

AN EFFICIENT PROTOCOL FOR REALIZING DISTRIBUTED SPATIAL DIVERSITY IN WIRELESS AD-HOC NETWORKS

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ABSTRACT

Modern wireless ad-hoc networks are central to the Army's Digital Battlefield concept. Such networks conserve energy and limit co-channel interference by utilizing multi-hop transmission via intermediate relay mobiles instead of direct transmission between widely separated mobiles. We develop energy-efficient transmission protocols for wireless networks that exploit spatial diversity available at distributed antennas to combat multipath fading through coordinated transmission and/or processing by several radios. We discuss the problem in a general network setting and focus on a multiple-access case with sufficient symmetry to make the presentation concise. In particular, we examine several possibilities for the strategy employed by the relays, including decoding and forwarding as well as amplifying and forwarding. To characterize performance, we develop outage regions and associated outage probabilities that indicate robustness of the transmissions to varying signal-to-noise ratios (SNRs). These outage measures can be readily interpreted in coded and uncoded settings. Our results suggest that the relays employ a threshold rule: for high SNR, the relays decide to cooperate and pass along each other's information by decoding and forwarding; for moderate SNR, the relays cooperate and pass along each other's information by amplifying and forwarding; and for low SNR, the relays decide not to cooperate and simply retransmit their own signals. This protocol yields diversity gains on the order of, e.g., 10 dB at typical outage levels.

1 INTRODUCTION

Wireless ad-hoc networks [1] provide for decentralized communication between low-power, mobile radios and have a critical role to play in enabling Army tactical communication in the context of the Digital Battlefield. Efficient utilization of power and other resources, and the effective management of interference, is critical to meeting target performance, reliability, and lifetime specifications for such networks.

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Fading due to multipath propagation is a particularly severe form of interference experienced in such networks, and diversity techniques are the means by which such interference is managed. In this paper, we develop a new class of techniques that exploit spatial diversity available among distributed antenna elements to combat fading and substantially reduce the power required to meet target network specifications.

Path-loss and fading in wireless networks make direct transmission between widely separated radios very expensive in terms of transmitted power required for reliable communication. High-power transmissions lead to faster battery drain (shorter network life) as well as increased interference at nearby radios. As alternatives to direct transmission, there are two basic and frequently-employed examples of relayed transmission for wireless networks. In cellular settings, for example, networks provide connectivity between low-power mobiles by providing local connections to high-power basestations that are relayed via a wireline basestation network. In sensor networks, and military battlefield communication networks in general, the use of wireline infrastructure is often precluded and the radios may be substantially power constrained; for these ad-hoc or peer-to-peer networks, transmissions can be relayed wirelessly. As these examples suggest, relayed transmission enlists two or more radios to perform multiple transmissions. The end-to-end transmissions potentially incur higher delay, but because the individual transmissions are over shorter distances (in the wireless case), or over high-quality cabling (in the wireline case), the power requirements for reliable communication can be much lower.

The basic relaying protocols described above are constructed from the sequential use of point-to-point links, where the links are essentially viewed at the network protocol layer; however, more general approaches are possible that involve the coordination of *both* the direct and relayed transmissions, at the network and lower protocol layers, and correspond to scenarios to which the classical relay channel model applies. (See [2], and related work in [3].)

To illustrate the main concepts, we consider the wireless network depicted in Fig. 1. At the physical layer, destination radios receive potentially useful signals from all transmitters that are active, and may combine multiple transmissions of the same signal to reduce variations in performance caused by signal fading, a technique referred to broadly as spatial diversity combining [4]. We refer to this form of spatial diversity as *distributed spatial diversity*,

