Power Efficient Broadcasting with Cooperative Diversity in Ad hoc Networks

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***Abstract*—Cooperative diversity entails the simultaneous transmission ofinformation by multiple nodes that are in the proximity of each other; this process emulates the functionality of an antenna array. The use of cooperative communications can help combat interference and fading and hence, significantly improve the reliability of the wireless channel without the physical deployment of cumbersome antenna arrays on mobile terminals. The increased reliability allows for nodes to use lower transmission power levels and yet, achieve the transmission range possible with traditional single-input single-output (SISO) communications. In this paper, we focus on saving energy while performing network-wide broadcasting in ad hoc networks by using cooperative diversity. We develop a new broadcast protocol that exploits *cooperative diversity links* to disseminate information to all the nodes in the network with much lower consumed power. Our simulation results demonstrate that our protocol maintains the coverage that is possible with broadcast schemes based on traditional SISO transmissions but with a significantly higher power efficiency.**

***Index Item*— Cooperative Diversity, Broadcasting, Ad hoc Networks**

I. INTRODUCTION

The use of antenna arrays in conjunction with space-time codes leads to significant diversity and/or multiplexing gain that can revolutionize the quality of communications over the wireless channel. Depending on whether multiple transmitting antennas (inputs) and/or multiple receiving antennas (outputs) are used, one could have a Multi-Input Single-Output (MISO) system, a Single-Input Multi-Output (SIMO) system or a Multi-Input Multi-Output (MIMO) system. The classic point-to-point communication, employed by most of the wireless standards at the moment, is simply denoted as SISO [1]. The deployment of antenna arrays on small mobile nodes, however, is infeasible due to the required size of these antennas. More specifically, the space between two elements of a multiple element antenna array must be at least of the order of $\frac{\lambda}{2}$, λ being the wavelength used for transmissions. For the commonly used 2.4 GHz frequency band, the required inter-element distance is 6.125 cm. Therefore, even an antenna with four elements can be too big to be mounted on a laptop and even more so on a PDA or a low cost sensor node.

Cooperative diversity[2] is a recent breakthrough at the physical layer, which exploits the broadcast nature of the wireless channel to emulate a MISO system. Nodes participating in an cooperative diversity scheme, broadcast the same packet simultaneously. By providing the receiver with multiple replicas of the same signal, one can achieve the same benefits of an antenna system mounted on a single node.

Laneman [4] was the first to introduce cooperative diversity and showed that it can achieve full diversity. For the case of two nodes, he proved that the outage probability decays in proportion to the inverse of the square of the signal-to-noise-ratio ($1/SNR^2$), rather then $1/SNR$ without cooperative diversity. Sendoranis et al. [8], introduced the cooperative diversity as a mean to increase capacity of the uplink in cellular networks. The size of mobile units is too small to accommodate an array of antennas, therefore the authors contend that the only way to enable the diversity gain is by user cooperation.

The research at the physical layer has proved the significant potential of cooperative diversity. The question raised to the protocol designer, however, is: How can we exploit this new physical layer technology to build upper

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[1]In the rest of the paper we use the terms SISO link and point-to-point interchangeably

[2]aka virtual antenna arrays

layer protocols with higher performance? In this paper we focus on the problem of the network-wide broadcasting, a key component that aids both routing and dissemination services in ad hoc networks. Broadcasting by its nature, is a transmission intense operation and hence, results in the consumption of significant power. For this reason, there have been efforts [9][6][2] toward designing energy efficient broadcast protocols for ad hoc networks. However, most of the previous work assumes SISO links to be deployed at the underlying physical layer.

In this paper we design of a distributed broadcast protocol that exploits cooperative diversity to disseminate information to the whole network, while achieving significant decrease in power consumption over protocols that use only SISO links. Through simulations, we show that our protocol can perform network-wide broadcasting with up to eight times lower power consumption than a corresponding protocol that uses SISO links. The savings in power are achieved without compromising the coverage achieved by the broadcast. In fact, our simulations show that we are able to also improve the coverage, especially in sparse networks.

