TRANSMIT BEAMFORMING COMBINED WITH DIVERSITY TECHNIQUES FOR CDMA2000 SYSTEMS

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ABSTRACT

With the advent of new wireless mobile internet technologies, there has been a significant increase in demand for capacity on the forward link of cellular systems. While significant enhancements to the system have improved the performance of the system, there continues to be a greater need for even more capacity on the forward link. Further capacity can only be derived by exploiting the spatial distribution of users. By intelligently steering energy related to a mobile only in the direction of a mobile, capacity can be increased. Use of intelligent antenna techniques coupled with transmit diversity techniques offer the most robust performance gains across a variety of environments. This paper discusses an antenna array architecture which exploits a combination of diversity and coherent antenna arrays to achieve peak performance in a *cdma2000* environment. Performance results are given for this antenna architecture under a number of fading conditions.

1. INTRODUCTION

Third generation cellular systems can provide an increase in capacity to system operators over existing second generation systems. The gain in capacity on the forward link can be attributed to improvements in coding techniques, fast forward power control, and transmit diversity techniques. While these enhancements can improve the performance of the system, system operators expect that with increased demand for data services, these capacity enhancements may not be enough.

Further capacity can be squeezed out of the system without modifying the standard by using multiple transmit antennas. Several options are discussed in [6]. Some of these require standards changes. We will focus in this paper on possibilities that do not require standards changes. The multiple transmit antennas can be configured in one of three possible configurations as supported by the standard. A widely separated pair of antennas can be used to get diversity gain in the system by two different methods in the *cdma2000* standard. Orthogonal transmit diversity (OTD) achieves diversity gain by relying on the interleaver and decoder to recover energy from the two paths. The coded symbols are de-multiplexed into two different streams, Walsh coded separately and transmitted via two different antennas. The gain of this scheme is a function of the strength of the convolutional or turbo code which is employed [1].

The *cdma2000* standard [3] also supports a scheme where two symbols may be space-time coded [4] and transmitted via the two widely separated antennas. This scheme is referred to as space-time spreading (STS) [1]. For this scheme, the received signal achieves true two-fold diversity gain regardless of decoder and interleaver structure. This could result in fairly significant gains in single path Rayleigh fading. Per user reductions of 2dB (at high speed) to 6dB (at low speed) in required transmit power are possible depending on speed [1]. Most importantly, these gains are provided in situations where they are needed most. These low-speed users can require the most output power for the base station. The gains are slightly less if additional temporally resolvable multi-path exists in the environment. With two equal power paths with Rayleigh fading, this gain becomes smaller and varies from 1 to 2dB reduction in per user transmit power depending again on speed.

Alternatively, a fully coherent beam-steered solution could be utilized to improve performance. In this case, the performance gains achieved would be a function of the number of transmit antenna elements employed in the antenna array. For a two element antenna array, 3 dB of aperture gain could be achieved neglecting implementation losses. A four element antenna array could achieve 6 dB of aperture gain neglecting implementation losses. These gains are also not speed dependent. However, use of this type of array could require an additional pilot signal per user to coherently demodulate the signal. These pilot signals could require significant energy and reduce the effective gain of such an antenna array solution. Per-user pilot signals are conjectured to reduce the effective aperture gain by 2 dB. Implementation losses associated with inaccurate calibration of the antenna array elements can further reduce these gains.

Clearly, both of these schemes offer some performance benefit. A third alternative would be a scheme which employs both diversity and some form of antenna steering. This system could particularly exploit the gains achieved for a diversity system at low speeds and use steering to obtain additional gains. In this paper, we will discuss the antenna architecture of a base station which combines the features of a widely spaced antenna array together with the features of a closely spaced antenna array specifically for *cdma2000*.

2. STEERED-STS ANTENNA ARCHITECTURE

Antenna architectures which employ a combination of transmit diversity and beam forming could be realized by spacing two different groups of antennas far apart (approximately 10 λ where λ is the wavelength associated with the carrier frequency). Antennas within each group could then be spaced closely together (nominally, these would be spaced $\lambda/2$ apart). This antenna configuration is depicted in Figure 1. For a total set of M antennas, many groupings are possible. For example, if four antennas are utilized, the two groups could equally split the two different antennas into two pairs.

Each group of antennas would transmit/receive a different diversity signal. For this system, we would achieve diversity gain and aperture gain associated with the two antenna arrays. For a four element antenna array, we could realize the full diversity gain together with the aperture gain associated with a two element steered array. Combining these two gains without any implementation loss, we could realize 5 to 9 dB of transmit power reduction over a single antenna transmit system. We will refer to this system which utilizes a combination of diversity pre-encoding together with beamforming as a Steered-STS antenna architecture. Note that this could be used with OTD as well.

