Asynchronous Cooperative Diversity [1]

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Abstract — **Cooperative diversity, which employs multiple nodes for the simultaneous relaying of a given packet in wireless ad hoc networks, has been shown to be an effective means of improving diversity, and, hence, mitigating the detrimental effects of multipath fading. However, in previously proposed cooperative diversity schemes, it has been assumed that coordination among the relays allows for accurate symbol-level timing synchronization and orthogonal channel allocation, which can be quite costly in terms of signaling overhead in mobile ad hoc networks, which are often *defined* by their lack of a fixed infrastructure and the difficulty of centralized control. In this paper, two cooperative diversity schemes are considered that do not require symbol-level timing synchronization or orthogonal channelization between the relays employed. In the process, a novel joint minimum mean-squared error (MMSE) receiver is designed for combining disparate inputs in the multiple-relay channel. Outage probability calculations and simulation results demonstrate the not unexpected significant performance gains of the proposed schemes over single-hop transmission, and, more importantly, demonstrate performance comparable to schemes requiring accurate symbol-level synchronization and orthogonal channelization.**

I. Introduction

An ad hoc wireless network is a collection of wireless mobile nodes that self-configure to form a network without the aid of any established infrastructure [1]. Thus, unlike cellular systems, which can afford infrastructures to employ fixed basestations to coordinate communications within predefined areas, ad hoc networks utilize other mobiles as relays to transfer information from a source to its destination.

The impairments caused by the multipath fading and the time-varying nature of the wireless channel must be considered in designing an ad hoc wireless network. The broadcast nature of the radio channel introduces characteristics in ad hoc wireless networks that can be exploited in the form of *cooperative diversity* [2], which is to ask cooperating nodes between the source and its destination to forward received data generated by the source to the destination after some processing at each relay terminal.

In [3]-[5], the authors developed and analyzed several energy-efficient cooperative diversity protocols that combat fading in wireless networks. In their work, different nodes in the wireless network share their antennas and resources to create a virtual array. First, the relay nodes fully decode the transmission from the source terminal. Next, they will either forward that information to the destination in the assigned slot, or they can cooperatively utilize a space-time code to allow the destination terminal to take advantage of distributed spatial diversity to average out the fading. The schemes proposed in [3]-[5] are essentially repetition based cooperative diversity algorithms, since each relay node simply forwards the fully decoded message from the source. In [6, 7, 8], to achieve a better tradeoff between energy and spectral efficiency while using similar orthogonal channel allocation schemes as in [3], various coding schemes were proposed across the source and the relay nodes, which achieve not only cooperative diversity gain but also coding gain. The aforementioned cooperative schemes assume orthogonal channel allocation and synchronization of the signals of the cooperating terminals *at the receiver*, both of which require significant overhead in the ad hoc wireless network. To the authors' knowledge, [9] is the only paper that deals with the case when the orthogonal channel allocation and symbol synchronization is impossible in an ad hoc wireless network. However, their proposed scheme requires intentionally increasing the data symbol period T_s to avoid inter-symbol-interference (ISI) caused by the asynchronous transmission of the same source signal to the receiver, which limits the efficiency of the scheme.

As seen from the above, finding schemes which relax the coordination among nodes in an ad hoc wireless network is important for achieving the cooperative diversity gain in practice. In this paper, this problem will be attacked with approaches that capture the essence of ad hoc networks from a physical layer design perspective.

This paper is organized as follows. Section II presents the model of an ad hoc wireless network with relay channels. In Section III, the justification to employ a generalized equalizer at the destination node is provided along with the two proposed approaches to cooperative diversity. The feedforward and feedback filter coefficients, as well as the closed form for the mean squared error of the proposed equalizer, are obtained in Section IV. Simulations results are presented in Section V. Conclusions and future work are contained in Section VI.

II. System model

Consider an ad hoc network with $K+2$ nodes, where the source node transmits messages to the destination node with the help of the K relays located between them. A mathematical model for such a situation is shown in Fig. 1. After some processing of the received signal $Y_{R_k}(t), k = 1, 2, \cdots, K$ from the source node N_S at the kth relay node N_{R_k}, N_{R_k} transmits the processed packets via $X_{R_k}(t)$ to the destination node N_D, where signals from all involved routes are processed jointly to achieve the diversity gain and/or coding gain. The derivation of processing algorithms of the received signals at N_{R_k} and N_D will be the main focus in this paper. Narrow-band transmission is assumed here, where the channel between any pair of nodes is frequency non-selective. In addition, quasi-static fading is assumed, where the path gains remain fixed during the transmission of a whole packet, but are independent from user to user. Time delays are introduced on each path from the source to the destination. This time delay incorporates the processing time at the relay nodes and the propagation delay of the whole route. For example, τ_0 is the delay from N_S to N_D, and τ_k is the cumulative delay for the transmission

