# On the Study of Cross-layer Optimization for Wireless Cooperative Networks

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***Abstract*— In this paper, we study the effect of cooperative transmission on the routing decision for wireless ad-hoc networks. The influence of cooperative transmission to the wireless link cost is first studied, with or without node selection, which shows that the quality of wireless links could be improved significantly. To reduce system overhead, a distributed strategy of node selection is proposed by carefully designing the carrier sensing protocol in the medium access control layer. Then routing optimization is investigated to understand the effects of improved link cost to the routing decision, where the optimal solution of the optimization problem is developed and later used as a quantitative criterion of the routing decision. Our developed analytical and simulation results show that the criteria using cooperative transmission typically yield more efficient routes than the non-cooperative schemes.**

## I. INTRODUCTION

Future wireless communication networks are expected to support the mixture of real-time applications, such as voice and multimedia teleconferencing, and non-real-time data applications, such as web browsing, messaging and file transfers. Compared with wired environments, the associated communication channels and traffic patterns in mobile wireless networks are more unpredictable. Hence all of these applications impose stringent and diversified Quality of Service (QoS) requirements, which cannot be satisfactorily addressed through the traditional layering network-protocol architecture. Correspondingly, there has recently been increased interest in protocols for wireless networks to exploit the significant interactions between various layers of the protocol stack for performance enhancements. And it has been shown that these cross-layer designs and protocols could be essential for wireless ad-hoc and sensor networks where unpredictable variables such as node mobility, node density and network dimensions make the diverse and stringent wireless QoS requirements difficult to satisfy.

Due to the unreliability of wireless links, it has been of interest to study the impacts of physical-layer techniques on the design of upper-layers, including medium access control (MAC), packet scheduling, power control, routing, transport protocol, and ultimately the QoS at the application level in wireless networks. Opportunistic scheduling could be seen as one of successful examples of cross-layer design, where scheduling protocols are designed by taking advantage of the knowledge of wireless link conditions [1], [2]. Among many candidates of physical-layer techniques, multiple-input multiple-output (MIMO) has received significant attention, which can provide spatial diversity and hence represents a powerful technique for interference mitigation and reduction [3], [4]. Cooperative communication provides an alternative way to achieve spatial diversity, where single-antenna terminals in a multiple-user environment share their antennas and form a cluster to assist each other with their data transmission [5], [6]. In [7] and [8] the authors study the cross-layer routing protocol design for energy-constrained networks, where the cooperative transmission technique is used to form a virtual antenna array. It is shown in [7] and [8] that the proposed protocol could yield a different route compared with traditionally non-cross-layer protocols if the circuit processing energy is considered, and the two protocols will choose the same route otherwise.

Recently the routing optimization is analyzed by using a probabilistic link model [9], which pints out that the broadcasting nature of wireless communications should be utilized by routing protocols to achieve robustness at the networking level. Recall that cooperative transmission has been recognized as an effective technology to utilize such feature of wireless communications [5], [10], [11]. Inspired by this observation, we focus on studying the effects of cooperative transmission on the routing decision in this paper. The effects of cooperative transmission to the link quality are first studied with or without node selection, and it is shown that cooperative transmission can improve the quality of a wireless link, such as lower power consumption or higher reliability. Although incorporation of a strategy of an appropriate node for cooperative transmission could yield more performance gain, but a centralized strategy could cause too much overhead. To reduce the system overhead, we propose a distributed strategy of node selection by using a carrier sensing protocol at the medium access control (MAC) layer.

The problem of routing optimization is then investigated in order to study the effects of improved link cost to the routing decision. The objective function of interest is to minimize the total power consumption with a given end-to-end reliability constraint. The optimal solution of this optimization problem indicates the minimum total power consumption of a route in order to satisfy the required error performance, which is then used as a criterion to compare and select the best among different routes. Our analytical results show that the route chosen by the cooperative criterion can consume much less transmission power compared with the route using only direct transmission. For certain path loss factors and provided that

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direct transmission is used only, it is observed that a source node will prefer to communicate with its destination node directly, which could result in transmission power higher than the saturation level due to the long source-destination distance. However, it is noticeable that the cooperative criterion still maintains the preference of multi-hop transmission to ensure the transmission power at each link below the given maximum limit.

This paper is organized as follows. The system architecture and assumptions used in the paper are first introduced in Section II. The effects of cooperative transmission on the link cost is studied in Section III. The routing optimization and protocol design are discussed in Section IV, where some simulation results are also provided. Finally, concluding remarks are given in Section V.

## II. SYSTEM ARCHITECTURE

In this paper, we consider a wireless ad-hoc network where nodes are assumed to be uniformly distributed in a region with the node density $\lambda$. Each node is equipped with one omnidirectional antenna element (although our results can be extended to more generalized cases with multiple antennas at each node). Time Division Multiple Access (TDMA) schemes are used here for two reasons. First, in case that there are multiple source-destination pairs communicating simultaneously, the TDMA assumption could allow us to only concentrate on one pair, and hence co-channel interference is eliminated automatically. Second, the fact that time division duplex channels are reciprocal naturally makes channel state information available at the transmitter. We employ a propagation model to consider path loss, shadow fading and Rayleigh fading [1], [7], [12]. The wireless link between the nodes $i$ and $j$ is modelled as

$$g_{ij} = \frac{h_{ij}}{d_{ij}^{k/2}} \tag{1}$$

where $d_{ij}$ is the distance between the nodes $i$ and $j$, $1/d_{ij}^{k/2}$ depicts 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. Furthermore, multiple nodes are separated apart enough to assume channel fading $h_{ij}$ independent and identically distributed (i.i.d.), complex Gaussian variables with zero mean and unit variance.

