$$Var\left(r^{\mathrm{Re}}(j)\right)=\sum_{k,l}\left(\left(h_{k,l}^{\mathrm{Re}}\right)^2 Var\left(x_k^{\mathrm{Re}}(j-l)\right)-\left(h_{k.l}^{\mathrm{Im}}\right)^2 Var\left(h_{k.l}^{\mathrm{Im}}E\left(x_k^{\mathrm{Im}}(j-l)\right)\right)\right)+\sigma^2 \qquad (14c)$$

$$Var\left(r^{\mathrm{Im}}(j)\right)=\sum_{k,l}\left(\left(h_{k,l}^{\mathrm{Im}}\right)^2 Var\left(x_k^{\mathrm{Re}}(j-l)\right)-\left(h_{k.l}^{\mathrm{Re}}\right)^2 Var\left(h_{k.l}^{\mathrm{Im}}E\left(x_k^{\mathrm{Im}}(j-l)\right)\right)\right)+\sigma^2 \qquad (14d)$$

$$\psi(j)=\sum_{k,l}h_{k,l}^{\mathrm{Re}}h_{k,l}^{\mathrm{Im}}\left(Var\left(x_k^{\mathrm{Re}}(j-l)\right)-Var\left(x_k^{\mathrm{Im}}(j-l)\right)\right) \qquad (15)$$

$$E\left(\mathrm{Re}\left(\overline{h_{k,l}}\zeta_{k,l}(j)\right)\right)=h_{k,l}^{\mathrm{Re}}E\left(x^{\mathrm{Re}}(j+l)\right)+h_{k,l}^{\mathrm{Im}}E\left(x^{\mathrm{Im}}(j+l)\right)-\left|h_{k,l}\right|^2 E\left(x_k^{\mathrm{Re}}(j)\right) \qquad (16a)$$

$$Var\left(\mathrm{Re}\left(\overline{h_{k,l}}\zeta_{k,l}(j)\right)\right)=\left(h_{k,l}^{\mathrm{Re}}\right)^2 Var\left(x^{\mathrm{Re}}(j+l)\right)+\left(h_{k,l}^{\mathrm{Im}}\right)^2 Vae\left(x^{\mathrm{Im}}(j+l)\right),$$
$$+2h_{k,l}^{\mathrm{Re}}x_k^{\mathrm{Im}}\psi(j+l)-\left|h_{k,l}\right|^4 Var\left(x_k^{\mathrm{Re}}(j)\right) \qquad (16b)$$

The phase shift due to $h_{k,l}$ is cancelled out in $\overline{h_{k,l}}r(j+l)$, which means that $\mathrm{Im}\overline{h_{k,l}}r(j+l)$ is not a function of $x_k^{\mathrm{Re}}(j)$. Therefore we get

$$e_{ESE}\left(x_k^{\mathrm{Re}}(j)\right)=\log\left(\frac{\Pr\left(\overline{r}^{\mathrm{Re}}(j+l)\middle|x_k^{\mathrm{Re}}(j)=+1\right)}{\Pr\left(\overline{r}^{\mathrm{Re}}(j+l)\middle|x_k^{\mathrm{Re}}(j)=-1\right)}\right)$$

$$= \log \frac{\exp\left(-\frac{\overline{r}^{\text{Re}}(j+l) - E\left(\overline{\zeta}_{k,l}(j) - |h_k(l)|^2\right)^2}{2Var\left(\overline{\zeta}_{k,l}(j)\right)}\right)}{\exp\left(-\frac{\overline{r}^{\text{Re}}(j+l) - E\left(\overline{\zeta}_{k,l}(j) + |h_k(l)|^2\right)^2}{2Var\left(\overline{\zeta}_{k,l}(j)\right)}\right)}$$

$$= 2|h_{k,l}|^2 \frac{\text{Re}\left(\overline{h_{k,l}}\zeta_{k,l}(j+l)\right) - E\left(\text{Re}\left(\overline{h_{k,l}}\zeta_{k,l}(j)\right)\right)}{Var\left(\text{Re}\left(\overline{h_{k,l}}\zeta_{k,l}(j)\right)\right)}$$