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from N_S to N_{R_k}, processing at N_{R_k} and for transmission from N_{R_k} to N_D. The noise processes $W_k(t), k = 0, 1, \cdots, K$ are independent complex white Gaussian noise with two-sided power spectral density $\mathcal{N}_0$. The complex channel gain $\alpha_{i,j}$ captures the effects of both pathloss and the quasi-static fading on transmissions from node N_i to node N_j, where $i \in \{S, R_1, \cdots, R_K\}$, and $j \in \{R_1, \cdots, R_K, D\}$. Statistically, $\alpha_{i,j}$ will be modeled as zero mean, mutually independent complex jointly Gaussian random variables with variances $\sigma^2_{i,j}$. The fading variances can be assigned using wireless path-loss models based on the network geometry [10]. Here, it is assumed that $\sigma^2_{i,j} \propto 1/d^{\mu}_{i,j}$, where $d_{i,j}$ is the distance from node N_i to N_j, and μ is a constant whose value, as estimated from field experiments, lies in the range $2 \leq \mu \leq 5$. It is assumed that $\alpha_{i,j}$ is estimated accurately at the receiver, but is not available to the transmitter.

A practical constraint prohibiting the relay nodes from transmitting and receiving at the same time [11] will be assumed, which results in orthogonality in time between the packet arriving at N_D via the direct path from N_s with the collection of packets arriving at N_D through relay nodes. Note that orthogonality between the signals $X_{R_1}(t), X_{R_2}(t), \cdots, X_{R_K}(t)$ transmitted from different relay nodes, $N_{R_1}, N_{R_2}, \cdots, N_{R_K}$, is *not* assumed and forms the crux of the problem. The difference $\tau_k - \tau_0$ includes the processing time of a whole packet at N_{R_k} in addition to the relative propagation delay between the kth relay path and the direct path. Without loss of generality, τ_0 is set to zero. Under the modeling assumed above, the signals in Fig. 1 are: $Y_{R_k}(t) = \alpha_{S,R_k} X_S(t) + W_k(t), k = 1, \cdots, K$, $Y_{D_s}(t) = \alpha_{S,D} X_S(t) + W_S(t)$, and $Y_{D_R}(t) = \sum_{j=1}^{K} \alpha_{R_j,D} X_{R_j}(t - \tau_j) + W_D(t)$, where $Y_{D_s}(t)$ and $Y_{D_R}(t)$ have no common support in the time domain, and $W_S(t)$ and $W_D(t)$ are independent and identically distributed white Gaussian random processes. The transmitted signal from the source is $X_S(t) = \sum_{k=-\infty}^{\infty} I_k h_{Tx}(t - kT)$, where $h_{Tx}(t)$ is the transmitter filter, T is the symbol period, and I_k is the kth QAM data symbol with $I_k = a_k + jb_k$, $\frac{1}{2}E\left[|I_k|^2\right] = \sigma^2_I = 1$, and $\{I_k\}$ is a sequence of uncorrelated symbols that is independent of $\{W_j(t)\}$. It is assumed that $h_{Tx}(t)$ has a squared root raised cosine (SRRC) impulse response with a filter roll-off factor $\beta \in [0, 1]$. Denote each front-end receiver filter response as $h_{Rx}(t)$, which is matched to the SRRC transmitter filter, i.e., $h_{Rx}(t) = h_{Tx}(-t)$. It is assumed that all nodes transmit with equal power $P = \sigma^2_I$.

III. System Overview and Protocols

A. System Overview

To handle the problem of the asynchronism of the relayed signals, a distributed version of delay diversity [12] is proposed to achieve the diversity gains promised by distributed space-time codes [5]. Unlike the extension of other approaches [13] to the synchronization problem in distributed space-time coding, the proposed system also admits a robust and easily trainable receiver when synchronization is not present in the system.

In the case of an ad hoc network with multiple relays as depicted in Fig.1, after processing received signals $Y_{R_k}(t)$ at N_{R_k}, the recovered signals at each relay node are not necessary identical due to the demodulation/decoding errors resulting from the presence of fading and thermal noise on the link from the source to the relay. To address this, an error detection scheme is employed such that relay nodes can perform the cyclic redundancy check (CRC) check [14] to determine whether the received packet matches the actual transmitted information sequence. If the received packet is error-free, the relay node will then forward the information packet to the destination, after possibly introducing an additional intentional artificial delay (see below). If not, this packet of data will be dropped at N_{R_k}. Assuming that the CRC code enables the relay nodes to correctly detect all frame errors in the received packets, the receiver at the destination node will see an equivalent multipath fading channel even in the presence of coding in the form of the artificially introduced relay delays. The channel impulse response relies on the number of available relay nodes which successfully forward the packets and their relative locations to node N_D. Denote the number of relay nodes receiving packets from the source N_S without errors as $M_R(s)$, where s represents the *source*, which is a random variable whose probability distribution function depends on the channel quality between the source and each relay terminal, and denote the set of those nodes as $\mathcal{D}_{\mathcal{R}}(s)$. The mobility of the nodes is assumed to be low enough that the inter-node distance can be taken as fixed during the transmission of one packet.

