TOWARDS SHANNON-THEORETIC LIMITS ON WIRELESS TIME-VARYING CHANNELS

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ABSTRACT

We survey our recent results on approaching the performance limits of wireless time-varying channels. In current practice, transceivers for such channels employ a large fraction of training or pilot overhead for channel estimation and tracking, together with coherent reception assuming that the channel estimates are accurate. In this paper, we discuss our progress in developing an alternative *noncoherent* approach, in which the channel and data are estimated jointly, heavily leveraging iterative decoding techniques.

1. INTRODUCTION

Since the introduction of turbo codes a decade ago [1], there have been many exciting advances in turbo-like codes and iterative decoding optimized to approach Shannon capacity for classical memoryless channel models, such as the binary symmetric channel, the binary erasures channel, and the additive white Gaussian noise (AWGN) channel. Clearly, such turbo-like techniques hold great promise for efficient communication for channels with memory as well [2]. Thus, the following Shannon-theoretic approach to transceiver design is expected to be broadly applicable: employ information-theoretic capacity computations to characterize "good" signaling formats that approach capacity, and then devise turbo-like code constructions and iterative decoding techniques based on such signaling formats. In the work discussed in this paper, this approach is applied for the design of coded modulation techniques for wireless time-varying channels.

We mainly focus attention on a block frequency-nonselective Rayleigh fading channel model, in which the channel gain is modeled as constant over a block of symbols. We argue in Section 1 that this is indeed a good model for operating regimes of practical interest. The generic code construction that we employ consists of a standard outer binary code, serially concatenated with an inner modulation code. Under the block fading channel model, the transmitted signal can be multiplied by arbitrary complex scalars. We consider noncoherent designs, in which explicit channel estimates (e.g., using pilots) are not available at the receiver, so that the receiver employs joint data and channel estimation. Since the channel is unknown (although constant over a block of symbols), the mapping from information bits to modulated signal over a block must be unchanged under complex scaling. Various forms of differential modulation, for example, have the required property, and this is indeed a choice that works very well with an appropriate choice of outer code.

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Section 2 discusses information-theoretic computations and their implications. Section 3 provides a summary of recent results on turbo-like coded modulation strategies. Section 4 discusses recent work on noncoherent receive beamforming for wideband systems, aimed at outdoor cellular uplinks where the base station receiver is equipped with multiple antennas.

2. SHANNON THEORY FOR TIME-VARYING CHANNELS

Consider a frequency-nonselective Rayleigh fading channel, in which the nth received sample is given by

$$y[n] = h[n]x[n] + w[n]$$

where $x[n]$ denotes the transmitted symbol, $h[n]$ the time-varying complex channel gain, and $w[n]$ denotes AWGN. Common models for $h[n]$ include Clarke's model (usually implemented using Jakes' simulator [3]), or a Gauss-Markov model. If $\{h[n]\}$ is stationary, then rather general results by Lapidoth and Moser [4], building upon earlier results of Lapidoth and Shamai [5], imply that, as the SNR gets large, the capacity of the preceding time-varying channel grows only as $\log \log SNR$, rather than the $\log SNR$ growth for a classical AWGN channel. Intuitively, this is because the effect of the errors in (implicit or explicit) estimation of the channel dominates the effect of noise at high SNR. Clearly, such a regime is extremely unattractive from the point of view of power efficiency. Fortunately, for applications such as outdoor cellular wireless, the typical combination of SNRs and channel time variations does not fall in this regime [6]. Indeed, the block fading channel model is a natural fit to many typical operating regimes. In this model, $h[n]$ is constant over a block of symbols (of length equal to the channel coherence length), with the implicit assumption that the variation of the channel realization across a block is small compared to the AWGN. The channel realization is assumed to be independent over different blocks, for convenience, which is consistent with the kind of interleaving employed

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in coded modulation for fading channels. Note that the block fading channel has been shown to exhibit $\log SNR$ growth at high SNR [7], which implies that conventional power-bandwidth tradeoffs are applicable as long as we avoid the extremely high SNRs where the results of Lapidoth and Moser [4] become applicable.

Marzetta and Hochwald [8] provided the first information-theoretic characterization of the block fading channel. Roughly speaking, their result indicates that, for moderate and low SNRs, and reasonable channel coherence lengths, independent and identically distributed (i.i.d.) Gaussian inputs are near-optimal. Since this is the same input that is optimal for the classical AWGN channel, it is natural to ask whether signal constellations employed for the AWGN channel would work well for the block fading channel. We verified [9] that this is indeed the case. Figure 4, reproduced from [9], shows mutual information versus SNR for various QAM and PSK constellations. Clearly, such constellations can be employed to approach capacity, when used in conjunction with appropriate codes. As for the AWGN channel, QAM is superior to PSK at higher SNR. Since we plan to employ noncoherent communication, therefore, this implies that techniques such as differential modulation (conventionally employed for PSK constellations) must be extended appropriately to QAM constellations as well.

