A PHY/MAC Approach to Wireless Routing

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***Abstract*— Routing data through a wireless network is made challenging by impairments in the wireless medium, such as fading. Nevertheless, wireless routing if implemented, will result in tremendous cost-savings in next generation wireless networks. This paper examines centralized and decentralized approaches for wireless routing from a PHY/MAC perspective. We show that decentralized routing strategies are capable of realizing full spatial diversity gain if an appropriate level of channel knowledge is available at the relay terminals. Furthermore, we propose a new carrier sensing random access based routing technique designed to avoid collision and conserve network power. A numerical example is provided to demonstrate that the technique is capable of realizing full spatial diversity gain.**

I. Introduction

With the rapid growth of wireless networks, routing data from a source terminal to a destination terminal through the wireless medium [1]-[3] (as opposed to the wireline medium) will become increasingly cost-effective. Traditional wireline routing techniques will in general not be feasible in the wireless context due to significant differences in the nature of the transmission medium (primarily due to multipath) and terminal capability (such as power constraints). Traditionally, data routing in communications networks has been tackled as a higher layer challenge in the protocol stack. In this paper we examine wireless routing from a combined physical layer (PHY) and medium access control (MAC) perspective.

Communications over wireless channels (unlike wireline channels) is severely impaired by random fluctuations in signal level known as fading. Diversity gain is a powerful means to combating fading, and is realized by providing the receiver with multiple (ideally independent) looks at the transmitted signal in space or time or frequency. Spatial (i.e., antenna) diversity techniques [4]-[8] are particularly attractive in point-to-point wireless systems since they do not incur an expenditure of time or bandwidth. Recently, a new method of realizing spatial diversity gain in wireless networks has been proposed under the name of *cooperative diversity* or *user cooperation diversity* [9]-[13]. Here, multiple single-antenna terminals pool their resources to form a virtual antenna array that realizes spatial diversity gain in a distributed fashion. The contents of this paper are motivated by the observation that *antenna selection diversity* (i.e., selecting the best antenna(s) to transmit/receive) in point-to-point multi-antenna systems [14]-[16] translates to routing in a cooperative diversity setup (i.e., selecting the best cooperating terminal(s) through which to route data).

Broadly, routing techniques can be classified as *centralized* or *decentralized*. In the centralized approach, network terminals are free to exchange information and cooperate to decide the (globally) optimal route. In decentralized routing, cooperation between terminals is limited or impossible, and hence routing decisions must be made locally, based on limited information of the network.

Contributions. The contributions reported in this paper can be summarized as follows:

- We systematically analyze wireless routing techniques from a *PHY/MAC perspective*, examining both *centralized* and *decentralized* approaches.
- We demonstrate that *decentralized routing can deliver full spatial diversity gain* if an appropriate level of channel knowledge is available at the relay terminals.
- We provide a *new decentralized strategy* for wireless routing based on *carrier sensing random access*. We provide a numerical example to show that this technique is capable of realizing *full spatial diversity gain*.

Relation to previous work. Decentralized routing based on inter-terminal separation, and carrier sensing with deterministic transmission delay has previously been considered in [1]. In our paper, decentralized routing decisions at the relay terminals are based on instantaneous signal-to-noise ratio (SNR) estimates. Hence our routing strategy incorporates microscopic fading (as opposed to only path loss, which is reflected by inter-terminal separation). Furthermore, we consider randomized transmission delay times (in addition to deterministic delay times) at the relay terminals to avoid collision and conserve network power. Finally, we firmly link the notion of routing in wireless networks to antenna selection

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diversity in point-to-point multi-antenna wireless systems.

Organization of the paper. The remainder of this paper is organized as follows. Section II introduces the channel and signal model used throughout this paper. Section III describes both centralized as well as decentralized routing strategies for the network under consideration, and the complexity-performance tradeoffs therein. We conclude with a summary in Section IV.

Notation. $\mathcal{E}$ stands for the expectation operator. A complex random variable $Z = X + jY$ is $\mathcal{CN}(0, N_o)$ if X and Y are i.i.d. $\mathcal{N}(0, N_o/2)$. $\Re^N$ denotes N-dimensional real space. $u(x)$ is the unit-step function defined as $u(x) = 1$ for $x \geq 0$ and 0 otherwise.

II. Channel and Signal Model

We consider a scenario (see Fig. 1) where data is to be routed from a single source terminal $\mathcal{S}$ to a single destination terminal $\mathcal{D}$ through one of K relay terminals $\mathcal{R}_k\,(k = 1, 2, ..., K)$. While we assume that all terminals in the network are equipped with single-antenna transceivers, the results presented in this paper can be easily generalized to a network with multi-antenna terminals.