To exploit the diversity gain available in such a relay network, a generalized decision feedback equalizer (DFE) is employed at the destination node. The DFE considered here will minimize the mean squared error (MMSE) at the decision point, which will mitigate ISI caused by the equivalent multipath channel between node N_S and N_D, as well as achieve the cooperative diversity gain.

Because outage probability is a more suitable metric than average error probabilities for quasi-static fading channels, the measure of performance is the outage probability of the frame error rate, which is defined as follows. An outage is declared when the frame error rate at N_D is above a predetermined threshold (e.g., 0.1). The outage probability will be obtained by then calculating the likelihood of such an event over the realizations of the random locations of all the nodes, which will result in the variation of the equivalent multipath channel in terms of altering the relative delays for every realization of such connection, statistics of fading gains, as well as the set $\mathcal{D}_{\mathcal{R}}(s)$.

B. Detailed Protocol Description

Two separate protocols (Protocol 1 and Protocol 2), each with two variants (Variant A and Variant B), will be considered for the relaying of packets from the source to the destination.

Protocol 1 In the first protocol, which is primarily intended to illustrate key aspects of the proposed ideas, the set of nodes that are closer to the destination than the source is formed, and the two nodes in this set that are closest to the source are selected as relays. During the broadcast period (the first of two time slots for a given packet), the source transmits a signal corresponding to a given packet. Each of the two potential relays attempts to decode the packet and, if successful, transmits during the relay period (the second of the two time slots for a given packet). The destination then runs the generalized DFE described in Section 4 to decode the packet.

Per above, Protocol 1 is intended to illustrate key ideas associated with the approach described here, since actual implementation would require the determination of the two nodes closest to the source, which is non-trivial.

Protocol 2 In the second protocol, all of the nodes in a given area are potential relays. During the first time slot, the source transmits the signal corresponding to a given packet, and all nodes that hear the transmission attempt to decode such. Those nodes that are successful in decoding then transmit during the relay period. The destination then runs the generalized DFE described in Section 4 to decode the packet.

Protocol 2 has the advantage that there is very little centralized control required in the base version, since any node that decodes a packet heard during the broadcast period simply transmits during the relay period. Although it might appear that this would be expensive in terms of total transmit energy expended across the network for the transmission of a single packet, the energy normalization will be considered in the numerical results.

Per above, two variants of the protocols will be considered.

Variant A In Variant A, each of the potential relays simply transmits during the relay period without introducing any artificial delay. As shown in the numerical results, its performance can be limited if the overall path delays of the relay nodes are similar, and, hence, the anticipated delay diversity is not always achieved.

Variant B In Variant B, a pool of possible artificial delays (e.g. $\{T, 2T, \ldots\}$) is available for use by the potential relays. Before a node transmits during the relay period, it delays the signal by its currently assigned artificial delay. Throughout this work, it will be assumed for Variant B that the allotment of artificial delays from the pool to the relay nodes is done well. In other words, nodes in close geographical proximity will employ different delays from the pool. Although we avoid complete specification of a medium access control (MAC) protocol to accomplish such, a general idea is described here to demonstrate that near-optimal assignment should be possible. Consider an ad hoc wireless network employing Protocol 2 described above, where each node carries with it a current artificial delay from the pool that it will employ whenever it is asked to serve as a relay. Now, whenever a source transmits a packet, it attaches at the end of that packet a few bits indicating the artificial delay from the pool it would employ *if* it were playing the role of relay. Per above, all potential relays hear the transmission and attempt decoding. If a node is successful, which is more likely if the node is near the source, and it realizes the source is employing the same artificial delay as itself, the node switches randomly to a different artificial delay from the pool. Although this does not impact performance for the current packet transmission, since the source will not transmit during the relay period, future transmissions where the geographically-close current source and current relay might both be asked to serve as relays, will be improved. In effect, this protocol encourages the desired condition - that nodes in close proximity are assigned different artificial delays from the pool - and will work to maintain such even under node mobility.

