On WCDMA Detection–A Review

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Abstract- This paper attempts to review the main research and development trends in the area of WCDMA detection in view of mobile communications for 3G and beyond. Main developments in single-user detection (SUD) and in multi-user detection (MUD) techniques are presented. It is concluded that both enhanced SUD and MUD combined with smart antennas and multi-code can be used to enhance performance and capacity of WCDMA.

I. Introduction

Recently, spread spectrum-based code division multiple-access (CDMA) has taken on a significant role in cellular and personal communications. CDMA has been found to be attractive because of such characteristics as potential capacity increase over the competing multiple access methods, anti multi-path capabilities, soft capacity, and soft handoff. Hence, CDMA has been selected as the multiple access technology for the third generation mobile (3G). Multiple-access techniques allow multiple users to share a common channel, while keeping interference below a certain level. There are a number of multiple access schemes including more than one type of CDMA.

Wideband code division multiple-access (WCDMA) has emerged as the mainstream air interface solution for the third-generation networks. Several WCDMA proposals have been made for third-generation wireless systems. They can be characterized by: provision of multi-rate services, packet data, complex spreading, a coherent uplink using a user dedicated pilot, additional pilot channel in the downlink for beam-forming, seamless inter-frequency handover, fast power control in the downlink, and optional multi user detection.

Recent developments suggest that Impulse Radio, combined with time-hopping spread-spectrum (TH-SS) and pulse position modulation (PPM), leading to the most common version of ultra-wideband (UWB) radio, is an excellent candidate for the design of flexible multi-user wireless communication systems. UWB, a widely used technique in radar and remote sensing applications, has recently received attention for its applicability to wireless communication systems [1].

II. Wide-Band Code-Division Multiple Access (WCDMA)

Third generation wireless systems will deploy wideband code division multiple access (CDMA) [2], [3] access technology to achieve data transmission at variable rates with different mobility and quality of service (QoS) requirements.

Standards [2] call for increasing the transmission rate from the 14.4 kb/s voice rate currently supported up to 384 kb/s for mobile users and 2 Mb/s for portable terminals. Current industrial concerns are how to provide such multirate services in the broadband channels of 5–15 MHz likely to become available. Significant improvement in spectrum efficiency stands out as a key requirement.
The call capacity of wireless CDMA systems is limited by the interference generated by transmissions to/from other mobiles within and outside the cell. On the up-link the interference is mainly that from other transmitting mobiles. Power control attempts to maintain the received powers at values that balance the interference observed by the various mobiles, however, fading and mobility contribute to produce excessive interference in many cases.

Specifically, a wideband CDMA (WCDMA) system is defined as one wherein the spread bandwidth of the underlying waveforms in the system typically exceed the coherence bandwidth of the channel over which the waveforms are transmitted (meaning irrespective of whether the channel is indoors, outdoor urban, outdoor suburban, etc.). This results in the channel appearing frequency-selective to those waveforms, and correspondingly results in enhanced system performance relative to that of a narrowband CDMA system, wherein the latter is defined as one which (too often) experiences flat fading. The justification, for the previous statement, is that a direct sequence system which experiences frequency-selective fading can, via the use of a rake receiver, resolve individual multipath components and then coherently combine them (i.e., it can make constructive use of the multipath). Finally, there is, of course, no distinct bandwidth threshold that separates narrowband CDMA from WCDMA [3]. However, based upon measured data, it appears that a spread bandwidth of about 10 MHz satisfies the intuitive requirement that the channel appears frequency selective to the transmitted waveform for a broad cross section of scenarios.

III. Detection for Code Division Multiple Access

A. CDMA using single-user detection

Current CDMA receivers are based on the RAKE receiver principle, which considers other users' signals as interference. However, in an optimum receiver all signals would be detected jointly or interference from other signals would be removed by subtracting them from the desired signal. The capacity of a direct sequence CDMA system using RAKE receiver is interference limited. In practice this means that when a new user, or interferer, enters the network, other users' service quality will go below the acceptable level [4].

B. Enhanced single-user detectors

Enhanced single-user detectors are only slightly more complex than matched filters; it allows improved BER and capacity. However, single-user schemes are only suitable for slow changing fading channels. For packet transmission, interference parameters could change fast with time. Enhanced single-user receivers equipped with adaptive filter banks deliver promising performance with reasonable complexity, especially in slowly varying channels.

Thus, the performance of single-user detectors is still of interest, particularly in the presence of non-Gaussian noise [5]. Besides adaptive filtering, other efforts aimed at mitigating the effect of MAI on the conventional detector include:

- Code waveform Design: Design of spreading codes with good cross-correlation properties.
- Power Control: To reduce the near-far effect
- Techniques to reduce the number of interferers: e.g., smart antennas
- Any combination of the above [6].

Table 1 summarizes main R&D in SUD.

