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Research Note

A Strategy for Cochannel Signals Extraction with Antenna Array in TDMA/FDMA Mobile Cellular Systems

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A novel strategy based on Capon method is proposed for multiple signals extraction with an antenna array in TDMA/FDMA mobile cellular systems. In this method, called SF-Capon, each Intercell Cochannel (IC) user is alternatively asked to decrease its transmitted power for a few bits. This enables the estimation of a so-called Signal-Free (SF) correlation matrix, which is then used in connection with Capon method to compute an improved beamforming weight vector, with reduced sensitivity to DOA error and angular spread. The superiority of the proposed SF-Capon strategy over standard Capon and data independent least-squares beamforming is demonstrated via simulation in a fast Rayleigh fading channel.

INTRODUCTION

As a result of the growing demand for cellular communication systems, a need for increasing their capacity and coverage has become evident. The use of spatially selective, adaptive antenna arrays at the Base Station (BS) for achieving this goal seems to be inevitable [1,2]. (Because of the difficulties associated with the use of antenna arrays at the mobile station, research efforts on adaptive arrays in wireless cellular communications have focused mostly on the BS.) Advantages of this approach include: Signal quality improvement, capacity increase, coverage expansion and decrease in the number of required cell sites, all this with minimum change in mobile systems and standards [3]. In FDMA/TDMA cellular mobile systems, antenna arrays can be used at the BS to increase capacity by allowing multiple mobile users in a cell to share the same time slot and frequency channel (these users shall be referred to as Intercell Cochannel (IC) users). In this method, sometimes called Space Division Multiple Access (SDMA), the receiving antenna array produces a distinct beamforming pattern for each of the IC users, so that their information signals may be extracted separately [4]. Ideally, the pattern should have relative nulls in the directions of interfering IC users and a main lobe in the direction of the desired IC user. The same concepts may be applied to the transmitting array.

Capon method is a popular approach for deriving beamforming weight vectors with such spatial properties. It is based on minimizing the beamformer output power subject to a constraint of unit gain in a desired look direction, which is equivalent to maximizing output signal-to-interference and noise (SINR) power for a point source [5,6]. Capon method assumes exact knowledge of the Direction Of Arrival (DOA) of the desired signal and treats energy arriving from other directions as undesirable. In the present mobile radio application, this poses serious difficulties. Indeed, only estimates of the DOAs of the IC user signals are available; furthermore, local scattering around the mobiles results in angular spreading as seen from the receiving array. Such discrepancies from the assumed model lead to desired signal cancellation and an increase in sidelobe levels; this, in turn, leads to a significant increase in the Bit Error Rate (BER) at the receiver output.

Here, the interest is in using antenna arrays at the BS (uplink) for multiple signal extraction in TDMA/FDMA cellular mobile systems. A new strategy is proposed for extracting signals, based on Capon's beamformer, which is applicable in such systems. In this method, named SF-Capon, each IC user is alter-

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natively asked to decrease its transmitted power for a short time duration (a few bits) while the other IC users are sending their own signal. This enables the computation of a so-called Signal-Free (SF) correlation matrix for each IC user. Based on Capon method, this correlation matrix is then used to compute a BF weight vector that minimizes the array output interference-plus-noise power. For DOA tracking of IC users, a modified form of the method in [7] is used that facilitates the implementation of the required intercell hand-off protocol [1].

The new method is investigated via computer simulations of multiple narrow band moving sources in a fast Rayleigh fading channel with angular spread. The results clearly show that it is capable of tracking and extracting the individual signal of each IC mobile user. When compared to standard Capon and conventional least-squares beamformers, the proposed strategy leads to a significant reduction in the Bit Error Rate (BER).

BACKGROUND MATERIAL

Received Signal Model

To simplify the discussion, the following model is used for the received signals [6]:

$$\mathbf{x}(m) = \mathbf{A}(m)\mathbf{s}(m) + \mathbf{n}(m), \tag{1}$$

$$\mathbf{s}(m) = [s_1(m)s_2(m)\cdots s_p(m)]^T, \tag{2}$$

$$\mathbf{A}(m) = [\mathbf{a}(\theta_1(m))\ \mathbf{a}(\theta_2(m))\cdots\mathbf{a}(\theta_p(m))], \tag{3}$$

