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Cooperative diversity routing and transmission for wireless sensor networks

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Abstract: In this study, the authors present a novel design framework aimed at developing 'cooperative diversity' in 802.11-based wireless sensor networks. The proposed scheme is a combination of a time-reversed space-time block code scheme at the physical layer and a cooperative routing protocol at the network layer. The core feature of this architecture is that the multiple routes are capable of assisting the transmission of each other, hence the reliability of 'all' the wireless links are enhanced simultaneously by cooperative diversity. This will involve the design of physical layer transmission schemes, medium access protocols and routing strategies. For the latter in particular, the authors present a cooperative routing protocol that is capable of exploiting full transmit diversity in wireless sensor networks. The authors restrict ourselves by imposing as few modifications to existing schemes as possible, so that integration to the existing infrastructure will be straightforward. Comprehensive simulations have been carried out to demonstrate the end-to-end performance of the proposed scheme. It is shown that a substantial gain can be achieved by cooperative diversity using a virtual multiple input multiple output system architecture.

1 Introduction

Wireless technologies, such as WiMAX [1], are becoming the dominant methods for data access of mobile subscribers. However, bandwidth limitations of wireless channels, interferences from other users and ever-changing channel variations prevent wireless networks from achieving reliable and high throughput communications. Deploying multiple antennas at mobile stations, commonly referred to as multiple input multiple output (MIMO) systems, could be a partial solution to these challenges, provided that each node is equipped with sufficient computational power.

Unfortunately, it may not always be practical to accommodate multiple antennas at the nodes, especially in a wireless sensor network, owing to cost, size and other hardware limitations. Bear in mind that the main characteristics of wireless sensor networks include power consumption constraints for battery powered sensor nodes and small size limitation only suitable for a single antenna.

As a remedy, the concept of 'cooperation' has been proposed [2–4], offering a new perspective to the challenges of wireless communications in sensor network. The revolutionary idea of cooperation is that, instead of suppressing the 'interference' signals from adjacent nodes, these signals are deliberately introduced to assist each other during transmission. Hence, a virtual MIMO (VMIMO) system can be formed, mimicking the behaviour of co-located MIMO systems. Cooperation could potentially benefit wireless sensor networks in at least one of the following aspects: increasing the data transmission reliability of the network, providing higher throughput, extending network coverage, reducing the transmission delay and saving the transmit power.

However, there are a number of challenges that have to be addressed before the above-mentioned benefits of cooperation can be fully exploited. Among them are relay selection, nodes' synchronisation, inter-symbol-interference (ISI) caused by frequency-selective channels and the use of a VMIMO structure. The relays that are capable of enhancing the performance of the wireless links should be selected in a distributed fashion, owing to the lack of a central control unit in a wireless sensor network. The majority of existing cooperation schemes [4–7] in the literature depend on additional control signals to select as well as maintain relays, which substantially reduces the effective throughput. As for the issue of synchronisation, time division multiple access (TDMA)-based synchronisation could possibly be a preferred approach for cooperative transmissions [8, 9]. Nonetheless, a TDMA-based system would be very costly in wireless sensor network environments owing to the lack of base station, nodes mobility and the large number of nodes. For practical applications, the authors of [5, 7, 10, 11] present cooperative schemes that are based on the IEEE 802.11 standard. Bear in mind that IEEE 802.11 standards mainly use the distributed coordination function (DCF), which is based on carrier-sense multiple access with collision avoidance (CSMA/CA). Unfortunately, CSMA/CA type schemes only allow a single node to transmit at any given time within the interference sensing range. Thus, a limited MIMO advantage is achievable.

Finally, although existing physical (PHY) layer MIMO technologies, such as space-time block coding (STBC) [12], beam-forming [13] etc., can be 'transplanted' to a cooperative wireless sensor network, they do not have a flexible structure to combat the ISI caused by frequency-selective channels subject to high-speed data-rate transmission.