C. CDMA using multiple-user detection

Multi-user detection techniques are essential for achieving near-optimal performance in communication systems where signals conveying the desired information are received in the presence of ambient noise plus multiple-access interference. With the exploding interest from both the research community and industry in wireless code-division multiple-access (CDMA) systems, the application of multi-user detection techniques to wireless systems is becoming increasingly important. Various aspects of multi-user detection include: low-complexity multi-user detection techniques, channel identification methods, blind equalization of multi-input multi-output channels as well as CDMA channels information-theoretic limits on the capabilities of multi-user detection, spatial-temporal processing, multicarrier CDMA systems, and achievable performance of coded CDMA systems.

The more the network can resist interference the more users can be served. Multiple access interference that disturbs a base or mobile station is a sum of both intra- and inter-cell interference. Multi-user detection (MUD), also called joint detection (JD) and interference cancellation (IC), provides a means of reducing the effect of multiple access interference, and hence increases the system capacity. In the first place MUD is considered to cancel only the intra-cell interference, meaning that in a practical system the capacity will be limited by the efficiency of the algorithm and the inter-cell interference. In addition to capacity improvement, MUD alleviates the near/far problem typical to DS-CDMA systems [6].

Since optimal MUD is very complex and in practice impossible to implement for any reasonable number of users, a number of suboptimum multi-user and interference cancellation receivers have been developed. For MUD, JD and IC are most prominent. JD requires elaborate matrix manipulations and delivers very low BER. IC requires estimates of channel and interfering data signals. Driven by BER and capacity requirements for 3G and beyond, MUD has been an active area of research over the last decade. However, there is no scheme yet that fulfills the low complexity, short delay and operation in different environments requirements [4].

The suboptimum receivers can be divided into two main categories: linear detectors and interference cancellation. Linear detectors apply a linear transform into the outputs of the matched filters that are trying to remove the multiple access interference. Examples of linear detectors are decorrelator and linear minimum mean square error (LMMSE) detectors. In interference cancellation multiple access interference is first estimated and then subtracted from the received signal. Parallel interference cancellation (PIC) and successive (serial) interference cancellation (SIC) are examples of interference cancellation. While multiple access interference (MAI) by other users has been recognized as the capacity limiting factor in DS-CDMA-based cellular communication systems, multi-user (MU) approaches have largely alleviated the problem when the noise process is additive Gaussian [7].

With the availability of MU detectors, inaccurate or inappropriate noise modeling assumptions seem to have become the issue again. Whereas MU detection has much to offer in the uplink, it does not at present appear to be feasible for the downlink due to the complexity involved and the lack of resistance against adjacent cell interference. Moreover, MU for the downlink requires the knowledge of all spreading codes, which is not possible in the tactical military environment, for instance.

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It is well known that the performance of a code division multiple access (CDMA) system can be limited by multiple access interference (MAI). Such problems arise from the use of the conventional single-user detector, which ignores the existence of other users. As a consequence, when the number of active users increases to a certain level or when some users' signals become extremely strong, weak users with the conventional single-user detection may lose communication because of the overwhelming MAI. The optimal detector [8] that jointly detects all users' signals can significantly eliminate the MAI and provide a substantial increase in system capacity. However, the complexity of the optimal detector is exponentially proportional to the number of users and that prohibits its practical implementation.

For the CDMA uplink the ratio of other cell interference (at base station for given sector)-to-own cell interference is given by f~0.55 [9]. Then the maximum gain in capacity achieved by using optimum MUD (and hence, removing all intra-cell interference) is given by (1+f)/f. For f = 0.55 reported in [9], the gain in capacity is bounded by 2.8. Although the gain in capacity obtained by MUD is considerable, it should not be overwhelmed by the complexity and cost of MUD.

Table 2 summarizes main R&D in MUD.

IV. Summary and Conclusions

Enhanced single-user detectors are only slightly more complex than matched filters; it allows improved BER and capacity. However, single-user schemes are only suitable for slow changing fading channels. For packet transmission, interference parameters could change fast with time.

For MUD, joint detection (JD) and subtractive interference cancellation (IC) are most prominent. JD requires elaborate matrix manipulations and delivers very low BER. IC requires estimates of channel and interfering data signals. Driven by BER and capacity requirements for 3G and beyond, MUD has been an active area of research over the last decade. However, there is no scheme yet that has low complexity, short delay and can operation in different environments (slow / fast fading; intra/ intercell interference)

Other related research areas include: smart antennas and multicode; combined with MUD.

- The joint application of multi-user detection, spatial–temporal processing and iterative decoding techniques holds the promise to achieve both interference suppression and large coding gains, thus allowing practical systems to operate close to capacity.
- Identification of multi-user channels represents one of the toughest challenges for the realization of effective multi-user detectors.

An excellent summary of literature on narrow band interference may be found in [10].

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Table 1 Single-user detection

<table>
<tr><th>Bank of Matched Filters (Conventional detectors)</th><th>Enhanced Single-User Techniques</th></tr>
<tr><td>
Forward error-correcting codes FECC
• Powerful error-correcting codes allow acceptable BER performance in interference channels.
• Turbo codes may be used especially on data signals.
• Space-time codes have a promise for providing acceptable BER performance over stressed MA channels.

