

A Design Framework for High-Density Wireless Ad Hoc Networks Achieving Cooperative Diversity

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Abstract—In this paper, we present a systematic design structure for high-density ad hoc networks aimed at achieving full cooperative diversity, based on which the PHY, MAC and Network layers of the system are specifically tailored. For the latter in particular, we present a cooperative routing protocol that is capable of exploiting full transmit diversity in ad-hoc networks. Simulation results are provided to demonstrate the substantial performance gain in terms of increased packet delivery reliability over high-throughput scenarios and reduced system delay, achieved by the cooperative diversity attained using a virtual MIMO system architecture.

I. INTRODUCTION

Although Multiple Input Multiple Output (MIMO) systems could meet the growing need for high-throughput and reliable transmissions, unfortunately, it may not always be practical to accommodate multiple antennas at the nodes, owing to cost, size and other hardware limitations. As a remedy, the concept of 'cooperation' has been proposed [1], where a Virtual MIMO (VMIMO) system can be formed, mimicking the behavior of the co-located MIMO systems. Cooperation could potentially benefit ad hoc networks at least one of the following aspects: increasing the data transmission reliability, providing higher throughput, extending network coverage, reducing the transmission delay and saving the transmit power.

However, there are a number of challenges have to be addressed before the above-mentioned benefits of cooperation can be fully exploited. Among them are relay selection, nodes' synchronization and the use of a VMIMO structure. The majority of existing cooperation schemes [2]–[4] depend on additional control signals to select and maintain relays, which reduces the effective throughput substantially. As for the issue of synchronization, TDMA-based synchronization could possibly be a preferred approach for cooperative transmissions [5]. Nonetheless, a TDMA-based system would be very costly in ad hoc network environments owing to the lack of base station, nodes mobility, and the large number of nodes. For practical applications, authors of [6] present cooperative schemes based on the IEEE 802.11 standard. Unfortunately, CSMA/CA type schemes only allow a single node to transmit at any given time within the interference sensing range.

In order to address the above-mentioned challenges of cooperation, PHY layer cooperation schemes [7] were proposed and to a more limited extent, to the MAC layer [5], [8]. To the best of our knowledge, there are very few designs that involve multiple layers for cooperative ad hoc networks. Although the benefits of cooperation is partially achieved in one way

or another [3], [6], these designs have two main issues. Firstly, the relay selection process is implemented in the MAC layer, which requires a significant amount of control packets to provide handshakes between source/destination and relay nodes. Secondly, the relays are prohibited from transmitting simultaneously, since the CSMA/CA protocol is invoked.

We present a systematic design structure for high-density ad hoc networks aimed at achieving full cooperative diversity, based on which the Network, MAC and PHY layers of the system are specifically tailored. More explicitly, the rationales and novelties of the proposed cooperation scheme are:

- Improved packet delivery reliability. Firstly, each intermediate node is protected by 'cooperative diversity'. Secondly, a multi-path protocol is proposed, namely, any single-path failure would not trigger link breakage.
- Reduced transmission delay. The major reason of delaying in 802.11 DCF-based ad hoc networks is the retransmission process triggered by packet errors, which also increases the contention window size resulting in multiple idle slots. By contrast, our cooperative scheme greatly reduces the probability of retransmission. Unlike some existing schemes [9], which only enable cooperative transmission when the first attempt fails, our approach provides cooperative diversity by default.
- Resistance to network topology variation, since as long as there is at least one cooperative node successfully retrieving the correct information during each hop, the data transmission is carried on.
- Synchronous transmissions in ad hoc networks. It is desirable to allow cooperative nodes to transmit simultaneously, although this is directly against the philosophy of the 802.11 DCF. However, with the help of necessary modifications over the Request to Send (RTS) and Clear to Send (CTS) signals, synchronous transmissions between cooperative nodes are achieved.
- Simplicity of the proposed protocol. We strive to make as few modifications as possible to the existing ad hoc network schemes, while achieving cooperative diversity.

We commence the detailed discourse in Section II by providing a description of the proposed cooperative framework. The cooperative routing protocol is described in Section III, followed by the detailed the MAC layer designs in Section IV. The PHY layer cooperative scheme is demonstrated in Section V. The simulation results are provided in Section VI. Finally, we conclude our discourse in Section VII.

