Cooperative Signal Reception and Down-Link Beam Forming in Cellular Mobile Communications

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***Abstract*—A cooperative signal reception and down-link beam-forming algorithm is proposed for mobile communication systems employing phase-shift-keying (PSK) modulation. Down-link beam optimality is defined as maximizing the desired reference user's *average* received power while keeping the noise power *plus* total amount of *average* powers received by other users less than or equal to a certain constant level. The proposed algorithm requires neither the detection of other user's signals nor knowledge about the direction-of-arrivals (DOA)'s of the incident path components.**

Results of a series of exhaustive simulations are presented to demonstrate the overall performance of the proposed algorithm. For a hexagonal cell layout, the distribution of signal-to-interference power ratio (SIR) in a reference (central) cell with the optimal down-link beam is evaluated and compared with that with a unit gain omnidirectional antenna through computer simulations for an eight-element circular array. The beam-forming performances are also evaluated under several sets of practical parameter values with regard to the fading correlation.

I. Introduction

MAKING efficient use of the spatial isolation of signals transmitted from different users has long been one of the key issues for the capacity enhancement of cellular communication systems. Various *static* techniques for spatial isolation such as sectorization and/or antenna tilting have been used in conjunction with the planning of frequency reuse patterns. However, since the *static* techniques rely on propagation predictions to find the worst case scenario, their potential for enhancing the spectrum efficiency is limited. Larger capacity improvements require more *dynamic* approaches that well utilize flexible traffic control and/or spatial isolation. The potential of dynamic channel assignment (DCA) [1] and adaptive antenna beam forming [2] have been noticed.

Besides capacity enhancement, the use of the adaptive beam-forming antennas has another impact on cellular system operation. With adaptive beam forming, careful propagation prediction, which conventional cell design relies on for spatial isolation, is no longer needed. The antenna beams are adaptively formed to *always* retain the optimality defined by the criteria for signal combining, given the propagation conditions of desired and interference users. This adaptation process takes place at each base station independently of other cells and so is autonomous. Even with beam imperfections due to some tradeoffs between performance and complexity, the autonomous behavior should relax the requirements placed on the frequency reuse pattern.

The conceptual basis of adaptive antenna beam forming is that it steers sensitivity nulls to interferers, thereby improving the signal-to-interference *plus* noise power ratio (SINR) on the desired signal component. References [3] and [4] evaluate the capacity enhancement achieved by a base-station array antenna with adaptive beam forming, and [5] analyzes the impact of base-station adaptive antennas on the capacity enhancement of a code-division multiple-access (CDMA) mobile communication system. References [6]–[8] propose, without counting on the null forming against interference, optimal signal combining, in which the antenna elements do not need to be located closely enough to achieve beam directivity.

Despite the volume of research dealing with signal reception possible with adaptive antennas for interference suppression, few have studied down-link signal transmission with adaptive beam forming. A major difficulty in down-link beam forming is that the transmitter requires knowledge about the complex vector channel which can only be estimated by receiving signals. While in the time-division duplex (TDD) system, the down-link channel state may be estimated from the up-link signals received by the base station, and the validity of this scheme is questionable for frequency-division duplex (FDD) systems. This is because the larger the frequency separation becomes, the more the down-link channel state differs from that of the up link.

References [9]–[11] propose the use of feedback of the channel states as seen by each mobile receiver to determine the optimum weights for FDD down-link beam forming. Reference [9] emphasized the effectiveness of the feedback of *instantaneous* channel vector estimates, to which a conceptual basis of [10] is equivalent in terms of the availability of the knowledge about the channel states. A major drawback of the *instantaneous* channel state feedback is that it requires high-feedback data rates to track the *instantaneous* channel vector. Reference [11] reduces the required data rate for feedback by effectively exploiting the subspace structure of the *instantaneous* channel vector. Although [11] still requires feedback, its main idea is that proper *averaging* can eliminate the effects of *instantaneous* channel variations; the subspaces in the sense of average, spanned by desired and interferer components, can be extracted. The subspace itself bears each user's direction-of-arrival (DOA) and *average* signal strength (ASS) information, which does not vary as quickly as the *instantaneous* channel variation due to fading.

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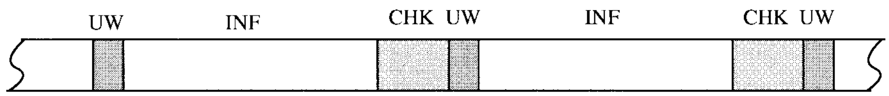

Fig. 1. Frame format.

An alternative to channel state feedback is to use the up-link signal's DOA and ASS information measured at the base station. This approach stands on the fact that bidirectional commonalty holds in DOA and ASS even if the up-link and down-link have different frequencies. The optimal weights for the down-link beam forming can be obtained based upon the DOA and ASS information measured at base receivers. However, performance with this straightforward approach may be severely damaged by errors in DOA and ASS measurements. In fact, [12] suggests that DOA detection of the up-link signals is rendered impractical in multipath-rich environments, although several algorithms [13], [14] are presently available.

Instead of directly measuring DOA's and ASS's at base stations, [15] makes effective use of the desired and interference signal subspaces extracted from the up-link signals. The impact of [15] is significant, even though it is a reasonable expansion of [11], since it eliminates the need for feedback. Despite the fruitful outcome of [15], because of the nature of the subspace schemes, the desired signal and interference *plus* noise subspaces need to be decomposed from the received composite space constructed from the snapshot vectors. Reference [16] proposes a blind algorithm for the subspace decomposition. Unfortunately, it is applicable only to the situation where the composite component, comprised of many interference signals and noise, can be regarded as a Gaussian process. This is not the case for many digital signaling schemes, for which maximum likelihood subspace estimation requires signal detection of multiple users (=desired and cochannel interference users) sharing the same frequency band simultaneously. This imposes impractical complexity upon the base receivers.

What should be emphasized at this stage is that the averaging process in subspace extraction offsets the definition of beam optimality. With the definition of the optimality in the *instantaneous* sense, the received *instantaneous* SINR is maximized, thereby, some diversity improvement is achieved if multiple propagation paths exist for the desired reference user [6]–[8]. On the contrary with the optimality definition in the *average* sense, no diversity improvement results. This imbalance is, however, a key motivation of this paper.