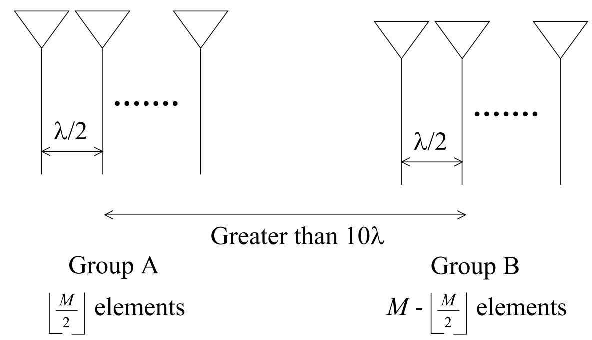

Figure 1: Steered-STS Antenna Configuration

3. STEERING ALGORITHMS

There are many different methods for steering the antenna array. The mobile could through training monitor the relative phase difference of the antennas and transmit to the base station this phase difference or a set of weights to obtain the maximum received energy. This is currently not supported by the *cdma2000* standard. Alternatively, we could infer the direction from the data available from the uplink (it would be shifted relative to the uplink frequency). Assuming reciprocity we can obtain an estimate of the angle of arrival which we could use as an angle of departure for the transmit antenna array [2]. This assumption has been verified using measured results.

If we assume that the received signal impinging on the antenna array can be modeled as a single plane wave, the received signal on each element of the antenna array will be:

$$r_i(t) = s(t)\gamma(t)e^{j\omega t}e^{j\frac{2\pi}{\lambda}d_i sin(\theta)} \tag{1}$$

where $s(t)$ is the information bearing signal and $\gamma(t)$ is the complex fading signal associated with this path. The angle θ is the angle of arrival relative to a perpendicular line drawn with the base of the array. The distance d_i is the distance between the i^{th} element and the first element of this array. For an array which has elements spaced $\lambda/2$ apart, this signal becomes:

$$r_i(t) = s(t)\gamma(t)e^{j\omega t}e^{j\cdot\pi\cdot i\cdot sin(\theta)} \tag{2}$$

We can estimate the angle θ by computing the correlation of adjacent antenna elements. For antenna 0 and 1, this correlation becomes:

$$E\{r_0(t)r_1(t)^*\} = |s(t)|^2|\gamma(t)|^2e^{-j\pi sin(\theta)} \tag{3}$$

If we assume that the signal has constant amplitude, $|s(t)|^2 = 1$ and that the channel does not introduce any gain, this correlation becomes:

$$\rho = E\{r_0(t)r_1(t)^*\} = e^{-j\pi sin(\theta)} \tag{4}$$

We can estimate ρ by averaging the uplink pilot information (over a long term to eliminate the effects of fading). Using the two uplink pilot signals associated with antenna 0, and antenna 1, the estimate for ρ becomes:

$$\hat{\rho}_{0,1}(n) = \alpha\hat{\rho}_{0,1}(n-1) + (1-\alpha)p_0(n)p_1(n)^* \qquad (5)$$

where $p_0(n)$ and $p_1(n)$ represent the pilot signals received on antenna 0 and antenna 1. We can similarly estimate all the $\rho_{0,i}$'s associated with each of the i elements. We can weight a downlink antenna array with an even number of antennas using the following weights:

$$\begin{aligned} v_0 = v_{M/2} &= 1 \\ v_1 = v_{M/2+1} &= \hat{\rho}_{0,1} \\ &\vdots \\ v_{M/2-1} = v_{M-1} &= \hat{\rho}_{0,M/2-1} \end{aligned} \qquad (6)$$

In order to realize the full gain of such an antenna array per user pilots may be also be similarly weighted by ρ. If degradation in performance can be tolerated, then the common pilot signal may be used for demodulation. In typical rural and suburban environments, the pilot signals will be nearly coherent with the data. The coherence will degrade as the angle spread gets very large.

4. APPLICATIONS TO CDMA2000

Many practical constraints are imposed on deployed antennas due to zoning restrictions, wind loading, and other requirements of service providers. Aside from practical issues of cost and complexity, this has kept equipment providers from deploying large scale arrays for cellular applications. If we restrict ourselves to the rather simple case of four antennas duplex-ed for receive and transmit, we can limit the number of cables and radomes deployed in the steered STS antenna configuration and still derive some benefit.

The antenna array architecture was simulated modeling most if not all of the physical layer features of the *cdma2000* standard. A spatial channel model was created which encompassed the effects of local scattering about the mobile and possessed directional sensitivity. Using this spatial channel model, directions of arrival and multi-path effects could be simulated. Full control over the spatial-temporal power delay profile of the channel is possible via this simulation model. For further discussion of this channel model, see Buehrer [5].

The focus of this paper has been on improving forward link capacity, and hence, we provide forward link simulation results for two different channel scenarios. The first case is single path Rayleigh fading. The algorithm as described earlier processes the pilot signals received from the uplink voice channel. The reverse link has a traffic to pilot ratio of 3.75 dB, and the traffic channel is a 9.6 kbps voice rate channel. It is a rate 1/3 convolutional coded channel. Inner and outer power control loops attempt to achieve a one percent frame error rate. The forward link consists of two pilot channel, a steered traffic channel, and a dummy channel. The two pilot channels are necessary for the mobile to identify both diversity signals and are as prescribed in the *cdma2000* standard [3].