The rest of the paper is organized as follows. In Section II, we describe the relevant physical layer background. In Section III we describe our protocol for broadcasting and some preliminary simulation results. The results from our simulations form Section IV. Our conclusions and future thoughts make up Section V.

II. Virtual MISO

In this section, we provide a brief discussion on space-time codes and the physical layer properties of links formed with cooperative diversity. Since multiple transmitters cooperate to communicate with a single receiver, we refer to such links as *virtual MISO links*.

Virtual MISO links and Space Time Codes: In a SISO system, at the physical layer, a group of l bits of a packet that are received from the MAC layer are converted to one of $M = 2^l$ *symbols* as per a chosen M-ary modulation scheme (note that there are 2^l possible l-bit groups). If the symbol duration is T_s, the symbol rate is $1/T_s$ symbols/second and the bit rate is l/T_s bps. If $M = 2$, we have a binary modulation scheme where each symbol has one bit (e.g., binary phase shift keying or BPSK). In the case of Quadriphase PSK (QPSK), 8-PSK and 16-QAM (quadrature amplitude modulation), 2, 3 and 4 bits are respectively mapped on to one symbol.

On a virtual MISO link, multiple transmitters will transmit the same symbols to a common destination; this joint transmission improves the signal quality and therefore, the reliability of received information at the destination node. The symbols are *replicated* in *space* and *time* in a specific manner that enables the destination node to combine the received symbols in a simple manner (linear) to reap the benefits of *diversity*. Such a replication is performed in blocks of k symbols and is hence referred to as space-time block coding. In the presence of independently flat Rayleigh fading channels between the many transmitters and the receiver, space-time block coding can provide large diversity gains.

On a virtual MISO link, there are N transmitters that transmit m complex symbols $\pm s_i, \pm s_i^*$ over kT_s seconds; here, s_i^* is simply the complex conjugate of the symbol s_i and $m \leq k$. In a SISO system, the single transmitter would send m symbols in mT_s seconds for a symbol rate of $1/T_s$. In the virtual MISO case, the symbol rate will be $\frac{m}{k}\frac{1}{T_s}$. The measure of bandwidth utilization is the *rate* of the space-time block code $R = m/k$. If $m = k$, then, $R = 1$ and the bandwidth is completely utilized; codes that facilitate this are referred to as *full-rate space-time block codes*.

Space-time block codes are characterized by a $k \times N$ matrix $\mathbf{S}$ that specifies the *pattern* as per which symbols must be transmitted by the N antennas in each of the k time units of duration T_s. The rows correspond to *time* (the times at which the symbols are transmitted) and the columns to *space* (the antenna elements on which they are transmitted). The well known *Alamouti Code* which is a 2×2 space-time block code [1]. This code has a utilization (rate) $R = m/k = 1$. The matrix $\mathbf{S_2}$ (the subscript 2 indicates that it is for a 2×2 space-time block code) corresponding this code is given by :

$$\mathbf{S_2} = \begin{bmatrix} s_0 & s_1 \\ -s_1^* & s_0^* \end{bmatrix} \qquad (1)$$

With this coding scheme, two symbols are transmitted by two transmitters over $2T_s$ time units (Tx_0 transmits the symbols s_0 and $-s_1^*$ in $(0, T_s)$ and $(T_s, 2T_s)$, respectively and, Tx_1 transmits the symbols s_1 and s_0^* in the same two time units).

We briefly describe how diversity is provisioned on a virtual MISO link using Alamouti codes[3]. Given that the Alamouti code is a 2×2 space-time block code, two cooperating transmitters are needed. Let us suppose that the channels between the two transmitters and the receiver are represented (in baseband) by the complex coefficients h_0 and h_1 respectively. In general $h_i = \alpha_i e^{j\phi_i}$ where α_i is the magnitude and ϕ_i is the phase response of the channel.

[3]A similar approach is possible with higher order space-time codes. However, a discussion on this is beyond the scope of this paper.