The main focus of this paper is adaptive down-link beam forming for phase-shift-keying (PSK) modulation based on subspace decomposition. A down-link beam-forming algorithm with reasonable complexity is proposed. *The desired signal subspace is extracted from the composite space in cooperation with the optimal beam forming for up-link signal reception*. Because of the diversity improvement inherent within optimal up-link signal reception, the desired user's up-link signal is more likely to be received with no error. With the assistance of error detection coding, only the snapshot vectors corresponding to the up-link signal detected error free are used for the subspace extraction for down-link beam forming.

This paper is organized as follows. Section II shows the system model used in this paper, describes mathematical expressions for the model, and formulates the problem of down-link beam forming from the viewpoint of subspace extraction. Section II then derives the optimal down-link beam to which the proposed algorithm should converge. Based upon the problem formulation, Section III derives a cooperative signal reception and down-link beam-forming algorithm. Section IV shows the results of computer simulations. For a hexagonal cell layout, the SIR distribution in a reference (central) cell with optimal down-link beam is first evaluated for an eight-element circular array to find the upper bound of performance. The SIR distribution is compared with that of the unit gain omnidirectional antenna. Several sets of practical parameter values are evaluated with regard to the fading correlation on the beam-forming performance.

II. System Model

A. Up Link

For up-link signal transmission, the symbol sequence to be transmitted is segmented into frames. Fig. 1 shows an example of the frame format. The information symbol sequence is encoded into an error-detection code whose parity check sequence is added to the tail of the information segment. The encoded symbol sequence is headed by a unique word sequence, resulting in an N-symbol frame. This process takes place in an asynchronous manner at each of the mobile transmitters. The train of N-symbol frames is transmitted successively to the base receiver.

The channel is assumed to be frequency nonselective. Signals transmitted from the users are received by an M-element antenna array for up-link signal reception. An equivalent complex baseband expression of the composite received signal vector $\mathbf{X}(t)$ at time t is given by

$$\mathbf{X}(t) = \sum_{j=1}^{L_D} \mathbf{a}(\theta_j) \cdot Z_{Df}^u(t) D^u(t) + \sum_{k=1}^{K} \sum_{l=1}^{L_{Ik}} \mathbf{a}(\varphi_{k,l}) \cdot Z_{Ik,l}^u(t) I_k^u(t) + \mathbf{Z}_g^u(t) \tag{1}$$

where it was assumed that there are one desired and K interference users, the desired user has L_D, and the kth interferer has L_{Ik} propagation paths. The desired user's jth path arrives at the array with an arrival angle θ_j and the kth interferer's lth path with $\varphi_{k,l}$. $\mathbf{a}(\theta)$ is the array response vector to the path arriving on angle θ, $Z_{Dj}^u(t)$ and $Z_{Ik,l}^u(t)$ are the up-link fading complex envelopes with, respectively, the jth path of the desired user and lth path of the kth interferer, and $D^u(t)$ and $I_k^u(t)$ are, respectively, the desired and kth interferer's up-link signal waveforms. $\mathbf{Z}_g^u(t)$ is the additive white Gaussian noise (AWGN) vector. Practicality is not lost by assuming each of $\mathbf{Z}_g^u(t)$'s M elements has equal power σ_g^{u2}.

The received signal vector $\mathbf{X}(t)$ is sampled every T s to construct the snapshot vector $\mathbf{x}(n) = \mathbf{X}(nT)$, where n is the sampling timing index. The sampling period T should not necessarily be equal to the symbol duration T_s, but in the proposed down-link algorithm, $T = T_s$ will be assumed. Up-link beam optimality is in the sense of *instantaneous* SINR maximization. The optimal weight vector for the up-link array is given as a Wiener–Hopf solution to a least square error problem related to the array output. The Wiener–Hopf solution may be obtained by applying a recursive adaptive algorithm, whose main advantage is its ability to adapt to the channel variation due to fading.

B. Down Link

The mobile user receives signals with a unit gain omnidirectional antenna. Because of the bidirectional commonalities in DOA and ASS,[1] with a weight vector $\mathbf{w}$ for the down-link array the desired reference user's received signal $y(t)$ can be expressed as

$$Y(t) + Z_g^d(t) = \mathbf{w}^H \left[\sum_{j=1}^{L_D} \mathbf{a}(\theta_j) Z_{Dj}^d(t) D^d(t) \right] + Z_g^d(t) \quad (2)$$

with $\langle |z_{Dj}^d(n)|^2 \rangle = \langle |z_{Dj}^u(n)|^2 \rangle$, where $z_{Dj}^d(n) = Z_{Dj}^d(nT)$ and $z_{Dj}^u(n) = Z_{Dj}^u(nT)$ with $Z_{Dj}^d(t)$ being the down-link fading complex envelope with the desired user's jth path, $D^d(t)$ is the desired user's down-link signal waveform, and $Z_g^d(t)$ is the AWGN component.

The desired user's down-link signal components are also received by other users. Let $V_k(t)$ denote the desired user's down-link signal received by the kth interferer. $V_k(t)$ is then given by

$$V_k(t) = \mathbf{w}^H \left[\sum_{l=1}^{L_{Ik}} \mathbf{a}(\varphi_{k,l}) \cdot Z_{Ik,l}^d(t) D^d(t) \right] \quad (3)$$

with $\langle |z_{Ik,l}^d(n)|^2 \rangle = \langle |z_{Ik,l}^u(n)|^2 \rangle$, where $z_{Ik,l}^d(n) = Z_{Ik,l}^d(nT)$ and $z_{Ik,l}^u(n) = Z_{Ik,l}^u(nT)$ with $Z_{Ik,l}^d(t)$ being the down-link fading complex envelope with the kth interferer's lth path.

