Guest Editorial
Spread Spectrum for Global Communications I

I. The Role of CDMA

SPREAD-spectrum technology, the basis of code division multiple access (CDMA), has been in practical use since the late 1950's [1], [2]. Its initial uses resulted from its suitability for covert message transmission and resistance to jamming. As a result, it found many applications in military systems. In such systems, transmit power, bandwidth, and total system efficiency are often not the most important system parameters. Rather, features such as security, reliability, robustness, and simplicity are more highly sought.

In the early 1980's, CDMA systems were proposed for private and commercial use for much the same reasons. In a commercial environment where the total desired volume of traffic is much higher and the requirements for cost much more stringent, the technology found less widespread acceptance. Systems based on the conventional correlator matched filter receiver had very low efficiency in terms of number of users supported versus bandwidth required, and the bit error rate (BER) performance of the system decreased dramatically as the number of simultaneous users, and therefore the multiple access interference (MAI), increased. The receiver was also highly sensitive to the "near–far" effect, which leads to the occurrence of the signal of a desired user's being overwhelmed by the signal of another user that has greater power.

The use of a correlator, or sequence matched filter receiver, is based on the assumption that the MAI associated with other system users is Gaussian in nature. At first examination, this assumption indeed appears correct. The combined user signal of a multiple access system does have a "Gaussian" distribution when the number of users is high (typically greater than ten users). A significant problem then arose as to why the system efficiency was so low, typically 10–20% of the spreading ratio (depending on the required error performance). By this, it is meant that if the number of users in a single cell attempting to access the system exceeds 10–20% of the spreading sequence length, the BER of all users degrades to what may be considered an unacceptable level. As the number of users increases, the degradation increases further.

A major breakthrough came in the mid-1980's, when researchers such as Kohno [3] and Verdu [4], [5] showed that the MAI limitation was not inherently part of CDMA modulation but a consequence of attempting to use the correlator receiver. The authors proposed the optimum multiple user, CDMA receiver based on a bank of matched filters, each followed by maximum likelihood sequence estimation (MLSE) detectors. The objective of MLSE is to find the input sequence that maximizes the conditional probability, or likelihood of the given output sequence. For asynchronous CDMA (where user transmissions are not coordinated), the MLSE may be implemented using the Viterbi algorithm [6].

As may be expected, however, with each receiver requiring an MLSE for each system user, this receiver required enormous computational complexity, which grows exponentially with the number of users in the system. It was therefore infeasible to implement, but did open the way for an enormous flurry of research on suboptimal, lower complexity receiver structures, which allowed the benefits of CDMA to be realized.

For indoor systems, CDMA holds promise, as it is able to effectively exploit the allocation of industrial, scientific, and medical bands, which are freely available for use by low-power users. Such unlicensed access means less expensive, less controlled, and more ad hoc use of the channel. With its high tolerance to interference, wide-band, multipath resistant nature, CDMA is ideally suited for operation in such environments. Accordingly, it has been adopted for use in commercially available wireless local-area networks (WLAN's) by some large computer manufacturers. The main concern for spread-spectrum WLAN's is achieving similar or higher data rates as conventional ethernet LAN's. Due to the availability of bandwidth at 2.4, 5.8, and 60 GHz (proposed), much work has been and is currently being done on channel modeling and system evaluation at these frequencies.

Another useful feature of CDMA for indoor systems is its low power spectral density. This allows a CDMA system to coexist with licensed communications systems, as well as allowing for operation in environments where low levels of electromagnetic interference are desirable, such as hospitals. In such environments, CDMA is ideally suited to high data rates' being transmitted over hostile fading channels with the minimum of interference to sensitive equipment.

CDMA holds great promise for cellular systems principally due to the low (possibly unity) frequency reuse factor. This means that, unlike narrow band, time division systems, there is no need to use different carrier frequencies and so different bandwidths in neighboring cells. For a cellular system based on regular hexagonal cell shape, this implies a seven-fold or 28-fold increase in bandwidth utilization [7] depending on whether one layer or two layers of cells must separate each carrier frequency in the cellular system. Of course, this figure may be reduced through the use of cell sectorization; however, significant frequency separation is still required.

