Cooperation Models and Cooperative Routing for Exploiting Hop-by-Hop Cooperative Diversity in Ad Hoc Networks

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ABSTRACT

In wireless ad hoc networks, nodes communicate with each other using multihop routed transmission in which hop-by-hop cooperative diversity can be effectively employed. This paper proposes (i) two cooperation models for per-link cooperation (PLC) and per-node cooperation (PNC) for exploiting cooperative diversity in wireless ad hoc networks and (ii) a cooperative routing algorithm for the above models in which best relays are selected for cooperative transmission. First, two cooperation models for PLC and PNC are introduced and represented as an edge-weighted graph with effective link quality. Then, the proposed models are transformed into a simplified graph and a cooperative routing algorithm with $O(n2)$ time is developed, where n is the number of nodes in the network. The effectiveness of the algorithm is confirmed for the two cooperation models using simulation.

Key words: Wireless ad hoc network, cooperative diversity, cooperation model, cooperative routing, relay selection.

1. INTRODUCTION

Cooperative communication refers to scenarios where distributed devices interact with each other for joint transmission of the information in wireless environment. In other words, wireless nodes in the network work in collaboration and not in opposition. Collaboration among wireless nodes at the physical layer is an efficient way to introduce diversity [2,3]. *Cooperative diversity* allows a collection of radio terminals to relay signals cooperatively for each other in wireless fading channels [4-6]. This improves the bit error rate (BER) of weak and noisy links significantly resulting in more reliable transmission and higher throughput. Throughout this paper, cooperative diversity means diversity exploited at the physical layer by multiple users or nodes.

Since wireless ad hoc networks are usually temporary constructs and typically operate in noisy and unstable environments exploiting cooperative diversity could be extremely useful and would significantly improve communication reliability and network throughput. It is reported that communication quality in ad hoc networks is low and users can experience strong fluctuation of link quality in practical operation environments [7]. The possibility of achieving cooperative diversity by employing multiple paths in dense multihop networks is noted in [8]. It is shown that performance can

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be improved by exploiting cooperative diversity in wireless sensor networks [9] and in wireless ad hoc networks [10] and also the importance of cooperative transmission in wireless ad hoc networks is noted [11,12].

A cooperation mechanism based on DSTC in wireless ad hoc networks was proposed in [13], where cooperative transmission is carried out through a series of relay discovery, transmission from sender to relay, and cooperative transmission from both sender and relay to receiver[1]. After transmitting a pseudo-noise code, a sender receives acknowledgements with signal-to-interference plus noise ratio (SINR) from potential relays and chooses the relay with the highest SINR. Then, the sender transmits two symbols of data to the relay in two consecutive time slots (symbol periods.) Now both sender and relay cooperatively transmit their two coded symbols based on DSTC to the receiver in two consecutive time slots, respectively. Finally, the receiver combines the two signals and detects the original symbol in each time slot.

To incorporate physical layer for cooperative diversity in wireless ad hoc networks, medium access control (MAC) mechanisms have been studied. In the distributed automatic repeat request [14], a source and cascaded relays simultaneously transmit the same data packet on a multihop routing path repeatedly until the source receives the correct acknowledgement from the destination. Cooperative MAC and routing protocols for wireless ad hoc networks are presented in [15], but it is assumed that sender and receiver receive all control packets from each other without cooperation and directional knowledge on neighbors is necessary for routing. A MAC protocol to support multiple relays is introduced in [16], but it has a short-

coming that if the sender uses k relays, the receiver must have at least k relays. For transmission, multiple relays should be chosen and they transmit pilot tones in orthogonal channels either in time or in code to estimate channel state information (CSI). Neighbor nodes are identified using 'hello' messages. More recently, a cooperative diversity MAC (CD-MAC), which exploits cooperative diversity via DSTC and can be implemented using the existing technologies such as IEEE 802.11, was proposed [17].

In this paper, we propose two cooperation models for per-link cooperation (*PLC*) and per-node cooperation (*PLC*) for exploiting cooperative diversity in wireless ad hoc networks. Then, we simplify these models and develop a cooperative routing algorithm with best relay selection[2] to support hop-by-hop cooperative diversity. For exploiting hop-by-hop cooperative diversity, the proposed PLC and PNC are represented as an edge-weighted graph with effective link quality and then, transformed into a simplified graph by which the cooperative routing algorithm with $O(n^2)$ time is developed, where n is the number of nodes in the network. Our computer simulation validates the effectiveness of the algorithm for cooperation models for PLC and PNC in a sample network. This paper is a revised and extended version of [1], in which some erroneous and inappropriate presentations are corrected, revised and extended significantly. In particular, system model is systematically reconstructed and performance evaluation is newly added for demonstrating the superiority of PLC and PNC.

The rest of the paper is constructed as follows: Section 2 examines the system model in question. Section 3 presents two cooperation models for PLC and PNC to exploit cooperative diversity in the wireless ad hoc networks with arbitrary topology. In Section 4, model transformation and cooperative

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1) To avoid getting confused, in this paper, source and destination denote the end-to-end nodes on a multihop path and sender and receiver denote the end nodes on a link.

2) To achieve cooperative diversity, cooperative routing requires best relay selection in terms of link quality.

routing are discussed. Section 5 discusses performance study including simulation environment and results. Finally, Section 6 offers conclusions.

