Multiplication of Cellular Radio Capacity by Blind Adaptive Spatial Filtering

William A. Gardner and Stephan V. Schell and Peter A. Murphy
Department of Electrical and Computer Engineering
University of California, Davis, CA 95616, USA

Abstract

Most current and proposed schemes for land mobile cellular radio systems rely solely on frequency, time, or code division multiplexing to allow multiple users in a cell to communicate simultaneously with the base station in that cell. In this paper, a scheme for greatly increasing the allowable number of simultaneous users in each cell is proposed. The scheme employs space-division multiplexing by means of an adaptive antenna array at the base station *i*) to separate the temporally and spectrally overlapping signals of users that arrive from different locations within the cell and to mitigate multipath fading and shadowing at the base station and *ii*) by reciprocity to transmit directively to minimize interfering signals arriving at the mobile units and to mitigate multipath fading and shadowing at the mobile units. A novel aspect of the proposed scheme is that no training signals are required for adaptation, nor are computationally intensive direction-finding methods required, nor is any calibration data required for the array. Results from computer simulations on the performance of the new scheme, which are presented here, show that the proposed scheme can accommodate up to 5 times as many users as a proposed CDMA scheme using the same system bandwidth.

I Introduction

Demand for mobile communication continues to increase as it becomes easier to use, is more widely available, and offers a greater variety of services, and as its benefits become more visible. The need for new mobile communication systems having increased spectral efficiency relative to current systems is compounded by increasing demand for radio spectrum allocations from other communication services. Various temporal processing schemes have been proposed for increasing spectral efficiency, including time division multiple access (TDMA) and frequency division multiple access (FDMA), although code division multiple access (CDMA) might offer the greatest potential increase in capacity (e.g., see [1],[2],[3]) in addition to inherently mitigating the effects of multipath. However, except for modifications of these schemes that use fixed multibeam or multisector antennas to further increase capacity, which is roughly equivalent to subdividing each cell into smaller cells, none of these schemes fully exploits the multiplicity of spatial channels that arises because each mobile user occupies a unique spatial location.

Some schemes that use space division multiple access (SDMA) by spatially filtering to separate spectrally overlapping signals from different users have been proposed with potential increases in spectral efficiency over conventional analog FM-FDMA schemes of a factor of 30 [4]. These schemes adapt the antenna array either by estimating the directions of arrival of the spectrally overlapping signals and then using these estimates to compute appropriate weights for the spatial filter [5], or by minimizing the time-averaged squared error between a known training signal and the output of the spatial filter [4, 6, 7, 8]. The schemes based on direction estimation have numerous disadvantages, including computationally intensive algorithms, poor performance in the presence of multipath signals arriving from different directions, the need to measure, store, and update array calibration data, and considerable sensitivity to errors in the array calibration data. The schemes that require a training signal have different disadvantages, including the need to use capacity to periodically transmit the training signal, the need to synchronize the received and locally generated copies of the training signal, and the need to adaptively increase or decrease the duration of the training signal to accommodate varying levels of interference.

The SDMA scheme proposed in this paper has some things in common with that proposed in [7], but unlike the scheme in [7] no reference (training) signal is needed here. An adaptive antenna array at the base station separates the temporally and spectrally overlapping received signals of different users in the cell and transmits directively to each user, exploiting multipath when present. Unlike schemes that rely solely on frequency, time, or code division multiplexing and thus use only one spatial channel, the proposed scheme exploits space as well as partial time and frequency division multiplexing and thus uses multiple spatial, temporal, and spectral channels. Users whose signals arriving at the base station are spatially separable can be assigned to spectral bands that are completely spectrally overlapping, and users whose signals arriving at the base station are spatially inseparable can be assigned to disjoint spectral bands. Also, signals coming from the individual users can be assigned to time intervals that are interleaved with those assigned to signals coming from the base station. Under the assumption that users are sufficiently well distributed throughout the cell, all available spatial and spectral channels can be used effectively. Since the number of multiple spatial channels that can be separated from each other by the antenna array is approximately equal to the number of antenna elements in the array (which can be quite large), overall capacity can be much greater than schemes using a single spatial channel. Also, unlike adaptive array schemes that require direction estimation processors or known training signals, the proposed scheme uses the SCORE algorithm [9] to exploit the spectral redundancy (cyclostationarity or spectral correlation) that is already present in essentially all digital communication signals [10, 11, 12], and thus does not require array calibration data or computationally intensive multidimensional searches nor does it waste channel capacity by transmitting a training signal.

