Successive Interference Cancellation Algorithms for Downlink W-CDMA Communications

Mohamed F. Madkour, *Member, IEEE*, Someshwar C. Gupta, *Fellow, IEEE*, and Yi-Pin Eric Wang

***Abstract*—In this paper, successive intracell interference cancellation (IIC) of the wideband-code division multiple access (W-CDMA) signal at the mobile unit is considered. Three new interference cancellation techniques suitable for the downlink of any CDMA system with orthogonal spreading are proposed. No prior knowledge of users' spreading codes or even their spreading factors are required for interference cancellation. A new term, effective spreading code, has been introduced in this paper which is defined as the interfering user physical code as seen by the desired user within the desired user symbol duration. The mobile receiver estimates the effective spreading codes of the interfering users regardless of their spreading factors using fast Walsh transform (FWT) correlators (instead of the regular correlators) and uses this information to suppress the intracell multiuser interference. Three different interference-suppressing techniques are studied: subtraction; combined interfering signal projection; and separate interfering signal subspace projection. The complexity of the proposed techniques is low compared to conventional interference cancellation techniques. For a W-CDMA system and the IMT-2000 vehicular channel model, a capacity increase of up to 150% of the original (without IIC) system capacity is shown.**

***Index Terms*—Downlink interference cancellation, multirate CDMA, multiuser detection, spread spectrum techniques, wideband CDMA.**

I. Introduction

THE third generation (3G) cellular mobile communications systems will support several kinds of communication services, including, e.g., voice, images, and even motion picture transmission [1]. Therefore, the users will be transmitting their information signals using different data rates and their performance requirements will vary from application to application. wideband-code division multiple access (W-CDMA) with variable spreading factor (SF) and multicode modulation as a multirate scheme [2], [4] is emerging as one of the air interfaces for the 3G mobile communications systems. The high and different user data rates and the large number of users together with multipath dispersive fading channels cause severe intercell and intracell multiuser interference. Fundamental investigations [5]–[8] have demonstrated huge potential capacity and performance improvements as a result of using multiuser detection at the expense of increasing complexity of optimum structures. In general, a major problem with multiuser detectors and interference cancellers is the maintenance of simplicity. Even the sub-optimal linear detectors require considerable complex processing.

There are several algorithms for interference cancellation for CDMA systems [9]–[11]. Most of these algorithms are designed for the uplink. For uplink interference cancellation, it is assumed that the receiver knows all the spreading codes. This assumption is however not true for the downlink where the mobile unit only knows its own spreading code. Furthermore, the complexity of the interference cancellation algorithms proposed up to date is very high. For the downlink, since interference cancellation has to be performed at a hand-held battery-operated terminal, cost and power consumption are of great concern. In this paper, we focus on the downlink communications. A successive intracell interference cancellation mobile receiver is proposed. The receiver estimates the interfering users' effective spreading codes and uses them to suppress the interference on the received signal.

Some researchers are trying to estimate the interfering user actual spreading code and then use it in the cancellation process using different ways, either by equalization idea or by subtractive cancellation, etc. [13], [14] (very few are dealing with variable spreading factor case). In this paper, we are not trying to estimate this physical code (because we will deal with variable spreading factor case), but rather estimating what we call effective spreading code (ESC). This is the effective spreading code of the interfering user as seen by the desired user within the desired user symbol duration. This ESC belongs to the Walsh space seen by the desired user. We combine this estimation process with the interference cancellation to get a better code estimate after every iteration and hence better cancellation and better performance. Three different techniques have been considered in the canceller: subtraction; combined interfering signals projection; and separate interfering signals subspace projection. In this paper, we deal with the intracell multiple-access interference (MAI), therefore, we assume all the own-cell users use the same scrambling code. Interference from other cells (intercell interference) is modeled as AWGN. Our work is different than previous work [10]–[15] in the sense that it is done for a multirate system and no prior knowledge of the users' spreading codes or spreading factors are needed at the mobile unit. Link-level simulation for the W-CDMA system in a frequency-selective fading channel (IMT-2000 vehicular channel model [1]) is used to test the proposed receivers.

This paper is organized as follows. In Section II, the downlink W-CDMA signals properties are discussed. The signal model for both fixed and variable processing gain is presented

Manuscript received July 11, 2000; revised October 18, 2000, July 12, 2001; accepted August 1, 2001. The editor coordinating the review of this paper and approving it for publication is R. Yates.

M. F. Madkour is with the Mobility Network Consulting, Ericsson Inc, Plano, TX 75024 USA.

S. C. Gupta is with the Electrical Engineering Department, Southern Methodist University, Dallas, TX 75275-0338 USA.

Y.-P. E. Wang is with the Ericsson Inc, Research Triangle Park, NC 27709 USA.

Publisher Item Identifier S 1536-1276(02)00188-5.

in Section III. The new proposed cancellation techniques are presented in Section IV. In Section V, we discuss how to reduce the complexity of the proposed techniques. The simulation results are presented in Section VI. Finally, Section VII concludes the paper.

II. Downlink W-CDMA Signal Properties

The downlink signals for different physical channels within a cell are transmitted synchronously by the base station [1], [2]. Typically, orthogonal spreading codes are assigned to distinct physical channels, thereby creating mutually orthogonal downlink signals. If the channel does not have delay spread, the orthogonality can be maintained at the despreader output of the receiver, thereby removing all multiple-access interference from the same cell. However, for dispersive channels, orthogonality can no longer be maintained at the receiver, giving rise to intracell multiuser interference, which will result in performance degradation. Such performance degradation could be severe if the near-far problem occurs. For the uplink, power control is used to alleviate the near-far problem. However, power control cannot alleviate the near-far problem for the downlink. Thus, in a highly dispersive channel, the system could suffer significant capacity loss as a result of loss of orthogonality between downlink signals. Also, it is well known that a signal of wider bandwidth can resolve more multipath [3]. As W-CDMA has 4 times as much bandwidth as IS-95, the channel experienced by the W-CDMA signal exhibits higher dispersion. As a result, the degradation due to intracell interference will be much more than IS-95 [3]. Moreover, W-CDMA utilizes variable spreading factors (SF) to provide various transmission data rates. The spreading factor varies from $4, 8, 16, \ldots$, to 512. Typically for voice channels, spreading factor 128 is used; and for very high-speed data services, a spreading factor as low as 4 can be used. The rate difference between the aforementioned two cases is a factor of 32. Normally, the same link quality (e.g., $E_{\rm b}/N_{\rm o}$ where $E_{\rm b}$ is the energy per information data bit) has to be maintained for both cases. This implies the signal with a low spreading factor has to be transmitted with much larger power than the one with a high spreading factor [6]. This scenario further deteriorates the performance when the orthogonality between the downlink signals is lost.

