Title

Succesive Interference Cancellation for Interception of the Forward Channel of Cellular CSMA Communications

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Successive Interference Cancellation for Interception of the Forward Channel of Cellular CDMA Communications

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Abstract

We develop and evaluate receiver signal processing algorithms for the detection of signals transmitted via the forward *link of a cell in a cellular system modeled after the IS-95 standard for direct-sequence spread-spectrum code-division multiple-access (CDMA) communications. Multiuser detectors on board airborne and terrestrial mobile interceptors or monitors attempt the simultaneous detection, in a single receiver, of all communication signals transmitted by the base station of interest. Due to the detrimental effects of transmitter, receiver and channel nonlinearities, very fast multipath fading, shadowing, path loss, Doppler spread, additive white Gaussian noise, and intracell and intercell multiple-access interference, the user signals are de-orthogonalized. This leads to performance degradation in conventional receivers that is too severe, especially when the powers of some of the interfering users are dominant. In order to improve upon the performance of conventional matched filter receivers, this article focuses on the development and evaluation of fast and reliable successive interference canceling (SIC) algorithms. The techniques we have developed can be used to relax the strict requirements on power control and to improve the capacity of CDMA systems.*

1 Introduction

To provide communication services to a large and growing number of users, CDMA cellular systems reuse the same frequencies within geographical cells. To further increase the capacity of cellular communications, new receiver structures are required to provide mitigation from the harmful effects of the resulting co-channel interference. The objective of the research reported in this article is the development and evaluation of reliable receiver signal processing algorithms to jointly demodulate the signals employed in the forward link of a single cell in a system modeled after the IS-95 standard for CDMA cellular communications. The signals are received at a single sensor on board an airborne or satellite interceptor/monitor and a terrestrial interceptor/monitor in the presence of transmitter, receiver and channel nonlinearities, very fast time varying multipath fading, shadowing, path loss, Doppler spread, intra-cell interference, inter-cell interference and additive white Gaussian noise (AWGN). The effects of nonlinearities and fading are independent from chip to chip, effectively de-orthogonalizing the transmitted signals. A multiuser detector on board the airborne and terrestrial interceptors attempts the simultaneous detection of all communication signals in a single receiver.

The techniques we have developed can be used to enable successful surveillance and/or reconnaissance of CDMA signals for law enforcement, defense, cellular fraud management, etc., to improve the capacity of existing and proposed ground to air and sea to air (maritime) communications systems, such as satellite and aeronautical communications platforms, and to potentially relax the stringent requirements on power control imposed on the IS-95 system.

The research is important for several reasons:

- The high deployment rate of new IS-95 cellular CDMA systems in the US and abroad, and the emergence of CDMA as a strong candidate for the air interface of the universal personal communications network planned for the near future, necessitate the design and implementation of practical, interference-resilient demodulators for co-channel spread-spectrum signals.
- The stringent requirements on power control imposed by the IS-95 system to combat the near-far problem may be relaxed if multiuser detection is employed. This work exploits this observation and proposes to apply multiuser detection to the signals transmitted on the downlink of IS-95. Power control dictates significant reductions in the transmitted powers of the strong users in order for the weaker users to achieve reliable communication. This can become self defeating since it can actually decrease the overall multiple access and anti jamming capabilities of the system. Before the emergence of solutions to the near-far problem based on multiuser detection, the only remedies available were power control and design of signals with ever more stringent cross correlation. Thus, solution to the near-far problem has been highlighted as an important task of multiuser detection.
- We believe that the problem is new. Although the general problem of signal interception has received some attention in the literature [1], and even though several multiuser detection schemes have been previously applied to CDMA signals [2–5], to our knowledge very little has been published on the interception of multiuser IS-95 signals. The few exceptions include [6, 7], which did not consider SIC nor airborne interception. References [3–5] have considered successive and parallel interference cancellation with convolutional coding and decoding, showing improved performance compared to the use of conventional matched filter receivers. References [8, 9] have demonstrated performance gains for multiuser detection on the forward link, but they did not consider SIC. Furthermore, most of the previously published performance results, including [2–7], consider the reverse link of CDMA communications. These results are not fully applicable to the scenario of signaling on the forward channel of IS-95 because the transmitter and the propagation channels of the forward link of IS-95 are substantially different than their counterparts for the reverse link. The problem offers some new twists – e.g., the particular structure of IS-95 signals, the fact that from the point of view of the interceptor, power control increases the dynamic range and worsens the near-far effect, and the fact that we are interested in intercepting the signals of ALL the users in a desired cell, rather than only a single user. Numerous articles, such as [8–12] reported on the relatively unsatisfactory performance of some conventional matched filter receivers in very harsh downlink propagation channels without multiuser detection and/or antenna diversity. This motivates the need to investigate multiuser receivers which are specifically designed for more practical and realistic models of the downlink of the IS-95 system and for the transmitter, channel and receiver nonlinearities and severe fading conditions which may be associated with the downlink under certain circumstances.