For FDD systems, $z_{Dj}^d(n) \neq z_{Dj}^u(n)$ and $z_{Ik,l}^d(n) \neq z_{Ik,l}^u(n)$ because of the frequency separation. Hence, instead of the *instantaneous* optimality, the down-link beam optimality is defined as maximizing the desired user's *average* received power while keeping the noise power *plus* total amount of *average* powers received by other users less than or equal to a certain constant level $P_{I\max}$ [15]. A mathematical expression of this optimality is given by

$$\begin{gathered} \langle |y(n)|^2 \rangle \to \max \\ \text{subject to} \\ \sigma_g^{d2} + \sum_{k=1}^{K} \langle |v_k(n)|^2 \rangle \leq P_{I\max} \end{gathered} \quad (4)$$

[1]The bidirectional commonalities of DOA and ASS may require the up- and down-link arrays to be closely located with a sufficient height so that they do not suffer from scattering caused by physical objects located in the near field of the arrays.

where $y(n) = Y(nT)$, $v_k(n) = V_k(nT)$, and $\sigma_g^{d2} = \langle |z_g^d(n)|^2 \rangle$ and $z_g^d(n) = Z_g^d(nT)$.

Obviously, (4) is equivalent to

$$\begin{gathered} \mathbf{w}^H R_D \mathbf{w} \to \max \\ \text{subject to} \\ \mathbf{w}^H R_I \mathbf{w} \leq P_{I\max} \end{gathered} \quad (5)$$

where

$$R_D = \left[\sum_{j=1}^{L_D} \left\langle \left| z_{Dj}^d(n) \right|^2 \right\rangle \mathbf{a}(\theta_j) \mathbf{a}(\theta_j)^H \right] \quad (6)$$

and

$$R_I = \frac{\sigma_g^{d2}}{P_T} I_M + \left[\sum_{k=1}^{K} \sum_{j=1}^{L_{Ik}} \left\langle \left| z_{Ik,l}^d(n) \right|^2 \right\rangle \mathbf{a}(\varphi_{k,l}) \mathbf{a}(\varphi_{k,l})^H \right] \quad (7)$$

with I_M being the $M \times M$ unit matrix, and $P_T = \mathbf{w}^H \mathbf{w}$ is the down-link transmitter power. Solution $\mathbf{w} = \mathbf{w}_{\text{opt}}$ to (5) is given as the eigen vector scaled by $P_{I\max}$, associated with the largest eigen value of the generalized eigen problem

$$R_D \mathbf{w} = \lambda_{\max} R_I \mathbf{w}. \quad (8)$$

Hence, if the desired and interference user's DOA's and ASS's are known, the optimal weight $\mathbf{w}_{\text{opt}}$ may be obtained. However, as mentioned in the Introduction, it is impractical to detect DOA's directly from the series of the snapshot vector $\mathbf{x}(n)$ under multipath-rich environments.

The desired signal subspace represented by R_D may be extracted from the composite space $R_X = \langle \mathbf{x}(n)\mathbf{x}(n)^H \rangle$. However, the extraction of R_D from R_X requires an estimate of the received up-link complex vector channel corresponding to the desired reference user, of which the maximum likelihood estimation requires joint detection of other users. This imposes unreasonable complexity.

III. Algorithm

The discussions in Section II suggest that the key to optimal down-link beam forming is how to extract the desired subspace R_D and undesired (=interference *plus* noise) subspace R_I from the composite space R_X. The goal of this paper is to develop an algorithm that can extract the subspaces R_D and R_I without detecting interferer's signals and not depending on DOA and ASS information. The down-link beam-forming process cooperates with up-link signal reception for the desired user. Signal processing for down-link beam forming is synchronous with the symbol timing nT_s with $T = T_s$.

Fig. 2 shows the block diagram of the proposed joint signal reception and down-link beam-forming scheme. The up-link beam is formed based upon the *instantaneous* SINR maximization criterion, thereby, some diversity improvement is inherent in the beam-forming process itself if there are more than one path to the desired user. Hence, the up-link signal is likely to be received without error. The up-link beam-former output is input to a decision circuit that corresponds to the modulation format used. When the up-link receiver receives

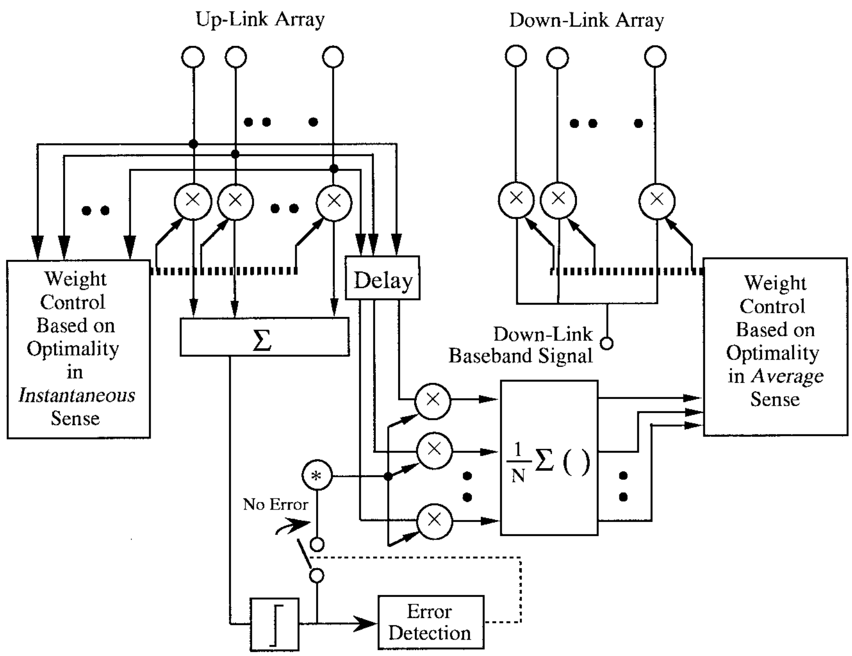

Fig. 2. Block diagram of proposed algorithm.