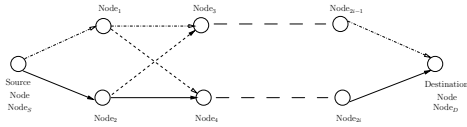


Figure 1. A cooperative multi-hop transmission scheme having $i = 1, 2, \dots, \dagger$ hops, which is selected by the Cooperative Dynamic Source Routing (CDSR) protocol of Section III, scheduled by the cooperative MAC protocol of Section IV and transmitting using the PHY scheme of Section V.

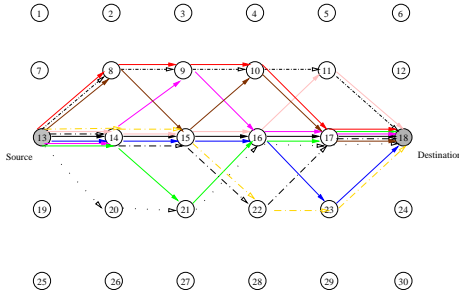


Figure 2. A grid ad hoc network employing the CDSR routing protocol, where Node₁₃ and Node₁₈ are the source and destination nodes, respectively.

II. SYSTEM STRUCTURE

The general framework of our proposed cooperative multi-hop transmission scheme having a total number of \dagger hops is depicted in Figure 1. By selecting a pair of routes that can assist the transmission of each other during every hop, the intermediate nodes of Figure 1 are protected by cooperative diversity, while the linkage between the source and destination nodes is enhanced by multiple paths. Note that our design of Figure 1 is specifically tailored for high-density networks under Rayleigh fading. When the nodes' density is low, any form of cooperation becomes either unfeasible or non-beneficial, since it is unlikely to select any helpful relays. We would like to emphasize that our scheme's structure in Figure 1 is unique, where multiple cooperative routes are equally important, in contrast to existing cooperative schemes, which merely use relays to 'enhance' an existing link. Secondly, our scheme's cooperative routes are selected '**jointly**' in order to assist each other in every hop, whereas existing schemes have to select relays hop-by-hop '**separately**'.

The implementation of cooperative diversity over ad hoc networks has to be a coordinated efforts from Network, MAC and Physical layers. More explicitly, the challenge of cooperative route selection and maintenance are addressed by the proposed Cooperative Dynamic Source Routing (CDSR) protocol of Section III, whereas the challenge of transmission synchronization is answered by the cooperative MAC scheduling protocol of Section IV. Finally, the STBC scheme discussed in Section V ensures full cooperative diversity, even at the presence of asynchronous reception.

III. NETWORK LAYER

In this section, the Dynamic Source Routing (DSR) [10] protocol is briefly reviewed. Based on this, we develop the diversity-oriented CDSR protocol.

Table I
THE ROUTING TABLE AT THE SOURCE NODE OF FIGURE 2. THE RREP LIMIT IS SET TO 11 AND λ_{total} DENOTES COOPERATION METRIC.

Route No.	$i = 1$	$i = 2$	$i = 3$	$i = 4$	λ_{total}
1	Node ₁₄	Node ₁₅	Node ₁₆	Node ₁₇	26
2	Node ₁₄	Node ₁₅	Node ₁₆	Node ₂₃	21
3	Node ₁₄	Node ₂₁	Node ₁₆	Node ₁₇	22
4	Node ₈	Node ₉	Node ₁₀	Node ₁₁	9
5	Node ₈	Node ₉	Node ₁₀	Node ₁₇	11
6	Node ₁₄	Node ₉	Node ₁₆	Node ₁₇	23
7	Node ₁₄	Node ₁₅	Node ₁₆	Node ₁₇	21
8	Node ₁₄	Node ₁₅	Node ₂₂	Node ₁₇	22
9	Node ₁₄	Node ₁₅	Node ₂₂	Node ₂₃	17
10	Node ₂₀	Node ₂₁	Node ₁₆	Node ₁₇	16
11	Node ₈	Node ₁₅	Node ₁₀	Node ₁₇	19

More explicitly, the on-demand DSR protocol initiates routing activities when a source node requests data transmissions. In the route discovery process, Route Request (RREQ) and Route Reply (RREP) packets are used to set up the route to the destination. Furthermore, routing information is exploited by all intermediate nodes and is stored in the corresponding route cache. In a single RREQ-RREP cycle, all nodes along the route can learn routes to every other node on the path. For Route Maintenance operations, the node forwarding the packet is responsible for confirming the successful packet reception by the next hop. If no acknowledgement (ACK) packet is received after the maximum number of retransmissions, the source node is notified by a Route Error (RERR), which would trigger a new route discovery process. Each node forwarding the RERR removes the broken link from its route cache.