Traditionally, the node $i$ communicates directly with the node $j$ in the physical layer, provided that the link $i \rightarrow j$ is delegated by the routing protocol. In this paper, we propose that each node $i$ tries to find one and only one useful relay node (other than the node $j$) to accomplish cooperative transmission when communicating with the node $j$. Since cooperative transmission can improve the quality of the wireless link, the existing routing protocols should be modified to take such effect into account. In order to design such a cross-layer routing protocol, it is important to first understand the kind of effects the physical layer technique can bring to the link quality, which will be discussed in detail in the next section.

## III. LINK COST USING COOPERATIVE TRANSMISSION

This section is to understand how much the quality of of wireless links can be improved by using cooperative transmission and what kind of physical characteristics will have the critical effects to the quality improvement. Consider a three-node scenario with nodes $i$ and $j$, and a relay node $R$, where the node $i$ wants to communicate with the node $j$ node with help of the relay node $R$. Such cooperative transmission consists of two stages in time [11]. At the first stage, the node $i$ transmits its information where both the nodes $j$ and $R$ are receiving. At the second stage, the relay decodes and forwards the information of the node $i$ to the node $j$ if decoding is successful. Otherwise the relay will keep silent and the node $i$ will transmit its information once again. For TDMA schemes, such cooperative transmission consumes two times of time slots compared with direct transmission, so data rate at each stage (or time slot) is chosen to be two times of that for direct transmission.

Define $d_{ij}$, $d_{iR}$, and $d_{Rj}$ as the distances among the node $i$, the relay node, and the node $j$. So during the first time slot, the node $j$ receives

$$y_{j,1} = \frac{h_{ij}}{d_{ij}^{k/2}} s_i + n_{j,1} \tag{2}$$

where $s_i$ is the information of the node $i$ and $n_j$ will be the white noise. And during the second time slot, the node $j$ receives

$$y_{j,2} = \begin{cases} \frac{h_{ij}}{d_{ij}^{k/2}} s_i + n_{j,2} & \text{if} \quad |\frac{h_{Ri}}{d_{Ri}^{k/2}}|^2 < q(\rho) \\ \frac{h_{Rj}}{d_{Rj}^{k/2}} s_i + n_{j,2} & \text{if} \quad |\frac{h_{Ri}}{d_{Ri}^{k/2}}|^2 \geq q(\rho) \end{cases} \tag{3}$$

where $q(\rho) = \frac{2^{2R}-1}{\rho}$ and $R$ is the data rate in $bits/s/Hz$. The signal-to-noise ratio (SNR) is defined as $\rho = E_b/N_0$ where $E_b$ denotes transmission energy per-bit and $N_0$ is the one-sided power spectral density of the withe noise. As can be seen from (3), the relay node could yield no performance gain if it has a poor link with the source node $i$, which means that the choice of the relay node could be critical to the system performance. So in the following two subsections, the effects of cooperative transmission on the link quality are analyzed with and without node selection.

### A. Random Choice of Relaying

Consider that a relay node is selected randomly. Hence the data rate such cooperative system is able to support can be shown as [11]

$$\mathcal{I}_{ij} = \begin{cases} \frac{1}{2}\log(1+2\rho|\frac{h_{ij}}{d_{ij}^{k/2}}|^2) & \text{if} \quad |\frac{h_{Ri}}{d_{Ri}^{k/2}}|^2 < q(\rho) \\ \frac{1}{2}\log(1+\rho[|\frac{h_{Rj}}{d_{Rj}^{k/2}}|^2 + |\frac{h_{ij}}{d_{ij}^{k/2}}|^2]) & \text{if} \quad |\frac{h_{Ri}}{d_{Ri}^{k/2}}|^2 \geq q(\rho) \end{cases} \tag{4}$$

By following the steps in [10], [11], [13], [14] the outage probability is also used here to evaluate error performance. Since $h_{ij}$ is assumed complex Gaussian variables with zero mean and unit variance, $|\frac{h_{ij}}{d_{ij}^{k/2}}|^2$ is an exponentially distributed variable with parameter $\frac{1}{d_{ij}^2}$. So using the results in [11] directly, we have the outage probability between the nodes $i$ and $j$ as

$$\begin{aligned} P_{ij}^{CT} &= P(\mathcal{I}_{ij} < R) && (5) \\ &\approx \frac{1}{2} d_{ij}^k (d_{iR}^k + d_{Rj}^k) \frac{(2^{2R}-1)^2}{\rho^2} \\ &= P_{ij}^{dr} \left[ \frac{(d_{iR}^k + d_{Rj}^k)(2^R-1)(2^R+1)^2}{2\rho} \right] && (6) \end{aligned}$$

where $R$ is the data rate in $bit/s/Hz$ defined by the QoS requirement and the outage probability of direct transmission between the nodes $i$ and $j$ is

$$P_{ij}^{DT} \approx d_{ij}^2 \frac{(2^R-1)}{\rho} \quad (7)$$

Comparing (6) and (7), the necessary condition to ensure cooperative transmission is better than direct transmission is

$$\left[ \frac{(d_{iR}^k + d_{Rj}^k)(2^R-1)(2^R+1)^2}{2\rho} \right] \leq 1 \quad (8)$$

Another scheme of interest is the traditional two-hop transmission scheme where the destination can only receive signals from the relay node. The outage probability for such two-hop transmission is

$$\begin{aligned} P_{ij}^{TH} &= 1-(1-P_{iR}^{DT})(1-P_{Rj}^{DT}) && (9) \\ &\approx d_{iR}^k \frac{(2^R-1)}{\rho} + \left(1 - d_{iR}^k \frac{(2^R-1)}{\rho}\right) d_{Rj}^k \frac{(2^R-1)}{\rho} \end{aligned}$$

where the approximation follows from (7).