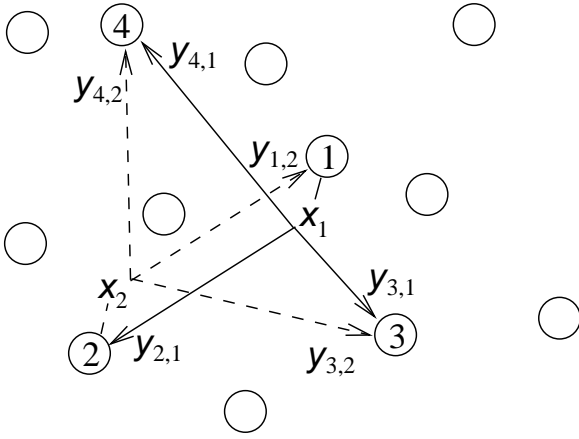


Figure 1. Example wireless network in which transmission protocols for exploiting distributed spatial diversity can be motivated. Indicated are transmitted signals x_i and received signals $y_{j,i}$.

in contrast to the currently more conventional forms of spatial diversity [5], because the radios essentially share their antennas and other resources to create a “virtual array” through distributed transmission and signal processing.

After developing a mathematical model in Section 2 for the network in Fig. 1, we scratch the surface of the rich set of design issues and options that arise in the context of exploiting distributed spatial diversity for wireless networks. Section 3 casts direct transmission into our framework, and explores a number of possibilities for diversity transmission and hybrid protocols, in terms of what signals the source and relay jointly transmit as well as how the relay and destination jointly process signals. Section 4 develops outage regions for the various transmission options, and Section 5 compares these regions and their corresponding outage probabilities. Performance comparisons in Section 5 suggest that our diversity transmission protocols are capable of overcoming the noisy channels between the distributed radio antennas to achieve diversity gain and outperform direct and multihop transmission in a variety of scenarios of interest.

2 SYSTEM MODEL

Our network model consists of a collection of M radios that share L orthogonal channels. A transmission period consists of two consecutive blocks, and the channels are allocated to (up to) L radios during each transmission period. During the first block of a transmission period, a radio transmits on its assigned channel, and receives on a separate channel. Radios might choose the strongest channel or might select a channel at random for reception. Such options complicate the story for $L > 2$, so we consider the case of $L = 2$ for simplicity of exposition. Depending upon the strength of the signal received on the selected channel, the radio decides between resending its own transmission (or, more generally, additional parity bits from a more efficient code, *e.g.*, rate-compatible

punctured codes) in the next block, or relaying the other radio’s transmission in the next block. As a result, equal bandwidth and power allocations seem to be a natural choice.

In our model for the wireless network depicted in Fig. 1, narrow-band transmissions suffer the effects of path loss and flat fading as arise in *e.g.*, slow-frequency-hop networks. Our analysis focuses on the case of slow fading to isolate the benefits of spatial diversity alone; however, we emphasize at the outset that our results extend naturally to the kinds of highly mobile scenarios in which faster fading is encountered.

Our baseband-equivalent discrete-time channel model for the network consists of two subchannels, orthogonal in, *e.g.*, adjacent frequencies. This decomposition is necessary because practical limitations in radio implementation prevent the relays from simultaneously transmitting and receiving on the same channel. Thus, radio 1 transmits on channel 1 and receives on channel 2 to potentially relay the signal transmitted by radio 2, and vice versa. The received signals at all four radios are modeled by

$$y_{j,i}[n] = a_{i,j} x_i[n] + z_{j,i}, \quad i = 1, 2, \quad j = 1, 2, 3, 4, \quad j \neq i. \quad (1)$$

Here $a_{i,j}$ captures the effects of path loss and static fading on transmissions from radio i to radio j , x_i is the transmitted signal of radio i having average energy \mathcal{E}_i , and $z_{j,i}[n]$ models additive receiver noise and other forms of interference at receiver j in channel i .

Statistically, we model the fading coefficients $a_{i,j}$ as zero-mean, mutually independent complex random variables with variances $\sigma_{a_{i,j}}^2$, and we model the additive noises $z_{j,i}[n]$ as zero-mean, mutually independent, white complex jointly Gaussian sequences with variance \mathcal{N}_j . We denote the signal-to-noise ratio (SNR) in each received signal as $\gamma_{i,j} = |a_{i,j}|^2 \mathcal{E}_i / \mathcal{N}_j$. The network geometry is assumed unknown or too dynamic to track, so the channels may be well modeled as having i.i.d. SNRs under an appropriate distribution. For example, under the Rayleigh fading model, the SNRs are independent exponential random variables.