The body of the paper is organized as follows. In Section II, the most relevant concepts from the theory of cyclostationary signals are summarized prior to their use in Section III, where the SCORE algorithm for blindly adapting an antenna array is summarized. In Section IV, the proposed space/time/frequency division multiple access (STFDMA) scheme is explained in detail. In Section V, the performance of the scheme is evaluated using computer simulations. Conclusions are given in Section VI.

II Cyclostationarity

In this section the most relevant concepts from the theory of cyclostationarity are reviewed prior to their use in Section III. More detailed treatments can be found in [10, 11, 12].

A vector-valued complex envelope $\boldsymbol{x}(n)$ exhibits cyclostationarity if it is correlated with either a frequency-shifted version of itself for any nonzero frequency shift α or a conjugated and

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frequency-shifted version of itself for any frequency shift α. Mathematically, this correlation is expressed in terms of the cyclic autocorrelation matrix $R^{\alpha}_{xx}(\tau)$ or the cyclic conjugate correlation matrix $R^{\alpha}_{xx^*}(\tau)$, respectively, where

$$R^{\alpha}_{xx}(\tau) \triangleq \left\langle x(n)\, x(n-\tau)^H\, e^{-j2\pi\alpha n}\right\rangle_{\infty} \quad (1)$$

$$R^{\alpha}_{xx^*}(\tau) \triangleq \left\langle x(n)\, x(n-\tau)^T\, e^{-j2\pi\alpha n}\right\rangle_{\infty}, \quad (2)$$

with $\langle f(n)\rangle_N \triangleq \frac{1}{N}\sum_{n=0}^{N-1} f(n)$ and where $(\cdot)^T$ and $(\cdot)^H$ denote the matrix transposition and matrix conjugate transposition operators, respectively. The values of α for which either of these correlation matrices are nonzero are the cycle frequencies of the signals comprising $x(n)$.

Most digital communication signals exhibit cyclostationarity as a result of the periodic sampling, gating, keying, and mixing operations in the modulator. For example, the cycle frequencies of BPSK are equal to the doubled carrier frequency offset, harmonics of the baud rate, and sums and differences of these. More specifically, if $x(n)$ contains a BPSK signal having carrier offset f_c (relative to the center of the reception band) and baud rate f_b, then $R^{\alpha}_{xx}(\tau)$ is not identically zero for $\alpha = kf_b$ for integers k, and $R^{\alpha}_{xx^*}(\tau)$ is not identically zero for $\alpha = 2f_c + kf_b$ for integers k. The useful values of τ in the correlation matrices are typically between 0 and $1/(2f_b)$. The only case of particular interest in this paper is the fact that for a scalar BPSK signal having carrier frequency offset f_c, the magnitude of the cyclic conjugate correlation $R^{2f_c}_{xx^*}(\tau)$ is maximized at $\tau = 0$ regardless of the pulse shape.

Measurements of these two types of cyclic correlations are useful because they select contributions from only the signal components that exhibit the specified cyclostationarity property and discriminate against all others. This is analogous to the property that measurements of the correlation between a desired signal corrupted by additive interference and noise and an uncorrupted version of the desired signal (e.g., the training signal) select only the contributions from the desired signal and discriminate against all others. The utility of exploiting cyclostationarity to gain signal-selectivity has been demonstrated for many applications, including adaptation of antenna arrays [9], estimation of directions of arrival [13, 14], estimation of time difference of arrival [15], detection [16], and others [10, 12].

III SCORE

In this section the SCORE algorithm for blindly adapting an antenna array is summarized. A more complete discussion can be found in [9].