The magnitude α_i is Rayleigh distributed. The received symbols in the two time units will be:

$$\begin{aligned} r_0 &= h_0 s_0 + h_1 s_1 + n_0 , && 0 \le t \le T_s \\ r_1 &= -h_0 s_1^* + h_1 s_0^* + n_1, && T_s \le t \le 2T_s \end{aligned} \quad (2)$$

where n_i for $i = 0, 1$ is the additive white Gaussian noise component. If the receiver has knowledge of the channel coefficients (as will be discussed below), in this case, the received symbols can be linearly combined to achieve diversity gain. The receiver estimates the transmitted symbols by computing their estimates $\tilde{s_i}$ for $i = 0, 1$ as:

$$\begin{aligned} \tilde{s_0} &= h_0^* r_0 + h_1 r_1^* \\ \tilde{s_1} &= h_1^* r_0 - h_0 r_1^* \end{aligned} \quad (3)$$

From (2) and (3), the estimates of the transmitted symbols at the receiver can be computed to be:

$$\begin{aligned} \tilde{s_0} &= (|\alpha_0^2 + \alpha_1^2|) s_0 + h_0^* n_0 + h_1 n_1 \\ \tilde{s_1} &= (|\alpha_0^2 + \alpha_1^2|) s_1 + h_1^* n_0 - h_0 n_1 \end{aligned} \quad (4)$$

Note that the estimated symbols are a function of $(|\alpha_0^2 + \alpha_1^2|)$ times the transmitted symbols. The diversity gain is due to the fact that the probability that both α_0 and α_1 will be small due to deep fades at the same time, is low. To get a sense of the diversity gain, consider a target bit error rate (BER) of 10^{-3}. With the virtual MISO link under consideration, for this target BER, the required E_b/N_0 is 15 dB, whereas for the same BER requirement, the needed E_b/N_0 is 25 dB on a SISO link [1] [3]; E_b refers to the energy in a bit and N_0 is the power spectral density of white noise. This implies that *with diversity gain, the signal can be recovered at a distance farther than the case where there is no diversity* (this is a direct consequence of the SNR requirement for a given bit error rate being reduced).

In the above discussion, as in most prior work, we assume that the channels from the different transmitters to the receiver on the virtual MISO link experience independent flat fading. A second assumption is that these channel coefficients do not change over a few symbol durations (the channel fades slowly), i.e., the nodes do not move at very high speeds.

III. Power Efficient Broadcasting

In this section, we describe our proposal to deploy cooperative diversity for achieving power efficient broadcasting in ad hoc networks. As mentioned earlier, the work is primarily motivated by two factors:

1) In a network-wide broadcast, the same information is to be disseminated to all nodes in the network. Thus, the same information is available and transmitted by multiple nodes over and over. Therefore, cooperative diversity seems to inherently fit this application.
2) The network-wide broadcast is a key component that aids both routing and dissemination services in wireless networks.

Due to the importance of broadcasting, there have been significant efforts [7] towards the design of efficient broadcast methods; however, these are not within the context of cooperative diversity. Simply put, broadcasting is invoked when a node wants to send a packet to all other nodes in the network. Because of the high number of communication messages that are to be exchanges, there has been a lot of research [9][6][2] on designing power optimal broadcast protocols. However all these work has been on the basis of SISO links.

Our objective is to translate the gains due to cooperative diversity, when applied to broadcasting, to savings in power consumption. Toward this objective, we design appropriate modifications to existing SISO based broadcast protocols to facilitate the new technology. A distributed approach could be derived from any of the (non-cooperative) broadcast schemes proposed in literature [7], with the appropriate changes. Adhering to our minimal set of assumptions, we choose to incorporate cooperative diversity in a *counter-based* broadcast scheme. The counter-based approach does not require the exchange or maintenance of any topological information. Furthermore, the scheme exhibits some nice properties. First, it is naturally adaptive to the topological construction and the dynamics of the network. In sparser regions of the network, all of the nodes would participate in the broadcast while in denser regions, many of the nodes would simply quell their broadcasts.

We provide an outline of the generic operations of our protocol. In this work, for simplicity, we assume that all the signals arrive at the receiver in phase and add constructively[4].