The paper is organized as follows. In Section 2, we present the problem which is addressed in this submission. Section 3 provides the models for the signal and the interference canceling receivers. Section 4 contains performance results generated from computer simulations, comparing the interference canceling detectors to the non-interference canceling detector and the single user bound. Finally, in Section 5, we provide some concluding remarks and issues to be researched in the future.

2 Statement of the Problem

The problem to be addressed is the following: given the received signal, a sum of K co-channel direct-sequence spread-spectrum signals in noise and interference, we wish to develop algorithms to simultaneously detect the digital messages x_{mk}, for all bit time instances m and all users $k = 1, 2, \ldots, K$. Using computer simulations, we have determined the bit-error-rate (BER) performance as a function of signal powers and number of users in the desired cell. Specifically, we have designed and implemented in software two successive interference cancellation schemes. Successive cancellation [2–4] is based on demodulating the strongest user using conventional methods, and remodulating the recovered message. The remodulated signal is then subtracted from the received composite signal, leaving an approximation to the sum of signals due to the remaining users. This process is then repeated, and each time the signal due to the strongest remaining user is subtracted, resulting in a waveform with substantially diminished interference. The disadvantages of the technique are it's suboptimal performance, it's requirements that the received amplitudes and phases be estimated with good accuracy, and that some power separation exist between the strongest signal and the next-strongest signal in each step of each successive cancellation stage; otherwise, its performance degrades.

Successive interference cancellation schemes are derived in [2–4], demonstrating significant performance improvements over the conventional receiver which does not employ interference cancellation. We have simulated in software a conventional matched filter receiver (CMF), a conventional multistage successive interference canceling receiver (CSIC) and a modified multistage successive interference cancellation (MSIC) scheme which employ coherent detection and pilot signals to obtain channel estimates. The results show that the modified successive interference canceler provides traffic capacity increase over the capacity of the conventional successive interference canceling receiver, which in turn provides capacity increase over the conventional matched filter receiver.

3 Signal Model and Interference Cancellation Receivers

The signal model is based on the IS-95 CDMA cellular system, which applies a universal one-cell frequency reuse: On the base station to mobile link, signals are transmitted over a common portion of the frequency spectrum. Each cell has a common pilot channel which is transmitted at all times by the base station on each active forward CDMA channel. The user signals are orthogonalized, as all signals emanating from the same base station transmitter are synchronized. When the propagation path between the base station of interest and the interceptor is an AWGN channel, the traffic channels are orthogonal and synchronous and multiuser detection is not necessary on the forward link, as a bank of simple correlation receivers (ie., the CMF receiver) is optimal.

We consider channel models in which this signal orthogonalization is not preserved. The communications between the base station and the airborne interceptor are assumed to take place over a Rician flat-fading mobile satellite channel, while the communications between the base station and a land-based mobile interceptor are assumed to take place over a Rayleigh frequency-selective fading mobile channel. For both channels, we assume very fast time-varying fading which is independent from chip to chip. We also incorporate, in all our simulations, the effects of transmitter, receiver and channel nonlinearities, all of which effectively destroy the orthogonality of the traffic channels on the forward link. Both channels introduce multipath interference, log-normal shadowing, path loss, Doppler spread, intracell interference, intercell interference and additive white Gaussian noise.