In order to address the above-mentioned challenges of cooperation, PHY layer cooperation schemes [14–19] were proposed and, to a limited extent, medium access control (MAC) layer schemes [8, 10, 20]. On the network layer, the network coding techniques [21] can be viewed as a form of cooperation as well. To the best of our knowledge, there are very few designs [6, 11] that involve multiple layers for cooperative wireless sensor networks. Although the benefits of cooperation is partially achieved in one way or another [6, 11], these designs have two main issues. Firstly, the relay selection process is implemented in the MAC layer, which would require a significant amount of control packets to provide handshakes between source/destination and relay nodes. Also, even a larger amount of control packets are necessary, when relays fail to deliver the packets. Secondly, the relays are prohibited from transmitting simultaneously, since the CSMA/CA protocol is invoked. Thus, only limited throughput enhancement [20] could be achieved, given that the relays experience robust channel conditions. In [22, 23], cross-layer designs are proposed, which combine cooperative diversity at the PHY layer with truncated Automatic Repeat-reQuest [24] at the link layer to improve the throughput performance. Both schemes utilise cooperative diversity only if the destination node receives an erroneous packet from the source node. For example, Dai and Letaief [22] utilise adaptive cooperative diversity and select the relay nodes according to the channel conditions for retransmission, whereas [23] is based on an optimised power arrangement to maximise the systems throughput. Both schemes consider a single hop scenario.

In this paper, however, our primary objective is to establish a multi-hop cooperative route from the source to the destination so that diversity can be achieved on a hop-by-hop basis through the entire cooperative path. As the result, the cooperative nodes will be systematically involved from the beginning, hence improving the first transmission attempt under fading channel conditions. The overall design structure is aimed at achieving full cooperative diversity, based on which the PHY, link and network layers of the system are specifically tailored. More explicitly, the rationales and novelties of the proposed cooperation scheme are:

- Improved packet delivery reliability. The increased robustness are 2-fold: firstly, each intermediate node is protected by 'cooperative diversity' and hence has a better chance of successful reception. Secondly, it is a multi-path protocol, namely, any single-path failure would not prevent the destination from receiving data packets.
- Reduced transmission delay. The major reason of delay wireless sensor networks is the retransmission process triggered by packet errors, which also increases the contention window size resulting in multiple idle slots. By contrast, our proposed scheme greatly reduces the probability of retransmission, thanks to 'cooperative diversity'.

Unlike some existing schemes [10], which only enable cooperative transmission when the first attempt transmission fails (highly likely in a fading environment), our approach provides cooperative diversity by default.

- Resistance to network topology variation caused by nodes' mobility or power failure. Since the proposed scheme is a multi-path cooperative protocol, individual node's temporary disfunction would not terminate the whole data transmissions, as long as there is at least one cooperative node successfully retrieving the correct information during each hop.
- Synchronous transmissions in wireless sensor networks. In order to maximise the benefits of 'cooperative diversity', it is desirable to allow cooperative nodes to transmit simultaneously, which 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. In this way, we implement a 'local synchronous' transmission within a 'macroscopically asynchronous network'.
- Even though synchronous transmission is achieved, the ISI incurred by multi-path propagation in frequency-selective fading channels has to be combatted. Hence, a state-of-the-art PHY layer cooperative diversity scheme termed as time-reversed-STBC (TR-STBC) [25–27], is employed to deal with this issue in order to maintain full diversity, while tolerating frequency-selective fading.
- Simplicity of the proposed protocol. We strive to make as few modifications as possible to the existing wireless sensor network schemes, while achieving cooperative diversity.

We commence the detailed discourse in Section 2 by providing a description of the proposed cooperative framework. The cooperative routing protocol is described in Section 3, followed by the detailed MAC layer designs in Section 4. The PHY layer cooperative scheme is demonstrated in Section 5. The simulation results are provided in Section 6 in order to demonstrate the benefits of cooperative diversity. Finally, we conclude our discourse in Section 7.