Clearly the location of the relay node has critical effects to the system performance. In the following, we first provide some simulation results to illustrate the effects, and compare the total power consumption of three transmission schemes. And then for a special location of the relay node, we provide some quantitative results for comparison.

*1) A special case:* Consider that the relay node is located at the center of the straight line between the nodes $i$ and $j$, which means $d_{iR} = d_{Rj} = \frac{1}{2} d_{ij}$. It shall be seen in the next section that with such system setup the two-hop and cooperative schemes shall achieve the best performance. From (6) the minimal total transmission power for the links using cooperative transmission, termed as cooperative links, to satisfy the end-to-end reliability (defined as one minus the outage probability ) will be

$$\begin{aligned} W_{CT} &= 2\rho N_0 RB = N_0 RB \sqrt{\frac{1}{2^k} d_{ij}^{2k} \frac{(2^{2R}-1)^2}{P_{ij}}} && (10) \\ &= N_0 RB \frac{d_{ij}^k (2^{2R}-1)}{2^{k/2}\sqrt{P_{ij}}} \end{aligned}$$

where $B$ is the assigned bandwidth, $P_{ij}$ is the pre-specified outage probability requirement, and the factor 2 is due to the fact that relaying transmission consumes extra energy. Similarly from (7), the minimal transmission power for direct transmission will be

$$W_{DT} = \rho N_0 RB = N_0 RB d_{ij}^k \frac{(2^R-1)}{P_{ij}} \quad (11)$$

So for the same outage probability, the ratio of transmission power consumed by the cooperative and direct transmission (DT) schemes can be written as

$$\begin{aligned} W_{CT}/W_{DT} &= 2\rho_{CT}/\rho_{DT} = 2\frac{d_{ij}^k (2^{2R}-1)}{2^{k/2}\sqrt{P_{ij}}} \Big/ d_{ij}^k \frac{(2^R-1)}{P_{ij}} \\ &= \frac{(2^R+1)\sqrt{P_{ij}}}{2^{k/2-1}}. && (12) \end{aligned}$$

Since the path loss exponent, $k$, is a system parameter determined by the propagation environment, only the data rate and the outage probability are adjustable. For a moderate data rate and small outage probability, it can be expected that this ratio is also much less than $1$ and hence cooperative transmission can reduce power consumption significantly.

For the two-hop scheme, the required SNR is the root of

$$\begin{aligned} P_{ij} &= 1-(1-P_{iR})(1-P_{Rj}) && (13) \\ &= d_{iR}^k \frac{c}{\rho} + d_{Rj}^k \frac{c}{\rho} - d_{Rj}^2 d_{iR}^k \frac{c^2}{\rho^2} \end{aligned}$$

and hence the required transmission power could be

$$W_{TH} = 2\rho_{TH} N_0 RB = 2N_0 RB \frac{d_{ij}^k c(1+\sqrt{1-P_{ij}})}{2^k P_{ij}} \quad (14)$$

where $c = 2^R - 1$. So the ratio of the transmission power consumed by the two-hop and direct transmission schemes will be

$$\begin{aligned} W_{TH}/W_{DT} &= 2\frac{d_{ij}^k c(1+\sqrt{1-P_{ij}})}{2^k P_{ij}} \Big/ d_{ij}^k \frac{c}{P_{ij}} \\ &\approx \frac{2-\frac{1}{2}P_{ij}}{2^{k-1}} \approx \frac{1}{2^{k-2}}, && (15) \end{aligned}$$

which implies that the two-hop transmission scheme does not offer any benefits of power consumption if the path loss factor is equal to 2. However, in the case that $k > 2$, the two-hop scheme is more energy efficient compared with direct transmission, which is consistent with the results provided in [9].

*2) A general case:* Consider a three-node scenario as shown in Fig. 1, where the relay node is located arbitrarily within the area defined by the circle whose diameter is the straight line between the nodes $i$ and $j$. To be compare, the distance between the nodes $i$ and $j$ is assumed to be $d_{ij} = 10m$. The required data rate is $R = 0.1 bit/s/Hz$ and the prefixed outage probability is $P_{ij} = 0.1$. The path loss exponent is set as $k = 2$. Define the normalized transmission power as $\tilde{W} = \frac{W}{RBN_0}$. For such system setup, the normalized power consumed by direct transmission is $\tilde{W} = d_{ij}^2 \frac{(2^R-1)}{P_{ij}} = 71$. The normalized power consumed by two-hop transmission and cooperative transmission is shown in Fig. 2 as a function of the location of the relay node on the x-y plane. Recall that the nodes $i$ and $j$ are located at $(-5, 0)$ and $(5, 0)$, respectively. As can be seen from the figure, both two transmission schemes can achieve its best performance if the relay node locates at the center of the circle on the x-y plane. And the cooperative scheme always consumes less transmission power than the two-hop scheme for the same location of the relay node. It is also interesting to observe that the use of two differently located relay nodes can result in the same performance as long as the relay nodes locate on the same circle. This can be clarified as the following. Recall from (5), the transmission power to satisfy a required outage probability is a function of $d_{iR}^2 + d_{Rj}^2$ which can be written as

$$d_{iR}^2+d_{Rj}^2 = ([(\frac{d_{ij}}{2}+x)^2+y^2]+[(\frac{d_{ij}}{2}-x)^2+y^2]) = 2(x^2+y^2)+\frac{d^2}{2}.$$

Hence if the two relays are located at the same circle, the value of $d_{iR}^2 + d_{Rj}^2$ will be the same and hence the use of two relays achieve the same performance.

