Simulation Results for an Interference-Limited Multiple-Input Multiple-Output Cellular System

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Abstract—We describe a simulation study of a cellular system using multiple-input multiple-output (MIMO) antenna techniques along with adaptive modulation and aggressive frequency reuse. We show, for the case of 3 transmit and 3 receive antennas, how much MIMO systems outperform systems with receive-diversity-only when noise dominates. When co-channel interference from surrounding cells dominates, the differences shrink, as do the absolute numbers. We quantify these reductions for the specific cases studied, and discuss further areas of research.

Index Terms—Adaptive arrays, adaptive modulation, adaptive signal processing, electromagnetic radiative interference, land mobile radio cellular systems, radio propagation.

I. BACKGROUND

RECENT research has shown that high theoretical wireless capacity can be achieved by using multiple antennas at both the transmit and receive sites in a rich scattering environment [1]. Furthermore, it has been reported that multiple antennas along with space-time coding and/or diversity techniques can aggressively exploit multipath propagation effects for communication [2]–[7]. In particular, in [6], the implementation of the so-called V-BLAST detection scheme in the laboratory has proven the feasibility of the multiple-input multiple-output (MIMO) concept by demonstrating spectral efficiencies of 20–40 bps/Hz under indoor conditions (slow fading environment). These results showed the potential advantage of MIMO system over more traditional approaches.

These enormous spectral efficiencies were obtained for a single link with no external interference. In a cellular environment, there will be channel reuse and therefore co-channel interference from other cells. Here, we describe a simulation study of MIMO techniques for cellular radio using *time-* and/or *frequency division multiple access* (TDMA and/or FDMA). We are motivated by the desire to quantify attainable MIMO performance in interference-limited cellular systems and to compare it to that of more traditional approaches under the same conditions.

II. SIMULATION APPROACH

A communication system that employs multiple transmitting and receiving antennas can be described as follows: A user's bit stream is demultiplexed among several transmitting antennas, each of which transmits an independently modulated signal, simultaneously and in the same frequency band. These signal components are received by an antenna array whose sensor outputs are processed such that the original data stream can be recovered.

We consider a MIMO system in a cellular environment for two scenarios. The first scenario considers an isolated link (downlink) between a base station located at the center of a hexagonal cell and a mobile user. This is the noise-dominated case. In the second scenario, one contiguous tier of six cells is added, with a frequency reuse in every cell. This is the interference-dominated case. The assumption of only one tier of interferers (made to simplify the simulations) is optimistic; we offset it, at least partially, with the pessimistic assumption that all co-channel interferers are transmitting all the time. The assumption of channel reuse in every cell is realistic; we have found that this is the choice (reuse factor = 1) for which the total cellular throughput is maximized under virtually all conditions.

In order to compare the performance of MIMO systems to more conventional approaches, we investigate three systems, denoted by (1, 1), (1, 3), and (3, 3), where the first number indicates the number of transmitters and the second one indicates the number of receivers. System (1, 1) uses no diversity and can be referred to as a single-input single-output (SISO) system. System (1, 3) uses diversity only at the receiver end and is a single-input multiple-output system (SIMO). More comprehensive findings on MIMO capabilities would require studying other transmit-receive antenna combinations as well, but the results given here are illustrative.

The simulation approach is as follows:

Terminal Location: We generate uniformly distributed random positions of the mobiles over the cell area.

Complex Path Gains: We simulate the complex path gains to the serving and interfering bases by considering the inverse distance law, the Rayleigh (complex Gaussian) fading, shadow fading, and the antenna pattern when sectoring is used in the multicell case. We use the following parameters values: path loss exponent $\gamma = 3.7$, log-normal shadow standard deviation $\sigma = 8$ dB and Ricean K-factor = 0. For the multicell case with sectoring, we assume three sector antennas per cell, each with a 3-dB beamwidth of $90°$.