Let the vector $x(n)$ denote the sampled complex envelopes of the output signals of M antennas having an arbitrary geometric arrangement and arbitrary directional characteristics (but preferably omnidirectional). To maximize spatial resolution while preventing grating lobes (ambiguities), the antennas are typically separated by approximately one half of the wavelength corresponding to the highest frequency in the reception band. It should be noted that this geometry is fundamentally different from that used in most space diversity systems, in which antennas are spaced many wavelengths apart so as to decorrelate multipath propagation parameters at the different antennas. Also, let $y(n) \triangleq w^H x(n)$ be the output of the spatial filter, where w is referred to as the weight vector. By choosing w appropriately, an adaptive receiver can enhance (steer beams in the direction of) desired signals, attenuate (steer nulls in the direction of) undesired signals, and minimize the contribution of additive noise (through coherent processing gain and by minimizing the height of sidelobes in the antenna pattern). In general, the sum of the number of beams and the number of nulls that can be controlled is equal to one less than the number M of antenna elements.

Instead of choosing w to maximize the degree of correlation between $y(n)$ and a known training signal as is typically done in conventional schemes, the SCORE method chooses w and an auxiliary spatial filter c to maximize the degree of correlation (correlation coefficient) between $y(n)$ and an auxiliary output signal $u(n) \triangleq c^H x(n-\tau)^*\, e^{j2\pi\alpha n}$:

$$\max_{w,c} \frac{|R_{yu}|^2}{R_{yy}\, R_{uu}} \;\Rightarrow\; \max_{w,c} \frac{\left|w^H R^{\alpha}_{xx^*}(\tau) c\right|^2}{[w^H R_{xx} w]\,[c^H R_{x^*x^*} c]}. \quad (3)$$

Under the assumption that L_α signals have cycle frequency α, it can be shown [9] that the solutions to (3) are given by the L_α most dominant eigenvectors w_l, for $l = 1, \ldots, L_\alpha$ that satisfy

$$R^{\alpha}_{xx^*}(\tau) R^{-1}_{x^*x^*} R^{\alpha H}_{xx^*}(\tau) w_l = \lambda_l R_{xx} w_l, \quad (4)$$

and similarly for c. It should be noted that only the most dominant eigenvector of (4) is needed when only one signal exhibits cyclic conjugate correlation at the chosen value of α, in which case the matrix product on the left-hand side of (4) has rank equal to one, and thus this eigenvector can be found using a simple iteration based on the power method (e.g., see [17]). In the STFDMA scheme proposed in Section IV, this is true in the absence of multipath reflections of the desired signal. In the presence of K spatially separable multipath reflections of the desired signal, each of the $K+1$ most dominant eigenvectors extracts a linear combination of the multipath reflections [9]; thus, the most dominant eigenvector can still be used to extract the desired signal, although an adaptive equalizer may be required to mitigate the smearing of the signal in time if the delay spread of the multipath is too great.

Alternatively, note that the desired signals (those having cycle frequency α) are the only ones common to both $x(n)$ and $x(n-\tau)^*\, e^{-j2\pi\alpha n}$ in the sense that the correlation between these two data sets is asymptotically equal to the correlation between the components due to the desired signals and their frequency-shifted and conjugated versions. From this point of view, estimating the desired signals is equivalent to estimating the common factors of the two data sets $x(n)$ and $x(n-\tau)^*\, e^{-j2\pi\alpha n}$. Common factor analysis (also called canonical correlation analysis) is a well-known technique in multivariate analysis (e.g., see [18]). Formulating the problem in this way leads to exactly the same solution (4).

The SCORE method can also estimate the desired signals that are common to both $x(n)$ and $x(n-\tau)\, e^{j2\pi\alpha n}$, in which case the conjugation symbols * are dropped from (4), although this variation is not used in this paper.

IV The Proposed STFDMA Scheme

In this section the proposed STFDMA scheme is presented. The description starts from the premise that spatial filtering is used at the base station and proceeds through various implications until the entire scheme has been motivated and explained. A simple example comparing the number of users per cell that can be accommodated by analog FM-FDMA, TDMA, CDMA, and the proposed STFDMA scheme is presented at the end of the section.