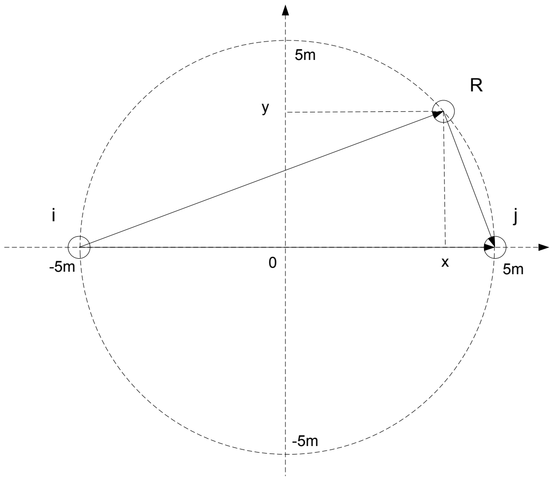


Fig. 1. A diagram for the three-node scenario. The distance between the nodes $i$ and $j$ is 10m. The relay node locates in the circle with its diameter siting on the straight line between the nodes $i$ and $j$.

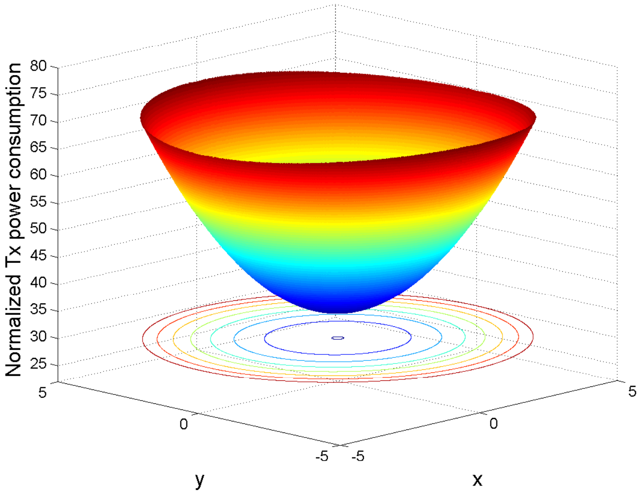
### B. Node Selection

As can be seen from Fig. 2, the location of the relay node could be critical to the system performance. Hence one possible criterion of node selection is to choose the node locating closest to the center of the circle. Recall that wireless signals suffer the large scale path loss as well as multi-path fading as shown in (1), and the latter can be dominant in many communication scenarios, such as indoor environments. Since the node location only provides the large scale loss, it would be interesting to study how to take the instantaneous multipath fading into account to evaluate the impacts of the relay node. To be specific, at each time interval, each relay participates in a competition to help communication between the source-destination pair and the "best" relay is chosen based on its instantaneous values of the Raleigh fading coefficients as well as the large scale path loss.

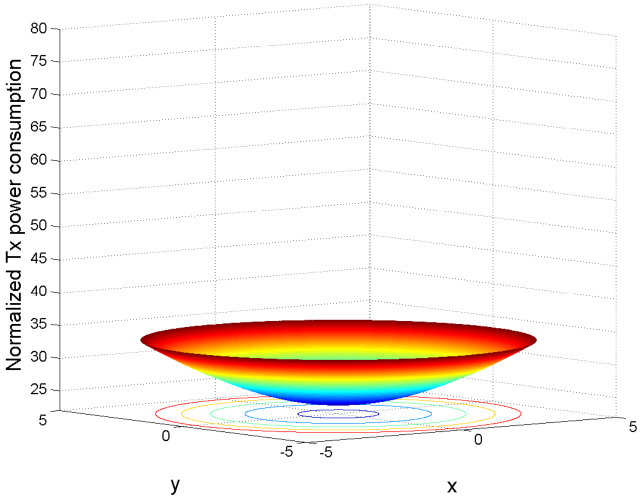
To fit to the non-infrastructure nature of ad-hoc networks, we propose a distributed strategy of node selection by carefully designing the carrier sensing protocol in the medium access control layer. A similar strategy of node selection has been proposed in [15] where the amplified-and-forward protocol was concentrated.

*1) Distributed Strategy of Node Selection:* Consider that each node has the knowledge of its incoming and outgoing channel information obtained by using training symbols or feedback. Similar to the transmission strategy with the randomly chosen relay, the node $i$ will be transmitting during the first slot where all of the $n$ relay nodes and the destination node $j$ are listening. Separately, each node will calculate the data rate which can be supported by its incoming channel, and then decide whether it is able to decode the information of the node $i$ correctly. Only the nodes which can receive information successfully will participate the next stage. Consider there are $m$ qualified relay nodes which can receive the source information successfully. It is of interest to devise a distributed mechanism to choose the node with the best outgoing channel condition among the $m$ candidates without requiring the existence of a control center which has access to all channels.

To accomplish such task, a new MAC protocol is proposed in this paper, where the backoff period of each node for carrier sensing is determined by its outgoing channel condition [15]. To be specific, each of the $m$ qualified nodes will calculate its



(a) Link cost without CT



(b) Link cost with CT

Fig. 2. Normalized transmission power consumption for the two schemes with or without cooperative transmission (CT). The data rate is set as $R = 0.1$ bit/s/Hz, and the outage probability is $P \leq 10\%$, and the source-destination distance is 10m. The lowest normalized transmission power to satisfy the end-to-end reliability is $23.5$ for the cooperative transmission scheme, and $34.9$ for the two-hop transmission scheme.

backoff period inversely proportional to its outgoing channel, such as $t_{R_l} \backsim \frac{1}{|g_{R_l j}|^2}$. Each node will continue monitoring the channel and start to forward the information of the node $i$ to the node $j$ node if there is no other node transmitting during the backoff period. Otherwise, it will keep silence and does not participate the second stage as one node better than it has been transmitting. In such way, the node with high quality of the outgoing link will have short backoff time, which means that it has more chance to be selected. One problem still remains that one of the relays, referred as hidden-node, does not realize there is already someone using the channel and it hence decide to transmit. So to avoid such hidden-node problems, the scheme requires the $j$ node (the destination) to send a short acknowledgment to the relays after receiving the forwarded data. All relay nodes will be wait and keep silent until they received such an acknowledgment from the destination node. In the worst case where no relay node can receive the information of the node $i$ correctly, all relay nodes will keep silent and the node $i$ will re-transmit its information to the node $j$. Hence by incorporating the physical layer condition into the medium access control protocol design, an opportunistic cooperative transmission strategy can be accomplished in a distributed manner.