IV. Generalized DFE Receiver

Denote the raised cosine (RC) pulse by $h_{RC}(t) = h_{Tx}(t) \otimes h_{Tx}(-t)$, where $\otimes$ is the convolution operation. Thus the equivalent complex baseband impulse response at the output of the receiver filter $h_{Rx}(t)$ of the destination for the transmissions from the relays is $h_D(t) = \sum_{i \in \mathcal{D}_{\mathcal{R}}(s)} \alpha_{i,D} h_{RC}(t - \tau_i)$. The complex noise at the output of the receiver filter $h_{Rx}(t)$ is $\nu_D(t) = W_D(t) \otimes h_{Rx}(t)$, which has autocorrelation function $\phi_{\nu_D}(\tau) = \frac{1}{2} E\left[\nu_D(t)\nu_D^*(t+\tau)\right] = \mathcal{N}_0 h_{RC}(\tau)$ for the SRRC receiver. The receiver structure is depicted in Fig. 2. Note the striking difference from the standard DFE, since the signal $Y_{D_S}(t)$ received while the source is transmitting must also be jointly processed. This structure, along with the joint optimization of such, is one of the contributions of this work. The continuous-time signal at the output of $h_{Rx}(t)$ at N_D during the time the relays are transmitting is $y_D(t) = h_{Rx}(t) \otimes Y_{D,R}(t) = \sum_{n=-\infty}^{\infty} I_n h_D(t - nT) + \nu_D(t)$. The fractional spaced (i.e., T/2 spaced) equalizer is considered due to its robust performance. Similar notation to [15] will be employed. The input-output relation for the discrete-time equivalent channel from the multiple relays to the input of the feedforward filter at the destination is $y_{D,k+\psi} \triangleq y_D\left[(k+\psi)T + t_0\right] = \sum_{n=0}^{L} I_{k-n} h_{D,n+\psi} + \nu_{D,k+\psi}$, where $h_{D,n+\psi} = h_D\left((n+\psi)T + t_0\right)$, $\nu_{D,k+\psi} = \nu_D(kT + \psi T + t_0)$ with k and n integer (int.), and $\psi \in \left\{0, \frac{1}{2}\right\}$. By properly selecting the initial sampling time t_0, the channel impulse response $h_D(t+t_0)$ is approximated as nonzero over the time interval $[0, LT]$, where L is an integer. The FFF is an anti-causal filter with L_f $T/2$-spaced taps and coefficients $\left\{c_{(1-L_f)/2}, \cdots, c_{-1}, c_{-1/2}, c_0\right\}$. The FBF is a causal filter with L_b T-spaced taps and coefficients $\{c_1, c_2, \cdots, c_{L_b}\}$. The length L_b of the FBF is assumed to be equal to the length of the channel, i.e., $L_b = L$. In practice, L_f is chosen one to five times the channel pre-cursor length, which is determined by the position of the peak amplitude response of $h_D(t+t_0)$ [16].

For the signal $Y_{D_S}(t)$ received while the source node is transmitting, whose support does not overlap that of $Y_{D,R}(t)$ per Section II, the equivalent discrete-time channel model at the output of the T-spaced sampler is

$$y_{S,k} = y_S(kT + t_0) = \alpha_{S,D} I_k + \nu_{S,k}, \tag{1}$$

where $y_S(t)$ is the output of the receiver filter during the time the source is transmitting and $\{\nu_{S,k}\}$ is a sequence of independent complex Gaussian random variables with zero mean and variance $E\left[|\nu_{S,k}|^2\right] = 2\mathcal{N}_0$ which are independent of $\{\nu_{D,k+\psi}\}$.

The coefficients of the FFF and FBF, as well as β_0 for the direct path $y_{S,k}$, can be obtained by assuming correct past decisions and minimizing the mean squared error (MSE) MSE $= E\left[\left|I_k - \mathbf{u}_k^T \mathbf{c}\right|^2\right]$, where the $\mathbf{x}^T$ denotes non-conjugate transpose of a vector $\mathbf{x}$. The data vector $\mathbf{u}_k$ is defined as

$$\begin{aligned} \mathbf{u}_k \triangleq & \left[y_{D,k+(L_f-1)/2}, \cdots, y_{D,k+1}, y_{D,k+1/2}, y_{D,k}, y_{S,k},\right. \\ & \left. I_{k-1}, I_{k-2}, \cdots, I_{k-L_b}\right]^T, \end{aligned} \tag{2}$$

and the vector of filter coefficients $\mathbf{c}$ is denoted as $\mathbf{c} \triangleq \left[c_{(1-L_f)/2}, \cdots, c_{-1/2}, c_0, \beta_0, c_1, c_2, \cdots, c_{L_b}\right]^T$.

By applying the orthogonality principle [17], i.e., $E\left[(I_k - z_k)\,\mathbf{u}_k^*\right] = 0$, where $z_k = \mathbf{u}_k^T \mathbf{c}$, the filter coefficients are determined as [18]: $\mathbf{c}_{(1-L_f)/2:0} = (1 - \beta_0 \alpha_{S,D}) \cdot \mathbf{\Omega}^{-1}\mathbf{p}$,

$$\beta_0 = \alpha_{S,D}^* \frac{1 - \tilde{U}_0}{\mathcal{N}_0 + |\alpha_{S,D}|^2 \left(1 - \tilde{U}_0\right)}, \tag{3}$$