where $\mathbf{x}(m)$ is the mth snapshot for the L element array, $s_i(m)$ is the ith received signal from (distinct) direction θ_i, $\mathbf{n}(m)$ is a noise vector which is assumed to be spatially and temporally white and uncorrelated with the signals, p is the number of IC users that are being tracked, T represents transposition and, finally, $\mathbf{a}(\theta)$ is the array steering vector for direction θ. For instance, in the case of an arbitrary planar geometry, the lth element of $\mathbf{a}(\theta)$ may be expressed as:

$$a_l(\theta) = g_l(\theta)e^{j(2\pi r_l/\lambda)\cos(\theta-\phi_l)} \overset{\text{def}}{=} g_l(\theta)e^{j\nu_l\cos(\theta-\phi_l)}, \tag{4}$$

where the pair (r_l, ϕ_l) represents the position of the lth element of the array in polar coordinates, $g_l(\theta)$ is the lth antenna element radiation pattern and λ is the signal wavelength.

It is noted that in wireless cellular systems, the actual received signals do not assume the simplified form of Equations 1 to 3. Indeed, as a result of local scattering around the mobile, each user signal is actually spread in an angle around its nominal DOA θ_i. That is, the received signal of each source is a combination of a multitude of point sources that are randomly delayed and scaled replicas of the same signal. Such a spatially distributed source may be modeled mathematically via a so-called angular signal density [8]. In addition, source motion results in Doppler spread and fast Rayleigh fading [9].

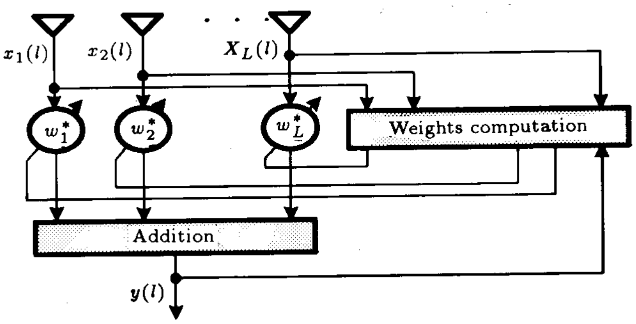


Figure 1. The structure of the array.

Minimum Variance (Capon) Beamformer

For narrowband signals, the beamformer output is computed simply by weighting and summing the received samples (see Figure 1), i.e.:

$$y(m) = \mathbf{w}^H\mathbf{x}(m), \tag{5}$$

where $\mathbf{w} = [w_1\cdots w_L]^T$ is the vector of complex weights and w_l and H represent Hermitian transposition. With a sophisticated choice of weights, it is possible to extract the desired signal when the number of signal sources is less than the number of array elements (i.e. $p < L$).

One method for cancelling undesired signal sources is Capon method [5,6]. In the latter, the desired weight vector is obtained by minimizing the output power of the array subject to a constraint of unit gain in the direction of the ith signal. The beamformer output power, at time m, may be expressed as:

$$P_{out} = E\{|y(m)|^2\} = \mathbf{w}_i^H E\{\mathbf{x}(m)\mathbf{x}^H(m)\}\mathbf{w}_i \overset{\text{def}}{=} \mathbf{w}_i^H\mathbf{R}\mathbf{w}_i, \tag{6}$$

where $\mathbf{R}$ is the $L\times L$ correlation matrix of the received signal vector. Thus, Capon weight vector for the ith signal, denoted $\mathbf{w}_i$, may be formulated as:

$$\min_{\mathbf{w}_i}\{\mathbf{w}_i^H\mathbf{R}\mathbf{w}_i\} \quad \text{subject to} \quad \mathbf{w}_i^H\mathbf{a}(\theta_i) = 1, \tag{7}$$

where θ_i is the assumed direction of the ith signal source. Solution of this optimization problem by use of Lagrange multipliers gives the following result:

$$\mathbf{w}_i = \frac{\mathbf{R}^{-1}\mathbf{a}(\theta_i)}{\mathbf{a}(\theta_i)^H\mathbf{R}^{-1}\mathbf{a}(\theta_i)}. \tag{8}$$