Through power control in the downlink, the power transmitted to close-in portables is reduced, while the signal to interference requirements of all portables are satisfied, increasing the overall capacity [10]. In our signal model, we consider power control models designed to follow the slow variations in received signal to interference ratio due to shadow fading and path loss (slow power control), as well as the fast variations due to fast multipath fading.

From the point of view of the airborne or land-based (terrestrial) interceptor, power control on the forward link can be a major problem, because the higher power allocated by the base station to transmit to mobiles which are further away from the base station can overwhelm the power transmitted by the base to mobiles which are close to the base. Hence, *from the point of view of the interceptor*, this particular power control scheme is not beneficial if the interceptor employs a conventional matched filter receiver which is not near-far resistant. However, as we show in the sequel, the power control scheme is beneficial if the interceptor employs successive cancellation, because the successive interference canceling detectors perform better when the signals are of distinctly different powers [2].

Note that in this project, we initially address only the two channel models mentioned above. This limits the scope of our work. The baseband models that we have developed in software for the forward traffic propagation channels are based on the multipath models described in [13–15]. For frequency-flat Rician fading (satellite or airborne interceptor), the channel parameters are set as in [13], and there is a direct line of sight path between the desired base station transmitter and the receiver; for frequency-selective Rayleigh fading (terrestrial interceptor), the delays between the received replicas of the transmitted signal, τ_c, are random integer multiples of the chip duration T_c, there is no direct line of sight path between the base station transmitter and the receiver, and the channel parameters are set according to [14, 15]. The total power transmitted by the base station is normalized to unity, with 20% of the power allocated to the pilot signal, and a fraction of the remainder of the power allocated for communicating with each portable which is in contact with the base station of interest.

To operate in the cochannel interference signal environment described above, we have implemented the conventional matched filter receiver and the conventional and modified multistage successive interference canceling receivers in software. The SIC receivers are shown in block diagram form in Figs. 1, 2, and 3. The conventional K-user demodulator commonly employed in practice is implemented as a bank of optimum detectors for single-user communications. There is one matched filter or RAKE receiver for each leg of the quadrature demodulator for each user, followed by one Viterbi decoder for the convolutional code of each user. The performance of this demodulator is used as one baseline against which we compare the conventional and modified multistage successive interference canceling receivers. For the interference canceling receivers, at each step of each stage of interference cancellation, we weight the re-spread and re-constructed user signal by a partial-cancellation factor. We employ this weighting procedure in order to reduce the effects of imperfect signal reconstruction and cancellation at each step of each stage of interference cancellation. This way, more reliable estimates (ie., those corresponding to users which were received with higher powers) receive higher weight in the multiple access interference reconstruction and subsequent cancellation operations. We determined the proper weights by an optimization procedure.

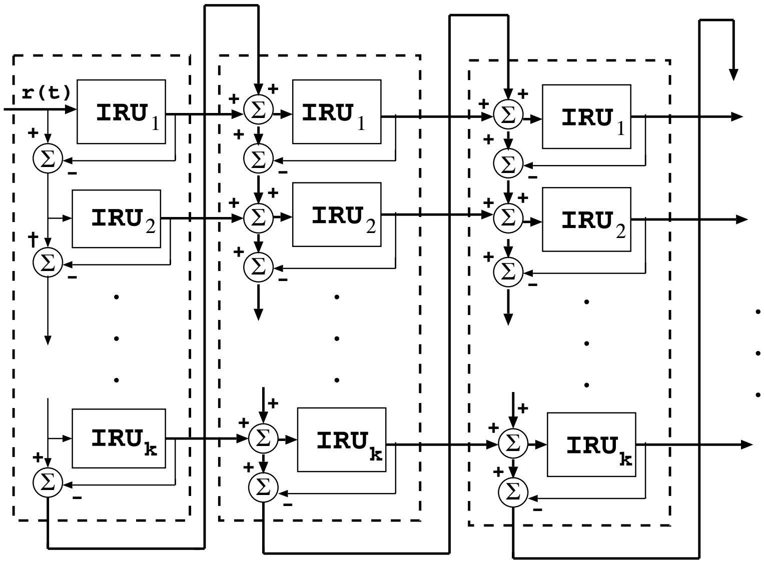

Figure 1: Multistage successive interference cancellation. The block IRU_k stands for interference regeneration unit for user $k = 1, 2, ..., K$ at each step of each stage.

