Transceiver design for the outdoor wireless channel: an information-theoretic perspective

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Abstract— **In this paper, we summarize some recent results on information-theoretic limits for the outdoor wireless mobile channel, with the aim of deriving transceiver design guidelines for fourth generation cellular systems. We consider two main themes, as follows: (a) The cost and accuracy of channel estimation must be factored into the derivation of information-theoretic limits for time-varying channels. To this end, we consider noncoherent communication, interpreted as joint channel and data estimation, over a flat Rayleigh fading channel. Results on both block and continuous fading channel models are presented. (b) An investigation of information-theoretic limits for the outdoor wireless channel must begin with channel models that reflect the outdoor environment accurately, while yielding analytical insight. We consider an idealized channel model, neglecting time variations, for wideband, frequency-selective, outdoor channels that accounts for rapidly decaying power-delay profiles for such channels, and provide results on outage rates and diversity.**

I. Introduction

While information theory has provided fundamental limits on the performance of communication systems since the time of Shannon, its practical significance for the link designer has been amplified by the advent of turbo-like codes and iterative decoding, which offer the hope of attaining these limits for a variety of channels. The purpose of this paper is to summarize some recently obtained information-theoretic insights into the outdoor wireless channel, which attempt to provide design prescriptions as a function of coarse system parameters such as Doppler, delay spread, and bandwidth. The two major themes considered are channel time variations and diversity. Time variations are studied in the context of a narrowband, flat fading channel in Section 2. A key departure from standard practice is our advocacy of explicitly accounting for the problem of channel estimation and tracking via adoption of the noncoherent paradigm, interpreted as joint channel and data estimation. The standard approach of channel estimation via pilots, with separate demodulation and decoding, may be viewed a suboptimal implementation within this paradigm. The second theme of diversity on typical outdoor channels is studied in the context of wideband, frequency-selective channels in Section 3. We abstract the vast literature on channel measurements into an idealized model that captures the key feature of rapidly decaying power-delay profiles, which limits the available frequency diversity.

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II. Flat fading channels

We consider the following discrete-time complex baseband model for single-antenna communication:

$$Y_n = H_n X_n + W_n$$

where $\{Y_n\}$ is the output sequence, $\{H_n\}$ is the sequence of channel gains, unknown *a priori* to the receiver under the noncoherent paradigm, $\{X_n\}$ is the channel input sequence, and $\{W_n\}$ is the noise sequence, assumed to be complex White Gaussian Noise (WGN).

Block Rayleigh fading: The channel gains $\{H_n\}$ are piecewise constant over T_c-length blocks, where T_c is the coherence interval. The gains on different blocks are assumed to be independent and identically distributed (i.i.d.) zero mean, circular Gaussian, random variables. Figure 1 shows the achievable rates for various standard constellations as a function of SNR for a block fading channel, compared with the capacity for unrestricted input in [5]. Note that

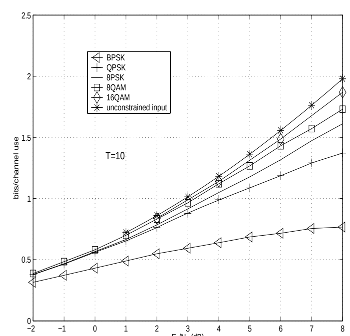

Fig. 1. Mutual information for standard constellations over the block fading channel ($T_c = 10$)

QPSK works well at low to moderate SNRs (BPSK does not, since it does not use both available dimensions). We have shown [1] that turbo-like codes and differential modulation, together with joint iterative decoding and noncoherent demodulation, approaches within 1.6 dB of the achievable rates for QPSK. However, at higher SNRs, QAM alphabets are needed to approach capacity. Current investigation therefore focuses on devising practical noncoherent communication schemes with low demodulation/decoding complexity for QAM alphabets.

Continuous Rayleigh fading: Consider a first-order Gauss-Markov model for the fading gains:

$$H_{n+1} = \alpha H_n + (1 - \alpha) U_n$$

where $\{U_n\}$ is zero mean circular Gaussian, and $0 \leq \alpha < 1$. We have shown [2] that the maximum achievable mutual information with Gaussian alphabets is of the order of $\log(1-\alpha^2)$, even as the SNR gets arbitrarily large. This is in stark contrast to the block fading model, for which the mutual information with Gaussian alphabets grows as $\log SNR$, as long as $T_c \geq 2$ [4].

In view of the preceding result, one possible design approach is to avoid the high SNR regime, using bandwidth rather than power to achieve high rates. For example, that for typical carrier frequencies and outdoor vehicular speeds, a moderate-SNR Orthogonal Frequency Division Multiplexed (OFDM) system with QPSK in each subcarrier might work well, but a standard 16-QAM alphabet with higher SNR might yield poor performance. Further investigation is needed into both good operating points and alternative constellation choices [2], [3].