IV.A Details of the STFDMA Scheme

Spatial filtering at the base station separates spectrally and temporally overlapping signals of multiple mobile units during transmission from and reception at the base station and mitigates multipath fading and shadowing. Spatial filtering at the mobile units is impractical because the presence of numerous scatterers and reflectors in the vicinity of a typical mobile unit renders spatial filtering at the mobile unit largely ineffective [19], and the cost and size of an array having the required number of elements would be an unreasonable burden on the mobile users. The lack of spatial filtering at the mobile unit implies that mobile units must (somehow) be prevented from interfering with each other, because spatial filtering at the base station does not prevent each mobile unit from receiving the signals broadcast by other mobile units, since these broadcasts are omnidirectional.

Similarly to the scheme in [7], reception at the base station from all mobile units is multiplexed in time with transmission from the base station to all mobile units. During the former phase, the base station adapts its antenna array using the SCORE algorithm (4) while saving the received data; at the end of this phase, the computed weights of the spatial filters are applied to the stored data to separate the signals sent by the mobile units. During the latter phase, the weights computed in the former phase are used to direct the transmission of each outgoing signal to the appropriate mobile unit. The duration of the phases is limited here primarily by the reciprocal of the fast fading rate (the maximum rate is approximately 100 fades/s, so the duration of each phase can be about half the reciprocal, or 5 ms) because the propagation conditions must remain relatively constant over this time for the spatial filtering to be effective. A "dead time" during which neither reception nor transmission occurs is inserted between each phase to allow the trailing edges of the signal from or to the farthest mobile unit to arrive at their destination and to allow the microwave hardware at the base station and the mobile unit to switch between transmission and reception modes (since the same spectral band is used for both). This dead time is negligible (approximately 5 μs in a cell having radius of 1 mile) compared to the reception and transmission times (approximately 5 ms). The cycle, summarized in Figure 1, is then repeated.

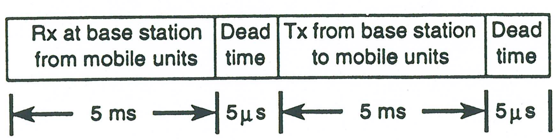

Figure 1: One reception-transmission cycle.

To avoid the waste of channel capacity and additional synchronization difficulties that occur when a training signal is used to adapt the array, the SCORE algorithm discussed in Section III, which is able to separate signals based on their differing carrier frequencies, is used. Thus, the SCORE algorithm (4) is implemented for each active user in the cell. Although it is conceivable that differing baud rates could also be used to separate signals, the additional complexity of accommodating a unique baud rate for each user is prohibitive. Consequently, each mobile unit is assigned a unique carrier frequency (accomplished during call initiation and hookup) according to the formula

$$f_l = f_0 + l\, f_{sep} \quad \text{for } l = 1, \ldots, L \qquad (5)$$

where f_l is the carrier frequency of the user numbered l, f_0 is the lowest frequency in the reception band, f_{sep} is the separation between adjacent carrier frequencies, and L is the maximum number of users that can be accommodated in the cell. This frequency allocation scheme is shown in Figure 2. The choice of f_{sep} is determined by the maximum Doppler shift (about 100 Hz in the land mobile cellular radio environment), and by some convergence-time considerations in the SCORE adaptation algorithm, namely the time required for an estimate of a cyclic conjugate correlation to adequately reject contributions from signals having adjacent carrier frequencies (at least 100 Hz separation is required for adequate rejection in the 5 ms during which adaptation occurs; this follows because the cycle resolution (see [12]) of the measurement of the cyclic conjugate correlation matrix, and thus the minimum separation of the doubled carriers, is equal to the reciprocal of the averaging time). The value of f_{sep} is also limited by the maximum number of spectrally overlapping users that can be separated by the antenna array. Because transmission from the base station to each mobile unit is highly directional, a smaller frequency reuse distance, such as three, can be tolerated in the proposed scheme than in the conventional analog FM scheme in which it is seven.