We assume no direct link between the source and destination terminal (caused by high path loss and/or heavy shadowing). Hence communication must be established via the relay terminals. We assume a two-hop relaying architecture. In the first hop, the source terminal broadcasts data to the relay terminals. In the second hop, one of the K relay terminals forwards the received data to the destination terminals. We will examine various routing options in the following section.

The signal received at the k-th relay terminal over the first hop, r_k, is given by

$$r_k = \rho^{\frac{1}{2}}\, h_k s + n_k, \;\; k = 1, 2, ..., K, \tag{1}$$

where ρ is the average receive signal-to-noise ratio (SNR) for the[1] $\mathcal{S} \rightarrow \mathcal{R}_k$ link (having accounted for path loss and shadowing), $h_k \sim \mathcal{CN}(0, 1)$ is the corresponding complex-valued channel gain, s is the unit average energy transmitted data symbol, and $n_k \sim \mathcal{CN}(0, 1)$ is additive noise. Each relay terminal maintains perfect channel state information (CSI) of the corresponding h_k and decodes its received signal.

Assuming that data is routed to the destination through $\mathcal{R}_i$, the signal received at $\mathcal{D}$ (in the second hop) is given by

$$y = \rho^{\frac{1}{2}}\, g_i \widehat{s}_i + z,$$

where ρ is the average receive SNR for the $\mathcal{R}_i \rightarrow \mathcal{D}$ link (having accounted for path loss and shadowing), $g_i \sim \mathcal{CN}(0, 1)$ is the corresponding complex-valued channel gain, $\widehat{s}_i$ is the decoded data symbol at $\mathcal{R}_i$ in the first hop, and $z \sim \mathcal{CN}(0, 1)$ is additive noise. Perfect CSI of g_i is assumed at $\mathcal{D}$. Throughout the paper, h_k and g_k are assumed independent across k.

[1] $\mathcal{A} \rightarrow \mathcal{B}$ signifies communication from terminal $\mathcal{A}$ to terminal $\mathcal{B}$.

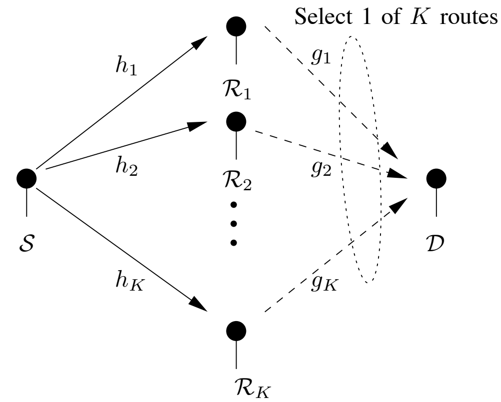

Fig. 1. *Schematic of network setup.*

Note that for the sake of clarity of exposition and to simplify analysis we have assumed the same average receive SNR (i.e., ρ) across all $\mathcal{S} \rightarrow \mathcal{R}_k$ and $\mathcal{R}_k \rightarrow \mathcal{D}$ links. In practice, this condition can be met through a combination of power control and relay terminal placement. The case of unequal average receive SNR across the network links can be dealt with through appropriate modifications of the channel and signal model. While such modifications may alter our results, we consider this simplistic scenario to gauge the performance gains that may be realized through our approach . Finally, propagation delay differences between network terminals are assumed to be negligible.

The case of different receive SNRs is difficult to analyze from a diversity point of view. However, one possible approach might be to constrain average receive SNRs to be a constant (in time, but differing across relays) fraction of SNR, in that way, the behavior of end-to-end error probability can be characterized as SNR goes to infinity. The general case seems rather difficult to characterize analytically.

III. Routing

In this section we examine the various options available to route data from the source to the destination terminal through one of the K relay terminals. Performance will be quantified in terms of the end-to-end *uncoded symbol error rate*. For the sake of simplicity we assume that the source employs BPSK (Binary Phase Shift Keying) modulation.

A. Centralized Routing

Centralized routing is based on the assumption that a global router exists that maintains perfect CSI of all network links and routes data accordingly.

