Coded Transmit Macrodiversity:
Block Space-Time Codes over Distributed Antennas

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Abstract

This paper considers the combination of space-time codes and macrodiversity to the cellular downlink. The antenna array used by the space-time code is comprised of the antennas of two or three geographically separated base stations. For ease of exposition and to reduce algorithmic complexity, we have restricted our attention in this paper to space-time block codes. Simulation results indicate a significant improvement in energy efficiency at remote locations when the proposed system is used.

1. Introduction

Diversity can dramatically improve the performance in the presence of fading by allowing multiple paths with various attenuations to be combined. The general concept of diversity can be divided into two categories: microdiversity and macrodiversity. With microdiversity, the signals travel over paths that are within a few wavelengths of one-another, for example from one antenna array to another. With macrodiversity, the signals travel over vastly different paths, for instance from a mobile handset to the antennas of two or more base stations [1].

The recent introduction of space-time codes [2] has generated considerable interest on the topic of coded transmit diversity. For the cellular downlink, use of space-time codes has the benefit of shifting the burden of diversity reception from the mobile to the base station. Thus a mobile with a single antenna could have a *virtual* antenna array provided that the base station has an array and the transmission is space-time encoded. Previous research in the area of space-time codes has only considered the microdiversity case, i.e. when all of the transmit antennas are located in the same general location, such as at a single base station in a cellular system. The same principles can be applied to macrodiversity systems by considering the antenna array to be located at geographically separated base stations.

Fig. 1 shows how space-time codes can be used to achieve transmit macrodiversity in a cellular system employing 120-degree sectorized antennas. The key is to consider the system to be comprised of edge-excited cells: Each cell has three base stations located along the perimeter. Then a standard space-time code designed for three transmit antennas (or even six, if each base has a pair of transmit antennas) can be used on the downlink.

In this paper, we consider the use of space-time codes to achieve coded transmit macrodiversity. We have chosen to use space-time block codes due to their simplicity [3], although the concepts presented here will apply if space-time trellis codes are used instead. In the remainder of the paper we will present our system model, discuss block space-time codes suitable for two or three transmit antennas, and present some simulation results. The simulation results will show the required transmit power required for the downlink as a function of mobile position. It will be shown that the proposed technique has the potential to improve performance at remote locations in a manner analogous to soft-handoff.

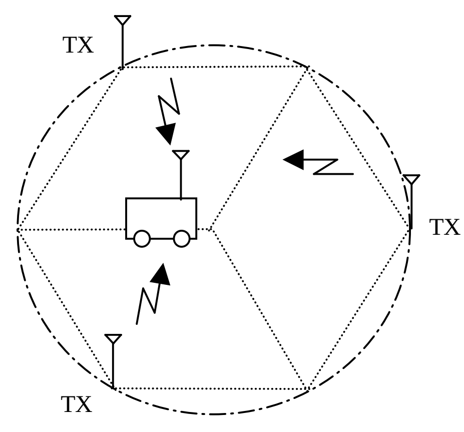

Fig. 1: Topology of macrodiveristy model.

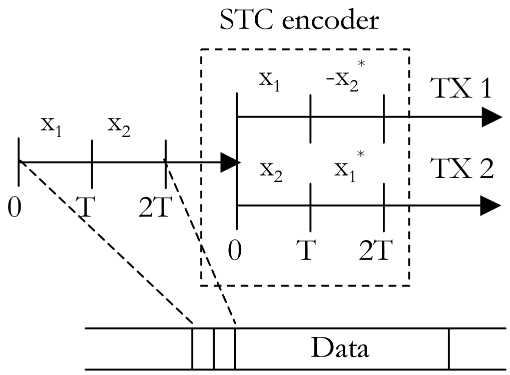

Fig. 2: Example block space-time code.

2. System Model

The system model employed in this study is identical to that presented in [3]. We assume that there are N transmit antennas located at adjacent base stations, and one receive antenna located at the mobile. There will be N distinct channel gains corresponding to the paths from the N transmit antenna to the one receive antenna. Each of these channel gains will be the product of two parts, a small-scale Rayleigh fading portion which is modeled by a complex Gaussian random variable, and a large-scale fading component which is a function of the distance between mobile and the appropriate base station.

