On the Design of a Quality-of-Service Driven Routing Protocol for Wireless Cooperative Networks

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Abstract—**In this paper, a quality-of-service driven routing protocol is proposed for wireless cooperative networks. The key contribution of the proposed protocol is to bring the performance gain of cooperative diversity from the physical layer up to the networking layer. Specifically, the proposed protocol uses a distributed algorithm to select the best relays based on link quality to form cooperative links for establishing a route with appropriate error performance from a source to a destination node. Furthermore, analytical results are developed to show that the proposed distributed routing protocol can perform close to the optimal in terms of error performance, especially for linear network topologies. Monte-Carlo simulation results are also provided for performance evaluation.**

I. INTRODUCTION

Recently, cooperative transmission (CT) has gained much attention as an effective technique to combat multi-path fading and enhance receiver reliability of wireless communication systems. The key feature of cooperative transmission is to encourage multiple single-antenna users/sensors to share their antennas cooperatively [1, 12]. In this way, a virtual antenna array can be constructed and hence reception reliability can be boosted significantly. Various cooperative transmission protocols have been developed at the physical layer to further increase the bandwidth efficiency of cooperative diversity. However, it is still not clear how such performance gain at physical layer can benefit the upper layers, which is the major motivation of this paper. To be specific, a novel routing protocol is constructed to realize the performance gain of cooperative diversity at the networking layer. The Lecture Hall Theorem [14] is utilized to ensure that a best route can constructed in a distributed way. For performance evaluation, we will analysis the relationship between the number of hops and bit error rate (BER) for linear network scenarios. Comparing with classical Destination-Sequenced Distance-Vector (DSDV) algorithm [8], we demonstrate the benefits of proposed cooperative routing scheme on hops saving and end-to-end BER reducing. Furthermore, we analytically obtain the gap ratio between our proposed routing algorithm and routing optimization solution in achieving minimal BER under a regular linear topology, which shows that the proposed distributed protocol can perform close to the optimal one.

II. SYSTEM ARCHITECTURE

In cooperative networks, each node acts two roles in the network transmission: source node and relay node. Here, relay transmission is a main feature of cooperative communication. Figure 1 shows a classic cooperative network model [1]:

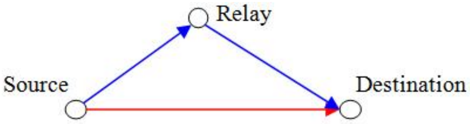

Fig. 1. An Example of Cooperative link

A cooperative link between the source and destination nodes includes two different transmission channels. The red line is direct transmission channel from the source directly to the destination, while the combined blue lines are relay transmission channels from the source through the relay to the destination. A typical cooperative transmission can be divided into two stages (i.e., time slots). During the first stage, the source broadcasts its information where all relays and destination nodes are listening. During the second stage, one or multiple relays forward the received information to the destination. Therefore, the destination node receives multiple copies of the same packets transmitted through different wireless channels, thus some degree of diversity can be obtained from such cooperative transmission strategies. The main advantage of cooperative communication is significant improvement of reception reliability which becomes an important criterion to measure the performance of cooperative transmissions and will be examined in following sections.

Time Division Multiple Access (TDMA) schemes are also considered in this paper for two reasons [2]. First, in order to simplify the problem and in case that there are multiple source destination pairs communicate simultaneously, the TDMA assumption could allow us to only concentrate on one pair, and hence remove co-channel interference between the terminals at the destination automatically. Second, the fact that time division duplex channels are reciprocal naturally makes channel state information (CSI) available at the transmitter.

A. Outage Behavior of Cooperative Transmission

According to [2], the wireless link ∂_{ij} between the node i and j could be further modelled as $\partial_{ij} = h_{ij}/d_{ij}^{k/2}$, where d_{ij} is the distance between the nodes i and j, describes the large-scale behavior of the channel gain, k is the path-loss exponent and h_{ij} captures the channel fading characteristics due to the rich scattering environment. In addition, channel fading parameter h_{ij} is assumed as independent and identically distributed (i.i.d), complex Gaussian variable with zero mean and unit variance. Furthermore, only one relay node is chosen to accomplish cooperative transmission between node i and j.

We consider that the quality of cooperative transmission is measured in terms of outage probabilities [1].