Tracking Algorithm

Tracking of mobile users is one of the most important aspects for practical application of antenna arrays in mobile communications [4]. For multiple point-target tracking, a robust algorithm was proposed in [7] with a moderate computational complexity. For a planar array geometry with omnidirectional elements, it may be summarized as follows:

$$\hat{\mathbf{A}}(k-1)=[\mathbf{a}(\hat{\theta}_1(k-1))\mathbf{a}(\hat{\theta}_2(k-1))\cdots\mathbf{a}(\hat{\theta}_p(k-1))], \tag{9}$$

$$\begin{aligned}\hat{\mathbf{s}}(k) &= \left(\hat{\mathbf{A}}(k-1)^H\hat{\mathbf{A}}(k-1)\right)^{-1}\hat{\mathbf{A}}(k-1)^H\mathbf{x}(k)\\ &\overset{\text{def}}{=} \mathbf{W}(k)^H\mathbf{x}(k),\end{aligned} \tag{10}$$

$$\tilde{\mathbf{A}}(k) = \hat{\mathbf{A}}(k-1) + \mu_1\left(\mathbf{x}(k) - \hat{\mathbf{A}}(k-1)\hat{\mathbf{s}}(k)\right)\hat{\mathbf{s}}^H(k), \tag{11}$$

$$\begin{aligned}\hat{\theta}_i(k) &= \hat{\theta}_i(k-1)\\ &+ \frac{\sum_{l=1}^{L}\nu_l\sin(\hat{\theta}_i(k-1)-\phi_l)\mathrm{Im}\{\ln(\tilde{\mathbf{A}}^*_{l,i}(k)\hat{\mathbf{A}}_{l,i}(k))\}}{\sum_{l=1}^{L}(\nu_l\sin(\hat{\theta}_i(k-1)-\phi_l))^2},\end{aligned} \tag{12}$$

where k is the discrete-time index (note that the sampling times for DOA estimation, as indexed by k, may be different from the sampling times associated with beamforming, as indexed by m), μ_1 is a real positive constant less than one, Im{.} represents the imaginary part of a complex number and $\hat{\theta}_i(k)$ is the DOA estimate of the ith signal source.

As discussed in [7], the beamforming pattern related to $\mathbf{w}_i(k)$, the ith column of $\mathbf{W}(k)$ in Equation 9, inserts deep nulls in the direction of all users other than the ith user. In fact, $\mathbf{W}(k)$ is the well-known Data Independent Least-Square (DILS) beamforming matrix for extraction of multiple signals with assumed DOAs $\hat{\theta}_i(k-1)$ [5].

THE SF-CAPON STRATEGY

Basic Principle

The DILS beamformer mentioned in the previous section is data independent in the sense that its weights are independent of data statistics [5]. It does not take into account the noise level, the power of the interfering sources and the angular spread. Thus, this kind of beamformer is not statistically optimum and will not result in maximum SINR at the array output.

The standard Capon method is very sensitive to the assumed DOA of the desired signal (i.e., θ_i in Equation 8), i.e., a small estimation error in that parameter may result in significant signal cancellation. This method is also known to behave poorly in the presence of correlated interference. For example, in the case of point sources, Capon method will process coherent multipath components in such a way as to cancel the desired signal [5]. As observed in the simulation experiments (see next section), a similar type of problem occurs when the desired signal source is distributed (i.e. angular spread). In all these cases, the signal cancellation is accompanied by huge sidelobes and/or mainlobe offset in the beampattern. Thus, the use of Capon method in cellular communication systems will result in an increase in the output noise as well as in the level of cochannel interference.

It is pointed out that all these problems with the standard Capon method may be attributed to the presence of the desired signal when computing the correlation matrix $\mathbf{R}$. As a result of DOA estimation error, the desired signal is viewed as interference, which, in turn, results in a notch in the beampattern in the direction of the true DOA and, thus, signal cancellation. In the same way, the presence of the signal component results in unwanted features of the beampattern and signal cancellation in the case of coherent multipath point and angularly spread signal sources.

In cellular communication systems, all the received user signals have, more or less, the same average power as a result of power control management, so that the above problems are, a priori, unavoidable. However, in such systems, if a particular user stops its signal transmission temporarily (or reduces its transmitted power significantly), while the other users are sending their own signal without any change, it will be possible to compute a Signal-Free Correlation Matrix (SFCM) that only contains the interference and noise components. In effect, this procedure may be realized for each IC user in alternance and, accordingly, for the SFCM of the ith IC user at the kth snapshot as is denoted by $\mathbf{R}_{SF,i}(k)$. Now, to avoid the above problems with the standard Capon method that are related to the presence of a signal component in the correlation matrix $\mathbf{R}$, the SFCM of the ith IC user, i.e., $\mathbf{R}_{SF,i}(k)$, may, instead, be used when computing the weight vector for that user. Thus, the weight vector for extracting the ith user signal with this philosophy, based on Equation 8, is:

$$\mathbf{w}_i^{SF} = \frac{\mathbf{R}_{SF,i}^{-1}\mathbf{a}(\theta_i)}{\mathbf{a}(\theta_i)^H\mathbf{R}_{SF,i}^{-1}\mathbf{a}(\theta_i)}. \tag{13}$$