2. SYSTEM MODEL

In wireless ad hoc networks, numerous nodes are spread over network area and communicate with each other using multihop routed transmission rather than direct connection. To exploit cooperative diversity for cooperative communication in wireless ad hoc networks, this study considers DSTC [18,19]. A relay decodes symbols received from the sender and then re-encodes and transmits them again to the receiver together with the sender. DSTC is used to obtain transmission diversity in virtual MISO transmission from both sender and relay to the receiver. Even though more than one relay can be assigned to each transmission, it is suggested that selecting a single best relay is better in terms of maximizing capacity [20-22]. For simplicity, one relay per sender is assumed in this study. Every node has a half-duplex antenna and the channel between the nodes is symmetric with the same transmission power.

In a wireless ad hoc network with DSTC-based cooperative diversity, the sender transmits two symbols s_1 and s_2 to its relay in two consecutive time slots or symbol periods (in time slots i and $i + 1$ in Fig. 1), respectively. Note here that the sender-relay channel should be much more reliable than both sender-receiver and relay-receiver channels. The relay decodes the received symbols and re-encodes them for cooperative transmission. Both the sender and the relay transmit their coded symbols based on DSTC simultaneously to the receiver in two consecutive time slots (in time slots $i + 2$ and $i + 3$ in Fig. 1), respectively. The symbol sequence (i.e., code symbol vector $\mathbf{C}$) transmitted by the sender-relay pair is

$$\mathbf{C} = \begin{bmatrix} c_1 & \hat{c}_2 \\ -c_2^* & \hat{c}_1^* \end{bmatrix} \tag{1}$$

where rows (time) refer to two consecutive time slots in up-to-down order and columns (space) represent code symbols transmitted by the sender and the relay, respectively, in left-to-right order and * denotes conjugation and ^ represents transmission from the relay. Then, the receiver receives two signals and combines them in each time slot. The two decoded symbols r1 and r2 can be represented as

$$r_1 = h_1 c_1 + h_2 \hat{c}_2 + n_1 \tag{2}$$

$$r_2 = -h_1 c_2^* + h_2 \hat{c}_1^* + n_2 \tag{3}$$

or in matrix form as

$$\begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} c_1 & \hat{c}_2 \\ -c_2^* & \hat{c}_1^* \end{bmatrix} \times \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \tag{4}$$

where h_1 and h_2 represent the channel gain or channel attenuation for sender-receiver and relay-receiver channels respectively, which are assumed to be scalar and constant over two consecutive symbol periods (time slots), and n_1 and n_2 represent the additive white Gaussian noise (AWGN) for two consecutive symbol periods respectively, and are modeled as independently and identically distributed (i.i.d.) zero-mean complex Gaussian random variables. The channel gains (sometimes called Rayleigh fading coefficient) h_1 and h_2 capture the combined effect of path loss, shadowing, and small scale and multipath fading. Note that the path loss attenuation is proportional to δ^{-a}, where δ is the distance between the sender and the receiver and a is a constant in the range $2 \leq a \leq 5$ [23]. Noises n_1 and n_2 represent thermal noise and other interference upon the receiver. It is assumed that CSI is fixed throughout the transmission block and estimated accurately at the receiver, but it is not available at the sender. Let $\mathbf{R} = [r_1, r_2]^T$ be the received signal vector, $\mathbf{H} = [h_1, h_2]^T$ be the scalar matrix of two constant channel gains, and $\mathbf{N} = [n_1, n_2]^T$ be the noise vector. Then, Equation (4) can be reduced as

$$\mathbf{R} = \mathbf{C} \times \mathbf{H} + \mathbf{N}. \tag{5}$$

Fig. 1 shows information symbols transmitted by the sender and the relay in consecutive time slots to exploit cooperative diversity based on DSTC.

Time slot	i	$i+1$	$i+2$	$i+3$
Sender	s_1	s_2	c_1	$-c^*_2$
Relay			$\hat{c}_2$	$\hat{c}^*_1$

Fig. 1. Information symbols transmitted by sender and relay in consecutive time slots.

Two metrics of *signal strength* (*SS*) and *signal-to-interference plus noise ratio* (*SINR*) can be used to indicate link quality that is used as a building block to derive path quality. SINR is used in this study because SS makes no account for interference and noise, both of which are important CSI. In general, wireless signals suffer from noise and interference. While the receiver receives one frame, other frames may arrive at the receiver resulting in interference. The effective noise level can be obtained by adding up the noise figure of a network interface card (NIC) onto the thermal noise [24]. As a result, the SINR of the receiving frame is calculated by

$$SINR = \frac{P_r}{\sum_{i \neq r} P_i + N} \tag{6}$$

where P_r is the received power (signal strength) of the frame, P_i stands for individual received power of other frames received by the receiver simultaneously, and N is the effective noise at the receiver.

3. TWO COOPERATION MODELS

In this section, two cooperation models for PLC and PNC are proposed and presented in terms of relay selection and link quality. They will be transformed into simplified models in the next section

to derive a cooperative routing algorithm.