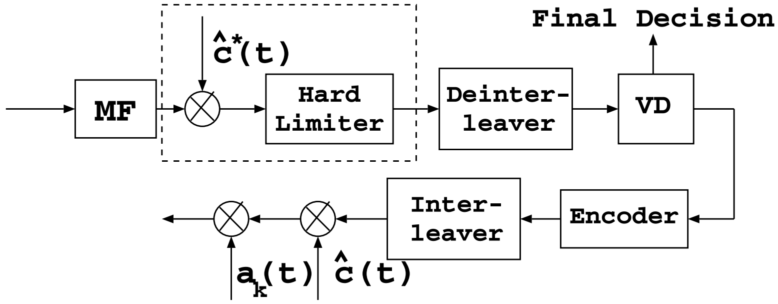

Figure 2: Details of each cancellation unit for the modified successive interference canceler (MSIC). The dashed block is used only with hard decision decoding. MF and VD stand for matched filter and Viterbi decoder, respectively. The quantity $\hat{c}(t)$ represents the channel estimate, $\hat{c}^*(t)$ it's complex conjugate, and $a_k(t)$ the spreading waveform for user k. The block diagram applies to the case of flat fading; for frequency-selective fading, there is one such cancellation unit for each finger of the RAKE receiver.

In IS-95, a block of reference symbols (the pilot sequence) is added in parallel to the data stream before transmission over the channel. The received signal is down-converted to baseband (in this project, we assume ideal carrier frequency and phase acquisition and tracking) and correlated with a locally generated replica of the known reference symbols to obtain unbiased but noisy preliminary channel estimates. The real and imaginary correlation values (obtained from the I- and Q- channels, respectively) are evaluated at the sampling instants and stored in memory for the entire length of the incoming sequence. The locally generated replica of the known pilot sequence is then shifted by one chip period, and the correlation procedure is repeated. The correlation vector contains the information needed for sequence synchronization: for the case of frequency-selective fading, the index of the maximum value of the correlation

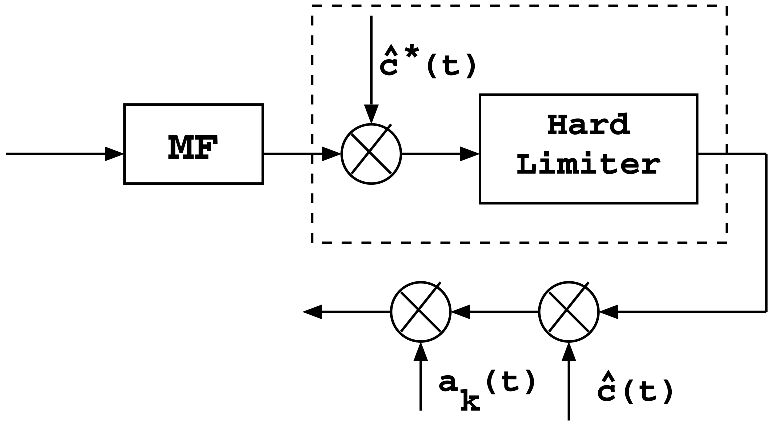

Figure 3: Details of each cancellation unit for the conventional successive interference canceler (CSIC). The dashed block is used only with hard decision decoding for a final hard decision if necessary. The block diagram applies to the case of flat fading; for frequency-selective fading, there is one such cancellation unit for each finger of the RAKE receiver.

vector gives the delay between the strongest incoming ray and the local pilot sequence, and the delays of the remaining trackable paths are found from successively searching for additional peaks in the correlation vector. The indices of the peaks and their magnitudes and phases are further processed using a subspace-based iterative algorithm to compensate for the delays, amplitude scalings, and phase rotations introduced by the channel, for every tracked path. The channel estimation algorithm is based upon the iterative method described in detail in [16].