*2) Performance Analysis:* To illustrate the impact of node selection, some analytical results are developed for a special case in the following. Consider that all relay nodes are within a small region located at the center of the circle in Fig. 1. Assume that there are $n$ nodes in the region, denoted as $R_1, \ldots, R_n$. To simplify the development, assume that the such region is small enough that each relay node in it has the same distance to the source and destination, $d_{iR_m} \approx d_{R_m j} \approx \frac{d_{ij}}{2}$, $\forall m \in [1, n]$.

The following theorem gives the outage probability of the cooperative scheme using the node selection strategy described previously.

**Theorem** *1:* Assume that multiple nodes are separated apart enough to have Raleigh channel fading $h_{ij}$ i.i.d. complex Gaussian variables with zero mean and unit variance. Outage probability of the cooperative transmission strategy with the proposed node selection can be written as

$$\begin{aligned} P_{CT,ij} &= \left[1 - e^{-q(\rho)\frac{d_{ij}^k}{2^k}}\right]^n [1 - e^{-q(2\rho)d_{ij}^k}] \\ &\quad + \sum_{m=1}^{n} \frac{n!}{(n-m)!m!} e^{-mg(\rho)\frac{d_{ij}^k}{2^k}} \left[1 - e^{-q(\rho)\frac{d_{ij}^k}{2^k}}\right]^{n-m} \\ &\quad \times \sum_{i=0}^{m} \frac{(-1)^i}{\frac{i}{2^k}+1} e^{-\frac{d_{ij}^k}{2^k}q(\rho)i} [1 - e^{-(\frac{d_{ij}^k}{2^k}i + d_{ij}^k)q(\rho)}]. \end{aligned} \tag{16}$$

*Proof:* See [16]. ■

To have the insight of the performance of the scheme, we can have

**Corollary** *2:* Provided that $\frac{d_{ij}^k}{2^k}q(\rho) < 1$, the expression of the outage probability of the cooperative transmission strategy with the proposed node selection can be reduced as

$$P_{ij}^{CT} \approx \frac{[2^{2R}-1]^{n+1} d_{ij}^{k(n+1)}}{2^{kn}\rho^{n+1}} \left[\sum_{m=1}^{n} \frac{n!}{(n-m)!(m+1)!} + \frac{1}{2}\right]$$

*Proof:* See [16]. ■

*3) Remarks and Numerical Results:* From Corollary 2, it is noticeable that there is a factor, $\frac{1}{\rho^{n+1}}$, in the outage probability expression of the cooperative system with the best relay node, which demonstrates that such cooperative system can achieve full spatial diversity. Compared with the scheme with random relay, such full diversity is achieved without requiring extra time slots for relaying transmission, hence the opportunistic relay scheme is spectrally efficient. Furthermore, according to Corollary 2, the transmission power consumed by such transmission strategy can be written as

$$\begin{aligned} 2\rho N_0 RB &= 2N_0 RB \frac{d_{ij}^k(2^{2R}-1)}{2^{kn/(n+1)}} \\ &\quad \times \left\{ \frac{1}{P_{ij}^{CT}} \left( \sum_{m=1}^{n} \frac{n!}{(n-m)!(m+1)!} + \frac{1}{2} \right) \right\}^{\frac{1}{n+1}} \end{aligned} \tag{17}$$

For the special case that there is only one relay candidate, $n = 1$, the system will have no other choice and the opportunistic relaying scheme is degraded to the scenario with a random-chosen node, where (17) can be shown exactly the same as (10).

In Fig. 3, we provide an example to illustrate the performance of such cooperative transmission, where the normalized transmission power is shown as a function of the number of relay candidates with fixed the data rate and the outage probability, $R = 0.1 bits/s/Hz$ and $P_{ij}^{CT} = 10\%$. The same assumption that the channels have the same large scale path loss is used here. As can be seen from the figure, the more relay candidates the system has, the better performance it will achieve. Such performance gain is reasonable as more candidates can give the system more freedom to find a better helping node. And it is interesting to notice that such performance gain by adding one more relay node can be significant when the original number of candidates is small. And with the number of candidates increasing, the performance of the opportunistic relaying scheme becomes saturated.

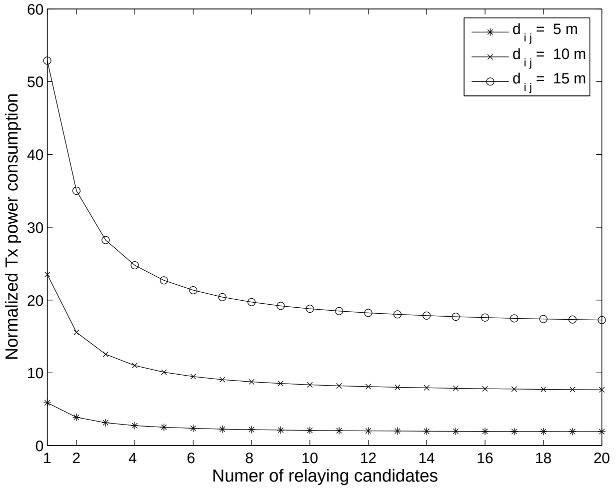


Fig. 3. Normalized transmission power consumption of the opportunistic relaying strategy vs the number of available relay candidates. The performance with the different distance between the nodes $i$ and $j$ is also shown. The outage probability is set as $P_{ij}^{CT} = 10\%$ and the required data rate is $R = 1 bit/s/Hz$.