and $c_j = -\sum_{i=(1-L_f)/2:0} h_{D,j-i} \cdot c_i$, for $j = 1, 2, \cdots, L_b$, where $(1-L_f)/2 : 0 = (L_f - 1)/2, \cdots, -1, -1/2, 0$, and $\mathbf{p}$ is a column vector of dimension L_f with $\mathbf{p}_i = h_{D,-i}^*$, $i = (1-L_f)/2 : 0$. The matrix $\mathbf{\Omega}$ is determined by the autocorrelation of the data vector $\mathbf{u}_k$, $\mathbf{\Omega} = \mathbf{\Gamma} - \mathbf{\Lambda}^* \mathbf{\Lambda}^T$, where the elements of matrices $\mathbf{\Gamma}$ and $\mathbf{\Lambda}$ are $\Gamma_{i,j} = \frac{1}{2} E\left[y_{D,k-i} y_{D,k-j}^*\right]$, for $i, j \in \left\{\frac{1-L_f}{2}, \cdots, -1, -1/2, 0\right\}$, and $\mathbf{\Lambda}_{i,j}^T = h_{D,i-j}$, for $i \in \{1, 2, \cdots, L_b\}$, $j \in \{(1-L_f)/2 : 0\}$. The scalar $\tilde{U}_0 = \mathbf{p}^\dagger \mathbf{\Omega}^{-1} \mathbf{p}$, where $\mathbf{p}^\dagger$ is the conjugate transpose of $\mathbf{p}$.

The minimum mean squared error of the generalized equalizer can be shown to be

$$(\mathrm{MSE})_o = \left(\tilde{\mathrm{MSE}}\right)_o \frac{\mathcal{N}_0 \sigma_c^2}{\mathcal{N}_0 \sigma_c^2 + |\alpha_{S,D}|^2 \left(\tilde{\mathrm{MSE}}\right)_o}. \tag{4}$$

where $\sigma_c^2 = 2\sigma_I^2$, and $\left(\tilde{\mathrm{MSE}}\right)_o = \sigma_c^2 (1 - \tilde{U}_0)$ is the MSE of a DFE-MMSE when the signal $Y_{D_S}(t)$ is not considered [18].

The input to the slicer z_k can be expressed in a generic way, i.e., $z_k = \mathbf{u}_k^T \mathbf{c} = I_k U_0 + \sum_{n \neq 0} I_{k-n} U_n + \tilde{\nu}_k$, where $\tilde{\nu}_k$ is Gaussian noise term which is independent of the ISI, and $\{U_n\}$ are ISI coefficients. The signal-to-interference-and-noise-ratio (SINR) at the input of the slicer is thus defined as [19] SINR $= \frac{|U_0|^2 \sigma_c^2}{\sigma_c^2 \sum_{n \neq 0} |U_n|^2 + E|\tilde{\nu}_k|^2}$, which can be shown to be

$$\mathrm{SINR} = \frac{\sigma_c^2 - (\mathrm{MSE})_o}{(\mathrm{MSE})_o} = \tilde{\mathrm{SINR}} + \frac{|\alpha_{S,D}|^2}{\mathcal{N}_0}, \tag{5}$$

where $\tilde{\mathrm{SINR}} = \frac{\sigma_c^2 - \left(\tilde{\mathrm{MSE}}\right)_o}{\left(\tilde{\mathrm{MSE}}\right)_o}$ is the SNR of the DFE-MMSE without utilizing the direct path knowledge $\{y_{S,k}\}$. Given the direct path signal as in (1), $\frac{|\alpha_{S,D}|^2}{\mathcal{N}_0}$ is the signal-to-noise ratio in $y_{S,k}$. Therefore, the joint DFE-MMSE estimation of the data sequence as proposed here achieves the sum of the SNR from the two channels *at the input to the slicer*. One channel is from relays in $\mathcal{D}_{\mathcal{R}}(s)$, and the other one is from the source N_S directly.

V. Simulation Results

The maximum propagation delay T_D along the diagonal line of a square area with one side length D_L is set as an integer number of symbol periods T, e.g., $T_D = 3T$. The pathloss coefficient is $\mu = 3$. The signal-to-noise ratio (SNR) at each transmitter side is $\sigma_I^2/\mathcal{N}_0 = 1/\mathcal{N}_0$. Each packet consists of $L_P = 200$ QPSK symbols, where $I_k = a_k + jb_k$, $a_k, b_k \in \{1, -1\}$. The SRRC transmit filter $h_{Tx}(t)$ is truncated to $[-4T, 4T]$, with a roll-off factor $\beta = 0.35$. The frame error rate at node R_j is $P_w^{(R_j)} = 1-(1-P_b^{(j)})^{2L_P}$, where the bit error rate $P_b^{(j)} = Q\left[\sqrt{|\alpha_{S,R_j}|^2/\mathcal{N}_0}\right]$ [17].At the node N_{R_j}, a binary random variable $\theta_j \in \{0, 1\}$ is generated with probability distribution function $P[\theta_j = 0] = P_w^{(R_j)}$. The relay node N_{R_j} is in the set $\mathcal{D}_{\mathcal{R}}$ if N_{R_j} is one of the possible relay nodes and $\theta_j = 1$.