3.1 Per-Link Cooperation (PLC) Model

Fig. 2 shows cooperative transmission with relays along a routing path based on the *PLC model* in which a relay is selected per link. Note that although many wireless nodes are randomly deployed, only the nodes along the cooperative routing path are shown Figs. 2 and 3 for simplicity. Each per-link relay transmits signals cooperatively with one of two end nodes in either direction if any of its two partners on the *main routing path* requests cooperation. The main routing path represents the routing path from the source to the destination without relays. For each link along the main routing path from the source s to the destination d, a relay should be selected so that best relaying quality is achieved. In Fig. 2, node i transmits a packet to its receiver j cooperatively with the link (i, j)'s relay r; likewise, the node j transmits a packet to the node i cooperatively with the same relay r through each node's half-duplex antenna. Note that data packets are transmitted from s to d while acknowledge packets go in the opposite direction.
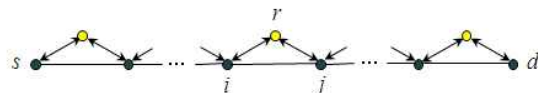

Fig. 2. Cooperative transmission with relays along routing path based on a PLC network.

A wireless ad hoc network with arbitrary topology and symmetric nodes where every link between the nodes has a specified link quality can be represented as an edge-weighted graph $G = (V, E)$ with weight function $w: E \rightarrow \mathbf{R}$. Note that weight $w(u, v)$ is the link quality (*i.e.,* SINR) of link (u, v). Without loss of generality, *weight function* and *link quality function* are used interchangeably in this paper. Now, we define the best two-hop relaying path of the link, the cooperatively combined quality of the link, and the path quality as follows:

Definition 1. The *best two-hop relaying path* of the link (u, v) in *PLC* is a two-hop relaying path with the path quality of $\max\limits_{r \in N(u) \cap N(v)} \min(w(u,r), w(r,v))$, where $N(u)$ and $N(v)$ are the sets of u's and v's one-hop away neighbors, respectively.

In general, a relay is not always found for a link. In case no relay is available for the link (u, v), no two-hop relaying path of link (u, v) is defined and, thus, $w(u, r) = w(r, v) = 0$ resulting in $\max\limits_{r \in N(u) \cap N(v)} \min(w(u,r), w(r,v))$.

Definition 2. *The cooperatively combined quality* of the link (u, v) and its best two-hop relaying path in *PLC* is

$$w_l(u,v) = w(u,v) + \max\limits_{r \in N(u) \cap N(v)} \min(w(u,r), w(r,v)) \quad (7)$$

where $N(u)$ and $N(v)$ are the sets of u's and v's one-hop away neighbors, respectively.

Definition 3. The *path quality* of a cooperative routing path i in *PLC* is $\min\limits_{j \in [0, l(i)-1]} w_l(v_{i,j}, v_{i,j+1})$, where $l(i)$ is the length of path i in which relaying links are not counted, $v_{i,j}$ is jth node of path i, and $w(v_{i,j}, v_{i,j+1})$ is the cooperatively combined quality of link $(v_{i,j}, v_{i,j+1})$ and its best two-hop relaying path.

In Definition 1 and 2, $N(u) \cap N(v)$ is the set of all possible relay candidates for the link (u, v). The path quality of serialized links is obtained by 'minimum' operation while that of parallel links exploiting cooperative diversity is given by 'sum' operation. The *per-hop path quality* of a cooperative routing path i can be represented as $\frac{1}{l(i)} \min\limits_{j \in [0, l(i)-1]} w_l(v_{i,j}, v_{i,j+1})$ and it can be used as a metric to find the cooperative routing path in a wireless ad hoc network. That is, among multiple possible paths, the cooperatively relaying path with the highest per-hop path quality should be the co-operative routing path.

3.2 Per-Node Cooperation (PNC) Model

Fig. 3 shows cooperative transmission with relays along a routing path based on the *PNC model*, in which a relay is selected per node. When the partner on the main routing path requests cooperation each per-node relay cooperatively transmits signals to either the proceeding or the succeeding node of its partner. The main routing path represents the routing path from the source to the destination without relays. For each node along the routing path from source s to destination d, a relay is selected so that the best relaying quality is achieved. In Fig. 3, a node i transmits a packet to its receiver j cooperatively with its relay r_i; likewise, the node j transmits a packet to the node i cooperatively with its relay r_j. Note that data packets are transmitted from s toward d while acknowledge packets go in the opposite direction. The author introduced a basic form of this model in [17] for MAC design.
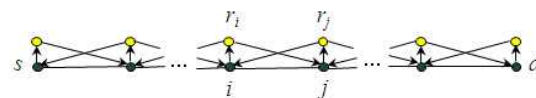

Fig. 3. Cooperative transmission with relays along a routing path on a PNC network.

As mentioned in Section 3.1, a wireless ad hoc network of arbitrary topology with symmetric nodes, where every link between the nodes has a specified link quality, can be represented as an edge-weighted graph $G = (V, E)$ with weight (quality) function $w: E \rightarrow \mathbf{R}$, where $w(u, v)$ is the link quality (*i.e.,* SINR) of link (u, v). The best two-hop relaying path of the link, the cooperatively combined quality of the link, and the path quality in the PNC model are defined as follows:

Definition 4. The *best two-hop relaying path* of the link (u, v) in *PNC* is a two-hop relaying path with the path quality of

$$\max_{r_u \in N(u), r_v \in N(v)} \min(w(u, r_u), w(r_u, v), w(v, r_v), w(r_v, u)),$$

where $N(u)$ and $N(v)$ are the sets of u's and v's one-hop away neighbors, respectively.