This multiple beamforming strategy is referred to as Signal-Free Capon (SF-Capon). The weight vector, $\mathbf{w}_i^{SF}$, found in this way minimizes the output noise and interference power, while providing a unit gain in the estimated direction of the desired signal. Again, since the SFCM contains no desired signal component, the resulting weight vector $\mathbf{w}_i^{SF}$ will not suffer from the previously mentioned problems. Thus, assuming that the interfering IC users are sufficiently separated in DOA from the desired user (typically greater than the resolution of an L-element antenna array), the SF-Capon strategy will produce a well-shaped beampattern with properly directed mainlobe and relatively low sidelobe levels, which are desirable attributes for mobile communications.

Analytical Result for Simple Situations

Below, analytical arguments are provided that demonstrate the superiority of the SF-Capon strategy over the standard Capon method in a simple situation.

Consider that there is only one point signal source in the environment, with true DOA θ_1. The correlation matrix $\mathbf{R}$ of the received array signal $\mathbf{x}(m)$, assuming unit power white noise, is then:

$$\mathbf{R} = \mathbf{I} + \gamma \mathbf{a}(\theta_1)\mathbf{a}(\theta_1)^H, \tag{14}$$

where the received signal power γ may be identified with the SNR. For simplicity, omnidirectional array elements are assumed with unit gain (i.e. $g(\theta) = 1$ in Equation 4), so that $\mathbf{a}(\theta_1)^H\mathbf{a}(\theta_1) = L$. In this case $\mathbf{R}^{-1}$ is given by [10]:

$$\mathbf{R}^{-1} = \mathbf{I} - \frac{\gamma}{1+\gamma L}\mathbf{a}(\theta_1)\mathbf{a}(\theta_1)^H. \tag{15}$$

Firstly, suppose that by mistake $\hat{\theta}_1$ has been considered equal to $\theta_1 + \Delta\theta$ as the desired signal DOA in Equation 8. With Capon method, the resulting weight vector (Equation 8) for extracting this signal takes the following form:

$$\mathbf{w} = \frac{\mathbf{R}^{-1}\mathbf{a}(\hat{\theta}_1)}{\mathbf{a}(\hat{\theta}_1)^H\mathbf{R}^{-1}\mathbf{a}(\hat{\theta}_1)}. \tag{16}$$

With this weight vector, the contribution of the signal coming from direction θ_1 at the beamformer output power is $\gamma|\mathbf{w}^H\mathbf{a}(\theta_1)|^2$, while the noise contribution is simply $\mathbf{w}^H\mathbf{w}$. Thus the array gain (i.e., output SNR over input SNR) will be:

$$AG = \frac{|\mathbf{w}^H\mathbf{a}(\theta_1)|^2}{\mathbf{w}^H\mathbf{w}} = \frac{|\mathbf{a}(\hat{\theta}_1)^H\mathbf{R}^{-1}\mathbf{a}(\theta_1)|^2}{\mathbf{a}(\hat{\theta}_1)^H\mathbf{R}^{-2}\mathbf{a}(\hat{\theta}_1)}. \tag{17}$$

Now consider the SF-Capon strategy, in which the signal power is set equal to zero when computing the correlation matrix. The resulting SFCM in this case is $\mathbf{R}_{SF,1} = \mathbf{I}$ (simply set $\gamma = 0$ in Equation 14). By analogy with Equation 17, the array gain for SF-Capon will, thus, be:

$$AG_{SF} = \frac{|\mathbf{a}(\hat{\theta}_1)^H\mathbf{a}(\theta_1)|^2}{L}. \tag{18}$$