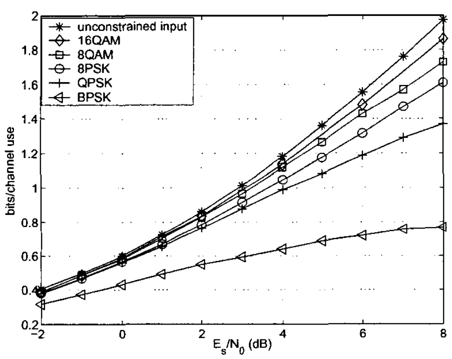

Fig. 1. Noncoherent block (length = 10) fading capacity

The preceding Shannon-theoretic considerations lead naturally to the efforts reported in the next section, which provide explicit noncoherent encoding and decoding strategies aimed at approaching capacity for the block fading channel.

3. TURBO NONCOHERENT COMMUNICATION

The key ideas, which are developed in more detail in [9] and [10] are as follows. A standard outer binary code is serially concatenated with an inner code amenable to noncoherent demodulation. The decoder uses iterative decoding for joint channel and data estimation, exchanging information between the demodulator and the decoder, similar to the information exchange between component decoders in a standard turbo code.

Noncoherent block demodulation, which exploits the fact that the channel is constant over a block of symbols, is used to avoid the conventional penalty due to differential demodulation. The complexity of block demodulation is exponential with block length, hence suboptimal techniques with linear complexity are critical for practical viability of such schemes. The basic idea behind the suboptimal implementation is to estimate, for each block, the unknown channel amplitude, and to quantize the unknown channel phase into bins. Coherent demodulation is employed for each bin, and the outputs are combined to obtain soft decisions fed to the decoder. In order to lower complexity further, a phase arbitration mechanism based on feedback from the decoder can be used to reduce the number of phase bins.

Some sample numerical results for a QAM constellation, using a convolutional code concatenated with differential modulation, are shown below. For the moderately high SNRs considered here, this constellation performs better than a PSK constellation of the same size. The gap from the Shannon limit for the constellation is 2.4 dB. In order to understand where to put the emphasis on design for closing this gap, we attempt to decompose it into two sources: decoder implementation and code construction. An estimate of the gap due to the code construction is obtained by deriving a coherent benchmark corresponding to a genie-aided decoder that knows the channel. Thus, in Figure 2, we observe that 1.6 dB can be attributed to code design, and the remaining 0.8 dB to unknown channel. We further decompose the gap due to decoder implementation into 0.3 dB for unknown phase and 0.5 dB for unknown amplitude. Our complexity reducing phase arbitration mechanism incurs only an additional 0.1 dB loss.

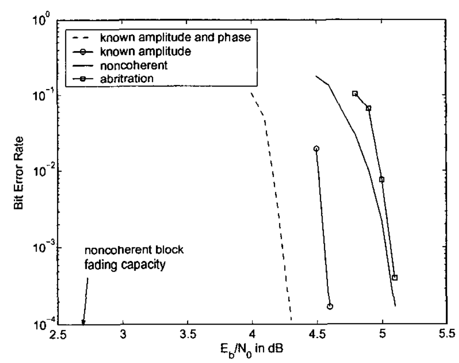

Fig. 2. Noncoherent 8QAM signaling on the block fading channel

With the complexity-reducing techniques in [9, 10], transceiver architectures based on the noncoherent paradigm are becoming computationally feasible. However, further work is needed on code construction for fading channels, in order to close the gap to capacity. Note that the block nonselective fading model that forms the basis for the architecture applies naturally to wideband Orthogonal Frequency Division Multiplexed (OFDM) systems, in which the channel gain in each time-frequency bin is a scalar which can be modeled as constant over time-frequency blocks of size determined by the channel coherence time and coherence bandwidth. The operating regime where this framework is of most interest is that of low to moderate mobility and SNR: the lower the mobility, the more feasible it is to operate at higher SNR and higher spectral efficiency using a large constellation. However, as the mobility (and hence the rate of channel time variations) increases, the block-wise constant channel model used here starts breaking down, and, as discussed in Section 1, it becomes extremely power-inefficient to operate at high SNR [4]. Indeed, even the structure of the noncoherent demodulator must be reconsidered in this setting [11].