Array Processing: We consider two alternative schemes for separating in the receiver the n transmitted signals from the base. One scheme linearly combines the received signals using a set of weights that yields the *minimum mean square error* between the estimate and the true signal (MMSE scheme). The second scheme, called *ordered successive interference cancellation* (OSIC-MMSE) is an improved version of MMSE suggested
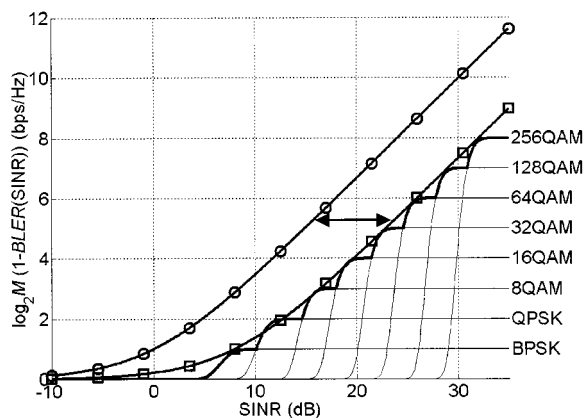
Fig. 1. Spectral efficiency (bps/Hz) versus SINR at the output of the combiner. The figure shown is for a block length of 500 symbols. ○ ideally coded signals throughput given by Shannon capacity: $\log_2(1 + \mathrm{SINR})$, □ uncoded signals throughput given by $\log_2 M(1 - \mathrm{BLER}(\mathrm{SINR}))$, ↔ shows the 8 dB shift between the two curves.

Fig. 2. Range from uncoded to ideally coded spectral efficiencies for systems (1, 1), (1, 3), (3, 3) in single cell environment ○ OSIC-MMSE processing, □ MMSE processing, ∗ no processing.

in [6] and [7]. It is a recursive procedure that sequentially detects the different signal components in an optimal order. First, MMSE combining is applied to the received vector signal. Then the substream with the highest output signal-to-(interference-plus-noise) ratio (SINR) is detected first, and its contribution is subtracted from the total received vector signal. The same process is repeated until all n substreams are detected.

Adaptive Modulation Rate: We assume an ideal algorithm that adapts the transmission rate on each transmit antenna (via the number of modulation levels), according to the radio channel and interference conditions. The per-user throughput is the sum of the throughputs of the n decoupled subchannels, where the throughput (T_i) of subchannel i is determined for two extremes cases: 1) *ideally coded signals* (perfect error correction), where throughput is bounded by the Shannon capacity $T_i = \log_2(1 + \mathrm{SINR}_i)$, SINR_i being the SINR at the ith output of the combiner,[1] and 2) *uncoded signals,* with perfect error detection in each block. In this case, the throughput is given by $T_i = \log_2 M_i(1 - \mathrm{BLER}(\mathrm{SINR}_i))$, where: $\log_2 M_i$ is the number of bits per symbol, and BLER is the block error rate for L-bit blocks. We plotted this term for an uncoded family of modulations (Fig. 1) and found that the Shannon capacity, shifted about 8 dB to the right, closely approximates the maximum throughput versus SINR (note the rightmost solid curve). This approximation holds for a large range of block lengths. In the low-SINR region (below ∼8 dB), the solid curve can be approximated by a system that uses BPSK with spectral spreading sequences.

Throughput Metric: We average the adapted throughput, for both ideally coded and uncoded signals, over the short-term Rayleigh fadings of the path gains. The ratio of this quantity to the signal bandwidth is a per-user quantity we denote by η. By repeating this procedure over 1000 random positions/sets of path gains, we find the probability distribution of η over the cell. In the present treatment, we compare systems (1, 1), (1, 3), and

(3, 3) in terms of the average of this distribution, $\overline{\eta}$. We choose the average (rather than, say, the median) because it has a specific and relevant meaning: In a typical system having many user channels, $\overline{\eta}$ is a close approximation to the total cell throughput per total system bandwidth. We refer to $\overline{\eta}$ hereafter as the *spectral efficiency,* in bps/Hz.

The key assumptions in this study are that the channel has a flat frequency response (delay spread is negligible), it is static during the burst duration (slow fading), and its complex path gains are uncorrelated. We also assume perfect adaptation of the modulation rate to the channel state. Finally, the total power transmitted on each link is the same, regardless of n, i.e., power P/n per transmit antenna.