III. Signal Model

A. Fixed Spreading Factor (FSF)

Let $s_k(t)$ be the signal for the kth user after spreading, but before scrambling.

$$s_k(t) = \sum_{i=-\infty}^{\infty} b_k(i) c_k(t - iNT_c) \tag{1}$$

where $b_k(i)$ is the ith data symbol for the kth user; $c_k(t)$ is the spreading waveform of the kth user; N is the spreading factor; and T_c is the chip duration. The spreading waveform is given by

$$c_k(t) = \sum_{j=0}^{N-1} m_k(j) \Pi_{T_c}(t - jT_c) \tag{2}$$

where Π_{T_c} is a rectangular pulse of duration T_c; and $m_k(j)$ is the jth chip of the spreading code of user k. Since the spreading codes are mutually orthogonal, then

$$\int_{-\infty}^{\infty} c_k(t) c_l^*(t) dt = 0, \quad k \neq l. \tag{3}$$

The base station combines all the signals and scrambles it by a base station specific scrambling code $a(t)$, which is given by

$$a(t) = \sum_{j=-\infty}^{\infty} a_j \Pi_{T_c}(t - jT_c). \tag{4}$$

The combined and scrambled signal is given by

$$x(t) = a(t) \sum_{k=1}^{K} \sqrt{P_k} s_k(t) \tag{5}$$

where K is the total number of users; and P_k is the transmitted power for the kth user signal. Assume that the physical channel (same for all users) is given by the complex low pass equivalent impulse response

$$h_c(t) = \sum_{l=1}^{L} \alpha_l \delta(t - \tau_l) \tag{6}$$

where L is the number of paths; α_1 and τ_l are the lth complex path gain and delay, respectively. We assume that the channel has fixed number of paths and introduces an Additive White Gaussian Noise (AWGN). Assume that the path gain and the delay are fixed, and that the channel is stationary over the longest symbol period. The envelope of each complex path amplitude has a Rayleigh distribution and each path phase $(\angle\alpha_l)$ has a uniform distribution over the interval $[0, 2\pi)$. α_l and τ_l are assumed to be known at the mobile unit by channel estimation (a perfect channel estimation will be assumed throughout this paper). The received signal can then be given by

$$r(t) = \sum_{l=1}^{L} \alpha_l x(t - \tau_l) + n(t) \tag{7}$$

where $n(t)$ is the Gaussian noise component which includes both thermal and intercell interference noise. A typical CDMA receiver for this case consists of L fingers for despreading. Despread values are weighted and combined to form a decision statistic. Without loss of generality, let's assume the demodulation of $b_1(0)$ (bit number zero of the 1st user signal). The lth finger output $(l = 1, \ldots, L)$ is $z_1^{(l)}$ where

$$\begin{aligned} z_1^{(l)} &= \int_{\tau_l}^{\tau_l + NT_c} r(t) a^*(t - \tau_l) c_1^*(t - \tau_l) dt \\ &= d_1^{(l)} + f_1^{(l)} + i_1^{(l)} + \eta_1^{(l)} \end{aligned} \tag{8}$$

where $d_1^{(l)}$ represents the lth finger correlator's output of the 1st user's desired signal; $f_1^{(l)}$ the output of its intersymbol interference (ISI) terms; $i_1^{(l)}$ the output of the multiuser interference terms; and $\eta_1^{(l)}$ the output of the noise signal (all corresponding

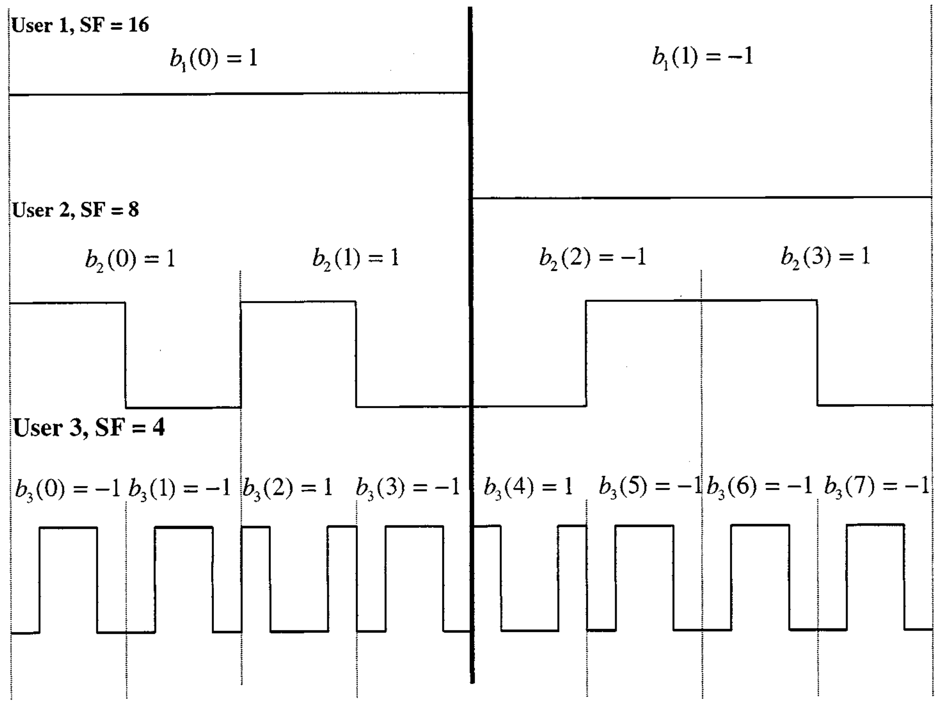

Fig. 1. An example of the various spreading factor case.