As we develop our transmission protocol in Section 3, it will be convenient to consider successive pairs of data blocks from the channel model in (1). Specifically, for blocklength N , we collect the appropriate samples into the vectors

$$\begin{aligned} \mathbf{x}_i[k] &= [x_i[kN] \quad x_i[kN + 1] \quad \cdots \quad x_i[kN + (N - 1)]]^T, \\ \mathbf{y}_{j,i}[k] &= [y_{j,i}[kN] \quad y_{j,i}[kN + 1] \quad \cdots \quad y_{j,i}[kN + (N - 1)]]^T, \\ \mathbf{z}_{j,i}[k] &= [z_{j,i}[kN] \quad z_{j,i}[kN + 1] \quad \cdots \quad z_{j,i}[kN + (N - 1)]]^T. \end{aligned} \quad (2)$$

3 TRANSMISSION PROTOCOL

Throughout this paper, we focus on relatively simple protocols that operate on two consecutive blocks indexed by $2k$ (even) and $2k + 1$ (odd). At a high level, our protocols involve the following steps:

- **Even Blocks:** Radios $i = 1, 2$ encode new information into blocks $\mathbf{x}_i[2k]$, respectively. Radios $j = 1, 2, 3, 4$ receive signals $\mathbf{y}_{j,i}[2k]$, $i = 1, 2$. Radios 3 and 4 defer their processing until the end of block $2k + 1$. The transmitting radios process their respective received signals and decide whether they will cooperate in the next block, and if so, how.
- **Odd Blocks:** Radios $i = 1, 2$ encode either their own or their partner's data into blocks $\mathbf{x}_i[2k + 1]$, respectively. Radio 3 receives signals $\mathbf{y}_{3,i}[2k + 1]$, $i = 1, 2$, and jointly processes these signals with $\mathbf{y}_{3,i}[2k]$, $i = 1, 2$, received in the previous block. Radio 4 operates on its respective received signals in similar fashion.

Among many possible coordination strategies, we consider a simple protocol in which the two cooperating radios accurately estimate the SNR $\gamma_{2,1} = \gamma_{1,2}$ between them and use this estimate to select a suitable cooperative action. Such a protocol allows the radios to retransmit (in the form of repetition codes or more sophisticated single-user coding schemes) their own information when $\gamma_{1,2}$ is too small to justify cooperation, and to transmit each other's information (again, in the form of repetition codes or more powerful joint encoding schemes) when $\gamma_{1,2}$ is large enough to justify cooperation and, in particular, to provide spatial diversity benefit to the transmitting radios. In any case, a destination radio can appropriately combine its received signals by exploiting control information in the protocol headers, *e.g.*, a field indicating the cooperative action taken by the transmitting radios. While the nature and amount of this control information, as well as the accuracy and consistency of the SNR estimates at the two cooperating radios, are important practical considerations, a detailed study of their impact on system performance is beyond the scope of this paper.

Assuming both radios estimate the realized value $\gamma_{1,2}$ perfectly, they will choose identical cooperation strategies due to the statistical symmetry of the channels implied by our model. We examine three options for the transmissions in (odd) block $2k + 1$:

- **Direct Transmission:** The coordinating radios ignore each other's transmissions and re-transmit their information from block $2k$.
- **Diversity Transmission:** The coordinating radios assist one another by transmitting each other's information in block $2k + 1$. Reasonable strategies explored in our previous work include amplifying and forwarding as well as decoding and forwarding.
 - **Amplify and Forward:** For situations in which $\gamma_{1,2}$ is small, a linear relay that simply amplifies its received signal can be shown to be more effective than decoding and forwarding.
 - **Decode and Forward:** If $\gamma_{1,2}$ is reasonably large, it is advantageous for the relay to decode the transmissions to suppress noise on the channel between the source and relay, and re-encode the signal, potentially with a different codebook, for transmission between the relay and destination.

To summarize, each protocol consists of a source codebook, a relay processing/coding scheme, and a destination decoder.