Step (ii): LLR Generation and Combining

$$e_{ESE}\left(x_k^{\text{Re}}(j)\right)_l = 2|h_{k,l}|^2 \frac{\text{Re}\left(\overline{h_{k,l}}\zeta_{k,l}(j+l)\right) - E\left(\text{Re}\left(\overline{h_{k,l}}\zeta_{k,l}(j)\right)\right)}{Var\left(\text{Re}\left(\overline{h_{k,l}}\zeta_{k,l}(j)\right)\right)} \quad (17a)$$

$$e_{ESE}\left(x_k(j)\right) = \sum_{l=0}^{L-1} e_{ESE}\left(x_k^{\text{Re}}(j)\right)_l \quad (17b)$$

Comments:

- We obtain $(14a)$–$(14d)$ using (12) and obtain $(16a)$ as follow (based on (8) and (13),

$$\text{Re}\left(\overline{h_{k,l}}\zeta_{k,l}(j)\right) = h_{k,l}^{\text{Re}} r^{\text{Re}}(j+l) + h_{k,l}^{\text{Im}} r^{\text{Im}}(j+l) - |h_{k,l}|^2 x_k^{\text{Re}}(j) \quad (18)$$

- It can be verified that $\psi(j)$ in (15) is the covariance of $x^{\text{Re}}(j)$

and $x^{\mathrm{Im}}(j)$. It is introduced for cost saving since it is shared by all users, costing L multiplications and $L/2$ additions per coded bit per user. (Recall hat there are two coded bits in a chip, one in each dimension.)

- For the derivation of (16b), see the Appendix.
- If the cost related to $\psi(j)$ is ignored, the complexity of Algorithm 3 per coded bit per user is approximately two times of that of Algorithm 2. It slightly increases by several additions and multiplications considering $\psi(j)$, but is still $O(L)$.

3.3.2 DEC Function

The DECs in Fig. 1 carry out APP decoding using the output of the ESE as the input. With BPSK signaling, their output is the extrinsic LLRs $\{e_{DEC}(x_k(j))\}$ of $\{x_k(j)\}$ defined in (1), which are used to generate the following statistic

$$E(x_k(j)) = \tanh(e_{DEC}(x_k(j))/2) \quad (19a)$$

$$Var(x_k(j)) = 1 - E((x_k(j)))^2 \quad (19b)$$

(With QPSK signaling, the DEC outputs are the extrinsic LLRs for

$\{x^{\mathrm{Re}}(j)\}$ and $\{x^{\mathrm{Im}}(j)\}$.) As discussed above, $\{E(x_k(j))\}$ and $\{Var(x_k(j))\}$ will be used in the ESE to update the interference mean and variance in the next iteration. Initially, we set $E(x_k(j))=0$ and $Var(x_k(j))=1$ for $\forall k, j$.

APP decoding is a standard operation [31] and so we will not discuss it in detail. We will only consider a special case of C in Fig. 1 that is formed by serially concatenating a sub-code C_{REP} (the same for every user) and a length-S repetition code C_{REP} . This scheme is not optimized from performance point of view, as the repetition code is actually a very "poor" code. However, this structure does have the advantage of flexibility regarding the rate.

The input data sequence of each user is first encoded by C_{FEC} , generating $\{b_k(i), i=1,2,...\}$. Then each $b_k(i)$ is repeated S times by C_{FEC} , producing $\{c_k(j)\}$. For simplicity, we focus on those replicas related to $b_k(1)$, i.e., $\{c_k(j), j=1,2,...,S\}$. The treatment for replicas of $b_k(i)$ with $i>1$ is similar. The DEC for C carries out the following operations. For simplicity, we assume BPSK modulation.

① Obtain the estimate of each $b_k(i)$ based on $\{e_{ESE}(x_k(j))\}$ from the ESE. We assume that $\{e_{ESE}(x_k(j)), \forall j\}$ are un-correlated (which is approximately true due to interleaving). From Fig.1, we have $c_k(j) = x_k(\pi_k(j))$. Then the a posteriori *LLR* for $b_k(1)$ can be computed from $\{e_{ESE}(x_k(j))\}$ as [25]

$$L(b_k(1)) = \sum_{j=1}^{S} \log\left(\frac{\Pr(x_k(\pi_k(j)) = +1 | r(\pi_k(j)))}{\Pr(x_k(\pi_k(j)) = -1 | r(\pi_k(j)))}\right) = \sum_{j=1}^{S} e_{ESE}(x_k(\pi_k(j))) \quad (20)$$

② Perform standard APP decoding for C_{FEC} using $\{L(b_k(i))\}$ as the input, and generate the a posteriori LLRs $\{L_{APP}(b_k(i))\}$ for $b_k(i)$.