4. NONCOHERENT EIGENBEAMFORMING

Outdoor cellular systems, in which channel time variations can be significant due to mobility at vehicular speeds, are an important target application for our work on noncoherent systems. Keeping this application in mind when extending our ideas to multi-antenna (or space-time) communication, we note that, while a base station may have multiple antennas, it is unlikely for a mobile to have more than one or two antennas. Furthermore, since pilot overhead can be shared by multiple mobiles on the downlink, noncoherent designs may be most attractive for uplinks, where they enable elimination or reduction of overhead sent separately from each mobile. Thus, we focus on noncoherent reception using multiple antennas. We consider a wideband OFDM system, given the emerging consensus that OFDM will be the technology of choice for fourth generation wireless systems.

For outdoor channels, the base station is often highly elevated, so that the power-angle profile of paths that reach the base station from a given mobile is typically quite narrow. Thus, the spatial channel covariance matrix has a small number of dominant eigenmodes. See [12, 13] for closely related results on outdoor downlinks. The key new ideas in our work are as follows. For an OFDM system, the spatial covariance matrix can be obtained by averaging over subcarriers, without requiring any pilot overhead. Beamforming along the dominant eigenmodes of the channel creates parallel noncoherent channels, one for each dominant eigenmode, which can now be processed using extensions of the iterative decoding methods in Section 2.

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.

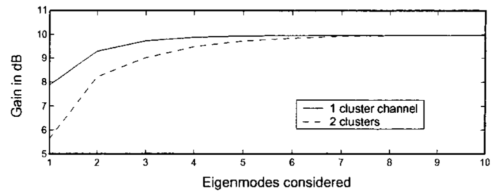

Fig. 3. Eigenbeamforming gain over a single antenna receiver

For a typical outdoor channel model, Figure 3 shows the beamforming gain as a function of the number of eigenmodes used for a 10 antenna system. The upper curve is for a channel with a single multipath cluster with a narrow power-angle profile. The lower plot is for two multipath clusters with widely different angles of arrival, but with each cluster having a narrow power-angle profile. The total receive power is normalized to be the same for both plots. Note that the beamforming gain quickly plateaus as a function of the number of eigenmodes used: 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.

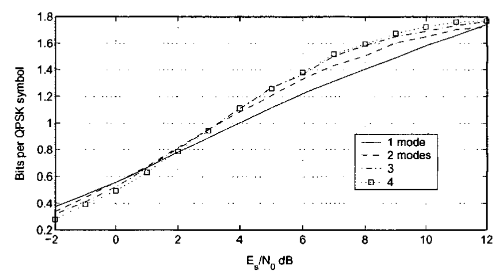

Fig. 4. Block fading capacity with varying number of dominant eigenmodes

Information-theoretic computations of capacity with QPSK signaling show that the performance is relatively insensitive to the number of dominant eigenmodes at low SNR, while there is a diversity gain of up to 2 dB at high SNR. Thus, the penalty due to the relatively few spatial eigenmodes for outdoor channels is small for OFDM systems, assuming that there is enough averaging across frequency and time.

Simulations of a simple extension (for diversity combining of soft outputs for each parallel branch) of our iterative decoding techniques in Section 2 are presented in the figure below. Rate-1/4 convolutional coding, serially concatenated with differential QPSK, is compared to capacity. We consider two cases: the channel has one or two dominant eigenmodes. For the low rate (0.45 bits/symbol) considered here, spatial diversity is not advantageous: having two modes actually leads to a 0.2 dB loss in Shannon capacity compared to one mode. Adding in the implementation loss due to the suboptimal diversity combining scheme, we find that the two-mode channel is about 0.7 dB worse than the one-mode channel. In either case, if the number of dominant modes remains small (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.

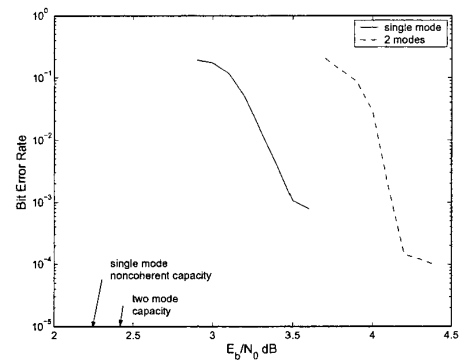

Fig. 5. One and two mode noncoherent diversity combining

5. CONCLUSIONS

Power- and bandwidth-efficient noncoherent transceiver designs are now available that give significantly better performance than conventional designs at only slightly larger computational complexity. Such techniques are directly applicable to the design of fourth generation wireless systems. However, further research is needed in code constructions for closing the 2-3 dB gap that still remains to Shannon capacity.

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