III. RESULTS

Fig. 2 shows the range of spectral efficiency $\overline{\eta}$ using systems (1, 1), (1, 3), and (3, 3) in a single-cell (or noise-limited) environment. No power control is used and the median SNR is 20 dB at the cell boundary. The uncoded spectral efficiencies for (1, 1), (1, 3), and (3, 3) are roughly 7, 9, and 19 bps/Hz [considering OSIC-MMSE for system (3, 3)], showing an obvious advantage for the MIMO system. Note also the improvement obtained when adding interference elimination to MMSE in the (3, 3) case.

Fig. 3 shows the range of spectral efficiency $\overline{\eta}$ for systems (1, 1), (1, 3), and (3, 3) in a multicell environment, i.e., in the presence of co-channel interferers. The parameters are the same as in the single cell; the frequency reuse factor is 1; and sectoring is used. The results are much degraded by the presence of interferers compared to the single-cell results. The uncoded spectral efficiencies for systems (1, 1), (1, 3), and (3, 3) are roughly 2.5, 6, and 7 bps/Hz [considering OSIC-MMSE for system (3, 3)]. One striking result is that the difference in the performance between systems (3, 3) and (1, 3) has reduced significantly by going to the multicell scenario. In fact, the uncoded result for system (3, 3) with MMSE processing is smaller than that of system (1, 3) and the result obtained with OSIC-MMSE is barely larger than that of system (1, 3). However, both systems (1, 3) and (3, 3) still clearly outperform system (1, 1), showing the advantage of diversity. The reason system (3, 3) no longer offers

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[1]We can assume the interference is spectrally white (just like the noise), which makes this formula for T_i precise. The reason is that we specify *sinc* pulses for the data streams, whose power density spectra are therefore flat over the signal bandwidth.
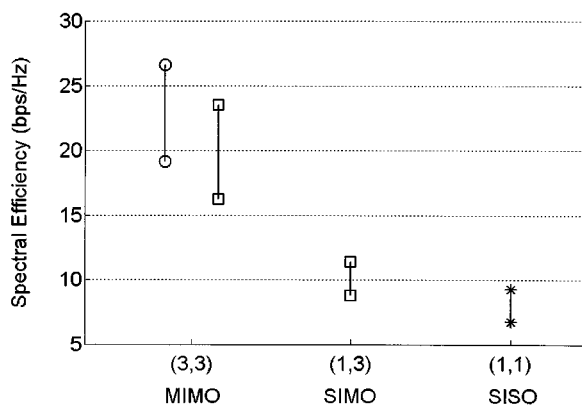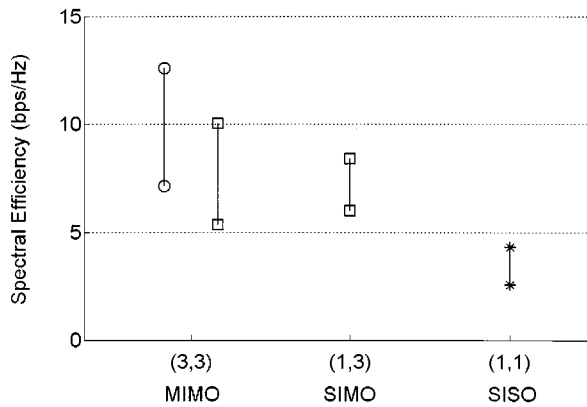
Fig. 3. Range from uncoded to ideally coded spectral efficiencies for systems (1, 1), (1, 3), (3, 3) with co-channel interferers ○ OSIC-MMSE processing, □ MMSE processing, * no processing.

a significant gain over system (1, 3) is that system (3, 3) has no degrees of freedom with which to cancel co-channel interferers after it separates the multiple data streams, whereas system (1, 3) does.

IV. CONCLUSION

MIMO systems offer dramatic data throughput gains over SIMO systems, but single-cell results are significantly reduced in going to a multicell environment when comparisons are made in terms of average throughput and the number of receivers is no greater than the number of transmitters. Increasing the number of receivers beyond the number of transmitters will add more de-grees of freedom for interference cancellation and thus will im-prove the throughput advantage of MIMO systems over SIMO systems. Limiting the modulation level to practical constellation sizes will increase this advantage further, as this will more seri-ously limit SIMO systems. Finally, other metrics not cited here have been studied, in addition to the average total throughput per bandwidth. These include the average as a function of user position (which decreases sharply with user distance) and the statistical spread among users (which increases with σ).

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