③ Recall that $c_k(j) = b_k(1)$ for $j = 1, \ldots, S$., we compute [25]

$$(x_k(\pi_k(j))) = e_{DEC}(c_k(j)) = L_{APP}(b_k(1)) - e_{ESE}(x_k(\pi_k(j))), j = 1, \ldots, S \quad (21a)$$

The subtraction above ensures that $e_{DEC}(x_k(\pi_k(j)))$ is extrinsic [22] Alternatively, we can use an approximation of (21a),

$$e_{DEC}(x_k(\pi_k(j))) = L_{APP}(b_k(1)) \qquad j = 1, \ldots, S \qquad (21b)$$

In this way, all the replicas of $b_k(i)$ have the same feedback from the DEC, so the memory usage can be greatly reduced (since we only need to store $\{L_{APP}(b_k(i))\}$ instead of $\{e_{DEC}(x_k(j))\}$. Equation (21b) may lead to certain performance loss compared with (21a). See Fig. 3(a) in Section IV below.

IV Simulation and Results

In this section, simulation results are provided to illustrate the performance of an un-coded IDMA system, together with an un-coded CDMA system. In the interest of investigating the performance of the un-coded IDMA system, a simulator has been developed using a well-known C++ simulation platform. For the un-coded CDMA, we use MatLab simulation platform.

For simplicity, we assume the un-coded IDAM system with BPSK signaling in single path AWGN channels. K is the number of users in the system. It is the iteration number for the detection process. Data length is 1024. Spreading length is 64. Chip length (interleaver length) is 1024*64. The number of block is 10. The same environment is applicable to CDMA system.

We first evaluate the performance of un-coded IDMA over AWGN channels. In Figure 2, we represent the BER performance of such an IDMA system versus the signal-to-noise ration (SNR) E_b/N_o (dB), in the cases that the number of users in simultaneous transmission is K=24, and iteration time It=1, 2, 3, 4, 5, 15 respectively. It is confirmed the viability of the semi-analytical method.

Figure 3 shows the performance comparison of un-coded IDMA and un-coded CDMA systems with single user in AWGN channels. From this figure, we are not able to distinguish that which performance is better.

Figure 4 shows the performance comparison of un-coded IDMA and un-coded CDMA systems with 16 and 32 users in AWGN channels. When user is set to 16, we also cannot make the difference between IDMA and CDMA. However, when user is set to 32, the difference between them is getting obvious.

Figure 5 shows the performance comparison of un-coded IDMA and un-coded CDMA systems with 1, 64 and 96 users in AWGN channels respectively. From the figure, we can easily find that the performance IDMA significantly outperforms CDMA. It is observed that near single users performance is achieved in the IDMA system even for K= 96 while it does not performance well in the conventional CDMA system. Therefore IDMA plays an outstanding role in multi-user wireless communications