The source first initiates the broadcast session by broadcasting the desired packet to all its neighbors via a SISO transmission. At the end of this transmission, the neighbors of the node that can perform transmissions (traditional carrier sensing is invoked to determine if a node is allowed to perform a transmission) cooperate to per-

[4]Phase synchronization of cooperative signals is an ongoing area of research in the physical layer community and a discussion on this is beyond the scope of this paper.

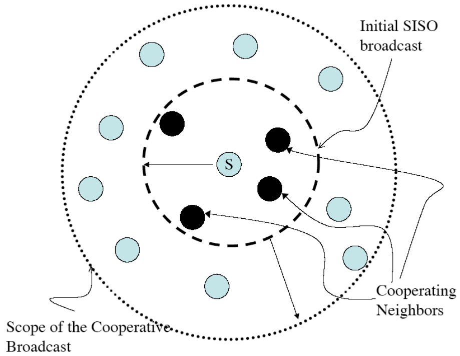

Fig. 1. A Cooperative Broadcast

form a virtual MISO broadcast. In our discussion on space time codes and virtual MISO links (in the previous section), it was assumed that the receiver has a priori knowledge of the channel coefficients h_i. Note that the transmitters do not need to have this information (there is no feedback) simplifying the process of communication. The channel information can be derived by the receiver if the transmitters insert pilot symbols periodically (depending on how quickly the channelchanges) [1]. There will be some degradation if the channel estimates are not accurate. The pilot symbols from the N transmitters have to be orthogonal (they can be transmitted sequentially in time or made orthogonal in code) [1]. Thus, each of the cooperating nodes, transmit pilot symbols (or tones) so that the receiver can estimate the channel with respect to each of the transmitting nodes. In our simulations, we simply assume that the nodes transmit pilot tones that are orthogonal in code, i.e., they transmit these signals simultaneously. Since the pilot tones consist of a *known set* of symbols, one may assume their *detection* as possible as long as the *average* power exceeds a certain preset threshold. In other words, even if these symbols were to experience harsh fades, they can be detected over fairly long distances. We assume that the pilot tones (transmitted via SISO) can be detected over the range of a virtual MISO link (as discussed previously). Since the receiver expects to receive a known sequence, it can compute the channel coefficients, even if the sequence is corrupted due to fading. Note here that, both for the initial SISO transmission by the initiating source and for the cooperative transmission,we deploy varying power levels that are much smaller than that are used in traditional SISO based communications. However, we point out that some minimum level of density would be needed (with the lowered transmit power the node density reduces) in order for cooperation to be feasible. We depict the process of a cooperative broadcast in Figure 1.

Nodes that receive the pilot tones can then successfully decode cooperative transmissions.

Every node that receives (by the above process) a broadcast packet is a candidate for invoking a further cooperative rebroadcast. To avoid collisions, each node sets a timer that expires after a uniformly chosen random time $t \in [0, T_{Max}]$, where T_{Max} is a system parameter. Before the timer expires, the node counts the number of other broadcasts of the same packet, that it overhears. If this number is above a preset threshold θ, the scheduled rebroadcast is aborted and the timer event is canceled. If not, when the timer expires, the node will instigate a cooperative broadcast with the help of all of its neighbors. Note that the node does not need to know how many neighbors its has; it simply elicits the cooperation of all of the nodes that are within its local broadcast scope.

Only those nodes that can cooperate, participate in the broadcast. Each cooperative broadcast is invoked as before i.e., via a preliminary broadcast followed by the transmission of pilot tones and finally, the cooperative transmission.

IV. SIMULATION ANALYSIS

In this subsection we present some preliminary simulation results that show the benefits of incorporating cooperative diversity in broadcasting. We have implemented our new protocol along with the simple (not using cooperative diversity) counter-based broadcasting, in a C++ based simulator.

To compare our protocols, we use the following performance metrics:

- **Power Consumption:** This is the power consumed by all the nodes in the network, from the moment the broadcast is initiated until the process comes to a halt. We measure the power consumption in arithmetic units, where every unit represents the power needed to reach the nominal coverage range of 250m.
- **Coverage:** This is the percentage of the nodes in the network that receive the broadcast packet.