one frame, decoding of the error-detection code takes place. If the received desired frame is detected in error, it is not used for down link beam forming. If the frame is found to have no errors, the desired user's up-link symbol sequence $d(n) = D^u(nT_s)$ is replicated, where $n \in F_m = [(m-1)N+1, mN]$ and m is the frame number currently being processed. The complex conjugate of the symbol sequence $d(n)$'s is multiplied by its corresponding snapshot sequence and summed to obtain $\mathbf{s}_m$ as

$$\begin{aligned}\mathbf{s}_m &= \sum_{n\in F_m} \mathbf{x}(n) d^u(n)^* \\ &= \sum_{n\in F_m}\left[\sum_{j=1}^{L_D} \mathbf{a}(\theta_j)\cdot z_{Dj}^u(n)d^u(n) + \sum_{k=1}^{K}\sum_{l=1}^{L_{Ik}} \mathbf{a}(\varphi_{k,l}) \right.\\ &\qquad \left.\cdot\, z_{Ik,l}^u(n) i_k^u(n) + \mathbf{z}_g^u(n)\right] d^u(n)^* \end{aligned} \tag{10}$$

where $i_k^u(n) = I_k^u(nT)$ and $\mathbf{z}_g^u(n) = \mathbf{Z}_g^u(nT)$.

If fading is slow enough compared with the frame length N, the fading complex envelopes $Z_{Dj}^u(t)$ may be regarded as constant over the interval F_m. Let the constant be denoted by $z_{Dj,m}^u(\equiv z_{Dj}^u(n)$ for $n \in F_m)$. This assumption leads to

$$\begin{aligned}\mathbf{s}_m &= N\sum_{j=1}^{L_D} \mathbf{a}(\theta_j)\cdot z_{Dj,m}^u + \sum_{n\in F_m} \\ &\quad \cdot \left[\sum_{k=1}^{K}\sum_{l=1}^{L_{Ik}} \mathbf{a}(\varphi_{k,l}) \cdot z_{Ik,l}^u(n) i_k^u(n) + \mathbf{z}_g^u(n)\right] d^u(n)^* \end{aligned} \tag{11}$$

where $d^u(n)d^u(n)^* = 1$ since PSK has been assumed as the modulation scheme.

An empirical covariance matrix $\tilde{R}_s$ of $\mathbf{s}_m$ is then calculated by averaging $\mathbf{s}_m\mathbf{s}_m^H$ over several frames as

$$\tilde{R}_s = \frac{1}{N_a}\sum_{m=1}^{N_a} \mathbf{s}_m\mathbf{s}_m^H \tag{12}$$

where N_a is the number of the frames averaged. More frames for averaging should yield a better approximation of the actual covariance matrix R_s. However, too large N_a may not keep DOA and ASS unchanged during the averaging period. Since $\langle d^u(n) i_k^u(n)^*\rangle = 0$ and $\langle d^u(n) z_g^u(n)^*\rangle = 0$, the second term of (11) approaches zero as the frame length N becomes large. Also, since $\langle z_{Dj,m}^u z_{Dj',m}^u{}^*\rangle = 0$ for different j and j', we have

$$\begin{aligned}\frac{1}{N_a}\sum_{m=1}^{N_a}\mathbf{s}_m\mathbf{s}_m^H \to N^2 \sum_{j=1}^{L_D}\left[\frac{1}{N_a}\sum_{m=1}^{N_a}\left|z_{Dj,m}^u\right|^2\right] \\ \cdot\,\mathbf{a}(\theta_j)\mathbf{a}(\theta_j)^H, \qquad \text{for large } N_a. \end{aligned} \tag{13}$$

Comparing (13) with (6), an estimate $\tilde{R}_D$ of the covariance matrix R_D of the desired user's up-link vector channel, representing its subspace, can finally be obtained as

$$\tilde{R}_D = \frac{\tilde{R}_s}{N^2}. \tag{14}$$

An empirical covariance matrix $\tilde{R}_I$ of interferers *plus* noise components can be estimated by

$$\begin{aligned}\tilde{R}_I &= \tilde{R}_x - \tilde{R}_D \\ &= \frac{1}{N_a}\sum_{m=1}^{N_a}\bar{\mathbf{x}}_m\bar{\mathbf{x}}_m^H - \tilde{R}_D \end{aligned} \tag{15}$$

where $\bar{\mathbf{x}}_m$ is a sample of $\mathbf{x}(n)$, $n \in F_m$, taken from the mth frame. $\bar{\mathbf{x}}_m = \mathbf{x}((m-1)N+1)$ may be a good choice. Using $\tilde{R}_D$ and $\tilde{R}_I$ instead of R_D and R_I, respectively, in (8) and

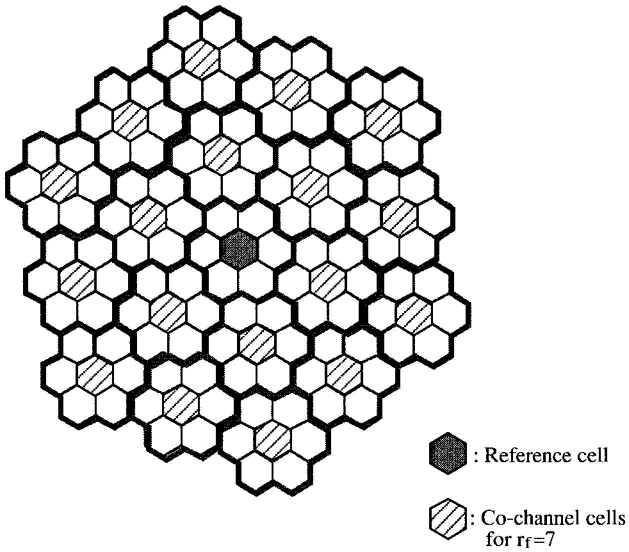

Fig. 3. Cell layout for simulations.

solving the corresponding generalized eigen problem yields the optimum weight vector $\mathbf{w}_{\rm opt}$.

The assumption that $Z^u_{Dj}(t)$ is constant over the frame of interest may not hold well for large N. Nevertheless, since for $n,\ n' \in F_m,\ z^u_{Dj}(n)$ is highly correlated with $z^u_{Dj}(n')$, only the desired user's fading components can be illuminated in $\mathbf{s}_m$. The effect of fading correlation on the beam-forming performance was evaluated through computer simulations and the results are presented in the next section.

