WIDEBAND SPACE-TIME COMMUNICATION: FROM PROPAGATION-BASED MODELS TO INFORMATION-THEORETIC DESIGN PRESCRIPTIONS

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ABSTRACT

While much of the activity on space-time, or multi-antenna, communication has focused on narrowband indoor systems, in this work, we consider the complementary setting of wideband outdoor channels typical of fourth generation cellular and fixed wireless systems, with a focus on Orthogonal Frequency Division Multiplexing (OFDM). Starting from propagation studies available in the literature, we obtain an analytical framework for information-theoretic design prescriptions that, compared to conventional space-time communication strategies, improve performance while reducing transceiver complexity. We introduce the notion of *implicit feedback,* applicable to both TDD and FDD systems, in which the base station learns the spatial covariance of the downlink spatial channel by averaging uplink measurements across frequency. We develop rules of thumb for optimizing antenna spacing for systems with such "free" feedback, and show that the number of antennas at the base station can be scaled up, thus increasing the beamforming gain, without any increase in complexity at the mobile. Spatial covariance estimation also simplifies receiver processing on the uplink, enabling a novel method of *noncoherent eigenbeamforming,* which yields beamforming gains without explicit channel estimation. Key to these results is the observation that, for appropriately spaced antenna elements, a typical outdoor cellular channel has a small number of dominant spatial eigenmodes, even as the number of antenna elements at the base station is scaled up.

1. INTRODUCTION

Space-time, or multiple-antenna, communication has received a great deal of attention lately. It is well accepted that indoor channels with rich scattering yield significant spatial diversity and multiplexing gains, and there is a significant ongoing effort in developing more robust and higher rate 802.11n Wireless Local Area Network (WLAN) technology that exploits such gains. In this paper, we ask how space-time communication can be exploited for outdoor communication, targeting fourth generation cellular systems, and emerging 802.16 and 802.20 Wireless Metropolitan Area Network (WMAN) standards. Space-time communication over indoor channels is typically narrowband, since the channel bandwidth is typically within the channel coherence bandwidth (which is large due to the small indoor delay spread). On the other hand, emerging high-speed outdoor communication systems can easily span a band which is several times the channel coherence bandwidth (which is small due to larger delay spreads in outdoor channels). Moreover, there is an asymmetry inherent in applications such as cellular and fixed wireless, in that the base station is significantly more capable than the subscriber unit: the base station can potentially have a large number of antennas, whereas the subscriber unit may have no more than one or two, and the base station is capable of more complex signal processing. In this paper, we review recent results [1, 2, 3, 4, 5] (the reader is referred to these papers for details omitted here) which demonstrate that rethinking the design of outdoor space-time communication with the preceding factors in mind leads to simultaneously better performance and simplified transceivers, compared to application of conventional space-time communication techniques developed for narrowband systems. We focus on OFDM systems, although some of our results may be of broader applicability.

We know from propagation measurements that outdoor channels typically have relatively small spatial spread, and one or two multipath clusters. Extensive propagation studies under the European COST program, as well as other measurement campaigns, have led to industry-standard statistical models for simulating such channels [6, 7]. A valid transceiver design must exhibit good performance at the nominal Signal-to-Noise Ratio (SNR) for "most" random channel realizations consistent with the statistical model. We employ an information-theoretic framework for evaluating transceiver designs, an approach that is validated by recent advances in turbo-like coded modulation, which imply that the Shannon theoretic limits that we obtain can be approached with practical transceiver architectures. The performance measures we adopt are the ergodic capacity and the outage rate, where the term "capacity" refers to mutual information attained by a standard Gaussian alphabet (in practice, this performance could be attained by appropriately sized PSK or QAM alphabets). The ergodic capacity is the mutual information averaged over the channel realizations. An outage is said to occur when the design does not work at the nominal SNR for a given channel realization. The outage rate at a given SNR is the rate sustainable for a specified fraction of the channel realizations (e.g., the 99% outage rate is achievable for 99% of the channels consistent with the statistical model).

In our system model, the base station has N_b antenna elements (N_b can be scaled up for improving performance), while the subscriber unit has N_s antenna elements (N_s is typically much smaller than N_b). A summary of our results is as follows:

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Tap Delay Line Model: We show that bandwidth-dependent tap delay line models, with parameters determined by measurable quantities such as power-delay profile and power-angle profile, give predictions of outage capacity that match those obtained by simulation-based channel models.

Outage Capacity Computation: For wideband systems, averaging performance across frequency implies that, for a variety of transceiver designs, the achievable rate is well modeled as a Gaussian random variable, invoking the central limit theorem. This, together with the TDL model, results in a simple analytical characterization of the outage capacity as a function of power-delay profile, power-angle profile, antenna array geometry, SNR, and transceiver strategy.