to the 0th transmitted bit). $d_1^{(l)}$; $f_1^{(l)}$; $i_1^{(l)}$; and $\eta_1^{(l)}$ can be shown to be

$$
\begin{aligned}
d_1^{(l)} =& \alpha_l \sqrt{P_1} b_1(0); \qquad (9)\\
f_1^{(l)} =& \sqrt{P_1} b_1(0) \int_{\tau_l}^{\tau_l + NT_c} \left(\sum_{\substack{p=1\\p\neq l}}^{L} \alpha_p a(t-\tau_p) c_1(t-\tau_p) \right)\\
& \times a^*(t-\tau_l) c_1^*(t-\tau_l) dt; \qquad (10)\\
i_1^{(l)} =& \int_{\tau_l}^{\tau_l + NT_c} \left(\sum_{\substack{p=1\\p\neq l}}^{L} \alpha_p a(t-\tau_p) \right.\\
& \left. \times \left(\sum_{k=2}^{K} \sqrt{P_k} b_k(0) c_k(t-\tau_p) \right) \right)\\
& \times a^*(t-\tau_l) c_1^*(t-\tau_l) dt; \text{ and} \qquad (11)\\
\eta_1^{(l)} =& \int_{\tau_l}^{\tau_l + NT_c} n(t) a^*(t-\tau_l) c_1^*(t-\tau_l) dt, \text{ respectively.} \qquad (12)
\end{aligned}
$$

Assuming $NT_c \gg \tau_L$, the ISI term, $f_1^{(l)}$, can be neglected. Neglecting the ISI is good for large spreading factors (low data rate voice users) but it might not be so good for low spreading factors (high data rate users). But as the main intracell interference in 3G will be from the data users with low spreading factor on the voice users with high spreading factors, we will focus on the performance of voice users in this paper.

B. Variable Spreading Factor (VSF)

In W-CDMA, various spreading factors are used to provide various symbol rates. In this case, Orthogonal Variable Spreading Factor (OVSF) codes are used [2]. With the OVSF codes, orthogonality between codes of same or different spreading factors is guaranteed. In order to perform interference cancellation in a multirate CDMA system in a similar manner as in a single rate system, the concept of *effective spreading code* (ESC) is introduced. The ESC for any interfering user depends on the SF, actual spreading code, and the information data symbols of that user and has the same duration as the spreading code of the desired user. Therefore, the ESC used by the interfering users belong to the Walsh set and vary from symbol to symbol depending on the information data symbols. Fig. 1 is an example illustrating the case that three users are using different spreading factors. The spreading factors for users 1, 2, and 3 are 16, 8, and 4, respectively. It can be shown that these signals are mutually orthogonal no matter which spreading factor (16, 8, or 4) is used for despreading. Assume user 1's signal is the desired signal. From Fig. 1, to the symbol $b_1(0)$, it appears that user 2 uses spreading code (1 1 1 1 −1 −1 −1 −1 1 1 1 1 −1 −1 −1 −1) which is a concatenation of two spreading code actually used by user 2. Similarly, to the symbol $b_1(1)$, it appears that user 2 uses spreading code (1 1 1 1 −1 −1 −1 −1 −1 −1 −1 −1 1 1 1 1), with a data symbol of −1. Thus, the spreading codes used by the interfering users (users 2 and 3) seem to be varying from symbol to symbol, depending on the data symbols of the interfering users. The mathematical illustration of that can be developed as follows. Let N, $N/2$, $N/4$ be the spreading factors for users #1, 2, and 3, respectively. The spread data signal of these users can be written as

$$s_1(t) = \sum_i b_1(i) c_1(t - iNT_c); \qquad (13)$$

$$s_2(t) = \sum_i b_2(i) c_2 \left(t - \frac{iNT_c}{2} \right); \text{ and} \qquad (14)$$

$$s_3(t) = \sum_i b_3(i) c_3 \left(t - \frac{iNT_c}{4} \right). \qquad (15)$$

The signal of user #2 can be rewritten as

$$s_2(t) = \sum_i \hat{b}_2(i)\hat{c}_{2,i}(t - iNT_c) \tag{16}$$

where $\hat{b}_2(i) = b_2(2i)$ and $\hat{c}_{2,i}(t)$, the effective spreading waveform of user #2 for the ith symbol of user #1, is

$$\hat{c}_{2,i}(t) = c_2(t) + b_2(2i)^* b_2(2i+1) c_2\left(t - \frac{NT_c}{2}\right). \tag{17}$$

Similarly, the signal of user #3 can be re-written as

$$s_3(t) = \sum_i \hat{b}_3(i)\hat{c}_{3,i}(t - iNT_c) \tag{18}$$

where $\hat{b}_3(i) = b_3(4i)$ and $\hat{c}_{3,i}(t)$, the effective spreading waveform of user #3 for the ith symbol of user 1, is

$$\begin{aligned}\hat{c}_{3,i}(t) =& c_3(t) + b_3(4i)^* b_3(4i+1) c_3\left(t - \frac{NT_c}{4}\right)\\ &+ b_3(4i)^* b_3(4i+2) c_3\left(t - \frac{NT_c}{2}\right)\\ &+ b_3(4i)^* b_3(4i+3) c_3\left(t - \frac{3NT_c}{4}\right).\end{aligned} \tag{19}$$

Using this concept, the intracell multiuser interference of VSF case can be shown to be

$$\begin{aligned} i_1^{(l)} = \int_{\tau_l}^{\tau_l + NT_c} & \left(\sum_{\substack{p=1\\ p\neq l}}^{L} \alpha_p a(t-\tau_p) \right.\\ & \left. \times \left(\sum_{k=2}^{K} \sqrt{P_k}\hat{b}_k(0)\hat{c}_{k,0}(t-\tau_p) \right) \right)\\ & \times a^*(t-\tau_l) c_1^*(t-\tau_l) dt \end{aligned} \tag{20}$$

where $\hat{c}_{k,i}(t)$ and $\hat{b}_k(i)$ are the kth user ith symbol effective spreading code and effective data symbol, respectively.

IV. Successive IIC Mobile Receivers

From (20), it is obvious that if the ESC; the effective data symbols and the power levels were known, the intracell multiuser interference would have been calculated and canceled out from $z_1^{(l)}$ on finger basis. Here, instead of using a conventional used correlator at each finger (correlates against the desired user's code), we consider a receiver uses a fast Walsh transform (FWT) to correlate against all N orthogonal codes. This corresponds to an $N\log_2(N)$-fold increase in complexity. After getting FWT at each finger, these values are combined according to the maximum ratio combining (MRC) principle. If a spreading code $\hat{c}_j(t)$ is used by the base station, at the MRC one would see that the energy of this code is higher than those not used. Thus, a code detector can compare the MRC outputs with a threshold. If the energy of a particular code is higher than the threshold, then that code is detected. Alternatively, the receiver can decide to detect only M codes with the highest energy. In either case, it is possible that there are codes present in the composite received signal not detected. This will result in a residual interference after cancellation. However, since the interference due to the codes with the highest energy is removed, the degradation caused by the residual interference is small. Finally, the modulation values can be also detected after the MRC. Based on that, we propose three different cancellation techniques. Two of them are based on combining the estimated interfering signals and then canceling their effects from the received baseband signal either by direct subtraction or by projecting the combined interfering signal onto the orthogonal direction to the received baseband signal. In our third technique, we propose not to combine the interfering users' signals. Instead, they are kept separate. Then, the received baseband signal is projected on the subspace orthogonal to the interfering signals' subspace on a symbol by symbol basis.