Note that we address the challenge of 'relay selection' in the Network layer, rather than in the MAC layer as of [3], [9]. This is because the routing information stored in the RREP packets is exploited aggressively, hence the source node could have more than enough information to select the desirable cooperative paths. By contrast, MAC layer relay selection schemes [3], [8], [9] ignore this valuable information within the RREP packets and require additional control packets to select/inform the relays.

A. Route Discovery of CDSR

The objective of the Route Discovery of the CDSR protocol is to discover and select adjacent routes in order to enable cooperative transmissions.

More explicitly, in the standard DSR protocol [10], since all the duplicated RREQs are discarded, some valuable routing paths remain hidden to the source node. For example, when *Route No-1*(13-14-15-16-17-18) of Figure 2 is selected, Route (13-8-15-16-17-18) could remain unknown to the source node. That is because Node₁₅ processes the RREQ from Node₁₄ and ignores the 'duplicated' RREQ from Node₈. Therefore, the following modification is made. Instead of discarding every duplicated RREQ, intermediate nodes will forward the RREQs whose Hop Counts are no bigger than that of the previously received RREQs. Therefore, the source node may receive multiple RREPs and obtain multiple paths to the destination. Furthermore, a RREP limit is imposed at the destination node in order to avoid excess overhead of the network. After reaching this limit, the destination will stop sending RREPs.

Particularly, Table III-A summarizes the eleven paths obtained by extracting the information from the RREPs. In

order to facilitate cooperation, the route selection process has to provide a pair of 'distinctive' paths that can 'assist' the transmission of each other. Note that Distinctive paths do not share any intermediate nodes. The 'distinctive' requirement guarantees the CDSR is a multi-path protocol, whereas 'assisting the transmission' ensures the intermediate nodes to achieve cooperative diversity. That is, we are aiming to select a pair of paths as illustrated in Figure 1. Take Figure 2 and the associated Table III-A as an example, a pair of cooperative paths obeying the above-mentioned criterion can be selected using the following steps:

1. Distinctive paths can be satisfied by choosing a pair of routes from Table III-A having no shared intermediate nodes. Thus, when trying all the combinations from Table III-A, three pair of distinctive routes are left, namely Route pairs No (1, 4), No (2, 5) and No (5, 7).
2. Calculating the cooperation metric λ for each node at a given hop count (i) in order to estimate a node's potential of achieving cooperative diversity. The more a node is selected by different routes, the more direct neighbors it could have. Hence, this node has a higher possibility of achieving cooperative diversity. For example, in Table III-A with $i = 1$, since Node₁₄ is selected seven times by Route No(1, 2, 3, 6, 7, 8, 9), it is defined to have a cooperation metric of $\lambda = 7$.
3. Calculating the aggregated cooperation metric λ_{total} for each route by adding the cooperation metrics of each node in Step 2, which is listed in Table III-A.
4. The distinctive route pair having the highest aggregated cooperation metric λ_{total} is selected as the cooperative routes. In our example of Table III-A, Route pair (1, 4) has an aggregated metric of $\lambda = 26 + 9 = 35$, Route pair (2, 5) and (5, 7) have an metric of $\lambda = 32$. Therefore, Route pair (1, 4) is selected by our CDSR protocol. If multiple Route pairs share an identical aggregated cooperation metric, a random pair is selected.
5. In order to ensure the route pair is indeed capable of assisting each other, the cross links between the selected Route pair are examined. For example, the source node knows that the linkage between Node₈ and Node₁₅ exists, which is recorded in Route No₁₁ of Table III-A.

Recall that our design is specifically tailored for high-density ad hoc networks. Therefore, it is reasonable to assume that a sufficient number of routes having identical hop numbers can be discovered. Finally, the cooperative routes having the structure of Figure 1 can be created using the proposed CDSR protocol for the ad hoc network example of Figure 2. Note that the data transmission becomes multi-cast, instead of uni-cast in the original DSR protocol. Therefore, the 'Source Route Option' header in [10] is modified to contain a pair of cooperative routes selected by the CDSR protocol, instead of a single path in the original DSR protocol.