For direct transmission, the outage probability is:

$$P_D^{out} = d_{s,d}^2 \left(\frac{2^R - 1}{\rho}\right) \tag{1}$$

where R is the data rate in bit/s/Hz which is defined by the quality of service (QoS) requirement, ρ is the transmission power to noise ratio and d is the distance between two nodes. Note that the mathematical details behind this equation are omitted due to space limitation and can be found from [2].

For cooperative link (Figure 1), the outage probability is:

$$P_C^{out} = \frac{1}{2} d_{s,d}^2 (d_{s,r}^2 + d_{r,d}^2) \frac{(2^{2R} - 1)^2}{\rho^2} \tag{2}$$

where the notation s, d and r denotes the source, destination and relay nodes, respectively.

B. Objective Function Design for Cooperative Routing

It is assumed that a route has been established between source and destination. Different from traditional routes, cooperative transmission is used to improve the link quality when source node communicates with destination node. The links involved in the route between the source and destination nodes can be categorized into two sets. The first set is defined as S_1 which includes all links using cooperative transmission and the other one, defined as S_2, includes the links using direct transmission without using any relay. In our model, we also assume identical transmission power for all nodes, thus the total transmission power is proportional to the total number of nodes involved in the route.

For the above scenario, by assuming the error performances among links are independent, the end-to-end outage probability is given by:

$$P_{end\_to\_end}^{out} = 1 - \prod_{ij \in S_1} (1 - P_{ij}^C) \prod_{ij \in S_2} (1 - P_{ij}^D) \tag{3}$$

where P_{ij}^C and P_{ij}^D denotes outage probability for cooperative link and for direct link, respectively.

For small outage probability $P_{ij}^C \ll 1$ and $P_{ij}^D \ll 1$, we have the following approximation:

$$P_{end\_to\_end}^{out} \approx \sum_{ij \in S_1} P_{ij}^C + \sum_{ij \in S_2} P_{ij}^D \tag{4}$$

Hence, putting Eq. (1) and (2) into the above, we obtain:

$$\begin{aligned} P_{end\_to\_end}^{out} &= \frac{(2^{2R} - 1)^2}{2\rho_{max}^2} \sum_{ij \in S_1} d_{ij}^k (d_{ir}^k + d_{rj}^k) \\ &\quad + \frac{(2^R - 1)}{\rho_{max}} \sum_{ij \in S_2} d_{ij}^k \end{aligned} \tag{5}$$

which combines two factors, one caused by cooperative transmission and the other one due to direct transmission.

III. DESCRIPTION OF THE QOS-DRIVEN ROUTING PROTOCOL

Based on the characteristics of cooperative transmission analysed at Section 1, we propose here a routing protocol to establish a cooperative route (where some of its links are cooperative links) that ensures the end-to-end bit error rate (BER) below a certain target level (constraint).

This is the algorithm for finding a cooperative route in an arbitrary network. The routing algorithm is as follows:

Initialize: Select the best possible relay node and establish a one-hop cooperative route (link) from the source to the destination to minimize the end-to-end BER of the route. Compare the route BER with the target BER (constraint).

Repeat: If the end-to-end BER of the constructed route is larger than the target BER (constraint), identify the link along the route with the highest link BER. Select a new relay node for this poorest link to improve its BER performance. Recompute the end-to-end BER for the new route.

Stop: If the end-to-end BER is equal or smaller than BER constrained, then the cooperative route is finalized. Otherwise, continue with the *repeat* step.

A flow chart of the routing algorithm is provided below:

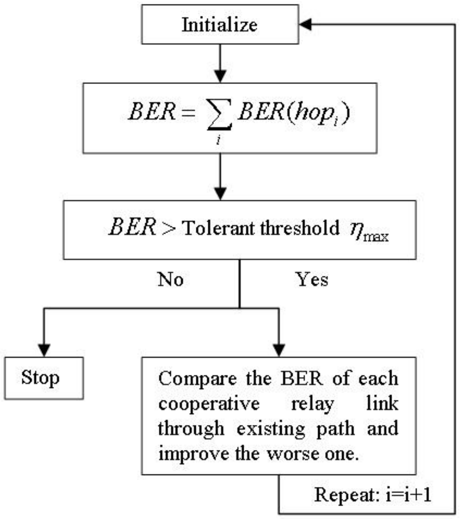

Fig. 2. Diagram for the Proposed Routing Algorithm

To fit the non-infrastructure nature of ad-hoc networks, it is desirable to devise a distributed mechanism to choose the relay node with the best incoming and outgoing channel condition among candidate nodes without using a central controller. The so-called Lecture Hall Theorem can be applied, which yields a relay selection strategy that combines the physical and medium access control (MAC) layer mechanisms to identify the best route in a cooperative and distributed way [14]. In the proposed algorithm, relays use carrier sensing scheme and go through a backoff period before sending received data to the destination. The best relay node can thus be chosen by selecting a short backoff time [5] through monitoring the quality of source-relay-destination route.