A. *Combined-Interfering Signals Receivers*

The proposed mobile unit receiver structure is shown in Fig. 2. The receiver estimates the effective spreading codes of the interfering users regardless of their spreading factors. The basic idea is decoding the strongest users and then canceling out their contributions from the received baseband signal and then using this modified received signal to have a better estimation of the effective spreading codes. Here, the strongest user is not known beforehand, but is detected from the strength of the output correlation values after the FWT processor. The receiver combines the N correlation values from the L fingers according to the maximum ratio combining principle. The desired user's correlation value is then fed into the decision circuit to be decoded. Here, we have the choice to stop or continuing cancellation according to a performance criterion (e.g., quality of service or CRC check). To continue cancellation, the other $(N-1)$ correlation values are passed on to a selector which determines the strongest correlation value (to save processing time, we can also choose to select the maximum M correlation values to cancel out M interfering signals at a time) and generates the Walsh code corresponding to the index of this value. The selected user's signal is then decoded, spread, scrambled and passed on to a regenerated version of the multipath channel, generating a baseband version of the interfering signal to be canceled out from the received baseband signal.

The cancellation process is done using two techniques; subtraction or projection. To illustrate these two techniques, let $r(t)$; $\widehat{I}(t)$; and $\tilde{r}(t)$ be the received baseband signal; the regenerated baseband interfering signal; and the modified received baseband signal, respectively. In the subtraction technique, the generated baseband interfering signal is directly subtracted from the received signal ($\tilde{r}(t) = r(t) - \widehat{I}(t)$). In the projection technique, we project the received baseband signal on to the orthogonal direction to the generated baseband interfering signal ($\tilde{r}(t) = r(t) - \left\langle r(t), \widehat{I}(t)\right\rangle \widehat{I}(t)$ where $\langle x, y\rangle$ denotes the inner product of x and y). Projection technique is a little bit more complex than the subtraction technique, however. The interference cancelled in the projection method requires unit energy constraint. It is to be noted that the proposed receiver cancels out the intracell multiuser interference using the combining correlation values after the MRC and not on a finger by finger

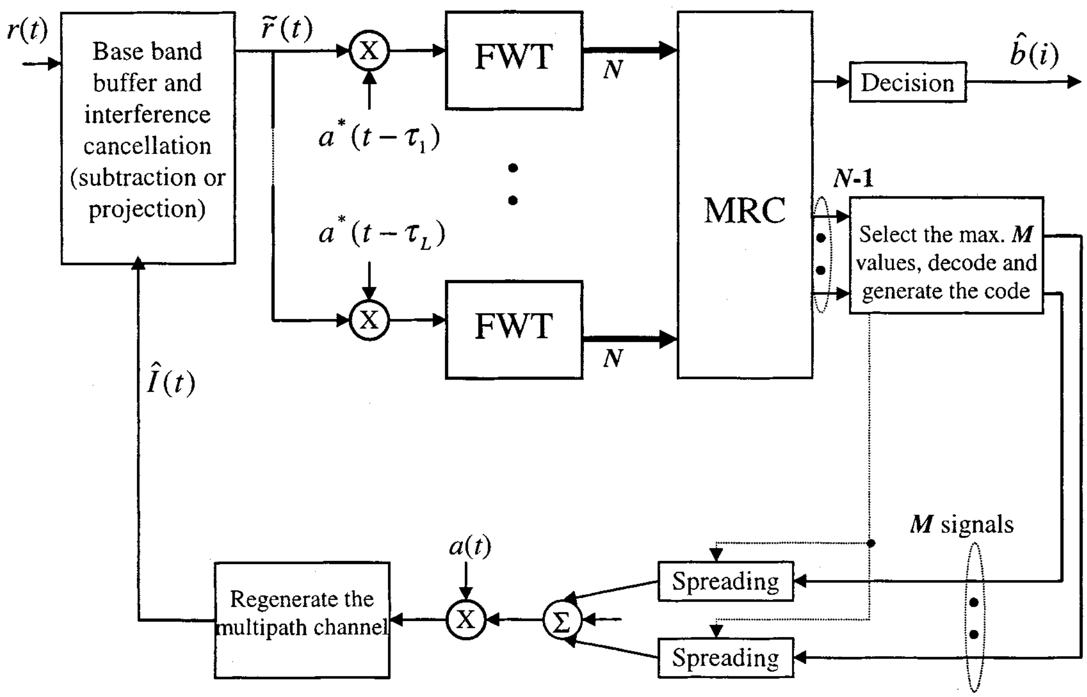

Fig. 2. The proposed downlink W-CDMA combined-interfering signals receiver.

basis as most of the interference cancellation schemes [11]. The process of estimating the ESC and its correlation value and regenerating an estimate of the interfering user signal has to be done on a symbol-by symbol basis, but when it comes to the cancellation process (the projection process), we can do it on a frame-by-frame basis, giving up some performance but reducing the processing power. What we do is that we save the regenerated interfering user symbols in a buffer until we have a whole frame and then projecting the received signal vector on it at one shot (making the system implementable even for very high data rates).

B. Subspace-Projection Receiver

In this receiver, we propose not to combine the interfering users' signals. Instead, they are kept separate. Then, the received signal is projected on the subspace orthogonal to the interfering signals' subspace on a symbol by symbol basis. The proposed mobile unit receiver structure is shown in Fig. 3. The receiver estimates the effective spreading codes of the interfering users regardless of their spreading factors using the same procedures as those in the previous combined-interfering signals receiver. The difference between the subspace approach and our previous techniques is that the selected users' signals (intracell interfering users) are kept separate from each other and passed individually on to a regenerated version of the multipath channel, generating an arbitrary number (subspace dimension) of baseband interfering signals. Now a subspace that spans these interfering signals is generated and the received signal is projected on to a subspace orthogonal to that space. The geometric representation of the subspace projection technique at the ith iteration is shown in Fig. 4. The modified received baseband signal is again passed on to the code detector to have a better estimate of the interfering users' effective spreading codes. These procedures are repeated until a satisfactory estimate has been reached. It is to be noted that although the code detection procedures have to be done on a symbol-by-symbol basis because of the VSF, the subspace projection procedures could be done on both symbol-by-symbol and frame-by-frame basis. However, as will be seen from the simulation results, symbol-by-symbol subspace projection gives better results at the expense of the increased computational complexity.