B. Route Maintenance of CDSR

Let's briefly review the route maintenance process in the original DSR protocol using 802.11 DCF in the MAC layer. When a transmitter fails to receive the correct ACK packet

(ACK = 0), the corresponding retransmission counter is checked. When the counter has reached its limit, a RERR packet is sent to the source node indicating a broken link. Otherwise, a RTS/CTS handshake is employed to re-establish the link, followed by the retransmission of the original data packet. Note that both the 'retransmission' and the additional route discovery processes triggered by the RERR packet are the major factors in contributing to transmission delays.

By contrast, our CDSR protocol is capable of reducing the system delay significantly, since the intermediate nodes are protected by the cooperative diversity. Secondly, a RERR packet is initiated only when *both* links to the next hop fail simultaneously. In the ideal case, both cooperative transmitters, should be acknowledged (ACK=2), if both receivers receive the packets correctly. However, if one (or both) of the transmitters fail to receive the correct ACK packets (ACK= 0, 1), the corresponding retransmission counters are checked. Only when both transmitters reach their retransmission limit, will a RERR packet be sent to the source node. Otherwise, a RTS packet is initiated by the transmitter granted the channel access right first, seeking potential retransmission. Note that the RTS packet has been modified to contain the packet sequence number, in order to identify the undelivered packet as well as to synchronize the cooperative transmitters. A detailed description of the synchronous transmission process using the modified RTS/CTS packets is provided in Section IV and illustrated later in Figure 4. At the moment, we focus on the route maintenance process of the CDSR protocol.

If both cooperative transmitters receive no ACKs (ACK=0), they will wait for the modified CTS packet to synchronously activate the retransmission process. If one of the transmitters does receive the correct ACK (ACK= 1), it will send a newly introduced Not-To-Send (NTS) packet in order to notify the other transmitter that 'Retransmission is not necessary and transmit the next packet'. The NTS packet should be given a higher priority than the CTS packet, which is guaranteed by the fact that the NTS packet only waits for a Very Short Inter-Frame Space (VSIFS). The cooperative (re)transmission process will be discussed in detail in Section IV and the modified RTS/CTS, together with the NTS packet formats, will be demonstrated in Figure 4.

Note that one assumption has been made when sending the NTS packet, namely the cooperative transmitters should be able to 'hear' each other. Given the system architecture of Figure 1, where the receiving nodes of each hop share the same pair of cooperative transmitters, it is highly likely that the cooperative transmitters can 'hear' each other. In the unlikely event that no communication link exists between the transmitters, a single link's failure would trigger the RERR packet, followed by a new route discovery process.

IV. MAC LAYER

In the MAC layer of our design framework, the 802.11 DCF is improved in a way that cooperative nodes are scheduled to transmit simultaneously, while keeping the macroscopic asynchronous nature of ad hoc networks.

In addition to its original functionality, the RTS/CTS and ACK packets in 802.11 DCF are modified in order to

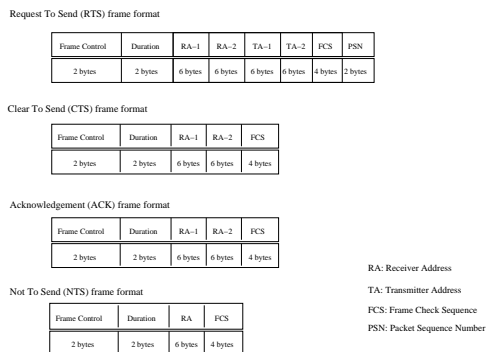


Figure 3. The modified RTS, CTS and ACK frame formats for cooperative ad hoc networks, as well as the frame format for the NTS packet.