IV. PERFORMANCE EVALUATION

In this section, we develop analytical results for our proposed routing algorithm and compare it with the classical Destination-Sequenced Distance-Vector (DSDV) algorithm and optimal routing solutions. In particular, we consider a *Regular Linear Topology* for later comparison where nodes have equal-distance from each other. The two analytical results are outlined below.

A. Numerical performance evaluation

Figure 3 shows a routing example which is established by our proposed protocol. The 100 nodes are uniformly distributed in $1000m \times 1000m$ topology with the source and destination nodes located at the top left corner (node 1) and the bottom right corner (node 100), respectively. Due to the long distances and the given end-to-end BER constraint 3×10^{-2}, we set transmission power to noise ratio to 50dB. The green dash line (located toward the upper right direction) is the DSDV routing, whereas the combined blue and red lines represent the proposed cooperative routing (blue line is relay link and red line is direct link). For example, the cooperative link between node 1 and 19 uses node 26 as its relay. As shown in this figure, our proposed algorithm establishes a totally different route path compared with the DSDV routing algorithm. Furthermore, when compared with 9 hops and 10% end-to-end BER for the DSDV algorithm, the route generated by our proposed algorithm yields much better performance in terms of delay and BER: 6 hops and 3% end-to-end BER.

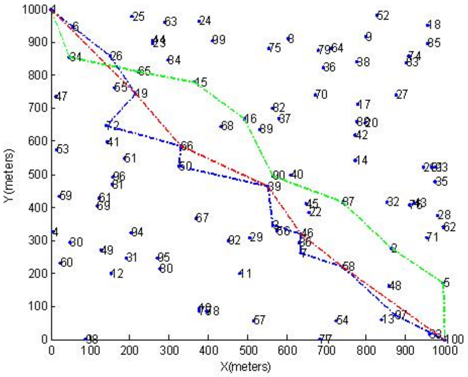

Fig. 3. Routing Comparison between Proposed Algorithm and Destination-Sequenced Distance-Vector (DSDV) algorithm

Using the similar topology in Figure 3, Figure 4 reports the end-to-end BER performance of routes with the same number of hops from the two algorithms from the source to destination. Results in Figure 4 are averaged over 100 simulation runs. As can be seen from the figure above, the proposed routing protocol can achieve much better error performance than the DSDV protocol as well as the scheme without cooperative transmission. It is clear the error performance of proposed algorithm improves as the node density increases. This is so because for low node density, the chance for finding a good relay to form a cooperative link is low. As the total number of nodes increases, there are more chances to locate good relay for establishing cooperative routing, thus significantly improving the end-to-end BER. In addition, due to performance enhancements of cooperative links, the proposed algorithm always achieves better BER performance than the scheme without cooperative transmission (blue line).

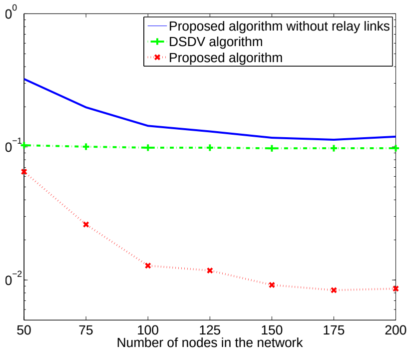

Fig. 4. Bit Error Rate vs. Total Number of Nodes

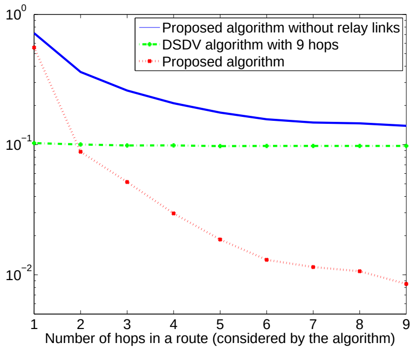

Fig. 5. Bit Error Rate vs. Total Number of Hops

Figure 5 further shows that for cooperative routing, the end-to-end BER improves as the number of hops in the selected route increases. It also shows that cooperative transmission can achieve better BER performance than the proposed scheme without cooperative transmission. We also observe in the figure the BER performance for the 2 hop cooperative route is already lower than the 9 hop DSDV optimal route. Such implies that our proposed algorithm can generate routes with a smaller number of hops and satisfactory end-to-end BER when compared with the optimal solution from the DSDV algorithm.