Given the enormous and accelerating increase in demand for personal mobile communications, the use of bandwidth-inefficient systems such as narrow-band FDMA/TDMA systems cannot exist for long. CDMA certainly offers one solution. The important factor, however, is still to achieve a high

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capacity in a single cell and to remove the strict user power control commonly required with the simple correlator based receivers.

Some attempts have been made to improve the efficiency of TDMA systems, such as the advanced TDMA (ATDMA) proposed as part of the upcoming "unifying" multiple access standards such as Universal Mobile Telecommunications Standard (UMTS) [8] designed to integrate all existing multiple access techniques for the next century; however, these modifications are yet to be tested in real systems.

At the time of writing, cellular mobile CDMA systems are expanding in the United States, Hong Kong, and Korea. CDMA wireless loop systems were being developed in many countries, and many more CDMA-based WLAN products are appearing on the market, offering flexibility, ease of installation, and reliable data rates on the order of 2–10 Mbps. The effort toward standardizing the third-generation UMTS, which relies heavily on CDMA techniques, is drawing to a close in Japan, Europe, and the United States.

A. Current CDMA Research Areas

CDMA is obviously still a maturing technology, but it shows great promise in mainstream mobile communications as well as in having many specialized, niche applications. The amount of serious, ongoing research effort in the physical layer and CDMA network issues is further evidence of this [9]–[15]. To fulfill the promised benefits, future mobile personal communications systems must be capable of supporting a wide range of data rates and grades of service and operate reliably in harsh propagation conditions. Urban and metropolitan environments pose a particular problem, as there is typically no line of sight (LOS) between the transmitter and receiver, and the transmitted signal will undergo significant fades. For mobile users, Doppler effects lead to the rate of fading increasing with increased mobility. The effect is exacerbated by the need to use higher and higher carrier frequencies as the competition for spectrum allocation increases. As the data-rate requirements for such systems increase, the further problem of frequency-selective fading arises, and late multipath components may lead to intersymbol interference (ISI) occurring across several symbols.

These propagation conditions lend themselves particularly well to the use of spread-spectrum-based CDMA communications systems. A problem associated with the use of conventional, RAKE receiver-based systems, however, is the low single-cell capacity and the requirements for large bandwidths to support a moderate number of users and reasonable data rates. The optimal receiver for single-user communications in multipath channels causing ISI is the maximum likelihood sequence detector (MLSD) [16], which requires that the channel is known. In practice, the channel must be estimated, and hence the MLSD receiver is decoupled into an estimator that estimates the received noiseless signal and a correlator, which correlates the received signal with this estimate [17]–[19]. The simplest suboptimal single-user receivers for DS systems are the correlation receivers [2]. The most widely used receiver in CDMA systems is the RAKE receiver, which consists of several correlators to receive several multipath components. Coherent, differentially coherent, or noncoherent RAKE receiver structures can be used depending on the bit error rate requirements and signaling formats. Usually maximal ratio combining is used with coherent RAKE receivers, whereas equal gain combining is more common with differentially coherent and noncoherent RAKE receivers. The third-generation CDMA systems support coherent RAKE receivers for both uplink and downlink, whereas either noncoherent or differentially coherent RAKE receivers are used in second-generation CDMA systems [20].

In wide-band CDMA systems, novel signal-processing schemes can be used to enhance the capacity. Several multiuser detection [21] based receivers have been proposed to enhance capacity. Unfortunately, most of these require information on other users, which may not be readily available to single-user receivers (user terminals), but highly suited to base-station receivers.

A possible solution to these problems is the use of linear minimum mean-square error (LMMSE) receivers. These receivers offer high single-cell capacity and lend themselves to the use of short spreading ratios, minimizing the bandwidth requirements [22]–[25]. Implementations of LMMSE receivers such as those based on the least mean squares (LMS) adaptation algorithms are simple to implement and robust to a wide range of system conditions, but are slow to converge. The convergence rate deteriorates as the number of simultaneous users increases, which makes them unable to support more than a few system users for moderate channel fade rates. Such receiver structures, however, are well suited to environments such as wireless local loop or indoor WLAN's.