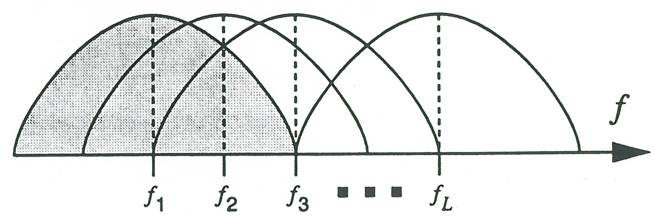

Figure 2: Frequency allocation in the proposed scheme. The spectrum of user number one is shaded to enhance clarity.

The success of the SCORE-STFDMA scheme depends on the ability to use spatial filters to spatially separate spectrally overlapping signals and the ability to use conventional spectral filters to separate spatially inseparable signals. The frequency allocation scheme just presented coupled with the use of the SCORE algorithm (4) accomplishes this under the assumption that spatially inseparable users can be assigned to disjoint spectral bands. One approach to accomplish this is to obtain and use knowledge of the directions of arrival of the signals from the mobile units. This in turn can be accomplished either by using a location sensing device (e.g., global positioning system) in each mobile unit, which could be prohibitively expensive, or by using the signal-selective Cyclic MUSIC or Cyclic Least Squares direction estimation algorithms [13] at the base station, or by using the SPECCOA or CPD time-difference-of-arrival algorithm [15] at multiple base stations. The Cyclic MUSIC and Cyclic Least Squares algorithms require the user of a calibrated array, but this array can be much smaller (e.g., only 4 elements) than the one used for spatial filtering because a unique carrier frequency is assigned to each mobile unit and the algorithms are signal selective. Also, it is possible to forego the task of locating mobile units and to assign frequencies at random and make reassignments whenever cochannel interference is detected after the spatial filter has converged. This detection can possibly be accomplished using the SCORE algorithm.

The modulation type is chosen for several reasons to be BPSK using Nyquist-shaped pulses having 100% excess bandwidth. The strength of the cyclic conjugate correlation $R_{xx^*}^{2f_c}$ for a BPSK signal having carrier offset f_c is the same as the strength of the signal itself, which speeds convergence of the SCORE adaptation algorithm. Although BPSK having 100% excess bandwidth is not as spectrally efficient as modulation types using less excess bandwidth and/or higher-order alphabets, it is less susceptible to noise, easier to synchronize to, and its 200% spectral redundancy (100% due to double sideband and 100% due to excess bandwidth) can be effectively exploited for equalization and reduction of residual cochannel interference [20]. Since the cyclic conjugate correlation characteristics of differential PSK (DPSK) are identical to those of BPSK, DPSK can be used for transmission from the base station so as to simplify the receiver in the mobile unit. The actual baud rate and thus the bandwidth of the BPSK signal depend on the rate of the vocoder used. As in many recent papers, a vocoder rate of 8 kb/s is used here. Since transmission and reception are multiplexed in time, the actual rate that must be supported by the channel is 16 kb/s, which yields a BPSK bandwidth of 32 kHz. In general, for a total system-bandwidth B_t, single-user channel-bandwidth B_c, and frequency-reuse factor r, the maximum number L of users that can be accommodated by the frequency allocation scheme in (5) is $L = (B_t/r - B_c)/f_{sep} + 1$. The number M of antenna elements required to separate these signals is bounded from below by the number K of users whose signals are spectrally overlapping with any given user's signal, where $M > K = 2(B_c/f_{sep} - 1)$. Using $B_c = 32$ kHz and $f_{sep} = 1$ kHz as above, at least 63 antenna elements (which can be omnidirectional) are needed to separate the signals of all users, assuming that the energy from each user arrives at the base station from a single direction, and assuming that the users are uniformly distributed throughout the cell. In practice, more antenna elements might be required to achieve adequate performance at full capacity in the presence of spatially separable multipath, although fewer antenna elements can suffice if a lower capacity is opted for and appropriate channel allocation is done. Also, adaptive equalization should follow the spatial filtering to mitigate the time-smearing effects of multipath.