It is straightforward to show that the end-to-end probability of error associated with routing data through terminal $\mathcal{R}_k$, for an instantaneous realization of the network (i.e., instantaneous realizations of the channels $h_k\,(k=1,2,...,K)$ and $g_k\,(k=1,2,...,K)$), is [17]

$$P_e^{(k)} = Q\left(\sqrt{2x_k}\right) + Q\left(\sqrt{2w_k}\right) - Q\left(\sqrt{2x_k}\right) Q\left(\sqrt{2w_k}\right), \quad (2)$$

where $x_k = |h_k|^2\rho$ and $w_k = |g_k|^2\rho$ are independent, exponentially distributed with mean ρ^2. For a given network realization, it is clear that the global router will route data through the relay terminal associated with the lowest instantaneous end-to-end symbol error probability. The instantaneous symbol error probability for centralized routing is therefore

$$P_{CENTRAL} = \min_k P_e^{(k)}, \quad (3)$$

and the corresponding average (averaged over the realizations of all network channels) symbol error probability is

$$\overline{P}_{CENTRAL} = \mathcal{E}_{\{h_k, g_k\}_{k=1}^K}\{P_{CENTRAL}\}. \quad (4)$$

It is straightforward to show that in the high-SNR regime (i.e., when $\rho \to \infty$) $\overline{P}_{CENTRAL}$ behaves as

$$\overline{P}_{CENTRAL} \sim \rho^{-K}, \quad (5)$$

indicating that centralized routing extracts a diversity order of [18], [19]

$$d = -\lim_{\rho\to\infty} \frac{\overline{P}_{CENTRAL}}{\log\rho} = K. \quad (6)$$

Hence centralized routing realizes a diversity order equal to the number of relay terminals (full spatial diversity gain). This result is not surprising: centralized routing resembles selection diversity in point-to-point multi-antenna systems. Selection diversity has been shown to extract full spatial diversity gain [4].

We conclude this subsection by noting that centralized routing is difficult, if not impossible, to realize in practice. The requirement that the centralized router maintain CSI of all network links and pass on route selection information to the appropriate relay terminal will incur increasingly large overheads in a growing network, rendering this technique infeasible. Nevertheless, centralized routing provides us with a theoretical bound, with which we can compare other routing strategies. In the following sections we will show that full spatial diversity gain can also be realized through decentralized routing approaches.

B. Carrier Sensing (CS) Based Routing

Carrier sensing is a means by which we can depart from a centralized routing approach. All the K relay terminals receive the signal transmitted in the first hop. In the second hop, the transmission medium is claimed by one of the K relay terminals, ideally by the relay terminal associated with the lowest instantaneous end-to-end error probability. On detecting that the medium has been claimed (through CS), the other relay terminals abort transmission.

In order to achieve the same performance as centralized routing (i.e., $\overline{P}_{CS} = \overline{P}_{CENTRAL}$, where $\overline{P}_{CS}$ is the average probability of error of CS based routing), each relay terminal must have perfect CSI of the corresponding h_k and g_k, based on which it determines a transmission delay $T(P_e^{(k)}) \geq 0$ that satisfies

$$T(x) > T(y) \ \text{ if } \ x > y. \quad (7)$$

Note that the mapping from error probability to transmission delay is deterministic and the same across all relay terminals. This ensures that the best route is always selected and that CS based routing achieves the same error rate performance as centralized routing.

CS based routing requires tight synchronization across the relay terminals (i.e., the zero-point from which transmission delay is measured for the second hop must be the same across relay terminals). This requirement is of course alleviated if the propagation delay differences between network terminals are negligible. A drawback of CS based routing compared to centralized routing is the additional delay that is incurred from variable transmission times at the relay terminals. However, this is a small penalty to pay when compared to the complexity of centralized routing. Furthermore, the additional delay incurred can be upper-bounded and in theory made arbitrarily small to meet network specifications (by virtue of the fact that $P_e^{(k)}$ is upper-bounded).

With perfect CSI of the corresponding g_k and h_k at each relay terminal, $T(P_e^{(k)})$ will be chosen so that the best route between source and destination is always selected. This is not the case if imperfect or partial CSI is available at the relay terminals (for instance, if each relay terminal knows only its h_k but not g_k). It is clear that under such circumstances the best route cannot be chosen accurately.

C. Carrier Sensing Random Access (CSRA) Based Routing

Maintaining CSI at a relay terminal is very challenging in practice, more so for the $\mathcal{R}_k \to \mathcal{D}$ link than for the $\mathcal{S} \to \mathcal{R}_k$ link. Knowledge of the $\mathcal{S} \to \mathcal{R}_k$ link can be maintained at a relay terminal via training and tracking, while knowledge of the $\mathcal{R}_k \to \mathcal{D}$ link can be maintained via a feedback link from the destination terminal. In general, the feedback link is a low bandwidth link of finite precision, say q bits. Through feedback, the destination terminal can inform $\mathcal{R}_k\ (k=1,2,...,K)$ of the one of 2^q non-intersecting quantization regions (denoted by $\sigma_1, \sigma_2, ..., \sigma_{2^q}$ with $\Re^1 = \sigma_1 \cup \sigma_2 \cup ... \cup \sigma_{2^q}$) in which the instantaneous SNR w_k lies. In the following, we denote the mapping from instantaneous SNR to a quantization region by $f(w_k)$. To simplify the ensuing

[2] $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-t^2/2}dt$

analysis by exploiting symmetry, we assume that each relay terminal, for the sake of determining its transmission delay[3], also quantizes the instantaneous SNR for the $\mathcal{S} \rightarrow \mathcal{R}_k$ link, x_k, with q bit precision using the mapping $f(x_k)$.