IV. Simulations Results

A. Down-Link SIR Distribution with the Optimal Beam

For a hexagonal cell layout, the SIR distribution in a reference (central) cell with the optimal down-link beam was first evaluated through computer simulations to determine the upper bound of the performance with the proposed algorithm. An eight-element circular array with a minimum interelement separation being half the wave length was assumed. The array has, in total, omnidirectional directivity. The SIR distribution with a unit gain omnidirectional antenna was also evaluated.

The 133 cells shown in Fig. 3 were considered in the simulations. The reuse factor r_f was assumed to be three, four, or seven. One user was located in each of the reference and the cochannel cells. The users' geographical locations in the cells were uniformly distributed within the cells. For each user, the propagation loss according to Okumura formula [18] with distance attenuation factor of $\alpha = 3.5$ was calculated for the distance between the user's position and each of the base stations operating with the reuse pattern of interest. The attenuation due to lognormal shadowing with a standard deviation 6.5 dB was then superimposed over the distance loss. The number L_p of the propagation paths takes an integer value uniformly distributed over $1 \le L_p \le 5$. The strength of the composite signal suffering from the distance and shadowing attenuations was uniformly randomly decomposed into L_p components, each of which was assigned to the one of the L_p propagation paths (the values were used as $\langle |z^d_{Dj}(n)|^2\rangle$'s or $\langle |z^d_{Ik,l}(n)|^2\rangle$'s for the desired or interference users, respectively, which were assumed to be known to the central base receiver). Hence, their total sum stays the same but each becomes a random variable.

It was assumed that the mobile receiver's noise power $\sigma^{d^2}_g \to 0$ (hence, the environment is interference-limited) and that without loss of generality $P_T = P_{I\max} = 1.0$. The DOA's with the L_p paths were assumed to distribute over $[0, 2\pi)$ and to be known to the central base receiver. Obviously, the total number of the interference path components incident to the up-link array exceeds the degree-of-freedom $M-1$ (=7) of the array. However, the distribution of the average powers of these path components has very large dynamic range since these path components, which are attenuated due to path loss and shadowing, are not only from the first tier cells but also farther cells. Hence, it is a reasonable approximation that the optimal down-link beam has nulls against the largest $M-1$ interferer's path components and that other interferer's path components only contribute to increasing the noise power $\sigma^{d^2}_g$ in (7).

Using these assumptions, the weight vector $\mathbf{w}_{\rm opt}$ for the optimal down-link beam was calculated by solving the generalized eigen problem given by (8). With the user locations fixed, the processes described above were repeated for all other operating base stations. The down-link SIR with the reference desired user was then obtained by calculating the received desired signal power emitted from the reference base station and interferer's signal powers emitted from the other base stations.

This entire process was repeated many times for different user locations to evaluate the SIR distribution within the reference cell. Fig. 4 shows the cumulative SIR distributions for $r_f = 3,\ 4$, and 7. The SIR distribution with a unit gain omnidirectional antenna is also plotted for $r_f = 7$. It is found that with the optimal down-link beam forming, the SIR distribution with $r_f = 3$ is still much better than that with the omnidirectional antenna with $r_f = 7$. Hence, with the optimal down-link antenna beam, the spectrum efficiency can be increased by more than $7/3$ times that with the $r_f = 7$ omnidirectional antenna.

B. Beam Performances

An exhaustive series of computer simulations was conducted in order to evaluate the proposed algorithm in terms of overall beam performances. Results of the simulations are described below.

1) Convergence: First, we determined how many frames are needed for beam convergence, given the symbol rate $1/T$, the maximum Doppler frequency f_D and frame length N. Two three-element circular arrays—one for up-link signal reception and the other for down-link signal transmission—were used in the simulations. Their minimum element separations were half the wave lengths of the up- and down-link frequencies, respectively. Two users were considered: one is the desired user and the other is the interferer. Each user was assumed to have two propagation paths with equal power. Furthermore, 0-dB up-link average SIR was assumed, i.e., $\langle |z^u_{D1}|^2\rangle = \langle |z^u_{D2}|^2\rangle = \langle |z^u_{I1,1}|^2\rangle = \langle |z^u_{I1,2}|^2\rangle$. Based upon Jakes' model [17], fading complex envelope variations were generated for

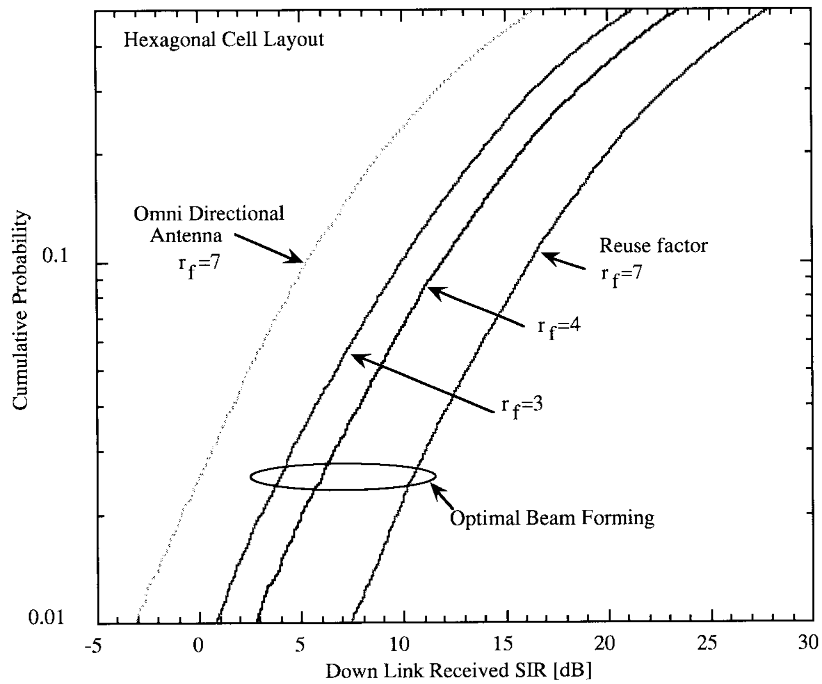

Fig. 4. SIR distributions with and without optimal beam forming.

the four propagation paths, which are statistically independent of each other. It was assumed that the two users move at the same speed. The generated envelopes were then sampled at the normalized symbol rate f_DT normalized by the maximum Doppler frequency f_D. The up-link fading samples were segmented into several blocks and used for those corresponding to the up-link frames.