Our combined analysis and empirical studies suggest that we may employ a pair of threshold tests on the SNR between the cooperating radios to choose the strategy with best expected performance, as measure by, *e.g.*, the lowest (conditional) outage probability. To develop this result, we examine the outage regions associated with each case in Section 4, and compare conditional outage probabilities in Section 5. We stress at the outset that none of the protocols we propose are necessarily optimal, but they represent reasonable protocols whose performance we can evaluate and begin to optimize. Improving upon these protocols, and developing others, is the subject of on-going work.

4 OUTAGE REGIONS

Generalizing upon our previous results for uncoded, *i.e.*, $N = 1$, single-user systems with a probability of bit-error performance measure [6], we characterize the performance of the various cooperation strategies in terms of outage regions and outage probabilities. Outage regions specified in terms of the SNR random variables $\gamma_{i,j}$ have convenient interpretations in both coded and uncoded settings, but we will develop our results from a coded perspective and determine events in which the realized capacity of the channel falls below a target transmission rate. We convert this event into an event defined in terms of the SNRs in the channel.

Since the capacity is a function of the SNR random variables of the channel, it too is a random variable. The event that this capacity random variable falls below some fixed rate R is referred to as an *outage event* (or *outage region* in terms of the SNR random variables), because reliable communication is not possible inside this region. The probability of an outage event is referred to as the *outage probability* of the channel,

$$P_{\text{out}}(R) = \Pr[C < R]. \quad (3)$$

We stress that outage regions are independent of the distribution of the underlying random variables, while outage probabilities are intimately tied to them. For example, if the outage region of a channel at a particular rate is a strict subset of the outage region of another channel at that rate, then the first channel has smaller outage probability regardless of the probability distribution on the channel parameters. Furthermore, as we will see, several of our cooperation strategies appear to have similar outage probabilities, but the structure of their outage regions is sufficiently different that we might prefer one over the other in various regimes. As a result, both outage regions and outage probabilities will be useful for characterizing our transmission protocols.

We consider transmission from radio s to radio d , with the potential of relaying the transmissions of radio r (and having radio r relay the transmissions of radio s). We parameterize the results in this form for compactness, but note that they can immediately be interpreted from the perspective of radio 1 by setting $s = 1$, $r = 2$,

and $d = 3$; similarly, to interpret the results from the perspective of radio 2, we set $s = 2$, $r = 1$, and $d = 4$.

In the following sections, we determine the outage regions for direct transmission, diversity transmission with amplifying and forwarding, and diversity transmission with decoding and forwarding.

4.1. Direct Transmission

Direct transmission in our setting corresponds to a point-to-point communications channel, to which we may readily apply classic information theoretic arguments [2]. Specifically, the capacity between the source and destination radios using repetition coding satisfies

$$C_{\text{SH}} = C_{s,d} = \frac{1}{2} \log(1 + 2\gamma_{s,d}), \quad (4)$$

with $\mathbf{x}_s[2k] = \mathbf{x}_s[2k + 1]$ (repetition coding) distributed as i.i.d. zero-mean complex Gaussian random variables each with variance \mathcal{E}_s . We note that, while in principle more powerful forms of coding than repetition are possible across the two blocks $\mathbf{x}_s[2k]$ and $\mathbf{x}_s[2k + 1]$, comparison to diversity transmission with amplifying and forwarding, inherently analogous to repetition, is most convenient in the repetition coded case.

Inspecting (4), we see that the outage event $C_{\text{SH}} < R$ can be readily manipulated into an event defined in terms of the SNR random variable between the source and destination, *i.e.*,

$$\gamma_{s,d} < t/2, \quad (5)$$

for an appropriate SNR threshold t that increases with increasing R .