Hence, the transmission delay time at a relay terminal will be determined based on one of 2^{2q} possibilities (partial CSI), possibly through a look-up table to minimize computation. It is clear that with deterministic delay and partial CSI, the probability of relay terminals simultaneously accessing the transmission medium (i.e., the probability of collision) in the second hop is non-zero. To avoid collision and minimize power consumption in the network, we randomize the transmission delay time at each relay terminal (in the spirit of Ethernet or Aloha protocols [20]). The probability density function (PDF) of transmission delay at a relay terminal is a function of its partial CSI and will in general be different across the relay terminals. Having the same PDF for transmission delay across relay terminals is equivalent to randomly selecting one of the relay terminals to fire and will provide no spatial diversity gain (i.e., unit diversity order) irrespective of the number of relay terminals. It is straightforward to see that the performance of random scheduling of the relay terminals is identical to round robin scheduling. The choice of the transmission delay PDFs across the relay terminals should clearly reflect the fact that relay terminals with good quality channels will forward data with a higher probability than relay terminals experiencing deep fades in channel quality.

In the following we shall assume that the transmission delay at each relay terminal $T_k(f(x_k), f(w_k))$ is exponentially distributed with mean delay $\lambda_k(f(x_k), f(w_k))$ calculated as a function of the partial CSI. $\lambda_k(f(x_k), f(w_k))$ is a symmetric function of two arguments (i.e., $\lambda_k(\alpha, \beta) = \lambda_k(\beta, \alpha)$) and hence for inputs $f(x_k)$ and $f(w_k)$ each quantized with q bits, has $\frac{2^{2q}+2^q}{2}$ distinct values.

Determining the mean transmission delay. For a given network realization, the probability that the k-th relay terminal claims the transmission medium is

$$\psi_k(\mathbf{x}, \mathbf{w}) = \frac{\lambda_k(f(x_k), f(w_k))}{\sum_{m=1}^{K} \lambda_m(f(x_m), f(w_m))}, \tag{8}$$

where $\mathbf{x} = [x_1 \ x_2 \ ... \ x_K]$ and $\mathbf{w} = [w_1 \ w_2 \ ... \ w_K]$. It follows that the average probability of error for CSRA based routing is

$$\overline{P}_{CSRA} = \sum_{k=1}^{K} \left(\int_{\Re^K} \int_{\Re^K} \psi_k(\mathbf{x}, \mathbf{w}) P_e^{(k)} g(\mathbf{x}) g(\mathbf{w}) d\mathbf{x} d\mathbf{w} \right) \tag{9}$$

with $g(\mathbf{x}) = \prod_{i=1}^{K} \left(\frac{1}{\rho} e^{-\frac{x_i}{\rho}} u(x_i) \right)$ and where $P_e^{(k)}$ is given in (2). Given the symmetry in the network it is clear that

$$\overline{P}_{CSRA} = K \left(\int_{\Re^K} \int_{\Re^K} \psi_k(\mathbf{x}, \mathbf{w}) P_e^{(k)} g(\mathbf{x}) g(\mathbf{w}) d\mathbf{x} d\mathbf{w} \right). \tag{10}$$

Now, since the mean transmission delay at a relay terminal is determined based on $f(x_k)$ and $f(w_k)$, the $\Re^K \times \Re^K$ space over which integration is performed in (10) may be decomposed into 2^{2Kq} non-intersecting subspaces $\mathbf{V}_i$ ($i = 1, 2, ..., 2^{2Kq}$) over which $\psi(\mathbf{x}, \mathbf{w}) = \psi(\mathbf{V}_i)$ is piecewise constant. It follows that

$$\overline{P}_{CSRA} = K \sum_{i=1}^{2^{2Kq}} \psi(\mathbf{V}_i) \zeta(\mathbf{V}_i), \tag{11}$$

where $\zeta(\mathbf{V}_i) = \int\int_{\mathbf{V}_i} P_e^{(k)} g(\mathbf{x}) g(\mathbf{w}) d\mathbf{x} d\mathbf{w}$. Now, the problem of minimizing the probability of error and finding the optimal mean transmission delays may be posed as