IV.B Capacity Example

For the purpose of comparing the potential increase in capacity due to the proposed SCORE-STFDMA scheme relative to the analog FM-FDMA, TDMA, and CDMA schemes as considered in [1], consider a total system-bandwidth of $B_t = 1.25$ MHz. In the following comparison, the number of channels needed by each user in the FM-FDMA, TDMA, and CDMA schemes is two (one for transmission and one for reception), and one channel is needed by each user in the proposed scheme because transmission and reception are multiplexed in time. With FM-FDMA, using a channel bandwidth of 30 kHz, 2 channels per user, and a cell reuse factor of 7 yields 3 users per cell. With TDMA, using a channel bandwidth of 30 kHz with three time slots for TDMA, 2 channels per user, and a cell reuse factor of 4 yields 15 users per cell. With CDMA, using 2 channels per user, a frequency reuse factor of 1, sectorization of 3, and voice activity factor of 3/8 yields 120 channels per cell [1] or 60 users per cell. With the proposed SCORE-STFDMA scheme, using a channel bandwidth of 32 kHz, 1 channel per user, a cell reuse factor of 3, and a carrier separation of 1 kHz yields up to 385 users per cell. Decreasing the carrier separation to 500 Hz allows up to 770 users per cell at the expense of doubling the number of antennas. If future evaluations of SCORE-STFDMA show that the spatial directivity at the base station allows the frequency reuse factor to drop from three to one, then the capacity of SCORE-STFDMA would triple.

These results are summarized in Table 1.

Scheme	FM-FDMA	TDMA	CDMA	SCORE-STFDMA $f_{sep} = 1$ kHz
Users/cell	3	15	60	385
Rel. Eff.	1	5	20	128

Table 1: Summary of capacity and relative efficiency.

V Performance

In this section results of computer simulations of the proposed SCORE-STFDMA scheme are presented to support the claims made in Section IV that numerous spectrally overlapping users can be accommodated by means of adaptive spatial filtering at the base station without using a training signal. Two performance dependencies are explored: 1) average output SINR of SCORE-STFDMA versus the input SNR and number of spectrally overlapping users and 2) average output SINR of SCORE-STFDMA versus the number of multipath reflections and the angular separation of each multipath reflection from its direct path.

The following parameters are used in both sets of simulations. The antenna array consists of 64 omnidirectional elements spaced one-half wavelength apart on a circle that is co-planar with the mobile units (i.e., the elevation angle is assumed to be negligible). This would require an array diameter of 3 meters for a system center frequency of 1 GHz. The noise is zero-mean complex temporally-white Gaussian noise that is independent and identically distributed for each sensor. The signal to noise ratio (SNR) of each signal is defined to be the power of this signal received along the direct path divided by the power of the noise on a single sensor. The signal to interference and noise ratio (SINR) of the output is defined to be the power of the desired signal components in the output divided by the power of everything else in the output. As discussed in Section IV, the signals from the mobile units are independent BPSK signals having Nyquist-shaped pulses with 100% excess bandwdith and baud rate of 16 kb/s. The carrier separation f_{sep} is 1 kHz, and the data collection interval is 5 ms. The average output SINR is computed for the signal having zero carrier offset, which is referred to hereafter as the desired signal. Although the direction of arrival of the desired signal is 0 degrees in these simulations, any direction of arrival is allowable since SCORE does not require knowledge of the directions of arrival of any of the signals.

In the first set of simulations, 10 independent trials are performed for each combination of 8, 16, 24, 30, 36, 42 and 48 users and 10 dB, 5 dB, and 0 dB input SNR of the desired signal. The signal of each remaining user has SNR of 10 dB. For example, if the desired signal arrives with SNR of 5 dB in the presence of 47 other users' signals each having SNR of 10 dB, then the input SINR is $3.16/(47 * 10 + 1) = -22$ dB. The directions of arrival of the signals from the mobile units are equally spaced on the interval $[-180, 180]$ degrees. In spite of this severe interference, the SCORE algorithm attains a high output SINR by spatially rejecting the signals of the other users as shown in Figure 3.