## IV. ROUTE OPTIMIZATION AND PROTOCOL DESIGN

Previous developed results show that cooperative transmission can bring some performance gain to the physical layer, specially to the quality of wireless links. It is of interest to study how such such physical layer benefits can have effects to the upper layer, such as the routing protocol design.

Consider that a route has been constructed between the source and destination. Without losing generality, the nodes sitting on the route are denoted as $S \to 1 \ldots \to n \to D$. Different to traditional routes, cooperative transmission is used to improve the link quality when the node $i$ is communicating with the node $j$. It is possible that a good helping node is not available for some pairs of the $n+1$ links of the route. In that case, direct transmission is used instead of relying on cooperative transmission. Hence the $n+1$ links can be categorized into two sets. One set, defined as $\mathcal{S}_1$, includes all links using cooperative transmission and the other one, defined as $\mathcal{S}_2$, includes the links using direct transmission. Note that $|\mathcal{S}_1| + |\mathcal{S}_2| = n+1$ since there are only $n+1$ links on the route.

Provided that the $i \to j$ link utilizes cooperative transmission, $ij \in \mathcal{S}_1$, define $\rho_{ij} = f_{CT}^{-1}(P_{ij}^{CT})$ where $\rho_{ij}$ is the required SNR for the link from the node $i$ node to the node $j$, and[1]

$$f_{CT}^{-1}(x) \;=\; (2^{2R}-1)\sqrt{\frac{d_{ij}^k(d_{iR}^k + d_{Rj}^k)}{2x}}. \tag{18}$$

Hence the transmission power for the $i \to j$ link is $W_{ij} = 2RBN_0\rho = 2RBN_0 f_{CT}^{-1}(P_{ij}^{CT})$. If $ij \in \mathcal{S}_2$, the transmission power for for the $i \to j$ link is $W_{ij} = RBN_0\rho = RBN_0 f_{DT}^{-1}(P_{ij}^{DT})$, where

$$f_{DT}^{-1}(x) = (2^R-1)\frac{d_{ij}^k}{x}.$$

The problem to minimize the total transmission power consumption with the constraint on the end-to-end reliability can be formulated as

$$\begin{aligned} \min_{P_{ij}^{DT}, P_{ij}^{CT}} \quad & \sum_{ij\in\mathcal{S}_1} W_{ij} + \sum_{ij\in\mathcal{S}_2} W_{ij} \\ s.t. \quad & 1 - \prod_{ij\in\mathcal{S}_1}(1-P_{ij}^{CT}) \prod_{ij\in\mathcal{S}_2}(1-P_{ij}^{DT}) \le P \end{aligned} \tag{19}$$

For small outage probability $P_{ij}^{DT} << 1$ and $P_{ij}^{CT} << 1$, we can have the following approximation

$$\begin{aligned} & 1 - \prod_{ij\in\mathcal{S}_1}(1-P_{ij}^{CT}) \prod_{ij\in\mathcal{S}_2}(1-P_{ij}^{CT}) \\ & \approx \sum_{ij\in\mathcal{S}_1} P_{ij}^{CT} + \sum_{ij\in\mathcal{S}_2} P_{ij}^{DT}. \end{aligned}$$

So the optimization problem can be simplified as

$$\begin{aligned} \min_{P_{ij}^{DT}, P_{ij}^{CT}} \quad & \sum_{ij\in\mathcal{S}_1} W_{ij} + \sum_{ij\in\mathcal{S}_2} W_{ij} \\ s.t. \quad & \sum_{ij\in\mathcal{S}_1} P_{ij}^{CT} + \sum_{ij\in\mathcal{S}_2} P_{ij}^{DT} \le P \end{aligned} \tag{20}$$

By introducing an auxiliary variable $z$, (20) can be written as

$$\begin{aligned} \min_{P_{ij}^{DT}, P_{ij}^{CT}, z} \quad & \sum_{ij\in\mathcal{S}_1} W_{ij} + \sum_{ij\in\mathcal{S}_2} W_{ij} \\ s.t. \quad & \sum_{ij\in\mathcal{S}_1} P_{ij}^{CT} \le P - z \\ & \sum_{ij\in\mathcal{S}_2} P_{ij}^{DT} \le z \\ & 0 \le z \le P \end{aligned} \tag{21}$$

Note that the transmission power is always positive, $W_{ij} \ge 0$, and both $f_{CT}^{-1}(x)$ and $f_{DT}^{-1}(x)$ are monotonic decreasing. Hence the optimization can be solved in two stages. First we treat $z$ as a constant and solve the following two optimization problems separately.

$$\begin{aligned} \min_{P_{ij}^{CT}} \quad & \textstyle\sum_{ij\in\mathcal{S}_1} W_{ij} & \min_{P_{ij}^{DT}} \quad & \textstyle\sum_{ij\in\mathcal{S}_2} W_{ij} \\ s.t. \quad & \textstyle\sum_{ij\in\mathcal{S}_1} P_{ij}^{CT} \le P - z & s.t. \quad & \textstyle\sum_{ij\in\mathcal{S}_2} P_{ij}^{DT} \le z \end{aligned} \tag{22}$$

which yields the two solutions

$$\begin{aligned} \sum_{ij\in\mathcal{S}_1} W_{ij} \;&=\; 2RBN_0\left(\frac{2^{2R}-1}{\sqrt{2(P-z)}}\right) \\ &\quad \times \left(\sum_{ij\in\mathcal{S}_1}\left[d_{ij}^k(d_{iR}^k + d_{Rj}^k)\right]^{\frac{1}{3}}\right)^{\frac{3}{2}} \end{aligned} \tag{23}$$

$$\sum_{ij\in\mathcal{S}_2} W_{ij} \;=\; RBN_0\frac{(2^R-1)\left(\sum_{ij\in\mathcal{S}} d_{ij}^{\frac{k}{2}}\right)^2}{z} \tag{24}$$