Downlink Optimization using Implicit Feedback: The base station can learn the downlink spatial covariance matrix by averaging across subcarriers on the uplink, thus providing implicit covariance feedback applicable to both FDD and TDD systems. A thought experiment on an idealized system indicates the rule of thumb that, for systems with covariance feedback, the antenna spacing should be optimized to create roughly N_s spatial eigenmodes, with the transmitter beamforming along these eigenmodes to create an effective $N_s \times N_s$ MIMO system. While beamforming gains can be increased by increasing the number N_b of antennas at the base station transmitter, the complexity of OFDM processing at the transmitter scales as N_s, the much smaller number of antennas at the subscriber unit, since the beamforming weights are independent of the subcarriers. See Figure 1. More importantly, the receiver in the subscriber unit only sees the effective $N_s \times N_s$ MIMO system, so that downlink performance can be improved by scaling up N_b, without any additional burden on the less capable receiver in the subscriber unit.

Uplink Optimization using Noncoherent Eigenbeamforming: On the uplink, estimation of the spatial covariance matrix allows the base station receiver to beamform along the small number of dominant spatial eigenmodes, providing large beamforming gains without requiring channel estimation. The received signal along each dominant eigenmode can be processed using turbo noncoherent communication techniques recently developed for single antenna systems, and the results can be soft combined to provide diversity. Such a noncoherent eigenbeamforming system, depicted in Figure 2, allows us to achieve both beamforming and diversity gains without requiring the transmission of pilot overhead from the subscriber units, and is shown to approach Shannon-theoretic limits.

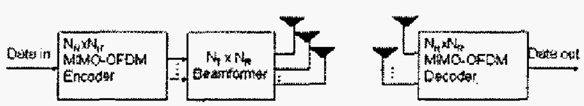

Fig. 1. MIMO-OFDM system with beamforming, where the number of transmit elements $N_T = N_b$, and the number of receive elements $N_R = N_s$.

2. CHANNEL MODEL AND PERFORMANCE WITH CONVENTIONAL STRATEGIES

The base station is assumed to be far away from the mobile, and at high enough altitude that there is little to no local scattering around

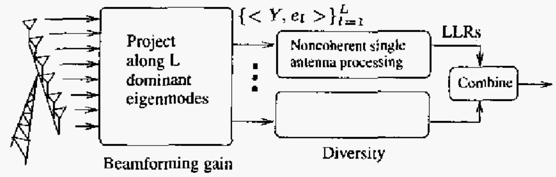

Fig. 2. Noncoherent eigenbeamforming on the uplink (N_b receive antennas)

it. Thus, both uplink and downlink signals for a given mobile are restricted to a fairly narrow spatial cone, from the viewpoint of the base station antenna array. In contrast, the mobile is assumed to be in a rich scattering environment. We assume a typical space-time channel model based on the superposition of specular rays, which are grouped into clusters as in the classic Saleh-Valenzuela model [6]. Each ray is parameterized by its delay, angle of departure (AOD), and amplitude. Experimental measurements of outdoor channels [7] indicate that the number of clusters is small, usually one or two, and that the power delay profile (PDP) and power angle profile (PAP) for each cluster as seen by the base station can be modeled as exponential and Laplacian, respectively.

The Vector Tap Delay Line Model: In [1, 2], we showed that the discrete ray channel model can be substituted by a vector TDL model with complex Gaussian taps without any loss of generality, applying the central limit theorem to the sum of unresolvable paths that are spaced less than $\frac{1}{W}$ apart. The tap weights have strength proportional to the square root of the PDP and covariance determined by the array geometry and PAP.

The Gaussian Approximation for Outage Rates: The spectral efficiency I_W for a system bandwidth of W is a random variable given by averaging the instantaneous mutual information at each frequency. From our TDL model, we can show that the channel gains at each frequency are identically distributed random vectors that decorrelate with frequency separation. Thus, application of the central limit theorem shows that I_W is well modeled as a Gaussian random variable. The mean is simply the ergodic capacity, which is bandwidth-independent. For a single transmit antenna, the variance is inversely proportional to a parameter that we call the *effective frequency diversity* D_f, which grows with the bandwidth and the spread in the power-delay profile. The effective frequency diversity can be physically interpreted as follows: the outage rate is the same as that of a system with D_f i.i.d. multipath components. Note that this notion of diversity does not appeal to high SNR asymptotics, unlike previous work (see [8] and references therein) on this subject. For multiple transmit antennas, the spectral efficiency is still Gaussian, and its mean is still bandwidth-independent. The variance is now inversely proportional to a product of the effective frequency diversity and the effective spatial diversity. The latter is a function of the array geometry and the power angle profile, and can be interpreted as the effective number of i.i.d. spatial paths.