Quarternary PSK (QPSK) was assumed. With a proper error-detection code, the probability that a received frame contains an undetectable error pattern can be made very small [18]. Hence, these simulations assume that this probability is zero: i.e., any error pattern can be detected with 100% probability. The frame length $N = 128$ was assumed including the unique word and parity check sequences. The recursive least square (RLS) algorithm [19] was used to track up-link beam optimality. Since the unique word pattern is known to both the mobile transmitter and base receiver, its corresponding symbol sequence was used during the unique word timing as the desired response of the array combiner output. On the contrary, during the information and parity-check timings, the decision circuit output was used as the desired response. Symbol timings of both desired and interference users are synchronous to each other. It was assumed that $\sigma_g^{u2} \to 0$ and $\sigma_g^{d2} \to 0$ and that, without loss of generality, $P_T = P_{I\max} = 1.0$.

Fig. 5(a) and (b) shows the down-link beam patterns formed by the proposed algorithm with the number N_a of frames for averaging, normalized by f_DT, as a parameter; Fig. 5(a) is for the frame length $N = 128$ and (b) for $N = 256$. The incident angle with the four propagation paths are shown in the figures. The optimal down-link beam form given as a solution to (8) is also shown. It is found that with $N_af_DT = 50.0$, the formed down-link beam pattern is almost equivalent to the optimal beam pattern with slight impairments in that the null depths are not as deep, and that the null direction of around 270° is somewhat offset from those of the optimal beams. With $N = 256$ and $N_af_DT = 5.0$, a null is produced at around 55° from which no interference components arrive. Hence, the sample size of $N_af_DT = 5.0$ is too small for $N = 256$ to form a reasonable directivity pattern with the proposed algorithm.

2) Received Signal Powers: The proposed algorithm assumes that the fading complex envelopes $Z_{Dj}^u(t)$'s with the desired user are constant over a frame. This assumption does not hold when the frame length N becomes large. However, since $z_{Dj}^u(n)$'s are highly correlated to each other within the frame, only the desired user's fading components can be discerned in $\mathbf{s}_m$ of (10). A major outcome of the fading variation is the offset of the formed down-link beam pattern from the optimal one which may result in decreased power emissions toward the desired user and increased power emission toward the interferers. With the weight vector $\mathbf{w}$, the signal powers received by the desired and interference users are given by $\mathbf{w}^H R_D \mathbf{w}$ and $\mathbf{w}^H R_I \mathbf{w}$, respectively.

The received signal powers $\mathbf{w}^H R_D \mathbf{w}$ and $\mathbf{w}^H R_I \mathbf{w}$ are compared with those with a unit gain omnidirectional antenna. Two eight-element circular arrays—one for up-link signal reception and the other for down-link signal transmission—were used; the minimum element separations were half the wave lengths of up- and down-link frequencies, respectively. There is one desired and three interference users, each of which has two equal power propagation paths. Fig. 6(a) and (b) shows, for $N = 128$, the received signal powers $\mathbf{w}^H R_D \mathbf{w}$ and $\mathbf{w}^H R_I \mathbf{w}$ normalized by those with the omnidirectional antenna versus the desired user's normalized maximum Doppler frequency f_DT with the up-link average SIR as a parameter: Fig. 6(a) and (b) is for the cases where all interferers are moving with a constant speed corresponding to $f_DT = 0.001$

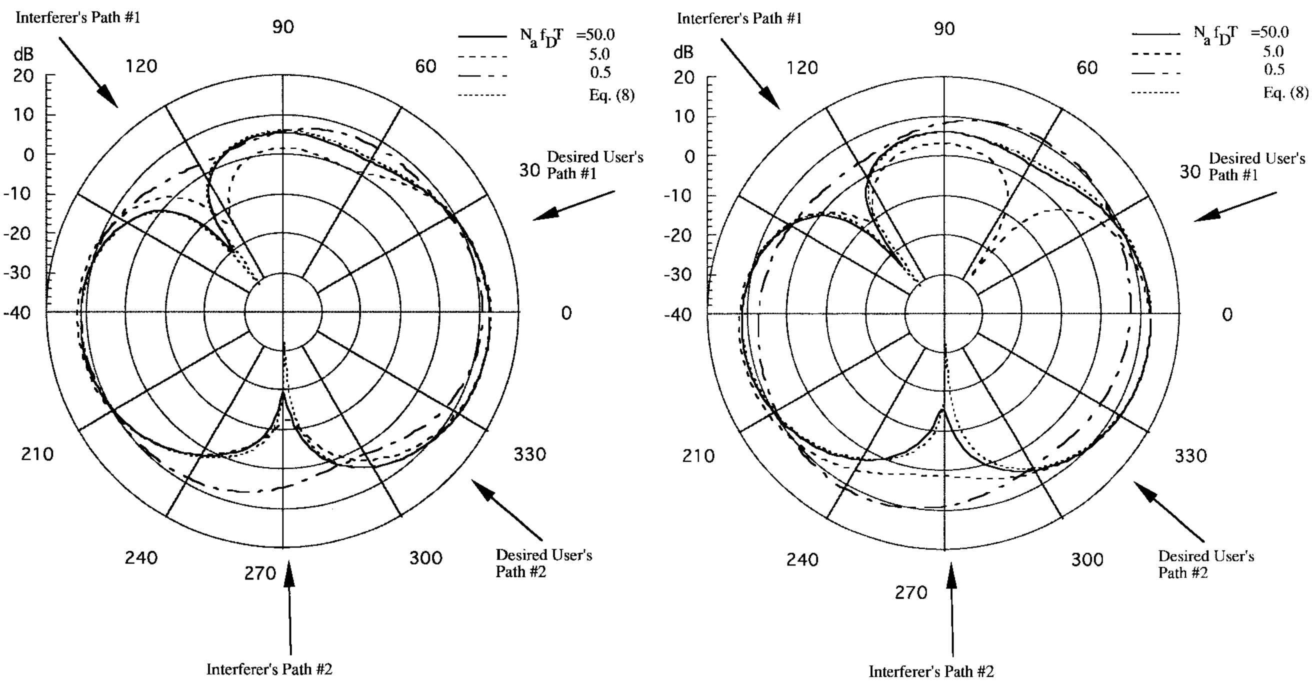

Fig. 5. Formed beam pattern for (a) $N = 128$ and (b) $N = 256$.