4.1 Un-coded IDMA Performance with Different Numbers of Iteration

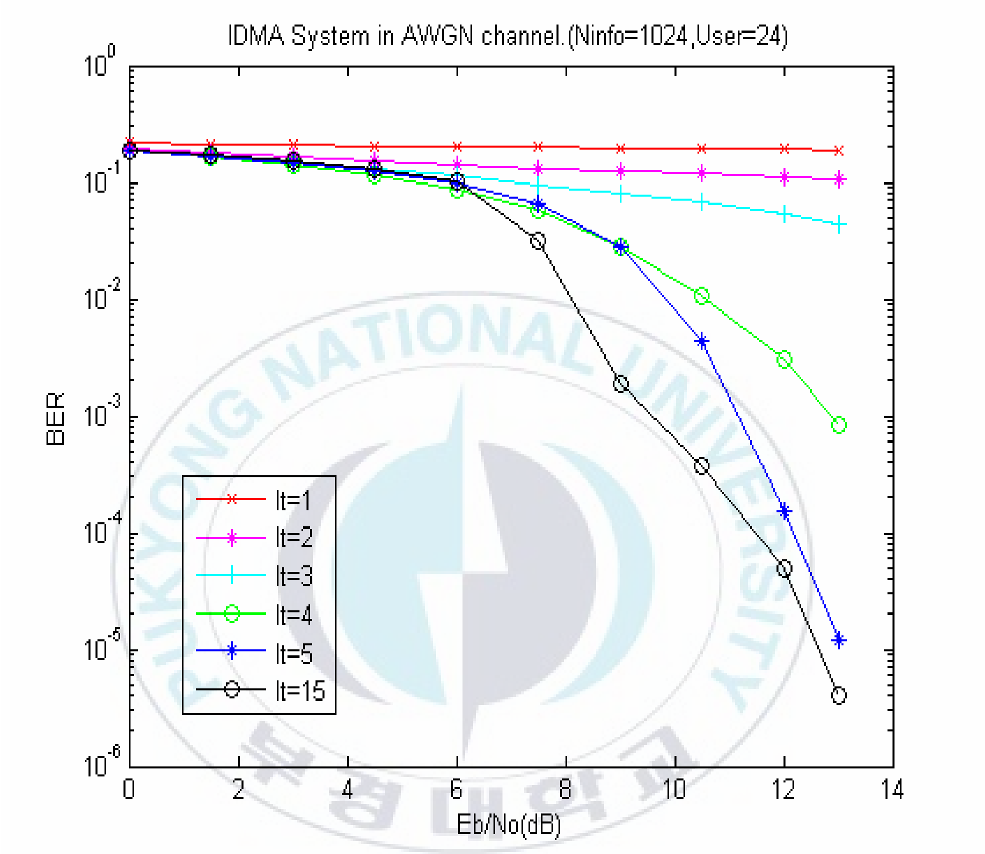

Fig.2 Performance un-coded IDMA system in AWNG channels for different iteration numbers It and user K=24