For the given channel realization (i.e., given set $\mathcal{D}_{\mathcal{R}}$, and all the realizations of the fading gains), a Gaussian approximation can be employed to calculate the receiver bit-error probability for the joint MMSE detection if the data modulation scheme is QPSK; thus, $P_b \approx Q\left[\sqrt{\text{SINR}}\right]$ [20]. For a packet of L_P QPSK symbols, the instantaneous package error rate P_w is then estimated as $P_w = 1 - (1 - P_b)^{2L_P}$ [20]. At the destination, the matched filter bound can serve as a benchmark for the instantaneous BER [21], which is $P_{b,mf} = Q\left[\sqrt{E_{s,mf}/\mathcal{N}_0}\right]$. The quantity $E_{s,mf}$ is given by $E_{s,mf} = \int_{-\infty}^{\infty} |h_{D,T}(t)|^2 \, dt + |\alpha_{S,D}|^2$, where $h_{D,T}(t) = \sum_{i\in\mathcal{D}_{\mathcal{R}}(s)} \alpha_{i,D} h_{Tx}(t - \tau_i)$. Thus the packet error rate using the matched filter bound is $P_{w,mf} = 1 - (1 - P_{b,mf})^{2L_P}$. The threshold P_o under which to declare an outage event is is set to 0.1 in the simulation results.

In Fig. 3, the outage probability using Protocol 1 is compared with that of [5] employing the Alamouti code [22] and assuming the synchronization of the symbol boundaries when both of the two nearest nodes are available to forward the correctly received packets. It is assumed that the total number of nodes in the area is $K+2 = 100$. Also considered for comparison is the single hop transmission without any relaying as indicated by the dotted-star line in Fig. 3, which increases its transmit power proportionally if $M_R(s)$ is larger than zero in the relaying schemes, i.e., the transmit SNR is $(1 + M_R(s))/\mathcal{N}_0$, to make a fair comparison. In order to see the impact of the density of the relay nodes on the performance, D_L is increased from 1 to 3 with the maximum delay T_D scaled proportionally from $1.5T$ to $4.5T$ while fixing $K + 2 = 100$, as well as the scaled transmitted SNRs.

From Fig. 3, it can be seen that proposed Protocol 1 using the DFE-MMSE at N_D can achieve a diversity gain over the single-hop scheme, as expected. More importantly, compared to [5] using the Alamouti code, there is nearly 3.5 dB loss for high SNR without introducing any intentional delays (i.e. Variant A) at the relay nodes. However, for Protocol 1, Variant B, Fig. 3 demonstrates that the performance is only slightly ($<$ 1 dB) worse than a synchronous system. Therefore, it is concluded that even if symbol synchronization is impossible due to the infrastructureless nature of an ad hoc wireless network, comparable performance can be obtained by employing the decision feedback equalizer at N_D and setting the delays as a new resource for the involved relay nodes to compete. Increasing the maximum delay T_D from $1.5T$ to $4.5T$ does not affect the gain much, which is expected since there are only at most two paths from the selected relays to the destination, and the performance will not improve due to the increasing of relative delays if the relative delay between these two paths is beyond a certain value [19] (e.g., $0.6T$).

Fig. 4 and Fig. 5 demonstrate the performance of Protocol 2, Variant A. In Fig. 4, it can be clearly observed as the number of nodes $N_{total} = K + 2$ in a given area with $D_L = 3$ and $T_D = 4.5T$ increases from 4 to 20, the slope of the curves in the high SNR region is becoming larger, which implies an increase of the diversity gain achieved by the DFE-MMSE at N_D. The dotted curves are the matched filter bound.

As more nodes are added in the given area, the received SNR has not been normalized in Fig. 4 – the transmit power is $1/\mathcal{N}_0$ for each transmit node, which leads to the increasing energy consumption of these involved relay nodes even if they do not have their own data to transmit. Therefore, energy normalization across the whole network is considered in Fig. 5 to show the performance contributed purely by the cooperative diversity gain. With the pathloss coefficient $\mu = 0$, if $M_R(s)$ nodes are involved in relaying, the total signal power collected from all these paths plus the one from the source directly is $(M_R(s) + 1)$. Then multiply $\mathcal{N}_0$ by a factor of $(M_R(s) + 1)/3$ if $M_R(s) \geq 2$ such that the transmit SNR for each node in $\mathcal{D}_{\mathcal{R}}$ is $\frac{3}{(M_R(s)+1)\mathcal{N}_0}$, where the coefficient 3 is for the purpose of comparing with the case of $K + 2 = 4$, in which $M_R(s) + 1 \leq 3$ (one is N_S, another 2 are relay nodes). Based on Fig. 5, it is concluded that even with energy normalization, more diversity gains can be achieved as more nodes are available for relaying. However, in terms of both simulation results and the matched filter bound, it can be observed that as $K + 2$ is increased from 4 to 100 in a given area, not much gain is observed. This is due to the increasing density of relay nodes in this area, which results in different clusters of nodes. The delays from N_S to the relay nodes in each cluster and then to N_D are similar. The number of clusters will determine the asymptotic diversity gain in a given area when equalizer is employed at N_D.