Data transmission requires acknowledgement as in IEEE 802.11 standard [25] and thus, for the link (u, v), both forward and backward links are taken into evaluation of the link quality. If either forward data transmission or backward acknowledgement fails, the whole hop transmission between u and v fails as well. Therefore, Definition 4 takes in consideration all the four relaying links . In case no relay is available for node u, no two-hop relaying path from u to v is defined and thus $w(u, r_u) = w(r_u, v) = 0$. Likewise, if no relay is available for node v, no two-hop relaying path from v to u is defined and thus $w(v, r_v) = w(r_v, u) = 0$. If neither r_u nor r_v is defined

$$\max_{r_u \in N(u), r_v \in N(v)} \min(w(u, r_u), w(r_u, v), w(v, r_v), w(r_v, u)) = 0.$$

Definition 5. The *cooperatively combined quality* of the link (u, v) and its best two-hop relaying path in *PNC* is

$$w_n(u,v) = w(u,v) + \max_{r_u \in N(u), r_v \cup N(v)} \min(w(u, r_u), w(r_u, v), w(v, r_v), w(r_v, u))$$
(8)

where $N(u)$ and $N(v)$ are the sets of u's and v's one-hop away neighbors, respectively.

Definition 6. The *path quality* of a cooperative routing path i in *PNC* is $\min_{j \in [0, l(i)-1]} w_n(v_{i,j}, v_{i,j+1})$, where $l(i)$ is the length of path i in which relaying links are not counted, $v_{i,j}$ is jth node of path i, and $w_n(v_{i,j}, v_{i,j+1})$ is the cooperatively combined quality of link $(v_{i,j}, v_{i,j+1})$ and its best two-hop relaying path.

Similarly to the PLC model, the *per-hop path quality* of a cooperative routing path i can be represented as $\dfrac{1}{l(i)} \min_{j \in [0, l(i)-1]} w_n(v_{i,j}, v_{i,j+1})$ and it can be used as a metric to find the cooperative routing

path. As in the PLC model, the cooperatively relaying path with the highest per-hop path quality should be the cooperative routing path among multiple candidates.

4. COOPERATIVE ROUTING

In this section, two cooperation models for PLC and PNC are transformed into a simplified graph and a cooperative routing algorithm is developed. Note here that, given a wireless ad hoc network of arbitrary topology with homogeneous nodes and symmetric links, the *cooperative routing algorithm* has to find the cooperative routing path (including relays) that fully exploits cooperative diversity. It is quite different from the conventional approaches [26,27] which do not exploit cooperative diversity. To transform the two graph models for PLC and PNC presented in Section 3 into a simplified model, we define a new graph $G' = (V, E')$ with weight (link quality) function $w': E' \to \mathbf{R}$. Note that the difference between the original graph G and the transformed graph G' is only the weight function of edges; *i.e.*, $w'(u, v)$ in G' is the *transformed link quality* (*i.e.*, *transformed SINR*) of the link (u, v) in G, which is either $w_l(u, v)$ in the PLC model or $w_n(u, v)$ in the PNC model:

$$w'(u,v) = \begin{cases} w_l(u,v), & \text{if PLC} \\ w_n(u,v), & \text{otherwise (if PNC).} \end{cases}$$
(9)

The new weight function $w': E' \to \mathbf{R}$ represents the cooperatively combined quality of link in $V(G)$ and its best two-hop relaying path(s), which can be obtained from the equations (7) and (8) for PLC and PNC, respectively. As a result, two graph models for PLC and PNC can be coherently transformed into a simplified model by replacing $w_l(u, v)$ or $w_n(u, v)$ by $w'(u, v)$. In this paper the *cooperative routing path* is defined as follows:

Definition 7. Given an edge-weighted graph $G' = (V, E')$ with weight (link quality) function $w': E' \to \mathbf{R}$, source vertex s and destination vertex d,

the *cooperative routing path* is a path with the per-hop path quality of $\max_{i \in U} \dfrac{1}{l(i)} \min_{j \in [0, l(i)-1]} w'(v_{i,j}, v_{i,j+1})$, where U is the set of all paths from s to d, $l(i)$ is the length of path i, and $v_{i,j}$ is jth node of path I.

Since a path in G' is a serially connected chain, the path quality is obtained by 'minimum' operation as defined by Definitions 3 and 6. For a path i with length $l(i)$, it can be represented as $\min_{j \in [0, l(i)-1]} w'(v_{i,j}, v_{i,j+1})$ and thus the per-hop path quality is $\dfrac{1}{l(i)} \min_{j \in [0, l(i)-1]} w'(v_{i,j}, v_{i,j+1})$, where $v_{i,j}$ is jth node of path i. Let U is the set of all paths from source s to destination d. Therefore, among $|U|$ paths from s to d in G', a path with $\max_{i \in U} \dfrac{1}{l(i)} \min_{j \in [0, l(i)-1]} w'(v_{i,j}, v_{i,j+1})$ has the best (or highest) per-hop path quality and thus it is the cooperative routing path.