The development of (23) and (24) is provided in [16]. Note that both $\sum_{ij\in\mathcal{S}_1} W_{ij}$ and $\sum_{ij\in\mathcal{S}_2} W_{ij}$ now becomes functions of the auxiliary variable $z$.

The second step is solve the following optimization

$$\begin{aligned} \min_{z} \quad & f_z(z) = RBN_0\frac{(2^R-1)\left(\sum_{ij\in\mathcal{S}} d_{ij}^{\frac{k}{2}}\right)^2}{z} \\ & +2RBN_0\left(\frac{2^{2R}-1}{\sqrt{2(P-z)}}\right)\left(\textstyle\sum_{ij\in\mathcal{S}_1}\left[d_{ij}^k(d_{iR}^k + d_{Rj}^k)\right]^{\frac{1}{3}}\right)^{\frac{3}{2}} \\ s.t. \quad & 0 \le z \le P \end{aligned} \tag{25}$$

which is difficult to solve directly as it could result in a equation with degree higher than 2. Note that $f_z(z)$ is a convex function for $0 \le z \le P$ since $\frac{d^2 f_z(z)}{d^2 z} \le 0$. Hence there will only one minimum for $0 \le z \le P$, defined as $z^*$. Provided that $\left.\frac{df_z(z)}{dz}\right|_{z=\frac{P}{2}} \ge 0$, it can be expected that $0 \le z^* \le \frac{P}{2}$, otherwise $\frac{P}{2} \le z^* \le P$. So in the following, the close form of $z^*$ will be shown as

$$z^* = \begin{cases} \frac{2P\sqrt{z_1}}{\sqrt{z_1}+\sqrt{z_2}} & \text{if} \quad \left.\frac{df_z(z)}{dz}\right|_{z=\frac{P}{2}} \ge 0 \\ P - \left(\frac{z_3}{2z_4}\right)^{2/3} & \text{if} \quad \left.\frac{df_z(z)}{dz}\right|_{z=\frac{P}{2}} < 0 \end{cases} \tag{26}$$

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[1] For the reason of simplicity, the expression of the scheme with a random-chosen node is used here, and the developed results can be extended to the opportunistic relaying scheme straightforward.

and the total power consumption is

$$W = \begin{cases} \frac{(\sqrt{z_1}+\sqrt{z_2})^2}{2P} & \text{if} \quad \left.\frac{df_z(z)}{dz}\right|_{z=\frac{P}{2}} \geq 0 \\ (2z_4)^{1/3} z_3^{2/3} + \frac{z_4(P)^2}{P-\left(\frac{z_3}{2z_4}\right)^{2/3}} & \text{if} \quad \left.\frac{df_z(z)}{dz}\right|_{z=\frac{P}{2}} < 0 \end{cases} \tag{27}$$

where $z_1 = RBN_0(2^R - 1)\left(\sum_{ij\in\mathcal{S}_2} d_{ij}^{\frac{k}{2}}\right)^2$, $z_2 = 2RBN_0\sqrt{2P}\left(2^{2R}-1\right)\left(\sum_{ij\in\mathcal{S}_1}\left[d_{ij}^k(d_{iR}^k + d_{Rj}^k)\right]^{\frac{1}{3}}\right)^{\frac{3}{2}}$, $z_3 = 2RBN_0\left(\frac{2^{2R}-1}{\sqrt{2}}\right)\left(\sum_{ij\in\mathcal{S}_1}\left[d_{ij}^k(d_{iR}^k + d_{Rj}^k)\right]^{\frac{1}{3}}\right)^{\frac{3}{2}}$ and $z_4 = RBN_0\frac{(2^R-1)\left(\sum_{ij\in\mathcal{S}} d_{ij}^{\frac{k}{2}}\right)^2}{(P)^2}$. The details of the derivation for (26) can be from the [16].

*4) A Special Case:* Consider the worst case where each $i \to j$ link can not find a good relay node satisfy (8). Then all links will use direct transmission, and hence the total power consumption will be

$$\begin{aligned} W &= z_4 P \qquad (28) \\ &= \frac{RBN_0(2^R-1)\left(\sum_{ij\in\mathcal{S}_2} d_{ij}^{\frac{k}{2}}\right)^2}{P}. \end{aligned}$$

In the case of $k = 2$, it is interesting to find that

$$W = \frac{RBN_0(2^R-1)\left(\sum_{ij\in\mathcal{S}_2} d_{ij}\right)^2}{P}. \tag{29}$$

For the two successive links $i \to j \to l$. we can have $d_{ij} + d_{jl} \geq d_{il}$ since they are three edges of a triangle. Hence the one-hop transmission from the source to the destination directly would be preferred by the criterion in (29).

*5) Route Selection:* For more general cases, the quality of one route will be determined jointly by the cooperative links as well as the direct-transmission links. Two rules for routing decision have been implied by the developed results. The preference of the cooperative links can be illustrated from the object function in (25). The power consumed by cooperative links is inverse proportional to the square of the outage probability whereas the power consumed by direct transmission is inverse proportional to the probability. Provided that both $z^*$ and $P$ are very small and at the same order, it can be expected that replacing a direct-transmission link with a cooperative link can reduce the power consumption. The preference for multiple-hop transmission can be illustrated by the following example.