4.2 Comparisons between un-coded CDMA and un-coded IDMA in AWGN

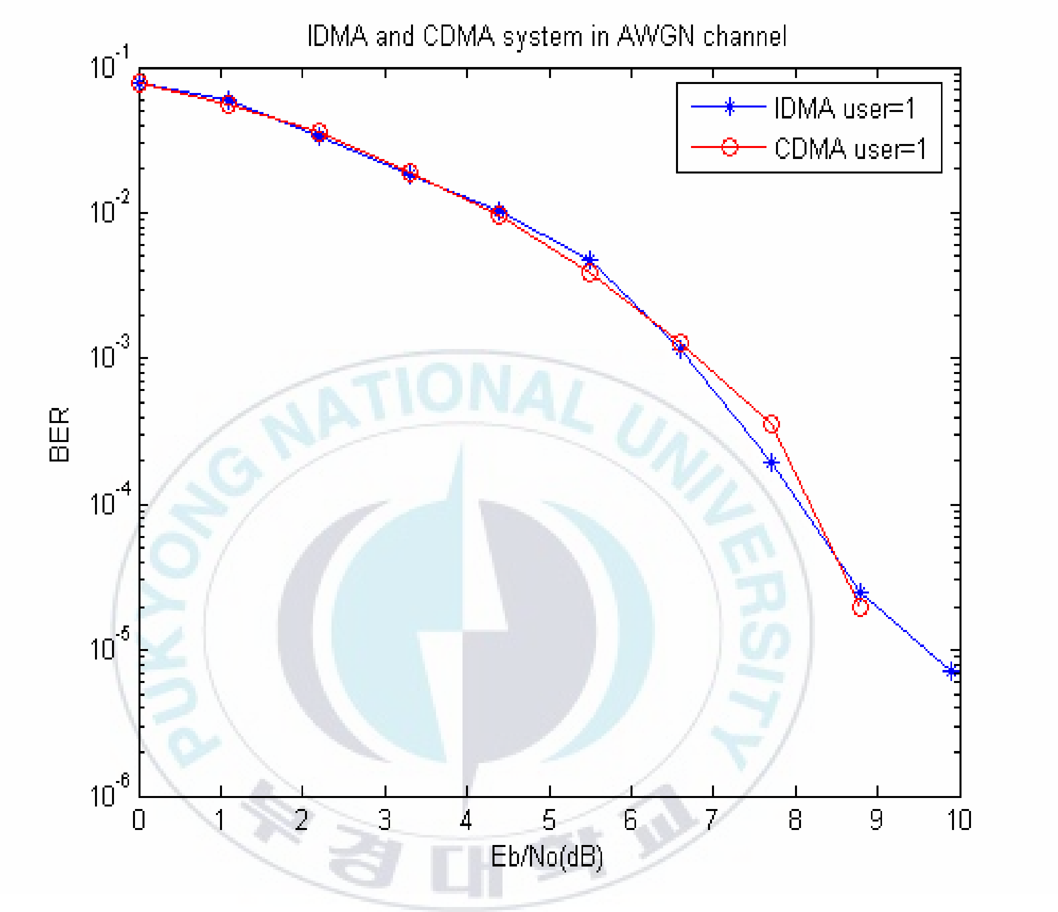

Fig.3 Performance of un-coded CDMA and IDMA system in AWGN channel with the single user. The iteration number is 15 for both CDMA and IDMA

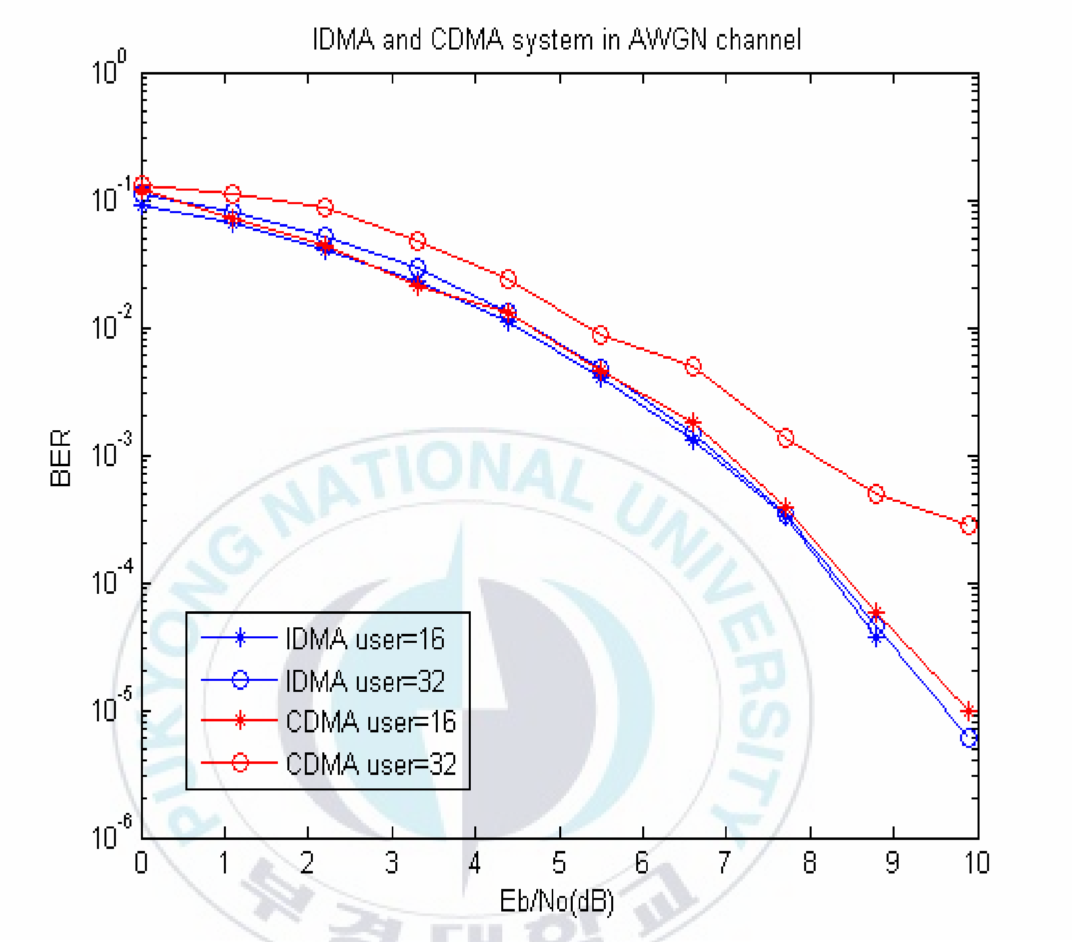

Fig.4 Performance of un-coded CDMA and IDMA system in AWGN channel with 16 and 32 users. The iteration number is 15 for both CDMA and IDMA