By investigating the cooperative routing path in the transformed graph G', we can deduce that it is analogous to the so-called *shortest path problem* [28] which is to find the shortest path from source to destination in an edge-weighted graph. Within a path, the 'minimum' operation of qualities on edges in our cooperative routing is analogous to the 'sum' operation of weights on edges in the shortest path problem. On the other hand, among the available paths, the 'maximum' operation of qualities on paths in the cooperative routing is analogous to the 'minimum' operation of weights on paths in the shortest path problem. Furthermore, computational complexity of the minimum, maximum and sum operations is the same. Therefore, the algorithm for finding the shortest path in an edge-weighted graph can be successfully used to find the cooperative routing path in G' with some modification of analogous operations. The typical algorithm to find the shortest path is *Dijkstra's algorithm* [28,29], which computes the shortest path in an edge-weighted graph in polynomial time. Note that computational complexity of the Dijkstra's algorithm is $O(|V|^2)$, $O(|E| \log |V|)$ or $O(|E| + |V| \log |V|)$ for representing data structures of array, binary heap or Fibonacci heap, respectively [28].

Fig. 4 shows the algorithm to find the cooperative routing path for exploiting cooperative diversity in a wireless ad hoc network. In Step 1, the algorithm computes the cooperatively combined quality for each link based on the cooperation model, which is then used to transform coherently G

Algorithm 1: Cooperative_Path(G, s, d, *model*)

Input: $G = (V, E)$ - edge-weighted graph (network) with weight (link quality) function $w: E \rightarrow \mathbf{R}$, which
is represented by a two-dimensional array
s - source node
d - destination node
model - cooperation model (PLC or PNC)

1: For every link $(u, v) \in E(G)$, compute the cooperatively combined quality $w'(u, v)$ of the link (u, v) and its best two-hop relaying path(s) according to:
1.1: Equation (7) if model = PLC.
1.2: Equation (8) otherwise (if model = PNC).
2: Generate $G' = (V, E')$ with new weight (link quality) function $w': E' \rightarrow \mathbf{R}$ from G.
3: Use the Dijkstra's shortest path algorithm with some modification of analogous operations; *i.e.*, substituting (i) 'minimum' operation for 'sum' operation within a path and (ii) 'maximum' operation for 'minimum' operation among paths.

Fig. 4. Algorithm to find the cooperative routing path.

= (V, E) into $G' = (V, E')$ in Step 2. Finally, in Step 3, it uses the Dijkstra's algorithm with some modification of analogous operations for finding the cooperative routing path. Theorem 1 presents the correctness and computational complexity of the proposed algorithm.

Theorem 1. Algorithm 1 finds the cooperative routing path for exploiting cooperative diversity in a wireless ad hoc network in $O(n^2)$ time, where n is the number of nodes in the network.

Proof. For every link $(u, v) \in E(G)$, the second terms of the right-hand side in equations (7) and (8) represent the best two-hop relaying path of link (u, v) by Definitions 1 and 4. Since the cooperatively combined quality of parallel links is obtained by 'sum' operation, the right-hand side in equations (7) and (8) computes the cooperatively combined quality $w'(u, v)$ of the link (u, v) and its best two-hop relaying path, which is obtained in Step 1 in Algorithm 1. A transformed graph $G' = (V, E')$ is generated by substituting the cooperatively combined quality $w'(u, v)$ for $w(u, v)$ in $G = (V, E)$ in Step 2. By substituting 'minimum' operation for 'sum' operation within a path and 'maximum' operation for 'minimum' operation among paths in the Dijkstra's algorithm, the path found in Step 3 is the cooperative routing path by Definition 7. In terms of computational complexity, Step 1 needs $O(|E|)$ since the number of neighbors is usually a small constant in wireless ad hoc networks, and Step 2 requires $O(|E|)$ operations. The computational complexity of Step 3 is $O(|V|^2)$ for representing data structures of array[3]. Thus, the total complexity becomes $O(|E|) + O(|E|) + O(|V|^2) = O(|V|^2)$ because $|E| < |V|^2$ in a graph. Therefore, Algorithm 1 finds the cooperative routing path in

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3) The time complexity of Dijkstra's shortest path algorithm can be O(|V|2), O(|E| log |V|) or O(|E| + |V| log |V|) for representing data structures of array, binary heap or Fibonacci heap, respectively [29].

$O(n^2)$ time, where n is the number of nodes in the network. **Q.E.D.**

Note here that there was no cooperative routing algorithm suitable for the two cooperation models for PLC and PNC since the models are newly proposed in this paper and, thus, we have designed the new cooperative routing algorithm. So, the algorithm may not be directly compared with others in terms of performance such as computational complexity. In wireless ad hoc networks, particularly in static networks such as in most sensor networks, autonomous self-configuration including topology discovery is a basic function. All the wireless links can be identified. This can be done by exchanging periodic hello messages between one-hop away neighboring nodes and collecting local connectivity information. The hello message can be usually implemented as so-called *beacon*. That is, when a wireless ad hoc network starts up, the nodes in the network may start the configuration algorithm to determine the overall topology and link qualities of the network, which is then used by the routing protocol in order to compute the best-quality per-hop relaying routing path for any pair of source and destination. Note here that the routing protocol should be modified to use topology information. The overall topology including link qualities can be represented as two-dimensional adjacent matrix of $|V| \times |V|$ (or $n \times n$), where each item in the matrix represents the respective link quality. Therefore, for a pair of source and destination, each node can compute whether or not it is involved in the routing path; more specifically, it can know whether it is a forwarding node or a relay for a cooperatively relaying routing path.

A simple implementation of the above algorithm is to use *source routing* mechanism. That is, the source computes the best-quality cooperatively relaying routing path and includes the routing path in the transmitted packet header. Then, intermediate nodes know the next hop nodes by prob-

ing the packet header. The packet is then coopera-
tively transmitted hop by hop as explained in
Section 2.