In order to further understand this subspace cancellation approach, a mathematical explanation of cancellation of the M strongest interferers using the Gramm-Schmidt technique [19] will now be provided. We will drop the symbol index, n, for ease notation. Let the M estimated interferers vectors at the ith iteration be $\mathbf{I}_1(i)$ through $\mathbf{I}_M(i)$. In order to find the subspace that spans the M interferers vectors at the ith iteration, the Gram-Schmidt procedures [19], operating on the ordered (descending order according to the correlation values) vector set $\{\mathbf{I}_m(i); m = 1, \dots, M\}$, is carried out. The Gram-Schmidt procedure is performed as follows.

$$\mathbf{g}_1(i) = \frac{\mathbf{I}_1(i)}{\sqrt{\mathbf{I}_1^H(i)\mathbf{I}_1(i)}} \tag{21}$$

$$\mathbf{v}_k(i) = \mathbf{I}_k(i) - \sum_{m=1}^{k-1} \left(\mathbf{g}_m^H(i)\mathbf{I}_k(i)\right) \mathbf{g}_m(i) \tag{22}$$

$$\mathbf{g}_k(i) = \frac{\mathbf{v}_k(i)}{\sqrt{\mathbf{v}_k^H(i)\mathbf{v}_k(i)}}, \quad k = 2, \dots, M \tag{23}$$

$$\mathbf{G}_M(i) = [\mathbf{g}_1(i) \quad \cdots \quad \mathbf{g}_M(i)] \tag{24}$$

where $\mathbf{g}_1(i), \dots, \mathbf{g}_M(i)$ denote unit vectors that span a subspace $S_M(i)$ defined by interferers $\mathbf{I}_1(i)$ through $\mathbf{I}_M(i)$. Projecting a vector onto the space orthogonal to $S_M(i)$ is achieved

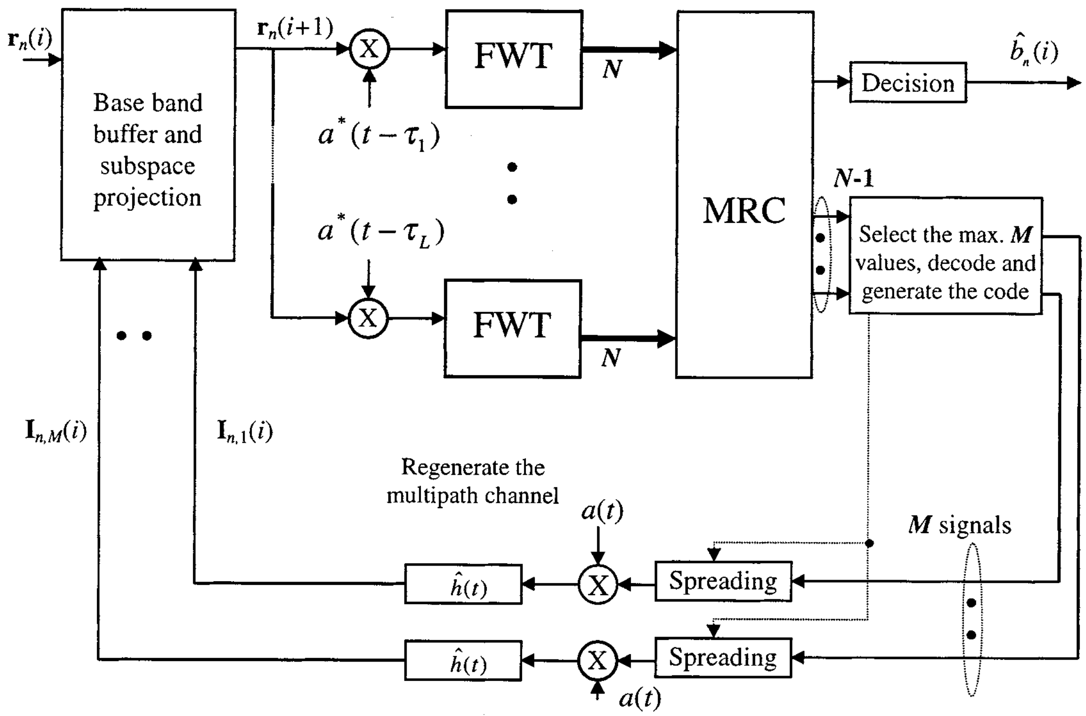

Fig. 3. The proposed downlink W-CDMA separate-interfering signals receiver (subspace approach).

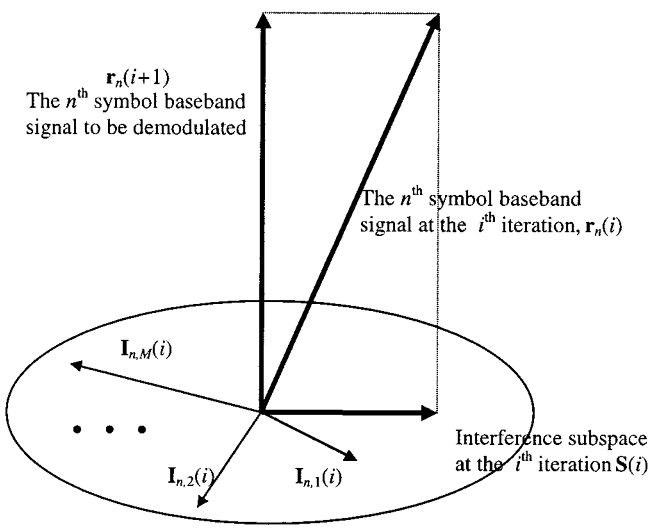

Fig. 4. Geometric representation of the subspace projection scheme at the ith iteration.

by left multiplication using the following projection matrix [18] (the iteration index, i, will be dropped for notational simplicity).

$$\mathbf{P}_{\mathbf{G}_M}^{\perp} = \mathbf{I}_{N\times N} - \mathbf{G}_M \left(\mathbf{G}_M^H \mathbf{G}_M\right)^{-1} \mathbf{G}_M^H \tag{25}$$

$$\mathbf{r}(i) = \mathbf{P}_{G_M}^{\perp}(i-1)\mathbf{r}(i-1) \tag{26}$$

where the initial value, $\mathbf{r}(0)$, is the received baseband signal vector r. Since the columns of $\mathbf{G}_M(i)$ are orthonormal vectors, (25) simplifies to

$$\mathbf{P}_{\mathbf{G}_M}^{\perp} = \mathbf{I}_{N\times N} - \sum_{m=1}^{M} \mathbf{g}_m^H \mathbf{g}_m. \tag{27}$$