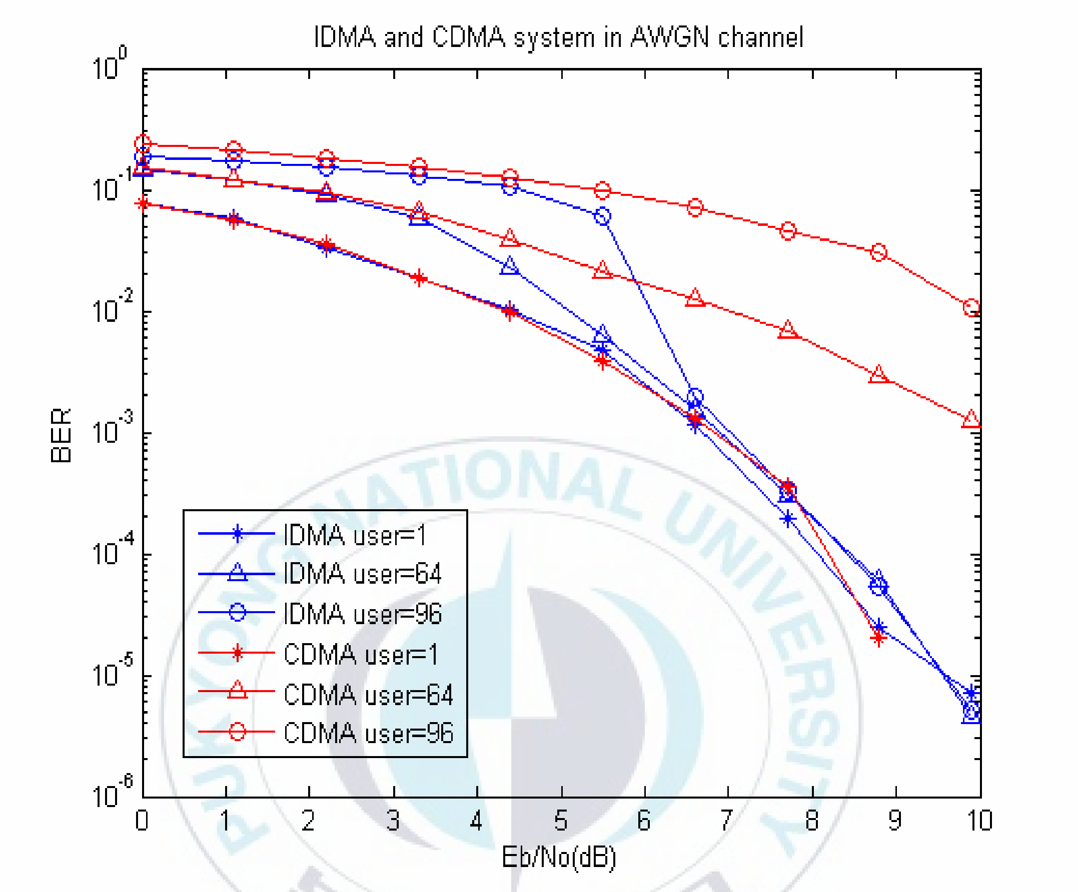

Fig.5 Performance of un-coded CDMA and IDMA system in AWGN channel with 1, 64 and 96 users. The iteration number is 15 for both CDMA and IDMA

V Conclusion

In summery, we have outlined the basic principles of IDMA and the accompanying chip-by-chip iterative MUD algorithms. The basic principle of the IDMA scheme is to employ interleavers as the only means for user separation. Although conceptually simple, the schemes offer very good performance. There are several consequences as list below.

- A very low-cost CBC detection algorithm can be used in both synchronous and asynchronous channels.
- A very large number of users can be processed shown in figure 3.
- Multi-path is no longer a serious issue as far as complexity is concerned
- IDMA scheme can achieve the performance close to a single user performance shown in figure 2.

In short, we have explained the feasibility and advantages of the IDMA scheme. These features indicate the potential application of the scheme in future wireless communication systems.

VI Future Work

In this section, we suggest some research works about IDMA for future studies.

This research only considers un-coded IDMA system. We can further improve system performance by using repetition code after convolutional coding, and by adding APP code at receiver.

Single-input single-out (SISO) system is only in view of this research. Multiple antennas will be a common feature for future wireless communication systems. Space-time coding can be employed to further improve performance of the IDMA scheme in multi-path fading channels.

IDMA as a new scheme has huge potential. We expect that the basic principle is able to be extended to other applications.

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