4.2. Diversity Transmission: Amplifying and Forwarding

Under diversity transmission with amplifying and forwarding, the relay scales its received sequence by

$$\beta = \sqrt{\frac{\mathcal{E}_r}{|a_{s,r}|^2 \mathcal{E}_s + \mathcal{N}_r}}$$

to satisfy its average power constraint. Note that we allow the amplifier gain to depend upon the fading coefficient $a_{s,r}$ between the source and relay, which the relay estimates to high accuracy. This transmission scheme can be viewed as repetition coding from two separate transmitters, except that the transmitters may have different power levels and the relay transmitter actually amplifies its receiver noise. Nevertheless, the channel can be viewed as a single-user Gaussian noise channel and has capacity

$$C_{\text{DA}} = \frac{1}{2} \log(1 + \gamma_{s,d} + f(\gamma_{s,r}, \gamma_{r,d})), \quad (6)$$

for $\mathbf{x}_s[2k]$ zero-mean complex Gaussian with variance \mathcal{E}_s , where

$$f(x, y) = [x^{-1} + y^{-1} + (xy)^{-1}]^{-1},$$

analogous to a parallel combination of resistances with values x , y , and xy , respectively.

The outage region becomes the SNR event

$$\gamma_{s,d} + f(\gamma_{s,r}, \gamma_{r,d}) < t, \quad (7)$$

and an outage region ‘‘boundary’’ for each realization of $\gamma_{s,r}$ follows after careful manipulation of (7), obtaining

$$\gamma_{r,d} = \begin{cases} 0, & \gamma_{s,d} \geq t \\ \frac{1 + \frac{1}{\gamma_{s,r}}}{\frac{1}{t - \gamma_{s,d}} - \frac{1}{\gamma_{s,r}}}, & t - \gamma_{s,r} < \gamma_{s,d} < t \\ +\infty, & \gamma_{s,d} < t - \gamma_{s,r} \end{cases}. \quad (8)$$

4.3. Diversity Transmission: Decoding and Forwarding

When the SNR between the source and relay is reasonably high, it is advantageous for the relay to decode the transmission and re-encode, potentially with a different codebook, for cooperative transmission to the destination. When the relay decodes successfully, the source and relay have the same information and can be viewed as antenna elements in a transmit diversity array that uses orthogonal channels (expands bandwidth) [5]. One can show that, under the constraint that the relay decodes perfectly, for $\mathbf{x}_r[2k + 1] = \hat{\mathbf{x}}_s[2k]$, *i.e.*, the codebook is a repetition code, the capacity satisfies

$$C_{\text{DD}} = \frac{1}{2} \min\{\log(1 + \gamma_{s,r}), \log(1 + \gamma_{s,d} + \gamma_{r,d})\}. \quad (9)$$

Since we require the relay to decode perfectly, the outage regions correspond to the SNR event

$$\gamma_{s,r} < t \quad \text{or} \quad \gamma_{s,d} + \gamma_{r,d} < t. \quad (10)$$

For each realization of $\gamma_{s,r}$, the boundary of the outage region (10) can be manipulated into the form

$$\gamma_{r,d} = \begin{cases} 0, & \gamma_{s,r} \geq t, \quad \gamma_{s,d} \geq t \\ t - \gamma_{s,d}, & \gamma_{s,r} \geq t, \quad \gamma_{s,d} < t \\ +\infty, & \gamma_{s,r} < t, \quad 0 \leq \gamma_{s,d} < \infty \end{cases}. \quad (11)$$

5. PROTOCOL DESIGN AND PERFORMANCE

Fig. 2 depicts the outage regions for direct and diversity transmission with repetition coding, and clearly indicates improved performance (successively smaller outage regions) for amplifying and forwarding with increasing $\gamma_{s,r}$, approaching the outage region of decoding and forwarding for $\gamma_{s,r}$ large relative to the threshold t . As we might expect, for a sufficiently large value of $\gamma_{s,r}$, the (conditional) outage probability for amplifying and forwarding will be smaller than that of direct transmission, even though the outage regions for direct and diversity transmission are not nested one way or the other. The same is true for comparisons between transmit antenna diversity systems (without beamforming)

with one and two antennas. In practice, the dual antenna systems perform better than the single antenna systems [5].