Code waveform design
• Design of spreading codes with good correlation properties.
• If all the cods are orthogonal, there would be no MAI.
• However it is not possible to design orthogonal codes that can remain orthogonal over multipath fading channels.
• Instead we design codes with lowest possible cross-correlation.

Power control
• Ensures that all users arrive at the same power.
• Two power control systems are used: Open loop and Closed loop
• Open loop: based on received signal, measures the interference conditions from the channel and adjusts the transmission power accordingly.
• Closed loop: based on received S/I, measures the S/I and sends commands to the transmitter on the other end to adjust the transmitter power.

Sectored / adaptive antennas
• Directed antennas focus reception over a narrow desired angle range.
• Hence, the desired signal is enhanced by the antenna gain, while the interfering signals arriving from the remaining angles are attenuated.
• The direction of the antenna can be fixed as in sector antennas or adjusted dynamically.
• Adaptive signal processing is used in the latter case to focus the antenna in the direction of the desired user(s).
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Minimum mean square error receivers (MMSE)

More insensitive to fixed timing errors than the adaptive filters presented in [3].

LMS filters

Here the bank of matched filters is replaced by an adaptive fractionally spaced least mean square filter. Prior to transmission the receiver is trained by a known sequence.
• Outperforms matched filter
• Suppresses NB and MAI
• Insensitive to differences of arrival times of users' signals
• Channel estimates and other user's codes are not required

Adaptive MMSE interference suppression filters

Adaptive filters presented in [3] consider the case where only a few strong interferers exist in the system so the adaptive filter can be simplified using fewer taps and thus converge faster.
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• Other users are considered noise
• No channel or signal information are needed
• Enhanced single-user detectors are only slightly more complex than matched filters; it allows improved BER and capacity.
• However, single-user schemes are only suitable for slow changing fading channels.
• For packet transmission, interference parameters could change fast with time.
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Table 2 Multi-user detection schemes

Interference Cancellation Schemes	Combined Schemes	Joint Detection
Successive interference cancellation (SIC) • It cancels stronger interferences first. • Requires only a minimal amount of additional hardware and has the potential to provide significant improvement over the conventional detector. • Initial data estimate must be correct, and must be correctly updated.	**Minimum mean square error / Parallel interference cancellation (MMSE/PIC)** • The receiver is three stages: blind MMSE detector which cancels itra-cell and intercell interference and generates the first estimate. • Followed by a PIC which removes intra-cell interference. • The final stage is a blind MMSE that cancels the remaining intercell interference.	**Maximum likelihood sequence estimator (MLSE)**. • Optimum. • Too complicated (2^k operations). • Not practical for any reasonable number of users K. • Its performance serves as a bench mark for the comparison of other MuD receivers.
Parallel interference cancellation (PIC) • An estimate of the interference effect of the k-1 users on the first user is obtained and cancelled simultaneously. • The process is repeated several times to obtain a better estimate. • Single stage PIC is not near-far resistant and either power control or multi-stage processing is required.	**Decorrelator/ PIC** • Uses a decorrelator at the first stage of the receiver to generate the initial decision statistics. • The multistage PIC detector with a decorrelator at the front end can outperform the conventional decorrelator.	**Decorrelator** # of operations increases linearly with the number of active users, however, involves matrix inversion. Two versions: • Multipath decorrelator (MD) detector completely removes interference but it enhances thermal noise. • Zero-forcing block linear equalizer (ZF-BLE) requires perfect channel estimate. More complex than MD, but has better BER performance and requires accurate channel estimate.
Hybrid interference cancellation (HIC) Combining some positive features of SIC and PIC into hybrid schemes offers considerable reduction of delay and complexity at the cost of some BER degradation.	**Decorrelating Decision feedback detector (decorrelator/SIC)** • Cancellation of MAI is is done after ranking the received signals according to strength and removing the strong signals first. • It has most advantages and disadvantages of SIC. If data estimates are correct, all users experience complete MAI reduction. It requires Cholesky decomposition and lower triangular matrix inversion	**Minimum mean square error detector (MMSE)** • Minimizes both noise and MAI • For high thermal noise its performance approaches the conventional matched filter • An adaptive MMSE replaces the traditional bank of matched filters by a bank of MMSE filters. It offers considerable performance improvement in multi-cellular environment. No need for channel estimation due to its adaptive nature. **Iterative multi-user detection** • New! Based on Turbo codes. • Requires manipulation of large matrices.

For MUD, joint detection (JD) and subtractive interference cancellation (IC) are most prominent.

JD requires elaborate matrix manipulations and delivers very low BER. IC requires estimates of channel and interfering data signals.

However, there is no scheme yet that fulfills the following main requirements:

- ❖ Low complexity
- ❖ Short delay
- ❖ Operation in different environments (slow / fast fading; intra/ intercell interference)

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