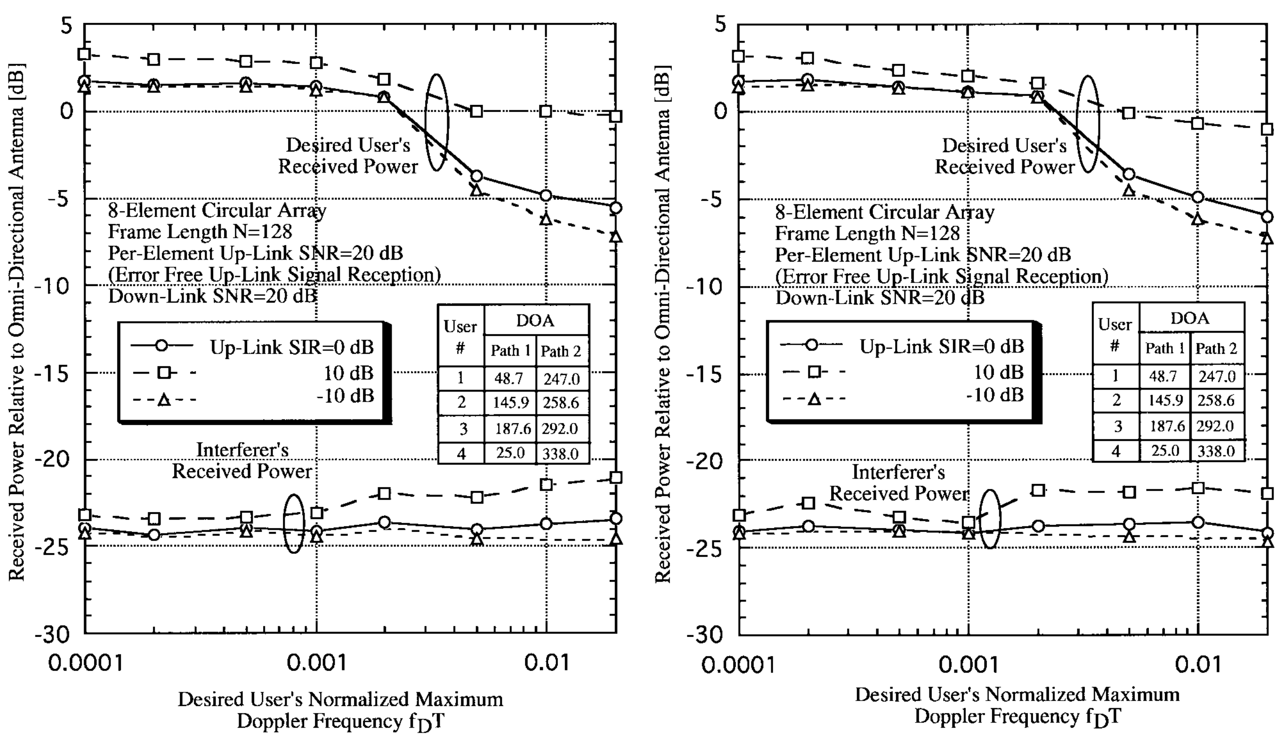

Fig. 6. (a) Signal powers received by desired and interference users versus desired user's maximum Doppler frequency: interferer's mobility (a) $f_D T = 0.001$ and (b) $f_D T = 0.01$.

and $f_D T = 0.01$, respectively. The incident angles of the paths are indicated in the figures. Both the up-link per-element and down-link average SNR's, $(\langle|z_{D1}^u|^2\rangle + \langle|z_{D2}^u|^2\rangle)/\sigma_g^{u2}$ and $(\langle|z_{D1}^d|^2\rangle + \langle|z_{D2}^d|^2\rangle)/\sigma_g^{d2}$, respectively, are assumed to be 20 dB. For each set of parameter values of interest, 5000 up-link frames were transmitted for down-link beam forming. The up-link frames were assumed to be always received with no error since the primary concern at this stage is evaluating the beam sensitivity to fading. Other simulation conditions are the same as those described in the previous section.

