An Efficient Protocol for Realizing Cooperative Diversity in Wireless Networks

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Abstract — **We develop two variants of an energy-efficient cooperative diversity protocol that combats fading induced by multipath propagation in wireless networks. The underlying techniques build upon the classical relay channel and related work and exploit space diversity available at distributed antennas through coordinated transmission and processing by cooperating radios. While applicable to any wireless setting, these protocols are particularly attractive in ad-hoc or peer-to-peer wireless networks, in which radios are typically constrained to employ a single antenna. Substantial energy-savings resulting from these protocols can lead to reduced battery drain, longer network lifetime, and improved network performance in terms of, *e.g.*, capacity.**

I. INTRODUCTION

In wireless networks, signal fading arising from multipath propagation is a particularly severe form of interference that can be mitigated through the use of *diversity* – transmission of redundant signals over essentially independent channel realizations in conjunction with suitable receiver combining to average the channel effects. Space, or multi-antenna, diversity techniques are particularly attractive as they can be readily combined with other forms of diversity, *e.g.*, time and frequency, and still offer dramatic performance gains when other forms of diversity are unavailable. In contrast to the more conventional forms of single-user space diversity, this work builds upon the classical relay channel model [1] and examines the problem of creating and exploiting space diversity using a collection of distributed antennas belonging to multiple users, each with their own information to transmit. We refer to this form of space diversity as *cooperative diversity* [2] because the users share their antennas and other resources to create a "virtual array" through distributed transmission and signal processing.

II. SYSTEM MODEL

In our model for the wireless channel, narrowband transmissions suffer the effects of independent, Rayleigh, flat-fading and additive noise, with average signal-to-noise ratio (SNR) ρ between mobiles. Our analysis focuses on the case of slow fading, and measures performance by outage probability, to isolate the benefits of space diversity; however, we emphasize that our results extend naturally to the kinds of highly mobile scenarios in which faster fading is encountered.

The network consists of constituent radios sharing orthogonal channels. A transmission period consists of two consecutive blocks; this decomposition is necessary because practical limitations in radio implementation prevent the relays from simultaneously transmitting and receiving on the same channel. During the first block, each user transmits on his assigned channel, and receives on a separate channel. In the sequel, users pair up at random; more generally, users might select the strongest channel for reception.

Protocol	P_{out}, high ρ_{norm}	Comment
Direct	$[\rho_{\text{norm}}]^{-1}$	-
Amplify-and-Forward	$\left[\left(\frac{2^{2R}-1}{2^{4R}-1}\right)\rho_{\text{norm}}\right]^{-2}$	-
Hybrid Decode-and-Forward	$\left[\left(\frac{2^{2R}-1}{2^{4R}-1}\right)\rho_{\text{norm}}\right]^{-2}$	Rep. codes
Transmit Diversity Bound	$\left[\frac{1}{\sqrt{2}}\rho_{\text{norm}}\right]^{-2}$	2 ant.

Table 1: Outage probabilities for large rate-normalized SNR, ρ_{norm}.

III. TRANSMISSION PROTOCOL

Among many possible coordination strategies, we consider simple protocols in which two cooperating users accurately estimate the realized SNR between them and use this estimate to select a suitable cooperative action; the users decide between continuing their own transmission in the second block, or relaying the other user's transmission in the second block, either by simply amplifying their received signals subject to their power constraint, or by fully decoding, re-encoding, and re-transmitting the messages. We refer to these two options generally as amplify-and-forward and decode-and-forward, respectively [3]. As a result, equal bandwidth and power allocations seem to be a natural choice. With direct and decode-and-forward transmission, the radios may employ repetition or more powerful codes. Destination radios can appropriately combine their received signals by exploiting control information in the protocol headers.

IV. OUTAGE PROBABILITY PERFORMANCE

Our analysis suggests that we may employ threshold tests on the measured SNR between the cooperating radios to choose the strategy with best expected performance, as measured by, *e.g.*, the lowest conditional outage probability for a given rate R (in bits per 2 dim.). Table 1 summarizes high average SNR approximations to the outage probabilities for several schemes as a function of the rate-normalized SNR $\rho_{\text{norm}} = 2\rho/(2^{2R}-1)$ [4]. We observe that each of our relaying protocols achieve full (*i.e.*, second-order) diversity. Furthermore, the amplify-and-forward strategy does asymptotically as well as a repetition-coded hybrid of direct and decode-and-forward transmission. At low rates, both schemes lose only 1.5 dB from the case of ideal transmit diversity, which gives a lower bound on outage probability [4]. More broadly, the relative attractiveness of amplify-and-forward and decode-and-forward can depend upon the network architecture and implementation considerations.

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