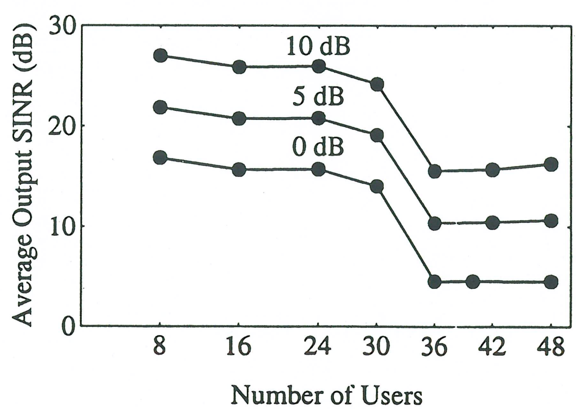

Figure 3: Average output SINR of SCORE-STFDMA scheme versus the number of spectrally-overlapping users for input SNRs of 0, 5, and 10 dB.

In the second set of simulations, 50 independent trials are performed for each combination of one and two multipath reflections having nominal angular separation of one and five degrees from the direct path. The direct-path signals and multipath reflections of 48 spectrally overlapping users are present, with each of the direct-path signals having SNR of 10 dB. The directions of arrival of the direct-path signals from the mobile units are nominally equally spaced on the interval $[-180, 180]$ degrees with a random perturbation in each direction of up to 2 degrees to more accurately model a typical environment. The multipath reflections each have SNR 0 dB (10 dB less than the direct-path signal) and have phases that are independent and uniformly distributed on the interval $[0, 2\pi]$ radians. Each reflection is nominally separated by 1 or 5 degrees from its direct-path signal with a random perturbation of up to 1 degree to more accurately model a typical environment. Even in the presence of this multipath, the SCORE algorithm attains a high average output SINR as shown in Table 2. Apparently, the exactly equal spacing of direct-path signals in the first set of simulations creates more difficulty for the spatial filter than does the perturbed spacing used in this set. Also, the results in Table 2 demonstrate that SCORE coherently combines the direct and reflected paths of the desired signal to increase the output SINR. Even more improvement is expected in the presence of stronger multipath. A typical antenna pattern of the spatial filter in this environment that extracts the desired signal and rejects the signals of other users is shown in Figure 4.

# of multipath reflections	0	1		2	
Angular sep. of multipath	-	1	5	1	5
Average output SINR (dB)	19.3	19.6	20.0	21.0	20.8

Table 2: Average output SINR of SCORE-SDMA scheme for different numbers of multipath reflections and angular separations. 48 spectrally overlapping users are present.

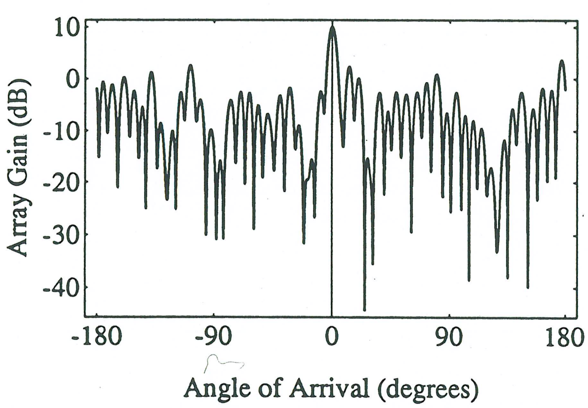

Figure 4: Typical antenna pattern of spatial filter found by SCORE. The desired signal arrives from 0 degrees and the signals of the remaining 47 users are roughly equally spaced on $[-180, 180]$ degrees.

VI Conclusion

In this paper, the SCORE-STFDMA scheme is proposed. The scheme uses blind adaptive spatial filtering at the base station to separate both signals received from and signals transmitted to the mobile units. Since the number of spectrally overlapping users' signals can be on the order of the number of antenna elements in the array at the base station (e.g., 64 or more), a substantial increase in capacity over competing schemes such as CDMA can be attained. The results of computer simulations show that SCORE-STFDMA performs sufficiently well with 48 spectrally overlapping users (i.e., from 15 to 20 dB output SINR even in the presence of multipath) that extremely high capacity (i.e., about 100 times that of analog FM-FDMA schemes and 5 times that of proposed CDMA schemes) and low bit-error rates can be attained.

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