Fig. 6 demonstrates that for Protocol 2, Variant B, randomly introducing the artificial delays to the signals transmitted by the active relay nodes can change the asymptotic tendency observed in Fig. 5 even in the relatively low transmit SNR region, which implies the improvement in diversity gain even if the density of nodes is increased. Note that this protocol requires no coordination of the relays whatsoever, and that the performance will be improved even further by the simple MAC of Section III. Hence, it is very suitable for implementation to achieve the gains promised by cooperative diversity.

VI. Conclusions

In this paper, two delayed diversity protocols are proposed to achieve the cooperative diversity gain in an ad hoc wireless network without requiring symbol synchronization. The physical layer approach of employing the DFE-MMSE at the destination was taken as a means to realize such diversity gains. A novel joint DFE-MMSE equalizer is derived. Based on the proposed outage probability criterion, simulation results demonstrate the performance improvements of the protocols over the single hop scheme, as well as the comparable performance compared with the protocols requiring strict symbol synchronization [5].

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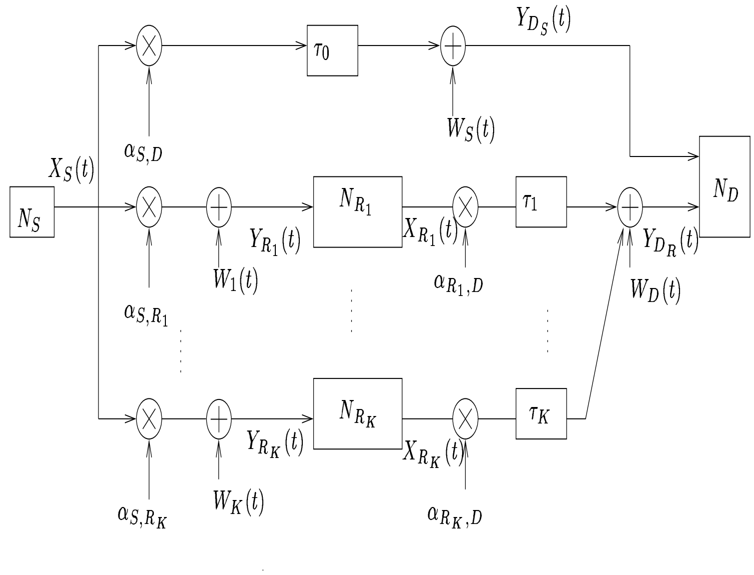

Figure 1: System model of an ad hoc wireless network

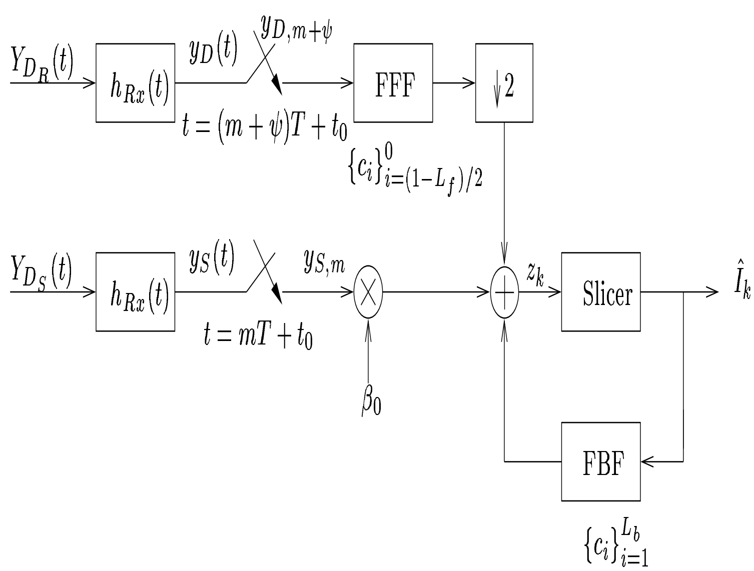

Figure 2: Functional description of the generalized DFE receiver. The signal $Y_{D_s}(t)$, and hence $y_{S,m}$, is collected by the receiver while the source is transmitting, and the signal $Y_{D_R}(t)$, and hence $y_{D,m+\psi}$, is collected by the receiver while the relays are transmitting, and then both are processed jointly.