Significant progress has been made improving the rate of adaptation of practical LMMSE receivers for both blind and trained implementations. However, the convergence rate of existing algorithms still limits the range of user mobility for a given data rate [26]–[30]. These receivers hold great promise for WLAN and broad-band wireless access however.

The use of more rapidly converging algorithms for LMMSE receiver implementations such as least squares and the iterative counterpart, recursive least squares, allows the receiver structure to be used in a wider range of applications, but such algorithms are far more complex, and some of the advantages of the simplicity and robustness of the LMS implementation are lost.

The investigation of interference cancellation and multiuser detection receivers has also generated a great deal of interest [31]–[41]. Interference cancellation receivers rely on available information of all user signals and allow successive removal of interference from the signal of the user of interest. The interference cancellation may be done serially (SIC) or in parallel (PIC). Such receiver structures may be used in fast fading channels (relative to the data rate) and seem to be very good candidates for future mobile systems.

The performance of the interference cancellation receiver depends entirely on the acquisition of very accurate information of the interfering user signals, including channel estimates, delay, power, and symbol estimates for each user. This also adds considerably to the complexity of the algorithm and so the final implementation. To a large extent, much of the required information is available, or required for other reasons at the controlling base station in a mobile network, so interference cancellation receivers seem well suited for use on the reverse link.

B. Scope and Motivation of This Special Issue

This issue covers many topics of current research in CDMA systems but has a particularly heavy focus on high-efficiency receiver techniques and performance of third-generation system aspects, particularly in a multicode or multiple data-rate system. This focus is particularly timely as new CDMA system proposals are being developed.

Several papers examine possibilities for improving CDMA receiver structures with a focus on future mobile systems. The approaches considered include interference cancellation, interference suppression, and hybrid techniques, which hold the most promise for high-efficiency applications under the multirate restrictions supported by UMTS proposals. Although the overall performance of the interference cancellation receiver is relatively good in the single-cell case, its performance is significantly degraded in multicell environments due to the presence of unknown signal components. Blind receiver concepts are proposed in one paper for improving receiver performance.

Practical issues such as synchronization and timing estimation are also well represented. As stated earlier, accurate user delay estimation and channel estimation are crucial to the performance of interference cancellation receiver structures.

Other papers examine the performance of advanced receivers combined with antenna arrays or turbo/iterative coding. Given the potential inclusion of these advanced features into the UMTS standard, these contributions are most timely. Time and frequency hopping comparisons for signal spreading in CDMA systems are also considered.

With the standardization work going on for terrestrial mobile systems, little scope is left for specifying air interface and multiple access strategies. For WLAN and satellite system, considerably more freedom is available. Multiple access protocols, which reside above CDMA, are presented in this issue for WLAN and satellite systems.

II. CONCLUSIONS

For many years, the application of CDMA in practical systems was limited by the low-efficiency resulting from the use of simple correlator receivers. Since the realization that this efficiency is not an inherent limit, enormous effort has been expended in developing high-efficiency, implementable algorithms for mobile communications systems. With the driving force of next-generation systems and the success already realized by second-generation CDMA systems, this area is attracting much attention.

This special issue presents some of the latest research in the areas of CDMA and multiuser receiver algorithms as well as provides an overview of achievements to date. As the pace of development grows, more issues will arise that require the application of research and engineering to realize the inherent benefits of wide-band CDMA.

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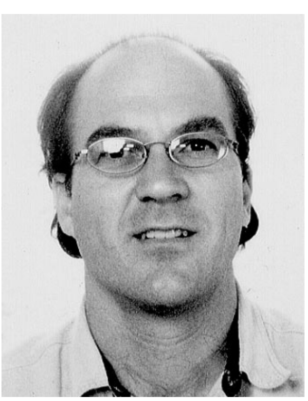

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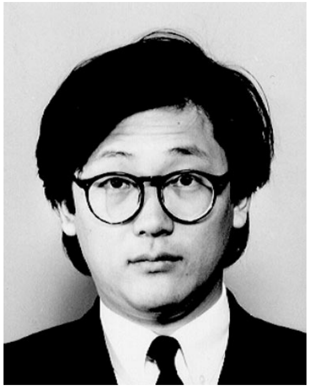

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