Preprints of [1] and [2] can be obtained from www.ece.ucsb.edu/Faculty/Madhow/publications.html

III. Wideband Frequency-Selective Channels

In order to understand the frequency diversity available on typical outdoor channels, consider the following quasi-static model, in which the (complex baseband) channel $h(t)$ is randomly chosen, but is time-invariant over the duration of the codeword. We implicitly consider an OFDM type system, in which a complex Gaussian constellation is used on each subcarrier (in practice, PSK or QAM alphabets may be used, depending on the SNR). Let I_W denote the spectral efficiency in bits per second per Hertz, as a function of the bandwidth W, so that the rate of information transfer is WI_W bits/sec. Note that I_W is a random variable, which is a function of the random channel realization $h(t)$, given by

$$I_W = \frac{1}{W}\int_{-\frac{W}{2}}^{\frac{W}{2}} \log_2(1 + SNR|H(f)|^2)df \qquad (1)$$

where $H(f)$ is the channel transfer function.

Most measurements of outdoor channels indicate that the channel contains a few (1-3) clusters of specular paths. In each cluster, the amplitudes of the paths decays rapidly with delay. We focus here on the effect of such power-delay profiles on diversity, and consider a single cluster for brevity. Conceptually, it is useful to consider an "infinite bandwidth" model, in which the paths in the cluster form a continuum, as follows:

$$h(t) = \int_0^\infty \sqrt{P(\tau)} e^{j\Theta(\tau)} \delta(t-\tau)\ d\tau$$

where $P(\tau) = \frac{1}{\tau_{rms}}\exp(-\frac{\tau}{\tau_{rms}})$ is an exponentially decaying power-delay profile (normalized to integrate to one), where τ_{rms} is the root mean squared delay spread, and the phases $\Theta(\tau)$ are modeled as i.i.d. uniform over $[0, 2\pi]$.

At any finite bandwidth W, the preceding model can be approximated as a discrete tap delay line model with spacing $\frac{1}{W}$, as follows:

$$h_W(t) = \sum_{i=0}^{\infty} \alpha_W(i)\delta(t - \frac{i}{W}) \qquad (2)$$

with each tap corresponding to a continuum of unresolvable paths. Invoking the central limit theorem, each $\alpha_W(i)$ can be approximated as zero mean complex Gaussian as in the standard model of Rayleigh fading, with exponentially decaying powers. Based on the infinite bandwidth model, we obtain that $E[|\alpha_W(i)|^2 \sim \beta_W^i$, where $\beta_W \approx e^{-\frac{1}{W\tau}} < 1$. By convention, we normalize the taps such that $\sum_{i=0}^{\infty} E[|\alpha_W(i)|^2] = 1$.

Given a target outage probability δ (e.g., $\delta = .01$ for 1% outage), we wish to characterize the *outage spectral efficiency* $r_W(\delta)$ achievable at a a given bandwidth W. A direct numerical approach is to compute I_W for multiple channel realizations, and to use its empirical cumulative distribution function (cdf) to estimate the outage rate. However, our goal is to obtain insight into the effect of various system parameters via simple analytical estimates, validated against such direct numerical computations.

We argue that I_W is well-modeled as Gaussian. Its mean is independent of W, and is given by the ergodic spectral efficiency $c(SNR) = E[\log_2(1 + SNR\ X)]$ of a Rayleigh fading channel, where X is exponential with mean one. Its variance is estimated as

$$Var[I_W] \approx [\frac{SNR}{SNR+1}]^2 \frac{1-\beta_W}{1+\beta_W}$$

The outage spectral efficiency is now approximated as

$$r_W(\delta) \approx \max\{c(SNR) - \sqrt{Var[I_W]}Q^{-1}(\delta), 0\}$$

where Q denotes the complementary cdf of a standard Gaussian.

While the estimate of $c(SNR)$ matches accurately with $E[I_W]$ computed from simulations, our variance estimate appears to be a little larger than the simulation-based values, so that our estimates of outage spectral efficiency are slightly pessimistic: for $\tau_{rms} = 0.5$ microseconds and a bandwidth of about 9 MHz, the spectral efficiency for 1% outage using simulations is 2.2 bits/sec/Hz, whereas the analytical estimate is 1.9 bits/sec/Hz. Nevertheless, our theory does yield insight into the effects of parameters such as delay spread, bandwidth, and number of clusters. Details, together with analogous results on the spatial diversity obtained from the relatively narrow range of spatial angles for paths between widely separated transmitters and receivers, will be presented at the workshop.

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