Simulation Models and Settings: Nodes are placed randomly in 5 unit $\times$ 5 unit flat topology. Each unit corresponds to $250m$, the nominal value for the range of transmission using a wireless card compliant with the IEEE 802.11 standard. In our simulations we have a physical channel that includes frequency non-selective Rayleigh fading and path loss with exponent 2 ; while some experiments were done with other values, they yielded similar results.

All the nodes in the network can choose to transmit with different power levels. Khandani et al. [5] have

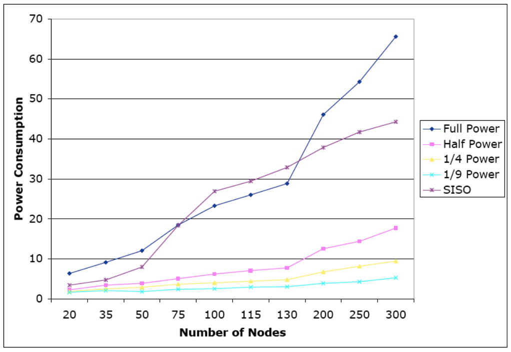

Fig. 2. Power Consumption vs. Number of Nodes.

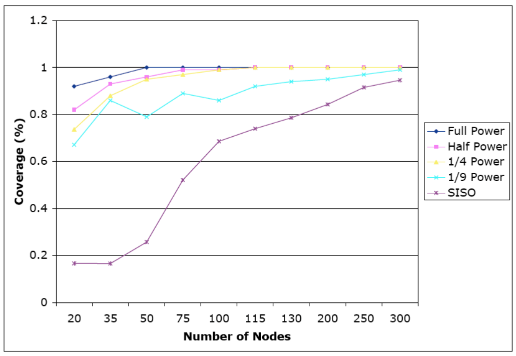

Fig. 3. Coverage vs. Number of Nodes.

computed the optimal power assignment for every cooperating node in order to minimize the power consumption of a cooperative transmission. However, that computation assumes ideal channel conditions, knowledge of the channels state at the transmitter (CST) and global knowledge of the topology. Obviously, this information is not available in a distributed setting (as in ad hoc networks). Therefore, we choose to have the nodes transmit at various fixed power levels, and measure the performance on the metrics defined above with these levels. This method is effective in demonstrating the significance of the power savings when our broadcasting scheme with cooperative diversity is used.

Simulations Results: The results from our simulation experiments in terms of power consumption are depicted in Figure 2. We vary the fixed power level used; in other words, we conduct experiments wherein with cooperation, nodes transmit either at the maximum possible power level, half of that power, one fourth of that power or one ninth. The non-cooperative protocol, denoted with SISO, uses only one power level, the maximum. As shown by the results, the power consumed by the use of our protocol (using cooperative diversity) is about eight times lower as compared to what is achieved with the non-cooperative method. At the same time, the coverage is not compromised; note that this is so, even though the nodes are using only a ninth of their full power. As shown in Figure 3, the coverage is actually increased with cooperative diversity even when the transmitted power level is a fraction of what is used by the non-cooperating protocol. This fact is due to the diversity gain achieved by the cooperation of the multiple nodes which leads to increased coverage range. In particular, when the node density is low, as shown in Figure 3, the increase in coverage is seen to help bridge partitions that can occur if only SISO transmissions are used and therefore can improve connectivity.

V. CONCLUSIONS

In this paper, we examine the benefits of cooperative diversity in achieving power efficiency in broadcasting in ad hoc networks. Cooperative diversity provides higher levels of robustness to fading by emulating an antenna array. This higher level of reliability can be exploited to facilitate lower power transmissions. We provide a methodology for performing network wide cooperative broadcasts and demonstrate that our protocol achieves power savings of up to eight times as compared to a corresponding SISO based broadcast scheme while ensuring that coverage is maintained. This work demonstrates the benefits achievable with cooperative diversity and is a harbinger for future protocol efforts that are equipped to exploit this new upcoming technology.

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