Table 1: Forward Link Simulation Parameters

Base Station Antennas:	1 (No Div.) & 2 & 4 (SSTS)
Bit Rate:	9600bps
Chip Rate:	1.2288Mcps
Coding:	Conv. (K = 9, R = 1/4)
Frame Duration:	20ms
Frequency:	1.9GHz
Mobile Geometry:	I_{or}/I_{oc}= 6 dB
Pilot E_c/I_{or}:	-10, -10 dB
Max/Min power allocation:	-3 dB/-40 dB
Inner-loop PC rate:	800Hz
PC command error rate:	4%
Inner loop PC step:	±0.5dB
Outer loop PC step:	1.0 dB
Outer loop PC:	1% FER target
Channel:	Rayleigh fading

The simulation parameters for the forward link are summarized in Table 1. The total transmit power spectral density is referred to in this text as I_{OR}. The fraction of the transmit power allocated on a per chip basis to the traffic channel is referred to as E_C/I_{OR}. The signal to noise ratio in the channel is controlled by the ratio of the total traffic power, I_{OR}, to the total out of cell interference power which also includes the thermal noise in the receiver which is denoted as I_{OC}.

The dummy channel is used to simulate loaded cell site conditions. This channel is allocated a spectral density equal to the remaining power available from the base station after the traffic channel and pilot channel powers are subtracted.

Figure 2 displays the transmit power requirements for one path Rayleigh fading for a range of speeds from 1 km/hr to 100 km/hr. The angle spread for this simulation example is a few degrees which is typical of a suburban environment. In this figure, we can see that the transmit diversity (STS) technique can reduce transmit power fractions 2 to 6 dB over one antenna. The

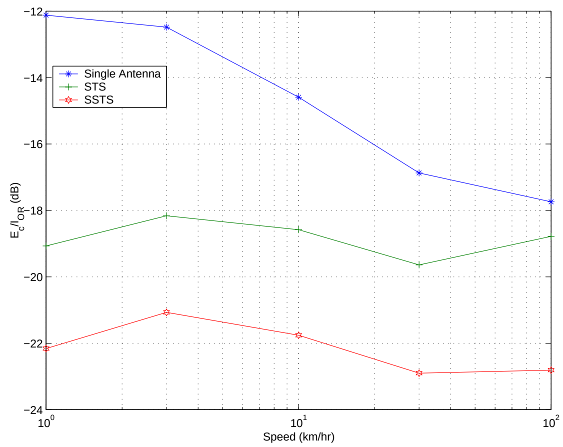

Figure 2: Transmit Power Requirements - Flat Fading

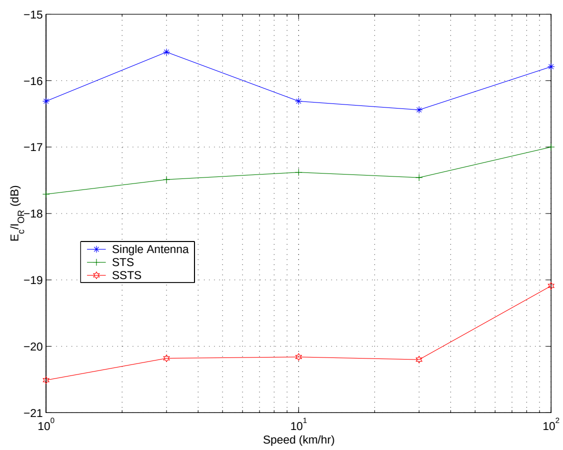

Figure 3: Transmit Power Requirements - Two Equal Power Paths

addition of the beam-steering can significantly improve performance further. It provides close to an additional 3 dB across the entire range of speeds. The authors believe that this simulation is unique to this paper and the earlier work of the authors [6]. This simulation model included the effects of power control errors, coding, channel estimation errors, spatial channel modeling and errors in estimation of the angles-of-arrival.

Figure 3 displays the results for two equal power paths. The two different paths which are temporally resolvable also have a spatial resolvability of 15^o. In this scenario, transmit diversity techniques can provide an additional 1 to 2 dB of gain over a single antenna. The addition of beam steering provides an additional 3 dB reduction in transmit power fraction.

5. CONCLUSION

This paper presented unique standard specific results which showed the benefits of applying a beamforming solution together with transmit diversity to obtain significant gains over a single transmit antenna. For a four antenna system with two pairs of widely spaced antennas, the gain over a single transmit antenna can be a 5 to 9 dB reduction in transmit power. The simulation model included numerous practical concerns which affect system performance. These items include cell-loading, power control bit errors, channel estimation errors, a spatial channel model and angle of arrival estimation errors.

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