Consider a route where each of its links, $i \to j$, can find a good-quality helping node in the middle of the strait line between the nodes $i$ and $j$. With such assumption, the total transmission power consumed by the route only using one hop can be written as

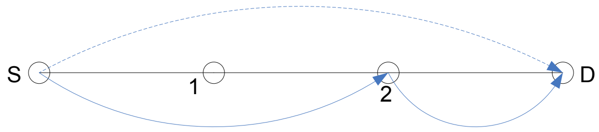
$$W_{onehop} = 2RBN_0\left(\frac{2^{2R}-1}{\sqrt{2P}}\right)\frac{d^2}{\sqrt{2}} = \frac{d^2(2^{2R}-1)}{2\sqrt{P}} \tag{30}$$

and the power consumption for the route using $n$-hop transmission can be shown as

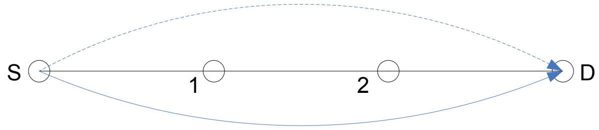
$$\begin{aligned} W_{nhop} &= 2RBN_0\left(\frac{2^{2R}-1}{\sqrt{2P}}\right)\left(n\left[\frac{d^2}{n^2}\frac{d^2}{2n^2}\right]^{\frac{1}{3}}\right)^{\frac{3}{2}} \qquad (31) \\ &= 2RBN_0\frac{n^{\frac{3}{2}}d^2(2^{2R}-1)}{2n^2\sqrt{P}} = \frac{1}{n^{1/2}}W_{onehop}, n \geq 2, \end{aligned}$$

which shows that the use of multiple-hop transmission can reduce the transmission power consumption.

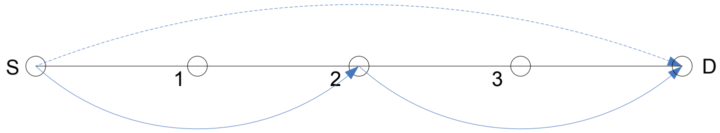
*6) Numerical Results:* In the following, we provide an example to show the effect of the criterion of minimizing the total transmission power with the constraint of the end-to-end reliability on the routing decision. The required data rate is $R = 0.1bit/s/Hz$ and $d_{SR} = 10m$. In the first setup, there are two intermediate nodes sitting on the straight line between the source and destination with $d_{S1} = d_{2D} = \frac{1}{3}d_{SD}$. The non-cooperative criterion in (29) will pick up the route $S \to D$ since there is no point to use multiple-hop transmission which yields the same power consumption, but more delay. However for the criterion proposed in (27), the route, $S \Rightarrow 2 \to D$, will be chosen for the mild requirement of the end-to-end reliability, where $\Rightarrow$ denotes a link using cooperative transmission. For the highly demanding reliability requirement, the error probability could be so small that the power consumed by the direct-transmission link $2 \to D$ will dominate the power consumption, which results the route $S \Rightarrow D$ as the preferred one. In Table I shows that these routes picked by the proposed criterion can reduce the power consumption significantly compared with the scheme only using direct transmission. For the second setup, there are three intermediate nodes sitting on the straight line between the source and destination with $d_{S1} = d_{2D} = \frac{1}{4}d_{SD}$. The situation is much easier where the route with multi-hop transmission will be chosen, and its performance is also shown in the Table I.



(a) Setup 1: Two intermediate nodes for $P > 0.043$



(b) Setup 1: Two intermediate nodes for $P \leq 0.043$



(c) Setup 2: Three intermediate nodes for all $P$

Fig. 4. Route selection with or without cooperative transmission (CT). The data rate is set as $R = 0.1$ bit/s/Hz, and the source-destination distance is 10m. The solid line presents the route which will be chosen by the criterion in (27), and the dash line presents the route chosen by the criterion without cooperative transmission ($|\mathcal{S}_1| = 0$).

TABLE I

NORMALIZED TRANSMIT POWER CONSUMPTION CHOSEN BY TWO CRITERIA

| $P$ | 0.1 | 0.05 | 0.01 | 0.005 | 0.001 |
|---|---|---|---|---|---|
| Direct trans., $S \rightarrow D$ | 71.773 | 143.55 | 717.73 | 1435.5 | 7177.3 |
| Setup 1, $S \Rightarrow 2 \rightarrow D$ | 43.144 | 68.235 | 268.18 | 426.11 | 1486.2 |
| Setup 1, $S \Rightarrow D$ | 49.566 | 70.097 | 156.74 | 221.67 | 495.66 |
| Setup 2, $S \Rightarrow 2 \Rightarrow D$ | 33.25 | 47.023 | 105.15 | 148.7 | 332.5 |

## V. CONCLUSION

In this paper, we have studied the effect of cooperative transmission on the routing decision for wireless ad-hoc networks. First the effect of cooperative transmission to the wireless link cost is studied with and without node selection, which shows that cooperative transmission could improve the quality of wireless links. To reduce system overhead, a distributed strategy of node selection is proposed by carefully designing the carrier sensing protocol in the medium access control layer. Then routing optimization is investigated to understand the effects of improved link cost to the routing decision. The objective function of interest is to minimize the total power consumption with the constraint of the end-to-end reliability. The optimal solution of this optimization problem indicates the minimum total power consumption of a route in order to satisfy the required error performance. Both analytical and simulation results are provided to show that the criteria using cooperative transmission typically yield more efficient routes than the non-cooperative schemes.

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