Using (26), (27) can be rewritten as

$$\mathbf{r}(i) = \mathbf{r}(i-1) - \sum_{m=1}^{M} \mathbf{g}_m(i-1)\mathbf{g}_m^H(i-1)\mathbf{r}(i-1). \tag{28}$$

For Q iterations, the modified received signal vector, $\tilde{\mathbf{r}}$, is

$$\tilde{\mathbf{r}} = \prod_{q=1}^{Q} \left(\mathbf{I}_{N\times N} - \sum_{m=1}^{M} \mathbf{g}_m(q)\mathbf{g}_m^H(q)\right)\mathbf{r}. \tag{29}$$

V. Reduced-Complexity Mobile Receiver

Here, we are dealing with the fixed data rate IS-95 system. Our proposed receivers in Sections I–IV were dealing with the multirate W-CDMA system, therefore, we need to do the ESC estimation per symbol because the user might change its data rate. In IS-95, we do not have to do that. We just do the ESC (which is the physical code in this case) estimation one time (during the first symbol) and then use it in the cancellation process for the coming symbols. Thus, the receiver structure shown in Fig. 2 might not be economical as far as the power consumption is concerned. In order to reduce the computational complexity, FWT is only used for detecting the codes. Since the codes change at very slow rate, the code detection block can be activated at much slower rate than the symbol rate. Once the codes are detected, the data symbols of interfering users can be detected by a conventional correlator bank.

VI. Simulation Results

We have K users simultaneously transmit their information data signals with different bit rates. Each user is assigned a Walsh code with different SF. Note that the same E_b/N_o is used

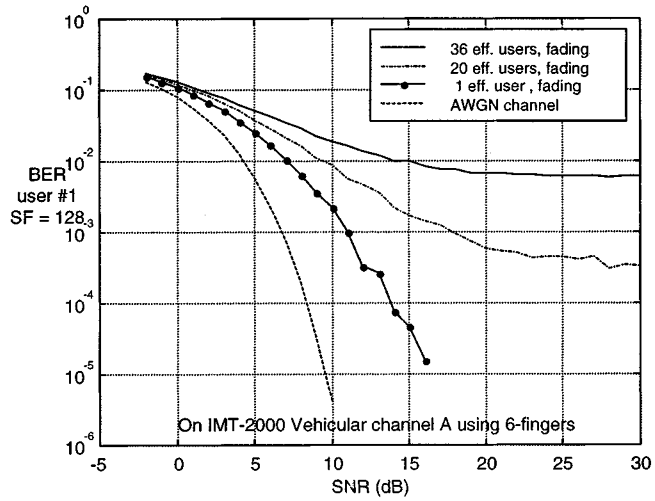

Fig. 5. Effect of intracell multiuser interference on the W-CDMA downlink.

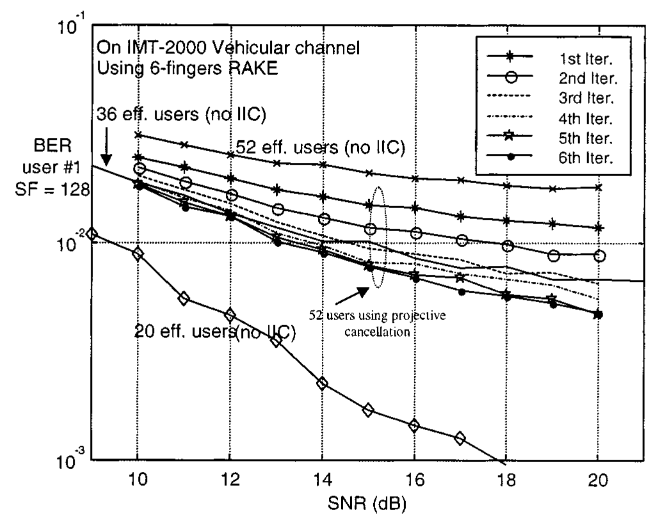

Fig. 6. Capacity enhancements using the projective cancellation scheme.

for all physical users (mobile terminals) regardless of their data rates. That makes the high data rate users have higher average power than the low data rate users do. For example, the average power of a user with data rate MR is M times that of the single rate user, therefore, an M-rate user can be considered as M single rate users (M effective users). The simulation was performed on the IMT-2000 vehicular channel A model, which has six multipaths of delays 0, 0.31, 0.71, 1.09, 1.73 and 2.51 μs and power $0, -1, -9, -10, -15$, and -20 dB, respectively. QPSK modulation is used for data with spreading factors ranging from 128 (voice) to 8 (data). The frame length is 10 msec. The RAKE receiver has six fingers. Finally, a complex gold code of length $2^{17}-1$ truncated to 40 960 chips was used as a cell scrambling code.

In Fig. 5, we demonstrate the effect of the intracell multiuser interference on the performance of the downlink W-CDMA signal. Different number of users with different spreading factors are used. We plot the average bit error rate (BER) of the single rate user $(\mathrm{SF} = 128)$ as a function of the signal-to-Gaussian-noise ratio (we model the intercell multiuser interference as a Gaussian noise). Both AWGN and

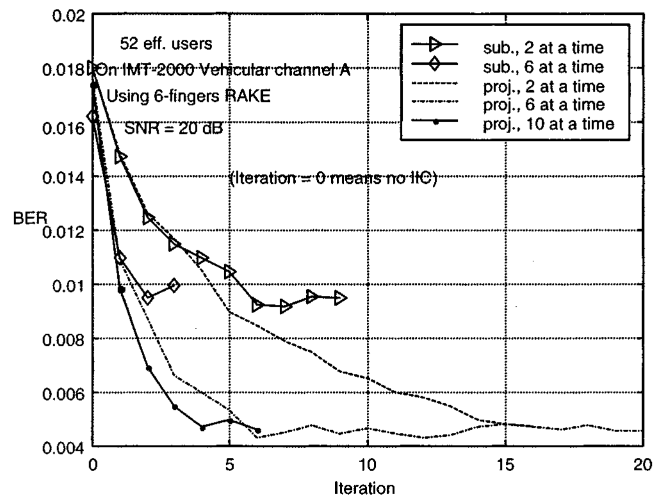

Fig. 7. Performance evaluation of different combined-interfering signals receivers.