5. PERFORMANCE EVALUATION

In this section, the performance of the two pro-
posed cooperation models for PLC and PNC is
evaluated using *ns-2* network simulator [30]. After
introducing the simulation environment including
parameters, simulation results are discussed. Note
here that the superiority of PLC and PNC is sys-
tematically and quantitatively demonstrated in
terms of network performance via extensive com-
puter simulation.

5.1 Simulation Environment

To take *bit error rate* (BER) into consideration
when determining the success or failure of the re-
ceived signal, the *ns-2* network simulator was
modified as in [17]. This is based on three-step
process: (1) compute SINR, (2) look up the
BER-SINR curve to obtain BER, and (3) calculate
frame error rate (FER) and determine whether to
receive or drop the frame. More detailed in-
formation about the process can be found in [17].

It is assumed that 50 mobile nodes move over
a square area of $300 \times 1500 m^2$. Each simulation has
been run for 900 seconds. The propagation channel
of two-ray ground reflection model is assumed
with a data rate of 2Mbps. The environment noise
level of -83dBm is modeled as a Gaussian random
variable with standard deviation of 1dB. Noise level
of -83dBm is used in this performance study to
simulate a *harsh communication environment* (see
the SINR equation in Section 2).

Four constant bit rate (CBR) sources transmit
UDP-based traffic of 2 packets per second and the
data payload of each packet is 512 bytes long.
Source-destination pairs are randomly selected.
Mobile nodes are assumed to move randomly ac-
cording to the *random waypoint model* [31] with

node speed of 0~5 m/sec. Pause time between
moves varies from 0 to 900 seconds. Note that the
pause time of 0 second simulates a constant mov-
ing, high mobility scenario. The pause time of 900
seconds simulates a static scenario. Ad-hoc
On-demand Distance Vector (AODV) [32] routing
protocol is used to discover a routing path for a
given source-destination pair. Note here that the
AODV routing protocol was modified to use top-
ology information as explained in Section 4.

Performance metrics are *packet loss ratio* and
per-route goodput which represent the high-level
multihop performance of error probability and ca-
pacity, respectively. (i) The packet loss ratio is the
ratio of the number of lost data packets over the
number of data packets sent by the source. (ii)
Per-route goodput is the application level through-
put which is sometimes given by the inverse of
the averaged end-to-end data packet delay.

5.2 Simulation Results and Discussion

Simulation results comparing three models for
PLC, PNC and no cooperation (NC) are presented
in this subsection. Fig. 5(a) shows the packet loss
ratio for PLC, PNC and NC with environment noise
level of -83dBm. As expected, PLC and PNC out-
perform NC regardless of mobility. This is due to
the fact that noisy environment makes wireless
links more unreliable and cooperative diversity is
effectively exploited in PLC and PNC. It is also ob-
served in the figure that PLC is slightly better than
PNC. Fig. 5(b) shows the per-route goodput with
PLC, PNC and NC for varying mobility. Except for
very high mobility, PNC and PLC achieve better
per-route goodput than NC for the given harsh en-
vironment (-83dBm). As in the packet loss ratio,
PLC yields slightly better goodput than PNC. In
Fig. 5, it may be unexpected that performance fluc-
tuates as pause time increases, particularly at
pause time less than 100 seconds. However, the
same trend has been consistently observed in other
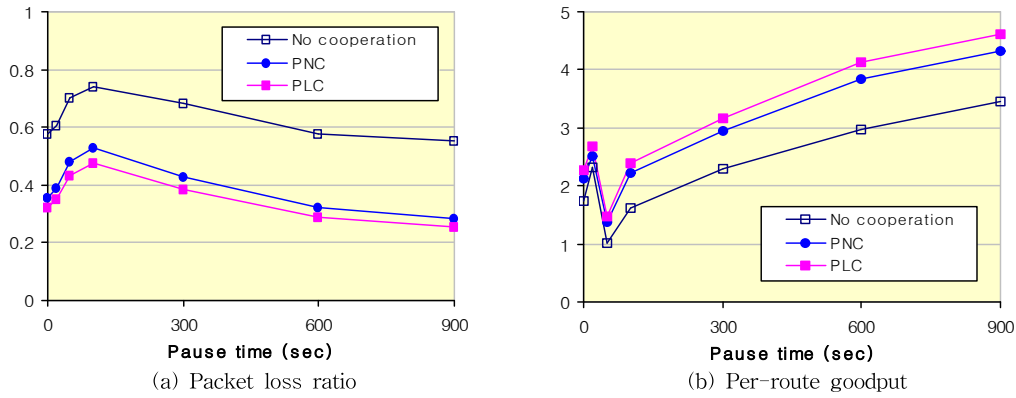simulation-based studies including [33,34]. This is

(a) Packet loss ratio   (b) Per-route goodput

Fig. 5. High-level multihop performance.