Because of the different path lengths, the mean SNR at the mobile will not be the same for all N channels. In particular, the mean SNR at the mobile over channel i is:

$$\Gamma_i = \frac{E_S}{N_0}\left(\frac{d_i}{d_r}\right)^{-n} \tag{1}$$

where d_i is the distance between the mobile and base station i, d_r is the distance from the mobile station to the closest base station, E_s/N_o is the received SNR of the strongest path (which is from the closest base station), and n is the path loss exponent, which we take to be 3 [4].

We consider two scenarios — one with two base stations (i.e. N=2) and another with three base stations (i.e. N=3). The block space-time encoder considered for the N=2 case is illustrated in Fig. 2. The encoder encodes two symbols at a time to produce a pair of orthogonal sequences that are transmitted over the two antennas located at the two base stations. This encoder can more compactly be represented in matrix form [3]:

$$G_2 = \begin{pmatrix} x_1 & x_2 \\ -x_2^* & x_1^* \end{pmatrix} \tag{2}$$

where the two columns correspond to the two antennas and the two rows correspond to the two time intervals. With QPSK modulation, the spectral efficiency of this encoder is 2 bps/Hz.

For the N=3 case the following encoder is used [3]:

$$G_3 = \begin{pmatrix} x_1 & x_2 & x_3 \\ -x_2 & x_1 & -x_4 \\ -x_3 & x_4 & x_1 \\ -x_4 & -x_3 & x_2 \\ x_1^* & x_2^* & x_3^* \\ -x_2^* & x_1^* & -x_4^* \\ -x_3^* & x_4^* & x_1^* \\ -x_x^* & -x_3^* & x_2^* \end{pmatrix} \tag{3}$$

3. Two Base Station Case

In the two base station case, we assume that the mobile moves along the line connecting the two base stations. BPSK modulation is assumed and it is assumed that the fading is quasi-static in the sense that there is no correlation between two consecutive blocks. To illustrate the performance of the proposed system, we allowed the mobile to move from one base station towards the other and plotted the minimum mean received SNR required to guarantee that the bit error rate (BER) is no higher than 10^{-3}. Results of this simulation are shown in Fig.3.

From Fig. 3, it is evident that the mobile will require a higher normalized SNR when it is closer to either base station than if it is halfway between the two base stations. This effect is partially due to the way that SNR was defined in (1) — the SNR is the average received power from the closer base station. When the mobile is close to one base, the signal from the distant base is negligible and does not improve performance. However, as the mobile gets closer to the center of the line connecting the two base stations, the signal from the distant base station becomes stronger and improves performance. .

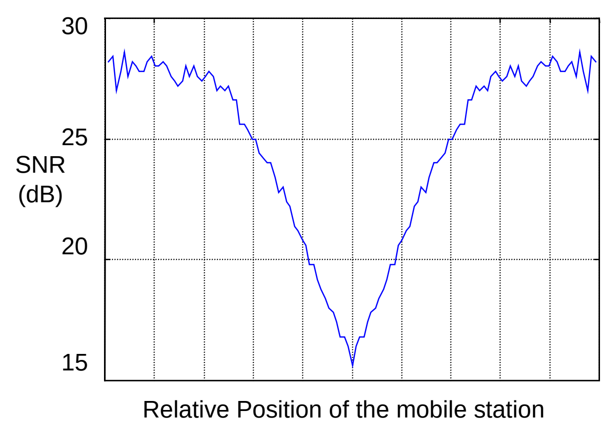

Fig. 3: SNR required for BER<10^{-3} as function of mobile's location between two base stations. Base stations are located at the left and right edges of plot.