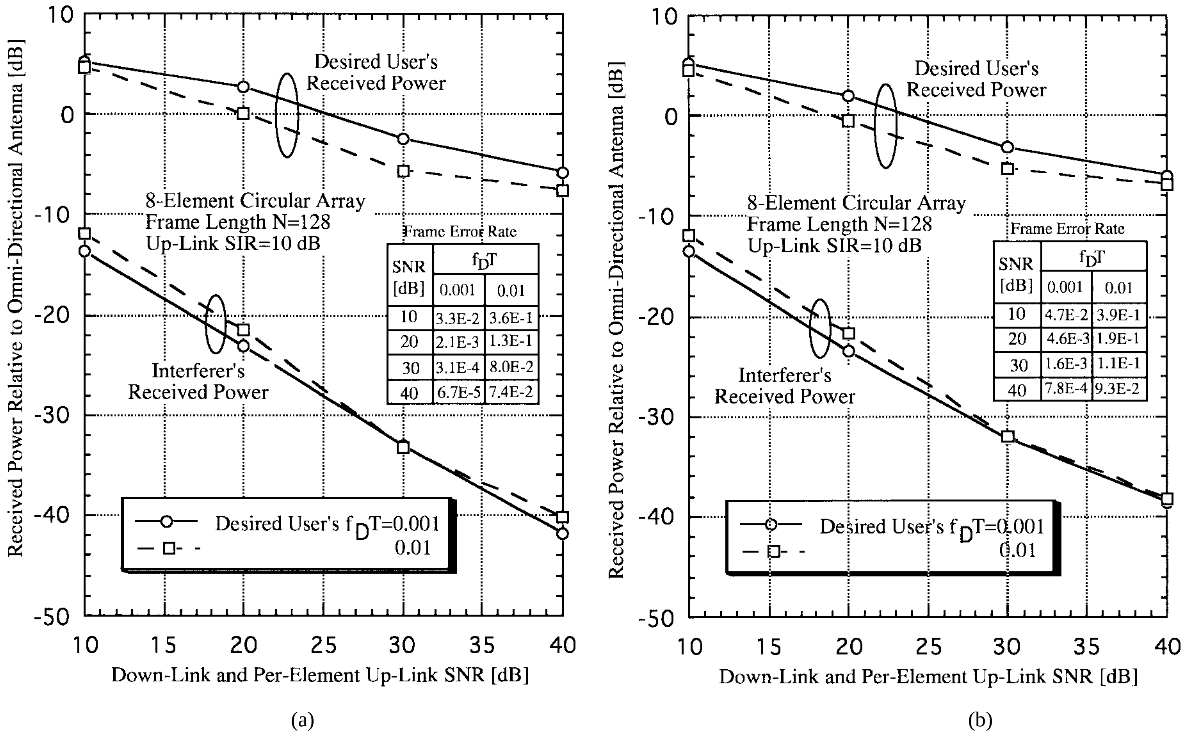

Fig. 7. Signal powers received by desired and interference users versus average SNR: interferer's mobility (a) $f_D T = 0.001$ and (b) $f_D T = 0.01$.

It is found from Figs. 6(a) and (b) that the general tendency of the $\mathbf{w}^H R_D \mathbf{w}$ and $\mathbf{w}^H R_I \mathbf{w}$ curves are almost identical regardless of the interferers' mobility. Surprisingly the desired signal power received by the interferers $\mathbf{w}^H R_I \mathbf{w}$ is less sensitive to the desired user's maximum Doppler frequency f_DT than that received by the desired user $\mathbf{w}^H R_D \mathbf{w}$. Hence, the decrease in $\mathbf{w}^H R_D \mathbf{w}$ due to the fading variation in one frame should be the major concern when examining beam performance. Fortunately, such a tendency is gradual. When the average SIR is 10 dB, the $\mathbf{w}^H R_D \mathbf{w}$ value even with $f_D T = 0.01$ is almost the same as with the unit gain omnidirectional antenna: when the average SIR's are 0 and -10 dB, the $\mathbf{w}^H R_D \mathbf{w}$ values are, respectively, 5 and 6 dB smaller than those of the omnidirectional antenna.

Fig. 7(a) and (b) shows for $N = 128$ and 10-dB up-link average SIR the received signal powers $\mathbf{w}^H R_D \mathbf{w}$ and $\mathbf{w}^H R_I \mathbf{w}$ normalized by those with the unit gain omnidirectional antenna versus the up-link per-element average SNR with the desired user's maximum Doppler frequency $f_D T$ as a parameter: Fig. 7(a) and (b) is for the cases where all interferers are moving with a constant speed corresponding to $f_D T = 0.001$ and $f_D T = 0.01$, respectively. The down-link average SNR was assumed to be the same as the up-link per-element average SNR. Only the up-link frames received without error were used for down-link beam forming. The value of the frame error rate for each plot is shown in the figures. It is found that the general tendency of the $\mathbf{w}^H R_D \mathbf{w}$ and $\mathbf{w}^H R_I \mathbf{w}$ curves versus the average received SNR is, again, almost identical regardless of the interferers' mobility. The larger the average SNR becomes, the more the desired user's received power $\mathbf{w}^H R_D \mathbf{w}$ decreases, however, the more rapidly the interferers' received power $\mathbf{w}^H R_I \mathbf{w}$ also decreases. This can easily be understood from the down-link beam optimality expressed by (4).

V. Conclusion

The main focus of this paper has been adaptive down-link beam forming for PSK modulation based on subspace decomposition. We have proposed a down-link beam-forming algorithm for mobile communication systems. The proposed algorithm works in cooperation with up-link signal reception, however, the definition of down-link beam optimality differs from that of the up-link optimality which is based on *instantaneous* SINR maximization. In contrast to this, down-link optimality is defined as maximizing the desired reference user's *average* received power while keeping the noise power *plus* total amount of *average* powers received by other users less than or equal to a certain constant level. It has been shown that with this optimality definition, the desired signal subspace can be effectively extracted from the composite space in conjunction with optimal beam forming for up-link signal reception.

A key assumption made in the algorithm is that the fading complex envelopes of the received desired path components are constant over the frame of interest. This assumption may not well hold when the frame length becomes large. However, fading correlation within the received frame still illuminates the desired path components alone since the desired and interferer's transmitted signals are independent of each other. The proposed algorithm requires neither detection of other user's signals nor knowledge about direction-of-arrival and average signal strength of the received path components. Hence, algorithm complexity stays within a practical level.

Results of computer simulations have been presented to demonstrate overall performances of the proposed algorithm. For a hexagonal cell layout, the SIR distribution in a reference (central) cell with the optimal down-link beam was first evaluated to find the upper bound of the proposed algorithm. The SIR distribution was then compared with that yielded by the unit gain omnidirectional antenna. It was shown that with optimal down-link beam forming, the SIR distribution with the reuse factor $r_f = 3$ is still much better than that with the $r_f = 7$ omnidirectional antenna.

The effects of the beam pattern impairments seen with practical parameter values with regard to the fading correlation were evaluated for an eight-element circular array. The desired and interference users' received signal powers, emitted by using an array weight vector determined by the proposed algorithm, were compared with those yielded by the unit gain omnidirectional antenna. It has been shown that the desired user's received signal power decreases as the desired user's mobility increases but such a tendency is relatively gradual. The interferer's received signal power is found to be less sensitive to the desired user's mobility.

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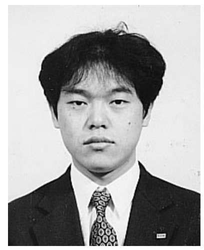

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