In decoding the binary convolutional code employed on the downlink, we have implemented a modified branch metric for use in the Viterbi algorithm: we use the estimates of the channel gain to compute the metric by evaluating the squared Euclidean distance between the samples at the outputs of the matched filters and the candidate symbols after weighing the latter by the channel gains. This enables us to provide information on channel reliability to the soft-decision Viterbi algorithm employed at the decoder. The essence of modifying the branch metrics is the relative accentuation of more credible information and the relative suppression of less credible information. Our numerical results demonstrate that the modified branch metric leads to improvements in BER performance compared to the case of hard decision decoding when channel estimation errors are present, which is the case in practice.

4 Single Cell Performance in Multicell Environment

In this section, we describe our study of the performance of the conventional matched filter receiver and the conventional and multistage successive interference canceling receivers in the cochannel interference environment.

We have conducted extensive computer simulations to estimate receiver performance. We have simulated the different powers assigned to different traffic channels (users), modifying the power separations between users at each Monte-Carlo run to account for user mobility. Performance is reported as average bit error rate (BER) as a function of the average bit energy to noise power spectral density E_b/N_o (both quantities are averaged over all active users in the cell of interest). The simulation model is composed of 7 hexagonal cells, each with a base station at its center. The base station of interest is located in the center of this cell cluster and is comprised of three contiguous sectors, each sector occupying 120°. Transmissions from the other six base stations interfere with the transmissions from the base station of interest. The interference from base stations outside these six is assumed insignificant.

We have investigated a potential major cause of performance degradation due to the active use of the same Walsh codes by base stations in both the desired cell and adjacent cells. Our model for intercell and intracell interference incorporates power allocation to the various traffic channels, soft handoff, mobile speed, spatial decorrelation of shadowing [14], path loss, Doppler spread and multipath. We pass the interfering signals from the undesired base stations through fading channels that are independent of the fading channel between the interceptor and the desired base station in the cell of interest. We assume the interceptors are much closer to the base station of interest than they are to the undesired base stations, and hence the received intercell interfering signals are attenuated compared to the desired signal. For simplicity, we assume that the number of users in each of the interfering cells is equal to the number of users in the desired cell, and the active users in the interfering cells are all using the same exact subset of Walsh codes as those used by the active users in the desired cell. The reuse of the same subset of Walsh codes in adjacent cells should result in worst-case performance of all receivers investigated in this study.

Figures 4 – 5 show the average BER performance per user vs. the average bit energy to noise power spectral density E_b/N_o. Results are shown for the conventional matched filter (CMF), conventional successive interference canceling (CSIC) and modified successive interference canceling (MSIC) receivers operating in a single cell, flat Rician fading environment with intercell and intracell multiuser interference. The CSIC and MSIC receivers employ two stages of cancellation each. For comparison purposes, baseline performance is given for a conventional receiver employing a rate 1/2, constraint length 9 convolutional encoding and decoding when only a single user is active in a single cell with no multicell interference, in flat Rician fading with perfect channel estimation of the fading parameters (amplitude and phase), but without any estimation of the AWGN. The performance of this receiver in this signal environment is equivalent to the performance of the optimal receiver in AWGN with coding [2]. When the number of users $K = 15$, the performance of the MSIC is the closest to the single-user bound ($K = 1$) among all receivers considered in this discussion and is superior to the CSIC and the CMF for $K = 15$. As the number of users increases, the gap in performance between the MSIC receiver and the other two receivers is even more pronounced, since the MSIC lowers the BER floors associated with the competing receivers.

In general, the intercellular to intracellular interference ratio is a random variable, since the interference powers from all surrounding cells will be a function of the random numbers of users in adjacent cells, as well as random path loss exponent, shadowing, Doppler spread and voice activity. However, in our simulations we assumed that the path loss exponent for intercell interference in all simulation runs were four and three for the airborne and terrestrial interceptors, respectively. We have also simulated the effects of errors in the power control algorithm. For BER of 10^{-3}, the capacity of the system, *from the point of view of the interceptor,* is virtually unchanged compared to the case of perfect power control, assuming the receiver is capable of accurately tracking the time-varying powers of the data channels[1]. This is because successive interference cancellation algorithms perform better when the power separations between users are more distinct [2]. This compares favorably with the capacity of the same system employing the conventional matched filter receiver and the conventional interference canceler.