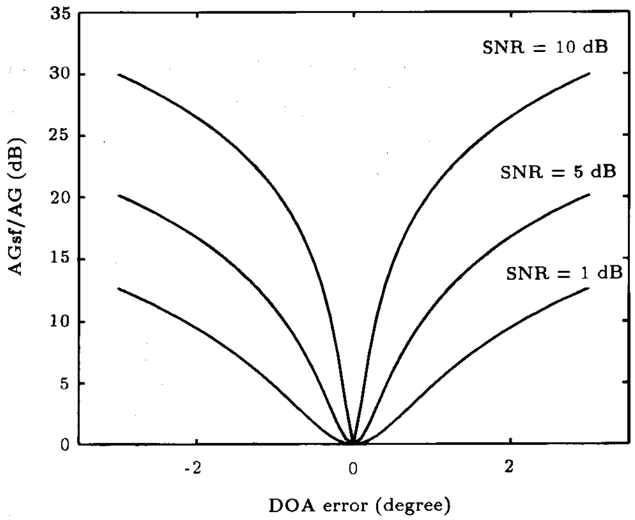


Figure 2. Ratio of AG_{SF}/AG versus DOA error for different values of input SNR.

Using Equations 15, 17 and 18, it can be verified that:

$$\frac{AG_{SF}}{AG} \geq 1 + (\gamma L)^2 \sin^2\phi, \tag{19}$$

where ϕ is the angle between the two vectors $\mathbf{a}(\theta_1)$ and $\mathbf{a}(\hat{\theta}_1)$, i.e., $\cos\phi = |\mathbf{a}(\theta_1)^H\mathbf{a}(\hat{\theta}_1)|/L$.

To illustrate the improvement in array gain resulting from SF-Capon, the ratio of AG_{SF}/AG versus $\Delta\theta$ for a UCA with $L = 13$ omnidirectional elements is shown in Figure 2. It can be seen that even for a very small error in DOA, performance of the standard Capon method abruptly decreases with respect to the SF-Capon strategy.

Implementation Considerations

For estimation of the SFCM $\mathbf{R}_{SF,i}$, the TDMA/FDMA signaling structure shown in Figure 3 is assumed. The data transmitted in a given frequency channel is divided into consecutive frames of length T, each frame being made up of 8 time slots. IC users share the same time slots and BS separately extracts the signals by beamforming. During each time slot there is a Reduced Transmitted Power (RTP) region for each user, which does not overlap with other IC users RTP regions.

Based on this configuration, $\mathbf{R}_{SF}$ may be estimated recursively as follows ($0 < \mu < 1$):

$$\mathbf{R}_{SF,i}(k) = \mu\mathbf{R}_{SF,i}(k-1) + (1-\mu)\mathbf{x}(kT+\tau_i)\mathbf{x}^H(kT+\tau_i), \tag{20}$$

where τ_i denotes the relative position of the ith IC of user RTP.

With all beamforming methods and SDMA strategies, an important problem should be noted. If the difference in DOA between two users becomes less