multipath fading channels are considered. From the plots, it is clear that as the number of active users increases, the BER increases. For example, adding a physical user of $\mathrm{SF} = 8$ (16 effective users) results in a 5-dB SNR loss at 1% BER. The simulation example in Fig. 6 uses the projection technique to cancel out the intracell multiuser interference. There are seven users with spreading factors of 128, 128, 64, 16, 16, 8, and 8 (52 effective users). We cancel out the maximum six correlation values at a time. We simulate up to 6 iterations. In order to demonstrate the capacity increase as a result of IIC, the performance of a 36 effective users-system without IIC has been computed. From the plots, it is clear that using an IIC scheme in a system of 52 effective users gives a better performance than a system of 36 effective users. It is about 50% system capacity increase. In Fig. 7, the BER has been plotted as a function of the number of iterations for all the combined-interfering signals schemes using the same system loading as that in the previous example (52 effective users) at $\mathrm{SNR} = 20$ dB. It is seen that the projection technique outperforms the subtraction technique when canceling the same number of interferers at each iteration. When canceling six interferers at a time using subtraction technique, the problem of over cancellation starts to occur after the 2nd iteration (the 3rd iteration is worse than the second iteration). Therefore, when using subtraction, it is better to cancel 1 or 2 correlation values at a time so that we will not have over cancellation. For the projection technique, we have the choice either to reduce the number of iterations (feedbacks) and increase the number of the correlation values canceled at a time (save the symbol processing time) or vice versa (it is almost a linear relationship). Also it is clear that the projection technique has a steady state error floor (irreducible error), however, there is no over cancellation.

Plots in Fig. 8 compare the subspace projection to the combined-interfering signals projection technique. We plot the average BER of the single rate user $(\mathrm{SF} = 128)$ as a function of the signal to Gaussian noise ratio for five different cases using the same system loading as in the previous example (52 effective users). The solid curve is for the noncancellation case (regular RAKE receiver). The bottom curve is the single user per-

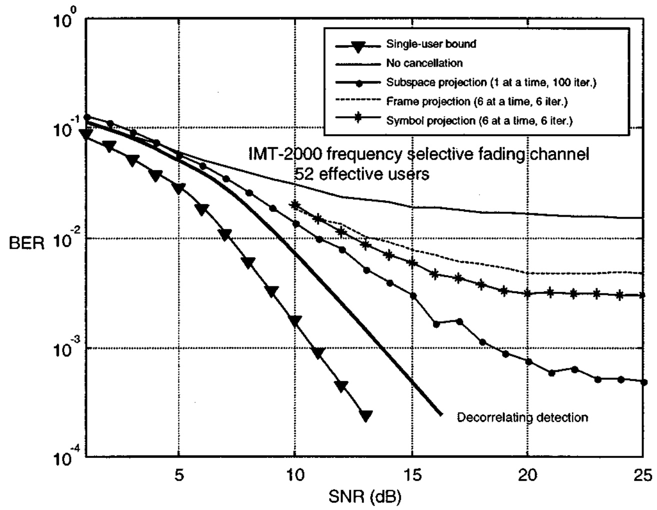

Fig. 8. BER versus the SNR for subspace; symbol; and frame projection interference cancellation schemes.

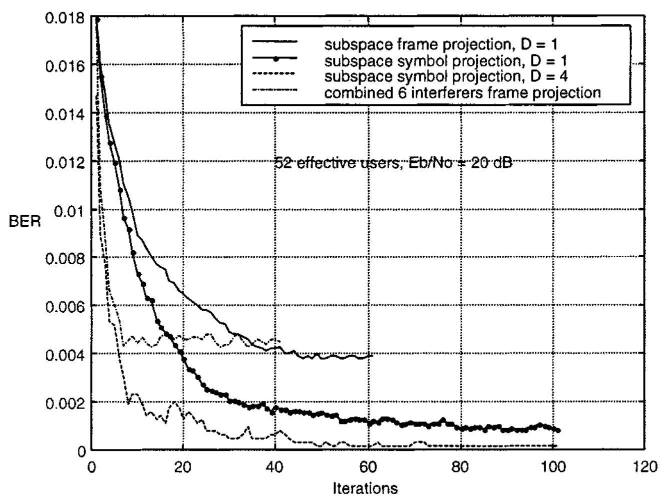

Fig. 9. Performance comparison between the subspace cancellation and other proposed cancellation schemes.

formance curve (for comparison issue). The dashed curve and the curve with a star are for the combined-interfering signals projection technique (6 iterations, cancellation of 6 interferers at a time) using frame and symbol projection, respectively. The dash-dotted curve is for the subspace projection. It can be seen that the subspace projection technique outperforms other cancellation techniques, however it is more complex. With SNR of 18 dB, the subspace cancellation for 52 effective users gives 0.1% BER which is the same as that for 20 effective users with no cancellation which means about 150% capacity increase. Also, in this figure, the performance curve of the centralized decorrelating detector has been shown for a number of 52 effective users. To get this performance curve, we followed the methodology in [8]. It is clear that the decorrelating detector outperforms our proposed receivers which is expected because it has the knowledge of users' SF as well as the spreading codes. The BER as a function of the number of iterations for the different proposed cancellation techniques is plotted in Fig. 9. It is seen from the plots that the subspace approach outperforms the other cancellation techniques, however, it needs more iterations (feedbacks) to have a good performance. When the subspace dimension is increased from $D = 1$ to $D = 4$, a tremendous improvement in the performance happens, e.g., a BER of 0.2% is achieved after 7 iterations (compare to 35 iterations when $D = 1$).

Unlike the uplink, the near-far problem in the downlink can not be alleviated by using power control. This is simply because the base station needs to reach users at the cell border using a stronger power than that required for users close to the base station. It is to be noted that the curve we have for 20 effective users can be viewed as a representative case at cell border because the desired user gets one twentieth of total transmitted power. We showed significant gains achieved by using interference cancellation for this case. Also, the curve for 52 effective users can be viewed as a representative case at cell center because the desired user gets only 1/52 of total transmitted power. For this case, the proposed techniques are also shown to be very effective in improving performance.

VII. Conclusion

We proposed new blind intracell interference cancellation techniques suitable for the downlink of any CDMA system with fixed or variable spreading factor. No extra information is required from the base station. A capacity increase of up to 150% of the original (without IIC) system capacity has been achieved. Even though the problem was addressed for the W-CDMA, it is also applicable to IS-95 or IS-2000.

Acknowledgment

The authors are thankful to the anonymous reviewers for their helpful comments and suggestions.