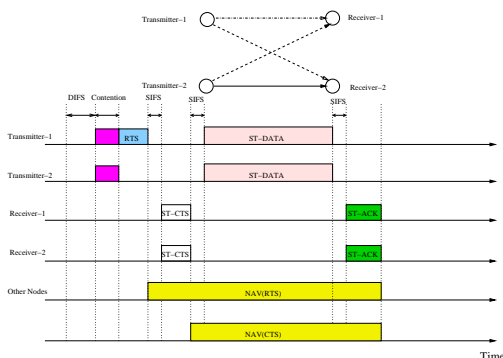


Figure 4. MAC layer with RTS/CTS: the sequence of packet transmissions over a VMIMO link.

achieve local synchronous-transmission. Furthermore, the Not-To-Send (NTS) packet is introduced by the route maintenance process of Section III-B in order to handle link breakage more wisely. The frame formats for the cooperation-oriented RTS, CTS, NTS and ACK are depicted in Figure 3. For the RTS, CTS and ACK packets, the addresses of the cooperative nodes are incorporated, since they are intended to communicate with both cooperative nodes. On the other hand, the NTS packet described in Section III-B is only used when a node needs to communicate with its cooperation partner, therefore it has a simple frame structure as seen in Figure 3. More importantly, the RTS packet contains 'Packet Sequence Number' (PSN) seen in Figure 3, which identifies the current data packet. Thus, in the case of retransmission, the cooperative transmitter would know which packet to retransmit.

Ideally, every stage of the transmissions of Figure 1 should form a (2×2) VMIMO structure having two transmitters and two receivers, created by the CDSR protocol of Section III. Furthermore, Figure 4 depicts the synchronous-transmission process, which is explained step-by-step as follows:

- 1) Contention: The cooperative transmitters compete for the right to initialize the transmission (see Figure 4).
- 2) Sending RTS packet: After waiting for a DIFS, the transmitter that wins the contention will multi-cast the RTS packet of Figure 3 to the two receivers. The other cooperative transmitter also expects to receive the CTS packet, hence it will not set the Network Allocation

Table II
THE VMIMO STRUCTURES FORMED AFTER THE RTS/ST-CTS.

No of RTS	No of ST-CTS	VMIMO Structure	Transmit diversity	Receive diversity	Total diversity
2	2	(2×2)	2	2	4
1	2	(2×1)	2	1	2
2	1	(1×2)	1	2	2
1	1	(1×1)	1	1	1
0	Route Maintenance of Section III-B				

Vector (NAV).

- 3) Sending the Space-Time coded CTS (ST-CTS) packets upon successfully receiving the RTS packet. The receiving nodes encode the CTS packet, and each node transmits a distinctive column of the space-time codeword.
- 4) Forming a VMIMO structure, depending on the successful receptions of RTS and ST-CTS packets of Figure 3, which is listed in Table II. If one of the receivers is capable of decoding the RTS packet, then at least one of the cooperative transmitters of Figure 4 will successfully decode the ST-CTS packet. That is because the length of the ST-CTS packet (20 bytes) is shorter than that of the RTS packet (34 bytes), and the channels' fluctuation is trivial within this short period of time. Therefore, a total number of five possible VMIMO systems can be formed, as listed in Table II. More explicitly, when *both* of cooperative transmitters of Figure 4 hear the ST-CTS packet, a cooperative transmit diversity of $D_{tx} = 2$ can be achieved; On the other hand, when *only one* of cooperative transmitters gets the ST-CTS packet, the cooperative diversity drops to $D_{tx} = 1$; The worse case scenario is that none of the receivers hears the RTS packet, which triggers the route maintenance process.
- 5) Transmitting the ST-coded data packets over the VMIMO link of Table II, as illustrated in Figure 4.
- 6) Sending ST-ACK packets to confirm the successful reception of the data packets.

In summary, the challenge of synchronous transmission among the cooperative nodes is addressed by using the modified RTS/CTS handshaking of Figure 4. Furthermore, an NTS packet is introduced to guarantee that a RERR packet is issued only when both of the cooperative receivers fail to receive the information, which reduces the system delay significantly.

V. PHYSICAL LAYER

The challenges addressed in the PHY layer are two fold. Firstly, the Space-Time Block Coding (STBC) schemes to achieve cooperative diversity over the VMIMO system of Table II are designed. Secondly, it is often the case that propagation delays experienced by the signals from cooperative nodes are different, even if these nodes are scheduled to transmit simultaneously. In this paper, we employed Time Reversed Space-Time Block Codes (TR-STBCs) [11] to address the issue of asynchronous reception.