Indeed, conditional outage probability calculations for the case of i.i.d. exponential SNRs confirm this hypothesis. Our results suggest thresholds for selecting among the various transmission strategies. Specifically, for $\gamma_{s,r}/t \lesssim 1/2$, direct transmission is preferable. For $1/2 \lesssim \gamma_{s,r}/t \lesssim 1$, bearing in mind that the conditional outage probability for diversity transmission with decoding and forwarding is 1 given $\gamma_{s,r}/t < 1$, we should employ diversity transmission with amplifying and forwarding. Finally, for $\gamma_{s,r}/t \gtrsim 1$, the decoding relay offers uniformly lower conditional outage probability than direct transmission or diversity transmission with amplifying and forwarding.

Fig. 3 shows empirical outage probabilities for our various protocols for the case in which all the SNRs in the channel are i.i.d. exponential random variables with mean $E[\gamma]$. These results suggest that energy savings on the order of 10 dB at $P_{\text{out}} = 10^{-3}$ can be obtained using protocols developed in this paper, because these protocols efficiently create multiple, independently-faded transmissions at separate radii that can be effectively combined at the destination receiver to achieve diversity gains. We also note that a protocol that always employs diversity transmission with amplifying and forwarding appears to perform almost as well as our optimized hybrid protocol.

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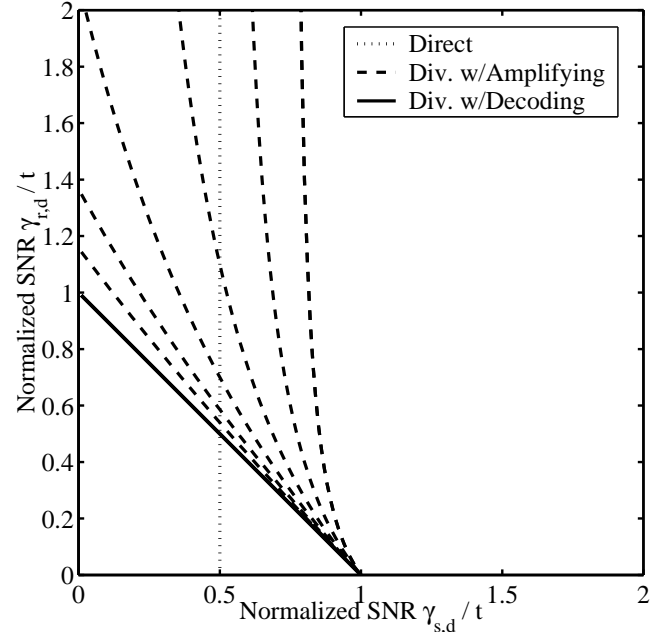


Figure 2. Outage region boundaries for repetition-code transmission protocols. Successively lower dashed curves correspond to diversity transmission with amplifying and forwarding assuming received signal strength measurements of $\gamma_{s,r}/t = 1/4, 1/2, 1, 2, 4, 8$. The outage regions lie below and/or to the left of the indicated lines, i.e., all include the point $(0, 0)$.

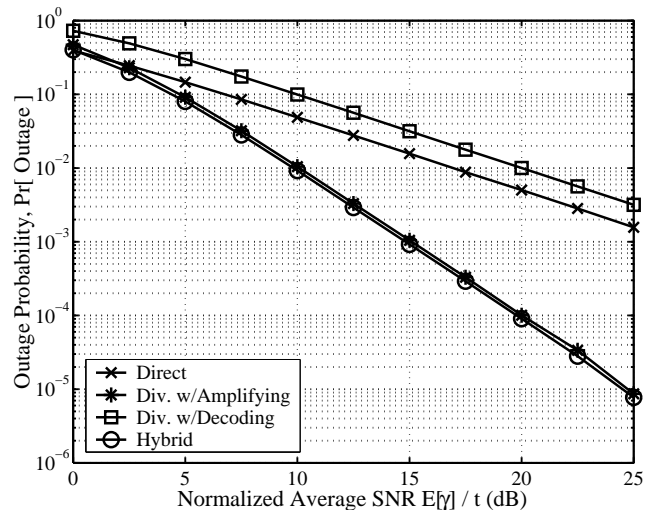


Figure 3. Outage probabilities for i.i.d. exponential SNRs.

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