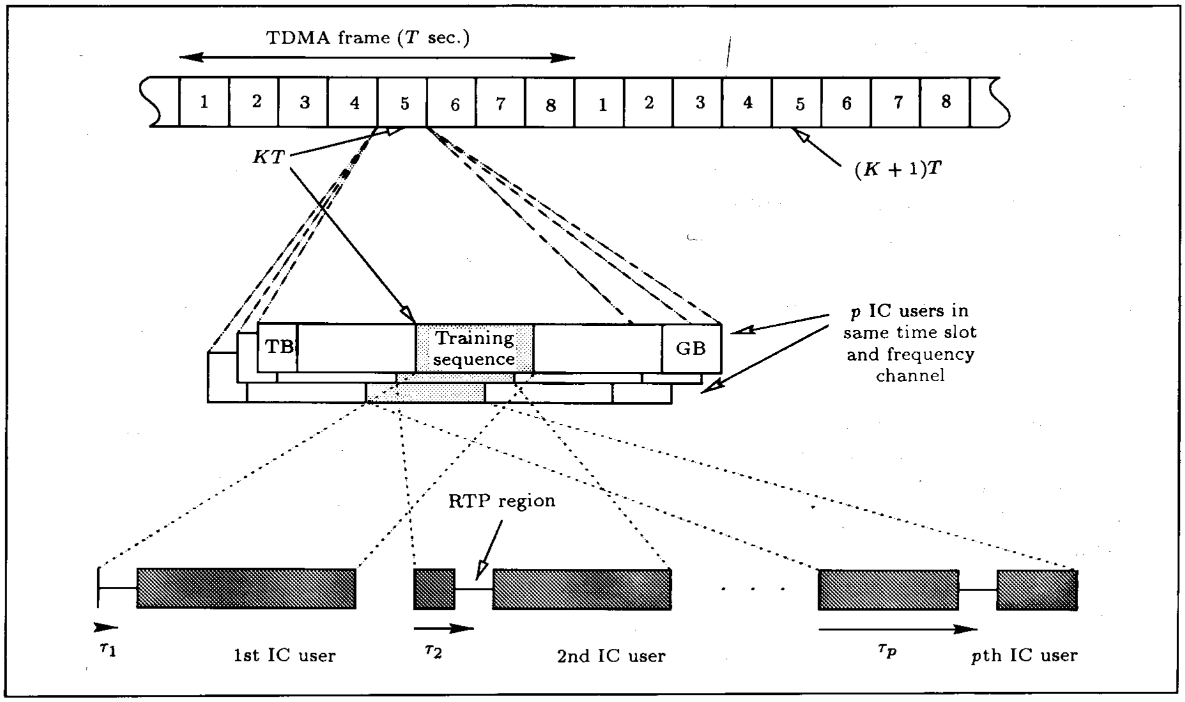


Figure 3. Suggested TDMA/FDMA signaling method.

than a predefined threshold and the two users settle in a common zone, there will be a need for intercell handoff for one of these users to another time slot and/or frequency channel. The precise value of the threshold depends on the spatial resolution of the L-element antenna array and the angular spread of the signal sources. Not implementing the handoff when the threshold has been reached would lead to an undesirable beampattern, which, in turn, would increase interference and noise.

If the tracking method (Equations 9 to 12) is used directly in a mobile environment, large fluctuations in DOA estimation will occur, resulting in frequent and unnecessary intercell handoffs. To avoid this problem, the following change to Equation 12 is proposed:

$$\hat{\theta}_i(k) = \hat{\theta}_i(k-1) + \mu_2 \times \frac{\sum_{l=1}^{l=L} \nu_l \sin(\hat{\theta}_i(k-1) - \phi_l)\mathrm{Im}\{\ln(\tilde{\mathbf{A}}^*_{l,i}(k)\hat{\mathbf{A}}_{l,i}(k))\}}{\sum_{l=1}^{l=L} (\nu_l \sin(\hat{\theta}_i(k-1) - \phi_l))^2}. \qquad (21)$$

The added μ_2 ($0 < \mu_2 < 1$) may be viewed as a relaxation parameter that helps to smooth the DOA tracker.

For initialization of the DOA tracker, a signal subspace algorithm such as MUSIC or DSPE (Distributed Signal Parameter Estimator) [8] should be applied to yield the initial estimates of the target DOA (i.e. $\hat{\theta}_i(0)$ for $i = 1, \cdots, p$). Fortunately, in cellular mobile communications, there is no difficulty with the number of targets when these algorithms need to be used since the number of IC users at a given time is known.

SIMULATION RESULTS

For computer simulations it is assumed that there is a Uniform Circular Array (UCA) with $L = 13$ omnidirectional elements at the BS of the cell. The distance between elements of this array is $\lambda/2$ and $\lambda = 0.3$ meter (1 GHz). It is assumed that the p mobile IC users are moving with a speed of 100 km/h at a distance of 400 meters from the UCA and that the received power from these users is the same. For simplicity, the effect of other cells is not considered.

The multipath channel modeling for antenna array (vector channel) in cellular mobile systems is complex. For channel simulations, the Geometrically Based Single Bounced Circular Model (GBSBCM) [11] has been used. In this model, the scatterers are uniformly distributed within a circular region of radius R_m around the mobile units. It is assumed that $R_m = 100\lambda$ [9]. This assumption is valid when the base station antenna array is installed in an altitude sufficiently higher than the surrounding buildings in an urban region. Based on this assumption, the angular spread of the received signal is 8.6°. More elaborate multipath vector channel models may be found in [11,12].

DOA tracking of the signal sources is accomplished with the tracking method that was exposed in previous section with $\mu_1 = 0.4$ (see Equation 11). For computing SFCM $\mathbf{R}_{SF,i}$, Equation 20 is used with $\mu = 0.95$ and $T = 4.6$ msec; thus, $\hat{\theta}_i(k)$, $\mathbf{R}_{SF,i}(k)$ and $\mathbf{w}_i(k)$ are updated every 4.6 msec [13]. For track initialization a uniformly distributed error is added between $-2.5°$ and $+2.5°$ (i.e., $\Delta\theta_i(0) \sim \bigcup[-2.5°; 2.5°]$) to the true DOA. To avoid the common zone problem, it is assumed that an inter-cell handoff will occur via system management if the angular separation of two users becomes less than 10°.