$$\min_{\lambda_k(\sigma_i, \sigma_j)(i,j=1,2,...,2^q)} \overline{P}_{CSRA}$$

subject to

$$\overline{T}_{min} \leq \lambda_k(\sigma_i, \sigma_j) \leq \overline{T}_{max}, \quad i, j = 1, 2, ..., 2^q$$

where we have imposed additional constraints (to meet network specifications) on the mean transmission delay with $\overline{T}_{max} > \overline{T}_{min} > 0$. From (8) and (11) it is clear that the objective function of the optimization problem is the *sum of linear fractional functions* (in $\lambda(\sigma_i, \sigma_j)$ ($i, j = 1, 2, ..., 2^q$)) and as a consequence the optimization is non-linear. A global optimization method proposed by Floudas and Visweswaran is quite appropriate to solve this problem [21], [22] and is used in the numerical example to follow.

Note that with CSRA based routing there is a non-zero probability that the best route between $\mathcal{S}$ and $\mathcal{D}$ for a given network realization is not chosen. However, with finer quantization (i.e., larger q) and flexibility in the choice of $\overline{T}_{min}$ and $\overline{T}_{max}$, this probability will be reduced. Note here that error probability performance depends on ratios of mean transmission delay ($\psi_k(\mathbf{x}, \mathbf{w})$) and not on absolute values.

Numerical example. We consider a network with 2 relay terminals and a single source-destination pair. Fig. 2 plots the symbol error rate as a function of SNR for centralized routing (note that this is equivalent to CS based routing with perfect CSI), round-robin routing, and CSRA based routing for $q = 4$ and $q = 10$. We have chosen $\overline{T}_{min} = 10^{-6}$s and $\overline{T}_{max} = 1$s for CSRA based routing. It is clear from Fig. 2

[3]Note that each relay terminal continues to decode the signal received on the $\mathcal{S} \rightarrow \mathcal{R}_k$ link using perfect CSI. If perfect CSI of the $\mathcal{S} \rightarrow \mathcal{R}_k$ link is used in combination with quantized CSI for the $\mathcal{R}_k \rightarrow \mathcal{D}$ link to determine transmission delay, the performance achieved will indeed be better. However, using quantized CSI for both the $\mathcal{S} \rightarrow \mathcal{R}_k$ and $\mathcal{R}_k \rightarrow \mathcal{D}$ links to determine transmission delay simplifies the optimization problem to follow considerably, while realizing significant performance gain.

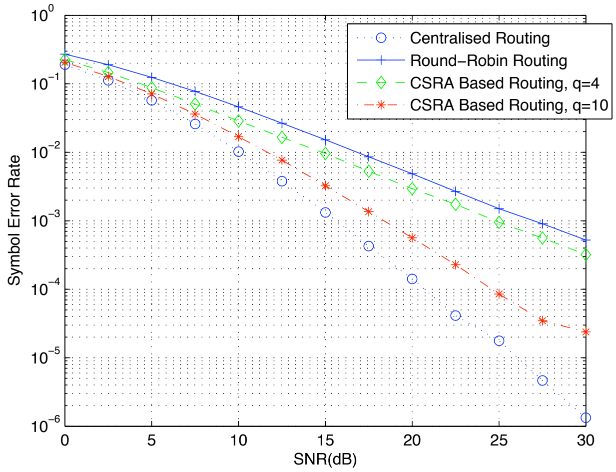

Fig. 2. *Performance comparison of routing strategies.*

that while centralized routing realizes full spatial diversity gain (reflected by the slope of the error rate curve), round-robin routing offers no diversity gain. Furthermore, the diversity gain offered by CSRA based routing depends on the quality of quantization. With coarse quantization (i.e., $q = 4$) CSRA routing provides no diversity advantage. Spatial diversity gain however is available with fine quantization (i.e., $q = 10$) as seen in Fig. 2.

With fine quantization, however, the motivation for CSRA based routing weakens, since the probability that relay terminals simultaneously access the transmission medium decreases. A deterministic delay mapping function will in this case be more appropriate since it ensures that the best route is always selected. Nevertheless, CSRA routing does have merits when quantization is coarse and does outperform round-robin routing by providing a coding gain (i.e., left offset in error rate curve), as seen in Fig. 2.

IV. Conclusion

We studied centralized and decentralized routing strategies for wireless networks from a PHY/MAC perspective and found that decentralized techniques are capable of realizing full spatial diversity gain with an appropriate level of channel knowledge at the relay terminals. We introduced a new carrier sensing random access based relaying strategy capable of realizing full spatial diversity gain.

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