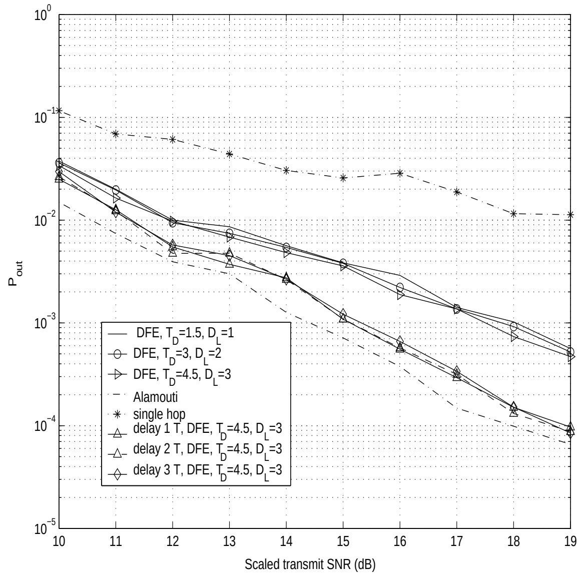

Figure 3: Comparison of Protocol 1 with that of [5] employing an Alamouti code. The pathloss coefficient $\mu = 3$. The number of nodes in an area is $K + 2 = 100$. Recall that D_L is the length of one side of the square region considered. T_D is the maximum propagation delay in the region in terms of the number of symbol periods. Curves labeled with "delay nT" correspond to Variant B of Protocol 1, while those without such a label correspond to Variant A.

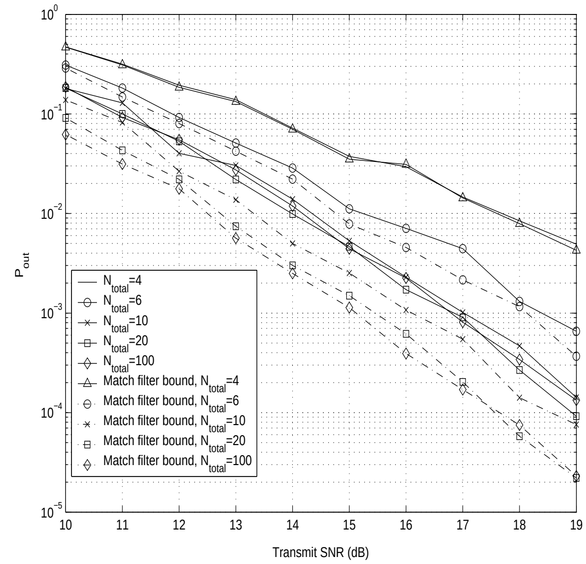

Figure 5: Performance of Protocol 2, Variant A with normalization of the received noise power. In simulations, the parameters are set as $\mu = 0$, $D_L = 3$, $T_D = 4.5T$.

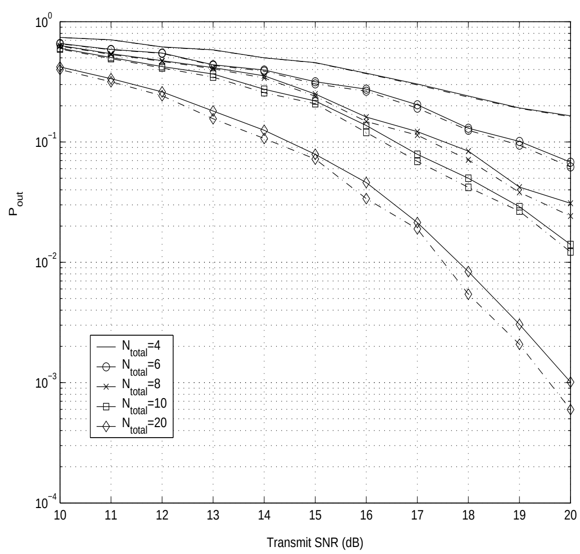

Figure 4: Performance of Protocol 2, Variant A without normalization of the received noise power. In simulations, the parameters are set as $\mu = 3$, $D_L = 3$, $T_D = 4.5T$.

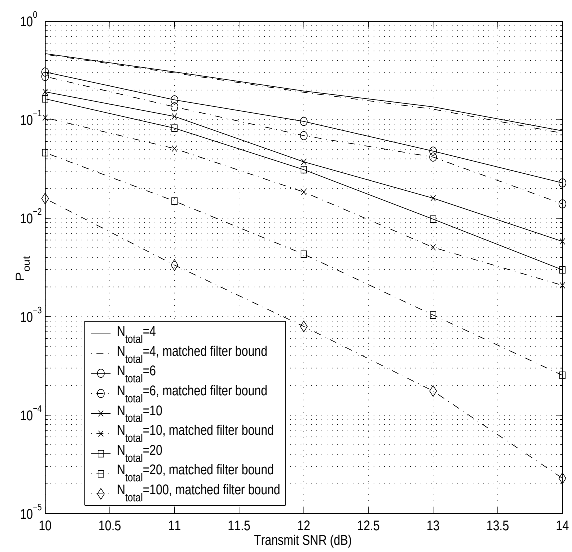

Figure 6: Performance of Protocol 2, Variant B with normalization of the received noise power. In simulations, the parameters are set as $\mu = 0$, $D_L = 3$, $T_D = 4.5T$. The pool of delays is $\{T, 2T, \cdots, 6T\}$ from which delays are randomly allocated to the packets transmitted by the active relays.