Assuming that there is only one user per cell (i.e., $p = 1$), Figure 4 shows the true DOA path and the DOA estimation of this user using Equations 9 to 11 and 21 with $\mu_2 = 0.1$ and 1. With $\mu_2 = 1$, the curve shows very rapid fluctuations and large deviations in DOA estimation. In this case, the DOA difference of two neighboring users will sometime fall below the predefined threshold by mistake and an unnecessary inter-cell handoff will occur. Besides, these deviations will degrade the performance of the beamforming methods. In contrast, the curve corresponding to $\mu_2 = 0.1$ is smoother and shows smaller deviations from the true path. Note, however, that the fluctuations of the DOA estimate are unavoidable in a mobile environment, due to the distributed nature of the source (multipath effect). Equations 9 to 11 and 21 with $\mu_2 = 0.1$ are used for tracking in the subsequent simulations.

Figure 5 shows the BER for standard Capon, DILS and SF-Capon beamformers when there are $p = 1, 2, 3, 4$ IC users in the cell; BPSK modulation is assumed. It is seen that standard Capon does not work (for the reasons explained previously). For $p \geq 2$, the performance of SF-Capon significantly exceeds that of DILS. For example, in the case $p = 3$ for a BER of 3×10^{-3}, SF-Capon requires an input SNR of 9.5 dB, while DILS requires 14.4 dB.

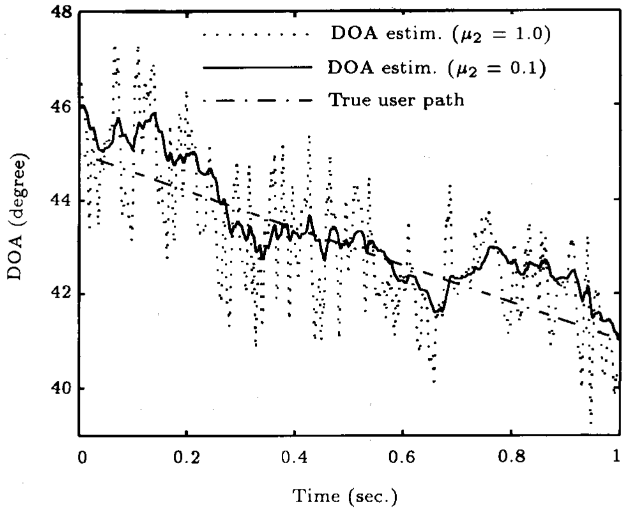
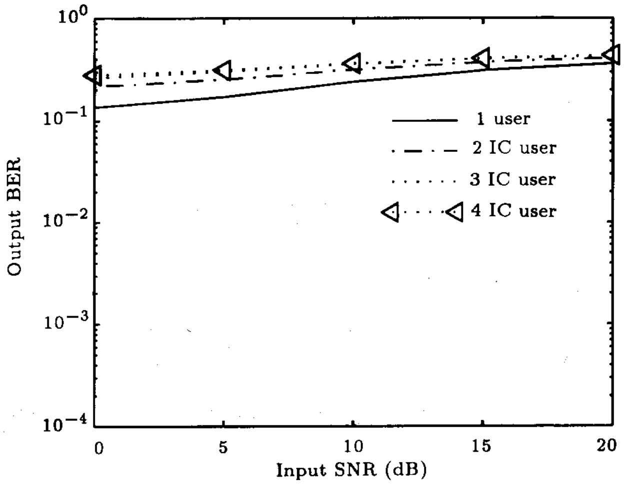
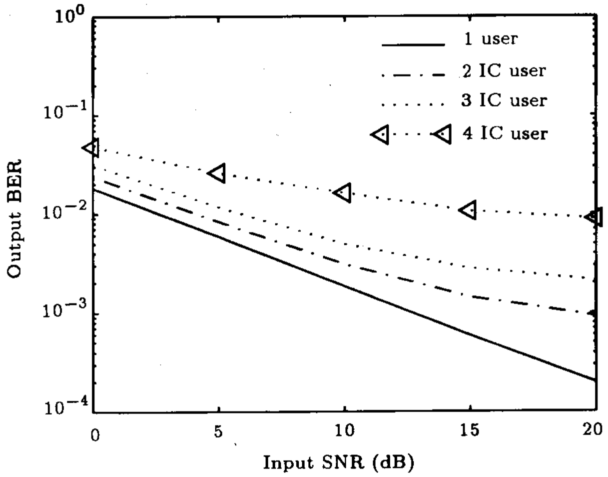


Figure 4. True DOA and DOA estimation of mobile source.