The Gaussian approximation for the spectral efficiency yields analytical estimates that match very well with simulation results. These estimates apply both to full-blown space-frequency codes, and to suboptimum schemes, such as an *alternating* scheme that alternates across transmit antenna elements for different subcarriers. Figure 3 shows, for typical parameters, the simulated 1% outage rates for a full-blown space-frequency code and the alternating scheme, along with the Gaussian approximations for these quantities. It turns out that the variance of the spectral efficiency is the same for both schemes, but the alternating scheme has a smaller mean, and hence a smaller outage rate, due to a "Jensen penalty."

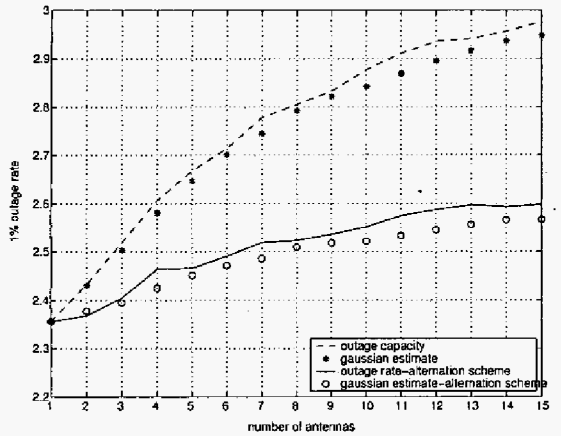

Fig. 3. Outage rates for a multi-antenna system.

In the next section, we will see that it is possible to improve performance *and* reduce complexity by exploiting the implicit covariance feedback that is available "for free" in wideband systems.

3. DOWNLINK OPTIMIZATION USING IMPLICIT COVARIANCE FEEDBACK

The preceding results were for systems without channel feedback at the transmitter. However, for OFDM systems, we show [3] that it is possible to obtain channel feedback without any overhead using the concept of *statistical reciprocity*. Since the space-time channels in each subcarrier are identically distributed random vectors, the base station can obtain their second order statistics by averaging across subcarriers on the uplink. This covariance feedback can be used to extract the dominant channel eigenmodes, and beamform along these eigenmodes on the downlink. Beamforming along K eigenmodes can be thought of as creating K virtual transmit elements: thus, a standard space-time code for K transmit elements can be employed with such a K-fold beamformer. For outdoor channels, the value of K is typically small, of the order of one or two. Since this method relies only on the channel statistics being the same for all frequencies, it works whether or not the uplink and downlink share the same frequency band. That is, it works for both Time Division Duplex (TDD) and Frequency Division Duplex (FDD) systems, and its robustness has been verified in both contexts [3, 4].

We provide an example of the performance gains from implicit covariance feedback for an FDD system that uses FDM on the uplink and TDM on the downlink. Note that implicit feedback on actual channel realization for each subcarrier using reciprocity is not available for FDD systems, so that, unless there is an explicit feedback channel, implicit covariance feedback is the only channel information available to the transmitter. Each mobile transmits using a fixed set of frequency bins which are equally spaced throughout the uplink spectrum so as to minimize the correlations between the channel responses. Half of the available spectrum

# subcarriers on user's uplink	C	R_o
no feedback	3.12	2.69
500	4.80	3.87
100	4.80	3.87
50	4.80	3.87
20	4.80	3.88
10	4.78	3.82

Table 1. Ergodic capacity and 1% outage rate in b/sHz when the BS station beamforms to the dominant eigenmode of $\hat{\mathbf{C}}_k$ computed using uplink measurements from the specified number of frequency bins.

(the left half) is reserved for the downlink. The BS forms $\hat{\mathbf{C}}_k$ from the feedback information in one OFDM uplink symbol and beamforms in the direction of the dominant eigenmode. In principle, if the base station estimates over too small a number of subcarriers when estimating the spatial covariance for a given mobile, then the inaccuracy in the resulting estimate may adversely impact performance. However, we see from Table 1, multiplexing mobiles onto different subcarriers causes a negligible decrease in capacity. For instance, the difference between one mobile using the 500 subcarriers on the uplink, and 50 mobiles sharing this spectrum is merely a 1% loss in outage rate. Thus, the system can support at least 50 users without incurring any performance degradation.