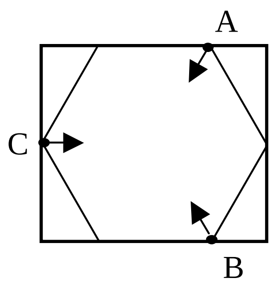

Fig. 4: Rectangular area encompassing the hexagonal cell used to generate the results shown in Fig. 5

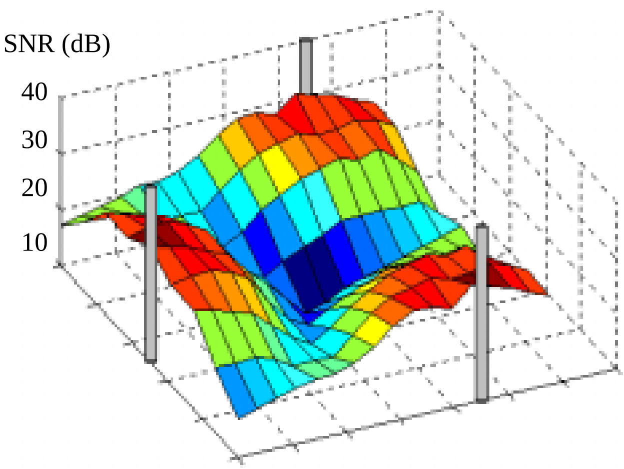

Fig. 5: SNR required for BER ≤ 10^{-3} for 120-degree sectorized antennas as function of mobile's location in the area given by Fig. 4. Base station locations are indicated by vertical bars.

4. Three Base Station Case

Earlier cellular systems were built using omnidirectional (i.e. isotrophic) antennas, and thus were represented as hexagonal cells with a base station in the center. Later, as the need for increased capacity arose, base stations were built using 120-degree sectorized antennas [4], which reduced the number of cochannel interferers in the first tier from 6 to only 2. It makes more sense to represent this system with hexagonal cells containing base stations on three corners, as shown in Fig. 1. Such a system is referred to as "edge-excited".

We simulated the performance of a system using three base stations, each with a single 120-degree sectorized antenna. The space-time code used QPSK modulation and encoder G3, as given by (3); thus the bandwidth efficiency was 1 bps/Hz. The mobile was repositioned throughout the rectangular area encompassing the hexagonal cell, as shown in Fig. 4. The base stations were located on equally spaced corners of the hexagon as indicated by the arrows.

The minimum received SNR required to achieve a BER of 10^{-3} is shown in Fig. 5. As with the two base station case, the required SNR is highest (around 30 dB) when the mobile is close to one of the base stations. This is due to the weak signals coming from the distant base stations. The performance improves when the mobile is midway between two base stations (around 17 dB) and is best when it lies precisely at the midpoint of the hexagonal cell (around 12 dB).

Performance is rather disappointing at the three corners that have no base stations (around 21 dB) due to the long relative path lengths to the base stations. This problem can be alleviated by using 60-degree sectorized antennas. With 60-degree sectorized antennas it is natural to represent the cell as an equilateral triangle, with base stations at each of the three corners, as shown in Fig. 6.

We simulated the performance of the 60-degree sectorized case by repositioning the mobile throughput the rectangular area encompassing the triangular cell, as shown in Fig. 6. Again QPSK modulation and encoder G3 were used for this simulation.

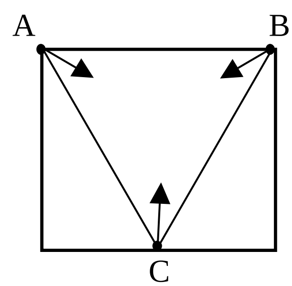

Fig. 6: Rectangular area encompassing the triangular cell used to generate the results shown in Fig. 7.