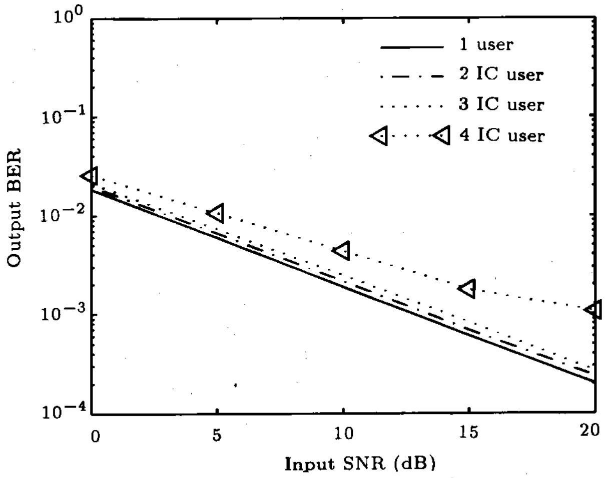
A saturation phenomenon may be observed in BER for the DILS beamformer as the input SNR increases. The reason for this saturation is that this kind of beamformer is data independent as mentioned



(a) Capon method



(b) DILS method



(c) SF-Capon method

Figure 5. Output BER versus input SNR for different numbers of IC-users.

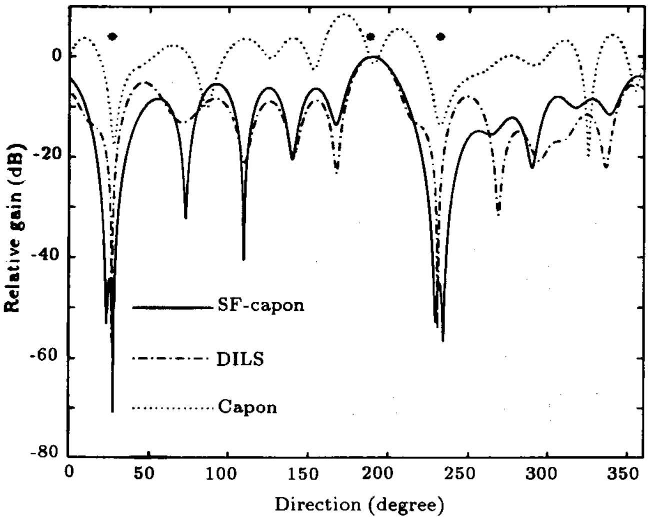


Figure 6. Array patterns of three beamforming methods.

previously. Thus, as the SNR increases, the level of the interference from other IC users increases and the DILS becomes ineffective, which translates into saturation of the BER.

In Figure 6, sample beampatterns of the UCA are shown for the three different beamforming methods, in the case $p = 3$ (direction of users is shown by * in this figure). It can be seen that SF-Capon produces deep, wide nulls in the direction of the interfering spread signal sources, while DILS produces sharp nulls in these directions, which is not adequate for this type of interference.

CONCLUSION

In this paper, it is shown that the minimum variance (Capon) beamformer, which maximizes the array output SINR, is not helpful for mobile communication systems due to the distributed nature of sources. A novel strategy has been proposed, based on Capon beamforming method, for extraction of multiple signals from an IC-user with an antenna array in TDMA/FDMA cellular mobile communications. In the proposed strategy, called SF-Capon, each IC-user is alternately asked to decrease (or halt) its transmitted power over a small window containing a few bits. This enables the estimation of the signal-free correlation matrix used to compute an improved beamforming weight vector.

Simulation results show that the SF-Capon strategy, in parallel with a proper DOA tracking method, enables a TDMA/FDMA cellular system to serve multiple IC-user with improved BER. Using this method, the produced beam pattern has a mainlobe in the direction of the desired user and relative nulls in the direction of interferers.

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