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[1] However, from the point of view of the mobile users communicating with the base station of interest, the capacity is adversely affected due to errors in the power control algorithm.

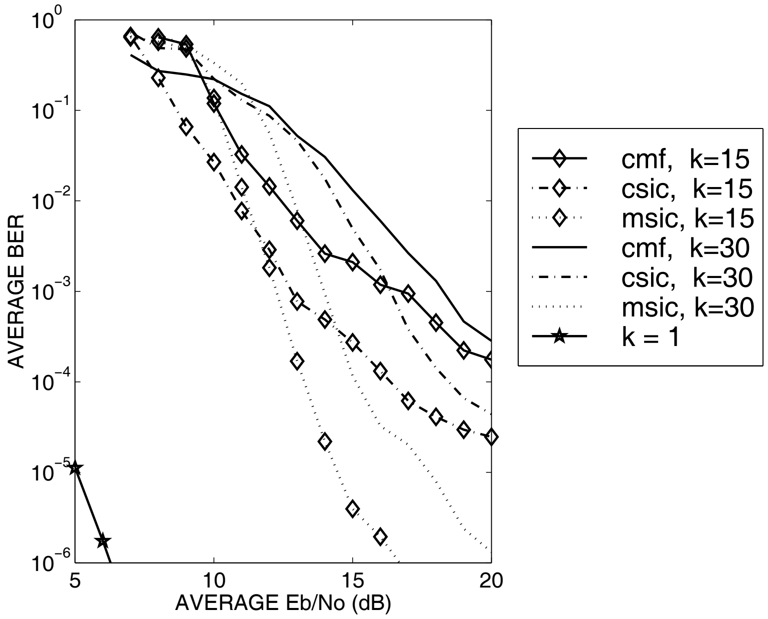

Figure 4: BER Performance of a conventional matched filter receiver, a conventional interference canceling receiver and a modified successive interference canceling receiver operating in a multi cell, frequency-flat Rician fading environment with multiuser interference, with k active users in the cell.

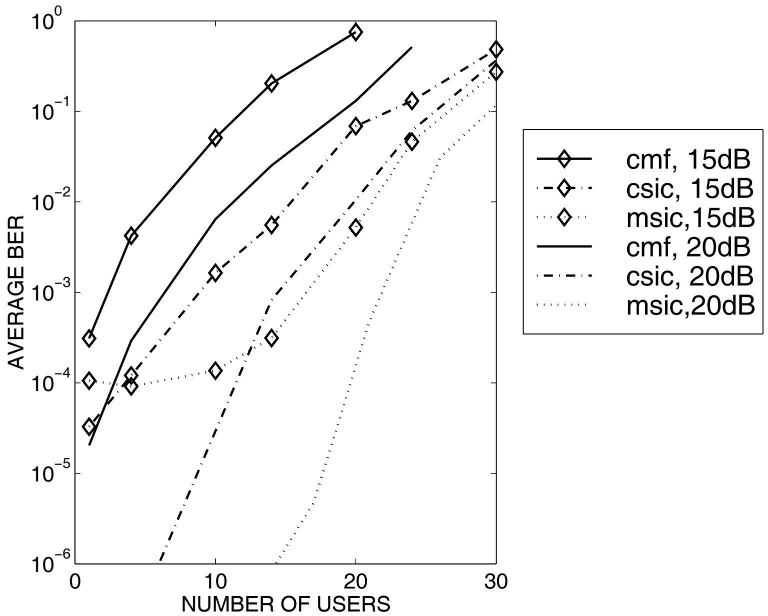

Figure 5: Capacity of a conventional matched filter receiver, a conventional interference canceling receiver and a modified successive interference canceling receiver operating in a multi cell, frequency-flat Rician fading environment with multiuser interference. The legend also indicates the average bit energy to noise power spectral density per user.