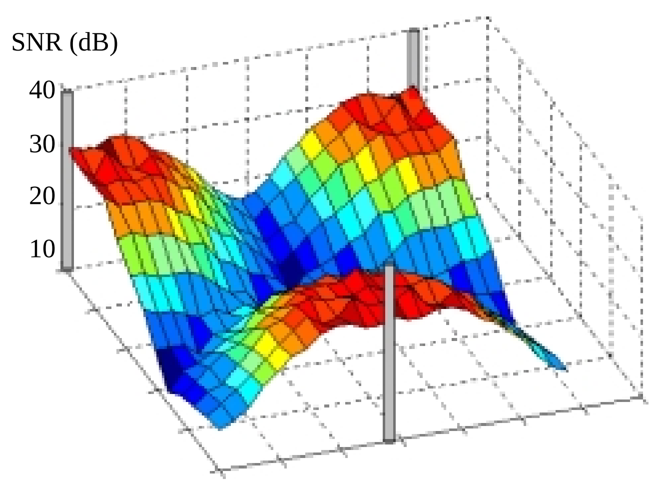

Fig. 7: SNR required for BER ≤ 10^{-3} for 60-degree sectorized antennas as function of mobile's location in the area given by Fig. 6. Base station locations are indicated by vertical bars.

The SNR required to guarantee BER $\leq 10^{-3}$ is shown in Fig. 7. As with the 120-degree sectorized case, performance is best at the center of the cell. Performance still degrades as the mobile moves away from the center, but is better than in the 120-degree case. Note that the performance at the center of the two vertical edges of the rectangle shown in Fig. 6 is identical to the performance at the center of the cell (about 12 dB). This is because these two locations are the centers of the neighboring triangular shaped cells. At these locations, the mobile station is still connected to two of the base stations in the original cell (although now it is using different sectors) as well as a new base station from an adjacent cell. Thus, we can see that the problem of poor performance in the cell corners when using 120-degree sectorized antennas and hexagonal shaped cells is solved by using 60-degree sectorized antennas and triangular shaped cells.

5. Comparison of Sectoring Schemes

For the base station topology shown in Fig. 8, the top figure shows the cells that correspond to 120-degree sectorization and the bottom shows the cells for 60-degree sectorization.

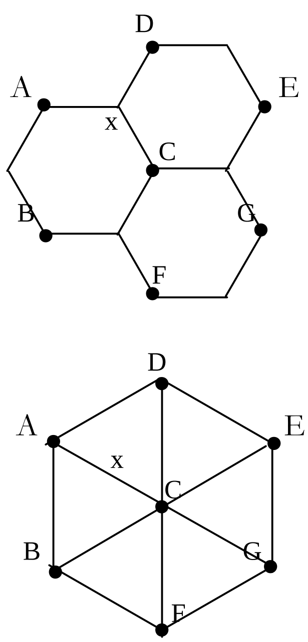

Fig. 8: Topology of 120-degree sectorized system (top) and 60-degree sectorized system (bottom).

Suppose the mobile station is randomly positioned at position x. In the 120-degree sectorized system, the mobile station is communicating with base stations A, B and C, but in the 60-degree sectorized system, the mobile station is communicating with base stations A, C and D. Since the distance between base station B and the mobile station is longer than the distance between base station D and the mobile station, the performance of the 60-degree sectorized system is better than 120-degree sectorized system. Thus, we can expect the capacity of the 60-degree sectorized antenna system will be more than that of the 120-degree sectorized system.

However, for the same antenna placement, the area per triangular cell for the 60-degree sectorized system is half that of the hexagonal cells of the 120-degree sectorized system, so more edge crossings occur when the mobile station is randomly moving. Thus, more handoffs are required. Furthermore, the trunking efficiency of the 60-degree sectorized system is worse than that of the 120-degree sectorized system [4]. Hence, a tradeoff exists between energy efficiency and handoff/trunking.

6. Conclusion

Multiple antennas implement full antenna diversity only if the distinct paths are uncorrelated with each other, which occurs when the antennas are sufficiently spaced apart. Transmit macrodiversity can be achieved by distributing the transmit antennas over a wide region, for instance at geographically separated cellular base stations. In this paper, we applied both macrodiversity and space time coding (STC) to the downlink of cellular systems comprised of two or three base stations per cell. Our investigation of macrodiversity and block STC has shown that the system can achieve the best performance when the mobile station is at the mid-point of all transmit antennas. For edge-excited cells, three base stations can be located in the corners of the cell. We considered and compared edge-excited cells that employ either 120-degree or 60-degree sectorized antennas. Simulation results confirm that the 60-degree system is more energy efficient, although this comes at the cost of a loss in trunking efficiency and more frequent handoff.

References

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