Compared to TDD systems, FDD systems has a smaller time delay between the acquisition of feedback on the uplink, and its use on the downlink. This may be desirable for high-mobility settings in which channel statistics may vary rapidly. However, our simulations for TDD systems show that our approach is very effective even with significant mobility: while channel realizations change rapidly, the channel statistics change much more slowly, which makes covariance feedback very robust.

Optimizing Antenna Spacing for Systems with Feedback: Covariance feedback informs us of the dominant eigenmodes of the channel, so that the transmitter can concentrate its energy along these directions. For a given antenna spacing and PAP, the number of dominant eigenmodes is fixed. However, this number, and hence the optimal transmit strategy and its performance, can be changed by varying the antenna spacing. We have derived results on optimal antenna spacing that can be roughly paraphrased as follows (with a number of caveats omitted due to lack of space): the antenna spacing should be chosen so as to create a number of dominant eigenmodes equal to the number N_R of receive antenna elements. For small N_R, we find that the optimal antenna spacing is much smaller than for systems without feedback, where capacity is maximized by spacing the base station antenna elements far enough apart so that they see uncorrelated channel responses. Detailed mathematical insight is obtained by conducting a thought experiment in which we are allowed complete control over the channel eigenmodes. The guidelines from the thought experiment are verified through numerical optimization in practical settings, where we only have partial control of eigenmodes through choice of antenna spacing. For example, for $N_T = 6$, $N_R = 2$ and a relatively narrow PAP, the ergodic capacity (with numerically optimized powers along each eigenmode) is plotted vs. d/λ in Figure 4. Below $d/\lambda = .82$, sending along 2 eigenmodes is optimal, and below $d/\lambda = .1$, beamforming is optimal. As expected, the maximum capacity occurs when 2 eigenmodes are dominant.

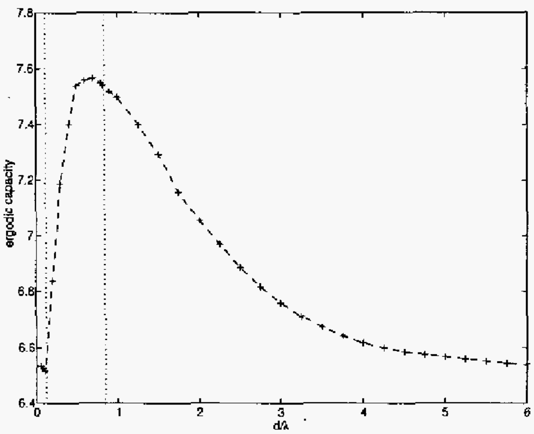

Fig. 4. Ergodic capacity vs. d/λ when $N_T = 6$, $N_R = 2$. In between the two vertical lines, "2 directional beamforming" is optimal. To the left of the left most line, beamforming is optimal.

4. UPLINK OPTIMIZATION USING NONCOHERENT EIGENBEAMFORMING

We next investigate wideband space-time communication on the uplink of an outdoor cellular system. We assume noncoherent reception at the base station, which incurs significantly less overhead than pilot-based estimation of the space-time channel from each mobile to the base station. We will again exploit the property that, for outdoor systems with elevated base stations, the incoming signal from a given mobile has a narrow power angle profile. We know from the previous section that the spatial channel covariance matrix is typically highly colored, having one or two dominant eigenmodes, and that it can be estimated by averaging across subcarriers.

For such a system, we propose the following noncoherent base station receiver architecture [5]:

(a) Estimate the spatial channel covariance matrix from the covariance matrix of the received signal, averaged across subcarriers (data demodulation is unnecessary, since data modulation on the subcarriers does not change the received covariance).

(b) Project the received signal in each subcarrier along the L dominant eigenmodes of the estimated spatial covariance matrix (L is typically much smaller than the number of receive elements N for a typical outdoor channel). This *eigenbeamforming* operation creates L parallel, independently fading, channels for the same transmitted data.

(c) For each of the L eigenmodes, use noncoherent coded modulation strategies with turbo-like joint data and channel estimation, as in prior work on single antenna channels [9, 10, 11, 12]. In such systems, the decoder and demodulator send extrinsic information to each other. A natural generalization yields a suboptimal but effective diversity combining technique: the decoder sends extrinsic information to each of L noncoherent demodulators running in parallel, and the extrinsic information from these L demodulators is summed before passing it to the decoder.

By appropriately exploiting the covariance estimate available in a wideband system, the preceding noncoherent receiver architecture provides many of the benefits of explicit space-time channel estimation without incurring its overhead. For example, beamforming gains in received SNR (relative to a single antenna system) are realized, while incurring reasonable complexity by using a small number of dominant eigenmodes for demodulation and decoding.