VI. SIMULATION RESULTS

In this section the performance of the proposed CDSR routing protocol is investigated by using our real-time network simulation testbed, where the IEEE 802.11b standard

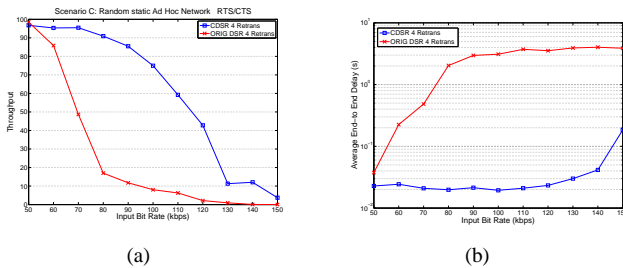


Figure 5. Random static ad hoc network. The proposed CDSR scheme is capable of attaining a better performance than the original DSR.

is invoked. In the simulations, the input data generated at a Constant Bit Rate, is encapsulated into fixed 500 bytes UDP packets. In the physical layer, the IEEE 802.11b data-rate is 2 Mbps and the noise factor is 10.0. Rayleigh fading is employed, where fading max velocity is 10.0. In the proposed CDSR, the transmit power of intermediate nodes is set as half of those in the original DSR, while the source and destination node's transmit power is set as the same as those in the original DSR. In this way, the total energy consumption of the DSR and CDSR protocols remains the same.

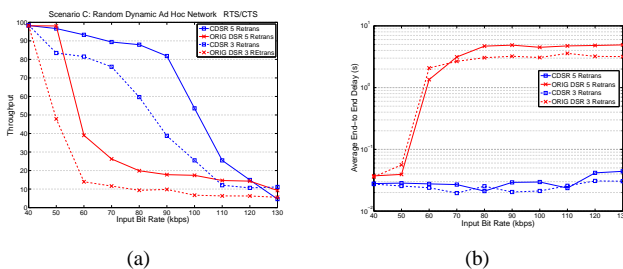


Figure 6. Random dynamic ad hoc network. Compared to the original DSR, the proposed CDSR scheme is robust in resisting network topology variation caused by nodes' mobility.

In Figures 5 and 6, the CDSR scheme is compared with the original DSR. In the CDSR scheme, nodes will flush their buffers when link break happens or an RERR message is received, in order to reduce congestion for the following route discovery process. In these figures, 40 nodes are placed randomly in a 1500 m \times 1500 m area. Specifically, in Figure 5 nodes are placed statically and the retransmissions counter is set to 4. By contrast, nodes are moving randomly at a speed of 2 mps in Figure 6, where 3 and 5 retransmissions are employed. As shown in Figures 5 and 6, the CDSR scheme is capable of attaining a better performance than the original DSR, not only in throughput but also in average end-to-end delay. Firstly, each intermediate relay in CDSR is protected by 'cooperative diversity' and hence has a higher packet delivery ratio. Secondly, since the CDSR is a multi-path protocol, any single-path failure would not lead to link breakage. Note that in the proposed CDSR, nodes will flush their buffers when link break happens or RERR message is received. Consequently, the average end-to-end delay is significantly reduced as demonstrated in Figures 5 and 6. Furthermore, due to the achievable cooperative diversity, fewer retransmissions are required for data packets to be delivered from the source to the

destination. Figure 6 demonstrates the CDSR scheme's robust resistance to network topology variation caused by nodes mobility. Since the CDSR scheme is a multi-path cooperative protocol, individual node temporary moving out of the range would not terminate the whole transmission, as long as there is at least one cooperative node successfully retrieving the correct information during each hop. It can also be seen from Figure 6 that increasing the retransmission numbers is helpful for both the CDSR and the original DSR to achieve a better throughput performance, at the expense of a longer delay performance. Finally, our simulation results of Figures 5 and 6 indicate that it is indeed straightforward to find cooperative routes in a high-density ad hoc network.

VII. CONCLUSION

In this paper, we proposed a cooperative diversity scheme for ad hoc networks. The core feature of this architecture is that cooperative routes can assist the transmission of each other, hence the reliability of all wireless links is enhanced simultaneously. As a result, the link breakage probability is significantly reduced and the system delay is improved. In the Network layer, multiple routes are selected based on their ability to cooperate with others. In the MAC layer, the modified RTS/CTS packets are employed to achieve synchronous transmission, whereas the NTS packet is introduced to allow the route maintenance process and to benefit from cooperative diversity. The simulation results demonstrated substantial improvement of packet delivery ratio and system delay in both static and mobile ad hoc networks.

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