Figs. 6 - 7 depict the performance of the two-stage successive interference canceling receivers with perfect power control, hexagonal cell geometry and path loss exponent of three on a frequency-selective Rayleigh fading channel. The channel model consists of two independent

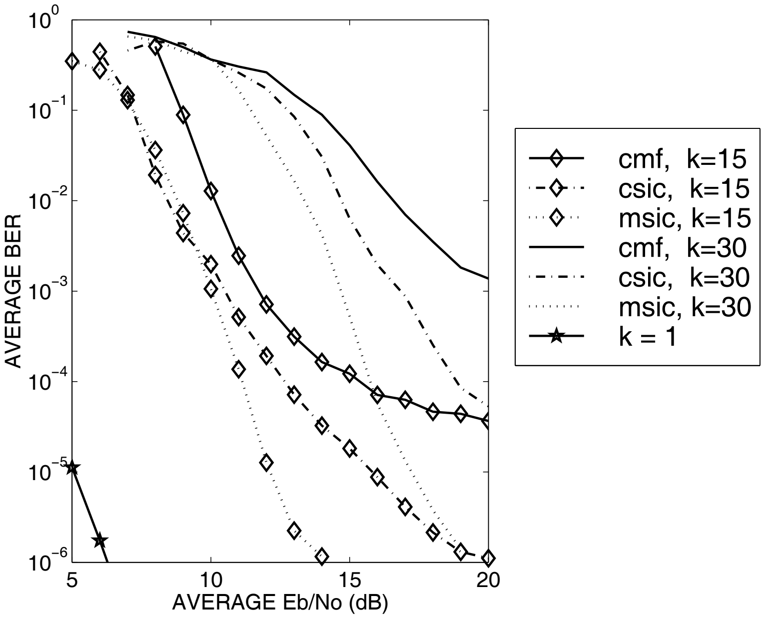

Figure 6: Performance of a conventional matched filter receiver, a conventional interference canceling receiver and a modified successive interference canceling receiver operating in a multi cell, frequency-selective Rayleigh fading environment with multiuser interference. The letter k denotes the number of active users in the cell.

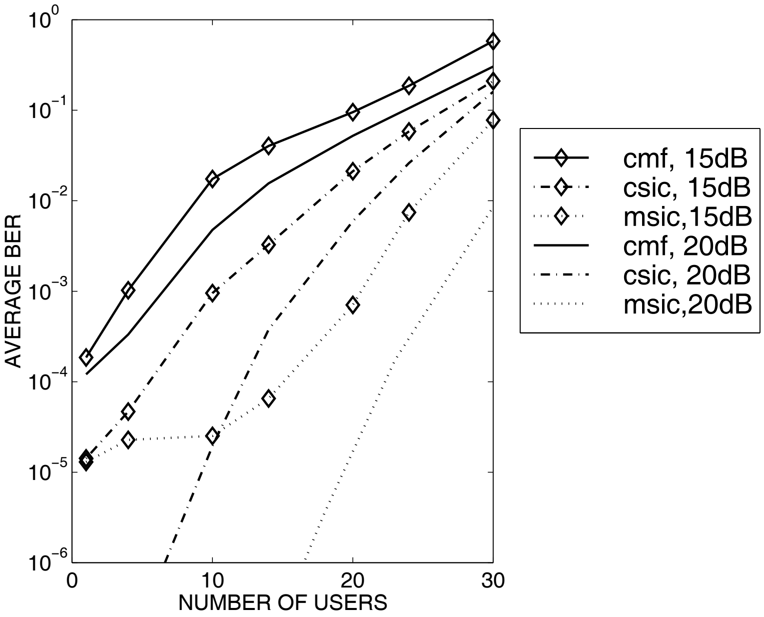

Figure 7: Capacity of a conventional matched filter receiver, a conventional interference canceling receiver and a modified successive interference canceling receiver operating in a multi cell, frequency-selective Rayleigh fading environment with multiuser interference.