From figure 5, a careful reader might notice that our proposed cooperative routing algorithm in fact represents a trade-off between the end-to-end BER and total number of hops for the selected route. As the number of hops increases, end-to-end BER is reduced correspondingly. In fact, we have proved that for a network with a linear topology, the end-to-end BER is approximately proportional to $\frac{1}{n^3}$, where n is the number of hops in the selected route as follow in Figure 6.

Theorem1: For a linear network scenario, the end-to-end BER is approximately proportional to $\frac{1}{n^3}$, where n is the total number of hops.

Proof: See Appendix A.

It is worthy pointing out that we include a BER constraint in our proposed routing protocol for the following reasons: First, our proposed algorithm starts with routes with a small number of hops. Implicitly, it does not explore routes with an excessive number of hops. Instead, our algorithm achieves a good tradeoff and balance between the hop count (which relates to delay) and end-to-end BER for routing, in order to achieve acceptable system performance. Second, for a given end-to-end BER constraint, we can reduce the total number of nodes involved. Hence other benefits such as energy saving, communication traffic reducing could be realized.

B. Performance evaluation by analysis

Following the ideas above, we compare the end-to-end minimum BER achieved by our proposed algorithm with that of the optimal routing solution [2] for a regular linear network scenario. Figure 6 shows a regular linear topology where nodes are located at equal distance from each other on a straight line. We assume that this distance between two adjunct nodes is D and the total number of nodes is N.

Fig. 6. Regular Linear Topology

Before proceeding further, let us define a gap ratio g, as the normalized difference between the BER for the best route established by our proposed algorithm and that of the optimal route:

$$g = \frac{BER_{proposed} - BER_{optimal}}{BER_{optimal}} \tag{6}$$

The following theorem provides the performance comparison between the optimal one and the proposed distributed one.

Theorem2: For a regular linear network with N nodes,

$$g = \begin{cases} 0, & \text{if } \log_2(N-1) or \log_2(N) = integer \\ \frac{11}{4}, & \text{if } \log_2(\frac{N-1}{3}) = integer \\ \frac{33}{2(N-1)}, & \text{otherwise for odd number nodes} \end{cases}$$

Proof: See Appendix B.

In general, theorem 2 tells us the proposed routing algorithm can have the BER performance close to the optimal one. For example, for the first case where N-1 or N is perfect power of 2, the proposed algorithm yields the exactly same BER as the optimal route. The gap ratio can be close to zero for the third case where the number of nodes is large enough. In addition to error performance, the proposed routing algorithm also provides advantage of delay reducing. For example, for the second case, compare with optimal solution, we can reduce hops and nodes involved when compared with optimal solution. For the third case, we can reduce 1 hop and 2 nodes involved.

V. CONCLUSIONS

In this paper, we have proposed a low complexity, quality-of-service driven routing protocol for wireless cooperative networks. The key contribution of the proposed protocol is to bring the performance gain of cooperative diversity from the physical layer up to the networking layer. With the help of Lecture Hall Theorem, cross-layer routing is accomplished in a distributed way. Furthermore, analytical results are developed to show that the proposed distributed routing protocol can perform close to the optimal.

APPENDIX A

In order to simplify our model and show the tendency between each other, a linear network scenario is assumed for analysis. We also assume the node density is large enough that we can always find a node at any given location, which is shown below:

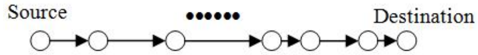

Fig. 7. Linear network topology

Here, the proposed optimization problem is:

Minimize **End-to-end BER**
Subject to. **Fixed relay transmission distances**

Using the equations in section 1, the problem above is equivalent to:

$$\begin{cases} BER = \frac{(2^{2R}-1)^2}{2\rho^2} D^2(x^2+y^2) \\ x+y=D \end{cases} \tag{7}$$

where the x, y and D are shown in the figure below.