For numerical evaluation of the proposed architecture, we approximate the fading gains for each eigenmode by an independent block fading channel [10]. In an OFDM system, such an approximation might be applied to blocks of contiguous time-frequency bins in which the channel may be approximated as constant. We focus attention on operation at relatively low SNR, using QPSK constellations. Our main results are as follows:

- We compute the capacity with QPSK signaling of L parallel block fading channels of possibly unequal strengths. This is done in a manner analogous to prior work on symmetric block fading models. Capacity plots showing the diversity gain as a function of the number of dominant eigenmodes are provided.
- We provide numerical results for iterative joint data and channel estimation for a constructive coded modulation scheme consisting of a convolutional code, serially concatenated with differential QPSK. For multiple dominant eigenmodes, optimal noncoherent processing is excessively complex, so that our numerical results compare the performance of a suboptimal diversity combining scheme with the information-theoretic benchmarks we have obtained.

Figure 5 shows the beamforming gain as a function of the number of eigenmodes used for a 10 antenna system. The upper curve is for a single cluster channel whose power angle profile is Laplacian with zero mean and angular spread 10°, where angular spread is defined as the variance of Ω. The lower plot is for a two cluster system where the first cluster's power angle profile is as above, and the second cluster's power angle profile is also Laplacian with angular spread 10°, but has its mean at 45° (both clusters with the same power). The total receive power is normalized to be the same for both plots. Note that the beamforming gain quickly plateaus as a function of L: thus, beamforming along the dominant eigenmode captures most of the channel energy for the one cluster system, while using the first two eigenmodes captures most of the channel energy in the two cluster system. Thus, for typical outdoor channels, estimation of the channel covariance enables the use of a small number of eigenmodes by the demodulator and decoder, limiting complexity while preserving the SNR advantage from scaling up the number of receive elements.

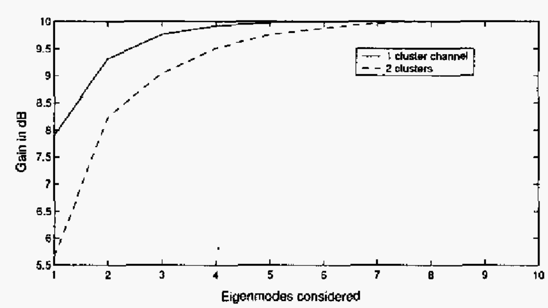

Fig. 5. Eigenbeamforming gain over a single antenna receiver

We have simulated the preceding diversity combining scheme with rate-3/4 convolutional coding and QPSK signaling, with iterative demodulation (with soft diversity combining) and decoding. Figure 6 compares the performance of our iterative demodulation and decoding scheme to capacity. We consider two cases: the channel has one or two dominant eigenmodes. At this data rate (1.35 bits per symbol), Shannon capacity predicts 1.8 dB improvement for the spatial diversity of two equal strength dominant eigenmodes, compared to the case of only one mode. Indeed, the linear combining scheme considered here yields a 1.4 dB gain for two channel modes, almost all of the predicted gain at this rate. We thus estimate the loss for (suboptimal) linear combining of parallel demodulator outputs as 0.4 dB. Note that, in either case, if the number of dominant modes is fixed (because of narrow power-angle profiles) while scaling up the number of receive elements, significant beamforming gains relative to a single antenna would be obtained.

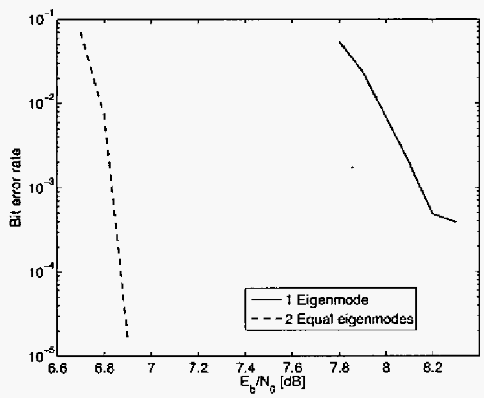

Fig. 6. One and two mode noncoherent diversity combining

5. CONCLUSIONS

We have shown that rethinking conventional space-time communication strategies in the specific context of wideband outdoor channels can have big payoffs, in terms of large performance gains, while at the same time reducing signal processing complexity at both the base station and the subscriber. In particular, our techniques enable performance enhancement by increasing the number of antennas at the base station, without *any* impact on transceiver complexity at the subscriber. While the information-theoretic benchmarks that we have computed show the promise of the proposed designs, an important topic for future work is to devise practical coded modulation strategies for approaching these benchmarks.

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