paths. The delays between the paths are assumed to be random integer multiples of the chip period T_c. Both paths are assumed to be tracked by a RAKE receiver utilizing the pilot sequence for channel estimation as described above. All receivers employ one matched filter for each user on each finger of the RAKE receiver; the outputs of the RAKE fingers are combined via equal-gain combining to yield a decision statistic that is used for data symbol estimation. For the successive interference cancellation schemes, there is one multistage successive interference canceler for each finger. The assumed path loss exponent for the intercell interference for the terrestrial interceptor is three. All receivers are operating in a multicell scenario with intercell and intracell multiuser interference (with the exception of the baseline receiver ($K = 1$) which does not suffer from multiuser interference.) When the number of users $K = 15$, the performance of the MSIC is the closest to the single-user bound (K =1) among all receivers considered in the figure, and superior to the CSIC and the CMF. As the number of users increases, the gap in performance between the MSIC receiver and the other two receivers is even more pronounced, since the MSIC lowers the BER floors associated with the competing receivers. For BER of 10^{-3}, the capacity of the system, from the point of view of the interceptor, degrades only slightly compared to the case of perfect power control, assuming the receiver can accurately track the data channel powers in the presence of power control errors.

The capacity of the system in a multicell scenario, like that for a single cell scenario, is slightly smaller with the flat Rician-fading channel than it is with the frequency-selective Rayleigh fading channel when the number of users is not too large. This is because the RAKE receiver employed in the frequency-selective channel provides additional processing gain by combining the outputs of the RAKE fingers dedicated to the signals from the two independently fading paths. However, the capacity in a frequency-flat fading channel is slightly better than that of a frequency-selective channel when the number of users is relatively large or when the signal to noise ratio is small, because then the signal at each RAKE finger suffers from too much interference from the signal that has propagated along the other path. In multicell scenarios, the detectors exhibit BER floors, due to the additional interference and the accumulated errors from imperfect regeneration and cancellation of other users.

5 Summary

We have employed successive interference cancellation techniques to simultaneously detect multiple cochannel signals transmitted on the forward link of the IS-95 CDMA cellular system. The signals are received at airborne and terrestrial mobile interceptors in the presence of transmitter, channel and receiver nonlinearities, very fast (chip to chip) time varying frequency-flat Rician fading and frequency-selective Rayleigh fading, shadowing, path loss, Doppler spread, additive white Gaussian noise, intracell interference and intercell interference. These transmitter, channel and receiver impairments act to severely damage the orthogonality of the traffic channels, necessitating multiuser detection. The forward channel employs power control, creating a near-far problem at the interceptor. The reference pilot channel was exploited for channel estimation and coherent detection as well as interference cancellation. We have shown that the reference pilot-channel assisted coherent multistage successive interference canceling receiver, which uses the decisions from the output of the error control decoder for signal regeneration at each step of each stage of interference cancellation, performs the closest to the coherent receiver which is using perfect channel estimates (ideal coherent receiver), providing capacity gains over the other detector implementations which were considered here.

The main drawbacks of the interference cancellation techniques discussed in this presentation are suboptimal performance, the need for accurate estimates of received signal amplitudes and chip, bit and frame timings, accurate estimates of carrier phase and frequency and signature codes of all desired users, some power separation between the strongest traffic channel and the next-strongest traffic channel in each successive cancellation stage[2], and processing delay. These parameter estimates are not easy to obtain in practice. Most of the required parameters can be estimated from the pilot channel, and the required signature codes can be estimated by using one of a number methods proposed in the literature for code waveform estimation, such as [17], for example. The requirements of minimum delay and implementation simplicity necessitate the need to limit the number of cancellations. However, we have shown that with careful design of system parameters, such as user signature code waveforms with very low cross-correlation properties, accurate power control, powerful forward error correcting channel codes and other system parameters, these interference cancellation methods can provide satisfactory performance, which tracks the performance of the optimum receiver, and they are near-far resistant. Furthermore, in general they are substantially easier to implement than the optimal receiver: successive cancellation requires computational complexity per symbol which is *linear* in the number of users K, in contrast to the optimum demodulator, which has complexity per symbol that is *exponential* in K.

In the near future, we intend to investigate the robustness of the receivers to parameter estimation errors and the application of antenna arrays combined with interference cancellation to the problem of signal interception.

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