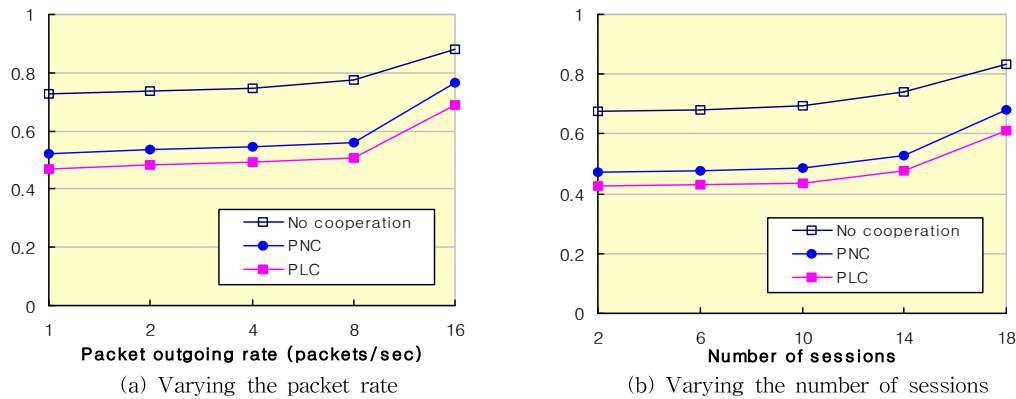(a) Varying the packet rate   (b) Varying the number of sessions

Fig. 6. Impact of network traffic on delivery performance.

due to the complex interplay among MAC- and routing-layer protocols in mobile ad hoc networks.

In bandwidth-limited wireless networks, network traffic is one of the most important system parameters. High traffic causes network congestion resulting in unexpected packet drops that badly degrade delivery performance. Fig. 6 shows the impact of the network traffic on packet loss ratio. During simulation, the pause time was fixed at 100 seconds and the two network traffic parameters of 4 sessions and 2 packets per second were applied as default values. As can be expected, more packets are lost or dropped as network traffic increases. The packet-loss ratio quickly increases when the traffic goes beyond a threshold of 8 packets per second and 14 sessions in the simulation as shown in Fig. 6(a) and 6(b), respectively. This

is because network overhead rapidly increases beyond the threshold resulting in network congestion. As in Fig. 5, PLC and PNC still outperform NC and PLC is slightly better than PNC.

6. CONCLUSIONS

In this paper, two *cooperation models* for *PLC* and *PNC* and a *cooperative routing algorithm* for exploiting cooperative diversity in wireless ad hoc networks were proposed. The proposed PLC and PNC are represented as an edge-weighted graph with effective link quality and, then, transformed into a simplified graph by which the cooperative routing algorithm with $O(n^2)$ time was developed, where n is the number of nodes in the network. According to computer simulation, the effective-

ness of the proposed algorithm for both cooperation models was proved in a sample network.

The proposed cooperation models can be applied to further studies of cooperative diversity in wireless ad hoc networks. The proposed cooperative routing algorithm can be more efficient for static networks which are the case for most sensor network scenarios. However, it becomes more complicated in case the network supports node mobility because periodical update of graph model is needed. Future studies should consider designing distributed algorithms and supporting node mobility.

REFERENCES

[1] S. Moh, "Two Cooperation Models and Their Optimal Routing for Cooperative Diversity in Wireless Ad Hoc Networks," *Proc. of 5th IEEE Int. Symp. on Wireless Communication Systems* (*ISWCS 2008*), pp. 57-61, 2008.

[2] Z. Lin, E. Erkip, and A. Stefanov, "Cooperative Regions and Partner Choice in Coded Cooperative Systems," *IEEE Trans. on Communications,* pp. 1323-1334, 2006.

[3] R. Ramanathan, "Challenges: A Radically New Architecture for Next Generation Mobile Ad Hoc Networks," Proc. *of 11th Annual Int. Conf. on Mobile Computing and Networking* (*Mobicom 2005*), pp. 132-139, 2005.

[4] J. N. Laneman, Cooperative Diversity: Models, Algorithms, and Architectures, F. H. P. Fitzek and M. D. Katz (Eds.), Chapter 6, Springer, Netherlands, 2006.

[5] A. Nosratinia, T. E. Hunter, and A. Hedayat, "Cooperative Communication in Wireless Networks," *IEEE Communication Magazine,* pp. 74-80, 2004.

[6] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative Diversity in Wireless Networks: Efficient protocols and Outage Behavior," *IEEE Trans. on Information Theory,* pp. 3062-3080, 2004.

[7] G. Gaertner and V. Cahill, "Understanding Link Quality in 802.11 Mobile Ad Hoc Networks," *IEEE Internet Computing,* pp. 55-60, 2004

[8] M. C. Valenti and N. Coreal, Exploiting Macrodiversity in Dense Multihop Networks and Relay Channels, *Proc. of IEEE Wireless Communications and Networking Conf.,* pp. 1877-1882, 2003.

[9] S.-H. Chen, U. Mitra, and B. Krishnamachari, "Cooperative Communication and Routing over Fading Channels in Wireless Sensor Networks," *Proc. of IEEE Int. Conf. on Wireless Networks, Communications, and Mobile Computing* (*WirelessCom*), 2005.

[10] A. Scaglione, D. L. Goeckel, and J. N. Laneman, "Cooperative Communications in Mobile Ad-Hoc Networks: Rethinking the Link Abstraction," *IEEE Signal Processing,* pp. 18-29, 2006.

[11] N. Jindal, U. Mitra, and A. "Goldsmith, Capacity of Ad-Hoc Networks with Node Cooperation," *Proc. of IEEE Int. Symp. on Information Theory,* 2003.