References

[1] T. Ojanpera and R. Prasad, *Wideband CDMA for Third Generation Mobile Communications*. Boston, MA: Artech House, 1998.

[2] *Specifications of Air-Interface for 3G Mobile System Version 1.0*, Association of Radio Industries and Business (ARIB), 1999.

[3] J. Proakis, *Digital Communications*, 3rd ed. New York: McGraw-Hill, Inc, 1995.

[4] T. Ottoson and A. Svensson, "Multi-rate schemes in DS/CDMA systems," in *Proc. IEEE VTC'95*, Chicago, IL, July 26–28, 1995, pp. 1006–1010.

[5] A. Klein, "Data detection algorithms specially designed for the downlink of CDMA mobile radio systems," in *Proc. IEEE VTC'97*, Phoenix, AZ, May 1997, pp. 203–207.

[6] A. Hottinen, H. Holma, and A. Toskala, "Multi-user detection for multi-rate CDMA communications," in *Proc. IEEE Int. Conf. Commun.*, Dallas, TX, June 24–28, 1996.

[7] M. J. Juntti, "System concept comparisons for multi-rate CDMA with multi-user detection," in *Proc. IEEE VTC'98*, Ottawa, Canada, May 1998, pp. 36–40.

[8] M. F. Madkour and S. C. Gupta, "Performance analysis of a wireless multirate direct-sequence CDMA using fast Walsh transform and decorrelating detection," *IEEE Trans. Commun.*, vol. 48, pp. 1405–1412, Aug. 2000.

[9] A. Johansson and A. Svensson, "Successive interference cancellation in multiple data rate DS/CDMA systems," in *Proc. IEEE VTC'95*, Chicago, IL, July 26–28, 1995.

[10] P. Teder, G. Larsson, B. Gudmundson, and M. Ewerbring, "CDMA with interference cancellation: A technique for high capacity wireless systems," in *Proc. IEEE Int. Conf. Commun.*, Geneva, Switzerland, 1993.

[11] P. Patel and J. Holtzman, "Analysis of a simple successive interference cancellation scheme in DS/CDMA system," *IEEE J. Select. Areas Commun.*, vol. 12, pp. 796–807, June 1994.

[12] X. Wang and H. V. Poor, "Blind multi-user detection: A subspace approach," *IEEE Trans. Inform. Theory*, vol. 44, pp. 677–690, Mar. 1998.

[13] M. Golanbari and G. E. Ford, "Signal monitoring on the downlink of cellular CDMA communications with interference cancellation," in *Proc. IEEE Wireless Communications and Networking Conf., WCNC'99*, New Orleans, LA, Sept. 21–25, 1999.

[14] K. Hooli, M. Latva-aho, and M. Juntti, "Multiple access interference suppression with linear chip equalizers in WCDMA downlink receivers," in *Proc. IEEE Global Telecommunications Conf. 1999, GLOBCOM'99*, vol. 1A, pp. 467–471.

[15] R. Kohno, H. Imai, M. Hatori, and S. Pasupathy, "Combination of an adaptive array antenna and a canceller of interference for direct-sequence spread-spectrum multiple access system," *IEEE J. Select. Areas Commun.*, vol. 8, pp. 675–681, May 1990.

[16] M. F. Madkour, S. C. Gupta, and Y.-P. E. Wang, "A novel downlink blind interference cancellation in a W-CDMA mobile communications system," in *Proc. IEEE Wireless Communications and Networking Conf., WCNC'99*, New Orleans, LA, Sept. 21–25, 1999.

[17] ——, "A novel downlink W-CDMA blind interference cancellation using the subspace approach," in *Proc. 33rd Asilomar Conf.*, Pacific Grove, CA, Oct. 24–27, 1999.

[18] G. E. Bottomley, "Improved successive cancellation of DS-CDMA signals using signal orthogonalization," in *Proc. IEEE Int. Conf. Universal Personal Communications, ICUPC'96*, Cambridge, MA, Sept.–Oct. 29–2, 1996, pp. 141–144.

[19] W. L. Brogan, *Modern Control Theory*. Englewood Cliffs, NJ: Prentice-Hall, 1982.

Mohamed F. Madkour (S'98-M'00) was born in Alexandria, Egypt, on May 25, 1968. He received the B.Sc. (with honors) and M.Sc. degrees in electrical engineering from Alexandria University, Alexandria, Egypt, in 1991 and 1994, respectively, and the Ph.D. degree in electrical engineering from Southern Methodist University (SMU), Dallas, TX, in 2001.

He joined the Department of Electrical Engineering, Alexandria University, in 1991, as a Teaching Assistant and Lab Instructor. From 1996 to 1999, he was a Research Assistant at the Department of Electrical Engineering, SMU. He has been a member of the Mobility Network Consulting Goup, Ericsson Inc., Plano, TX, since 1999. His current research interests include mobile, spread-spectrum communications and third generation wireless.

Dr. Madkour received the SMU Outstanding Graduate Student Award in 1999. He also received the Best Graduate Paper Award from the IEEE Communications and Vehicular Technology Societies, Dallas Chapter in 1999.

Someshwar C. Gupta (S'61-M'63–SM'65-F'99) received the B.S. (with honors) and M.S. degrees in mathematics from Punjab University, India, the B.S. (with honors) degree in electrical engineering from Glasgow University, U.K., and the M.S.E.E. and Ph.D. degrees from the University of California, Berkeley.

He taught at Carnegie Mellon University and Arizona State University prior to joining Southern Methodist University, Dallas, TX, in 1967. Presently, he is the Cecil H. Green Professor of Engineering. He has considerable teaching, research supervision, academic administration, and industrial experience. He has been very active in the areas of cellular and personal communications for the last 18 years. He is the author or co-author of three widely used textbooks and a over 100 technical papers. Almost all his research has been supported by federal agencies such as NSF, NASA, USAF, DCA, AFOSR, and industrial companies such as GE, Ericsson, Nortel, LCCI, and Raytheon. He has supervised over 60 Ph.D. dissertations.

Yi-Pin Eric Wang received the B.S. degree in electrical engineering from National Taiwan University in 1988, and the M.S. and Ph.D. degrees, both in electrical engineering, from the University of Michigan, Ann Arbor, in 1991 and 1995, respectively.

He has been a member of the Advanced Development and Research group of Ericsson Inc., Research Triangle Park, NC, since 1995. His work focuses on wireless communications, including mobile satellite communication systems and terrestrial cellular systems. His research interests include coding, modulation, synchronization, and interference cancellation in CDMA systems.