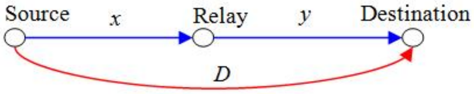

Fig. 8. A linear network using proposed algorithm at stage 1

For further simplification, the problem in Eq.(8) leads to

$$\begin{cases} \text{Minimize} & L = x^2+y^2 \\ \text{S.T} & x+y=D \end{cases} \tag{8}$$

Set up the Lagrangian for this problem, we have:

$$L = x^2 + y^2 + \lambda(x+y-D) \tag{9}$$

The first order conditions are:

$$\frac{\partial L}{\partial x} = 2x + \lambda = 0, \frac{\partial L}{\partial y} = 2y + \lambda = 0 \tag{10}$$

Hence, $x = -\lambda/2$ and $y = -\lambda/2$. Then, substituting the results into Eq.(9), we then have $x = y = D/2$. Using the optimal conclusion above and our proposed routing algorithm, we can establish the BER-hops relationship as follows.

Suppose the total number of hops is n and distance between the source to the destination shown in figure 7 is D:

If $log_2(N) = integer$, then:

$$\begin{aligned} BER_{end\_to\_end} &= n\frac{(2^{2R}-1)^2}{2\rho^2}(\frac{D}{n})^2(\frac{D^2}{4n^2}+\frac{D^2}{4n^2}) \\ &= \frac{D^4(2^{2R}-1)^2}{4\rho^2 n^3} \end{aligned} \tag{11}$$

Otherwise, find two nearest integers A and B which next to n and satisfy $A < n < B$. Both $log_2(A)$ and $log_2(B) = integer$. Using the relationship $A = 2B$, we have:

$$BER_{end\_to\_end} = \frac{D^4(2^{2R}-1)^2(15B-7n)}{32B^4\rho^2} \tag{12}$$

APPENDIX B

A. Routing Optimization Solution

In order to achieve the minimal end-to-end BER in such regular linear topology, the optimal solution for cooperative routing found by simulation (e.g., an exhaustive-search method) is shown below:

For even number N:

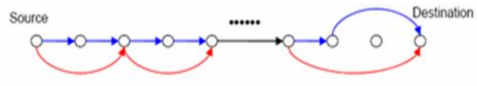

Fig. 9. Optimal Route for Scenarios with an even number of nodes

For even *N*, there are an odd number of links. Hence, the optimal routing above can achieve the minimal end-to-end BER. Using Eq.(2), the corresponding BER is (D is the distance between source and destination):

$$BER_{optimal} = \frac{(2^{2R}-1)^2}{2\rho^2}(4ND^4 + 29D^4) \tag{13}$$

For odd number N:

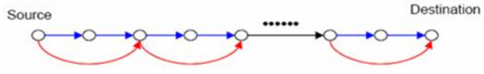

Fig. 10. Optimal Route for Scenarios with an odd number of nodes

For odd *N*, there are an even number of links. Hence, all the links could be equally distributed to form the same cooperative links. Then, the minimal end-to-end BER is:

$$BER_{optimal} = \frac{2D^4(2^{2R}-1)^2(N-1)}{\rho^2} \tag{14}$$

B. Proposed Algorithm for Cooperative Routing

Using our proposed routing algorithm, we obtain the minimal end-to-end BER as follows:

For any value N which satisfies the above condition 1 and 2, the proposed routing topology is the following:

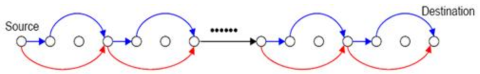

Fig. 11. Proposed Solution for Condition (b) Scenario

We can obtain the $BER_{end\_to\_end} = \frac{(2^{2R}-1)^2}{2\rho^2}(2D^4N + 64D^4)$. Then, put this into with Eq.(7) yields $g = 11/4$. However, compared with the optimal solution, we can reduce $2^{log_2\frac{N-1}{3}-1}$ hops and $(N-1)/3$ nodes involved.

For condition 3, the routing topology is:

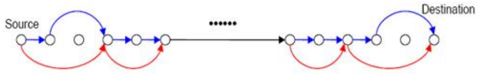

Fig. 12. Proposed Solution for Condition (c) scenario

Using the same argument, the end-to-end BER is $BER_{end\_to\_end} = \frac{(2^{2R}-1)^2}{2\rho^2}(2D^4N + 31D^4)$. Similarly, the gap ratio is $\frac{33}{2(N-1)}$. However, compared with the optimal solution, we can reduce 1 hop and 2 nodes involved.

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