[12] M. Haenggi, "Analysis and Design of Diversity Schemes for Ad Hoc Wireless Networks," *IEEE Journal on Selected Areas in Communications,* pp. 19-27, 2005.

[13] S. Barbarossa, L. Pescosolido, D. Ludovici, L. Barbetta, and G. Scutari, "Cooperative Wireless Networks Based on Distributed Space-Time Coding," *Proc. of Int. Workshop on Wireless Ad-Hoc Networks* (*IWWAN*), 2004.

[14] E. Kojima, T. Fujii, Y. Kamiya, and Y. Suzuki, "Distributed ARQ Using STBC for OFDM Ad-Hoc Networks," *Proc. of 14th IST Mobile and Wireless Communications Summit,* Jun. 2005.

[15] A. Azgin, Y. Altunbasak, and G. AlRegib, "Cooperative MAC and Routing Protocols for Wireless Ad Hoc Networks," *Proc. of IEEE GLOBECOM,* 2005.

[16] G. Jakllari, S. V. Krishnamurthy, M. Faloutsos, P. V. Krishnamurthy, and O. Ercertin, "A Framework for Distributed Spatio-Temporal Communications in Mobile Ad Hoc Networks," *Proc. of IEEE INFOCOM*, 2006.

[17] S. Moh, C. Yu, S.-M. Park, H.-N. Kim, and J. Park, "CD-MAC: Cooperative Diversity MAC for Robust Communication in Wireless Ad Hoc Networks," *Proc. of 2007 IEEE Int. Conf. on Communications (IEEE ICC-2007)*, Glasgow, Scotland, 2007.

[18] J. N. Laneman and G. W. Wornell, "Distributed Space-Time Coded Protocols for Exploiting Cooperative Diversity in Wireless Networks," *IEEE Trans. on Information Theory,* pp. 2415-2425, 2003

[19] G. Scutari and S. Barbarossa, "Distributed Space-Time Coding for Regenerative Relay Networks," *IEEE Trans. on Wireless Communications,* pp. 2387-2399, 2005.

[20] Y. Fan and J. S. Thompson, "MIMO Configurations for Relay Channels: Theory and Practice," *IEEE Trans. on Wireless Communications,* pp. 1774-1786, 2007.

[21] J. S. Thompson, P. M. Grant, and Y. Fan, "An Introduction to Multihop Multi-Antenna Communications," *Frequenz (Journal of RF-Engineering and Telecommunications),* invited paper, 2005.

[22] A. Bletsas, A. Khisti, D. P. Reed, and A. Lippman, "A Simple Cooperative Diversity Method Based on Network Path Selection," *IEEE Journal on Selected Areas in Communications,* pp. 659-672, 2006.

[23] S. Wei, D. L. Goeckel, and M. Valenti, "Asynchronous Cooperative Diversity," *IEEE Trans. on Wireless Communications,* pp. 1547-1557, 2006

[24] IEEE P802.11-94/132, Wireless Access Methods and Physical Layer Specifications: Elaborate Clear-Channel Assessment for Indoor Communication Systems Operating in Uncontrolled UHF & Microwave Bands, July 1994. Available from http://grouper.ieee.org/groups/802/11/Documents/DocumentArchives/1994_docs/1194132.doc, 2010.

[25] IEEE Std 802.11-1999, Local and Metropolitan Area Network, Specific Requirements, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, 1999. Available from http://standards.ieee.org/getieee802/download/802.11-1999.pdf, 2010.

[26] T. Kim and S. Tak, "A Reputation Based Cooperative Routing Scheme for End-to-End Reliable Communications in Multi-hop Wireless Networks," *Journal of Korea Multimedia Society,* Vol. 12, No. 11, pp. 1593-1608, Nov. 2009.

[27] J. Park, S. Moh, and I. Chung, "SINR-Based Multipath Routing for Wireless Ad Hoc Networks," *Journal of Korea Multimedia Society,* Vol. 13, No. 6, pp. 849-864, June 2010.

[28] T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein, "*Introduction to Algorithms,*" 2nd Ed., MIT Press, 2001.

[29] E. W. Dijkstra, "A Note on Two Problems in Connection with Graphs," *Nuerische Mathematik.* pp. 269-271, 1959

[30] The Network Simulator ns-2, http://www.isi.edu/nsnam/ns/, 2011.

[31] J. Broch, D, A, Maltz, D. Johnson, Y.-C. Hu, and J. Jetcheva, "A Performance Comparison of Multi-Hop Wireless Ad Hoc Network Routing Protocols," *Proc. of ACM/IEEE MobiCom,* pp. 85-97, 1998.

[32] C. E. Perkins and E. Royer, "Ad-hoc On-Demand Distance Vector Routing," *Proc. of IEEE Workshop on Mobile Computing Systems and Applications,* 1999.

[33] J. Broch, D.A. Maltz, D.B. Johnson, Y.-C. Hu, and J. Jetcheva, "Performance Comparison of Multi-Hop Wireless Ad Hoc Network Routing Protocols," *Proc. ACM/IEEE MobiCom,* 1998.

[34] C. Yu, S. Park, and H. Kim, "Every Node Is Born Equal: Attacking Preferential Attachment in Peer-to-Peer Mobile Multihop Networks," *Proc. IEEE Percom Workshop Mobile Peer-to-Peer Computing (MP2P '05)*, 2005.

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