2 System structure

The general framework of our proposed cooperative multi-hop transmission scheme having a total number of $i+1$ hops is depicted in Fig. 1*a*, which is designed with achieving full cooperative diversity in mind. By selecting a pair of routes that can assist the transmission of each other during every hop, the intermediate nodes of Fig. 1*a* are protected by cooperative diversity, whereas the linkage between the source and destination nodes is enhanced by multiple paths. Since our design of Fig. 1*a* is capable of achieving full cooperative diversity for every hop, it is our optimal solution and has the highest priority to be selected for wireless sensor networks under Rayleigh fading. When the nodes' density is high, each hop will have cooperation nodes to assist transmission, as shown in Fig. 1*a*. However, we should point out that it is not necessary to have all cooperation nodes available at the same time. Even in cases where only one node becomes available (as seen in Fig. 1*b*), diversity can be still achieved and performance can be improved. In other words, when the optimal solution of Fig. 1*a* is not available, the suboptimal solution of Fig. 1*b* will be used to achieve partial diversity. In the worst case, where diversity is not available at all, traditional routing protocols and single route solutions will be employed. We would like to emphasise that our scheme's structure in Figs. 1*a* and *b* is unique, where multiple

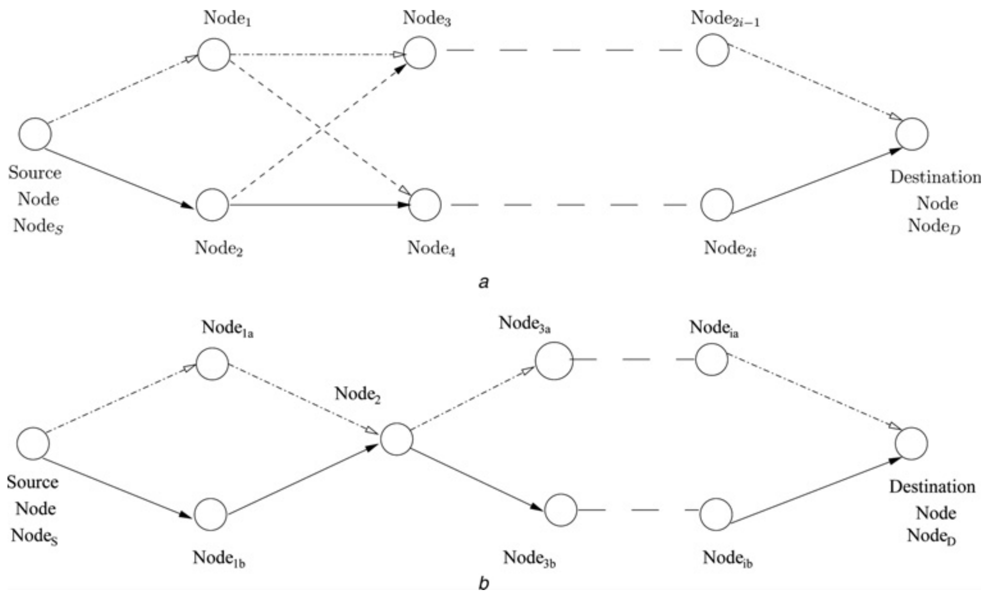

Fig. 1 *Solutions of the proposed cooperative multi-hop transmission scheme, which is selected by CDSR protocol of Section 3, scheduled by the cooperative MAC protocol of Section 4 and transmitted using TR-STBC of Section 5*

a Optimal solution where the intermediate nodes cooperate with each other
b Suboptimal solution where the selected pair of paths share one or more intermediate nodes

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 wireless sensor networks has to be coordinated efforts from network, MAC as well as PHY layers. More explicitly, the challenge of cooperative route selection and maintenance are addressed by the proposed cooperative dynamic source routing (CDSR) protocol of Section 3, whereas the challenge of transmission synchronisation is answered by the cooperative MAC scheduling protocol of Section 4.

Finally, the TR-STBC scheme that ensures full cooperative diversity, even in the presence of ISI caused by frequency-selective fading, is presented in Section 5.

3 Network layer

In this section, the dynamic source routing (DSR) [28] protocol is briefly reviewed. Based on this we develop the diversity-oriented CDSR protocol.

More explicitly, the on-demand DSR protocol [28] initiates routing activities when a source node requests data transmissions. For example, Fig. 2 illustrates an wireless sensor network, where the source node (Node$_{13}$) intends to transmit data packets to the destination node (Node$_{18}$). For

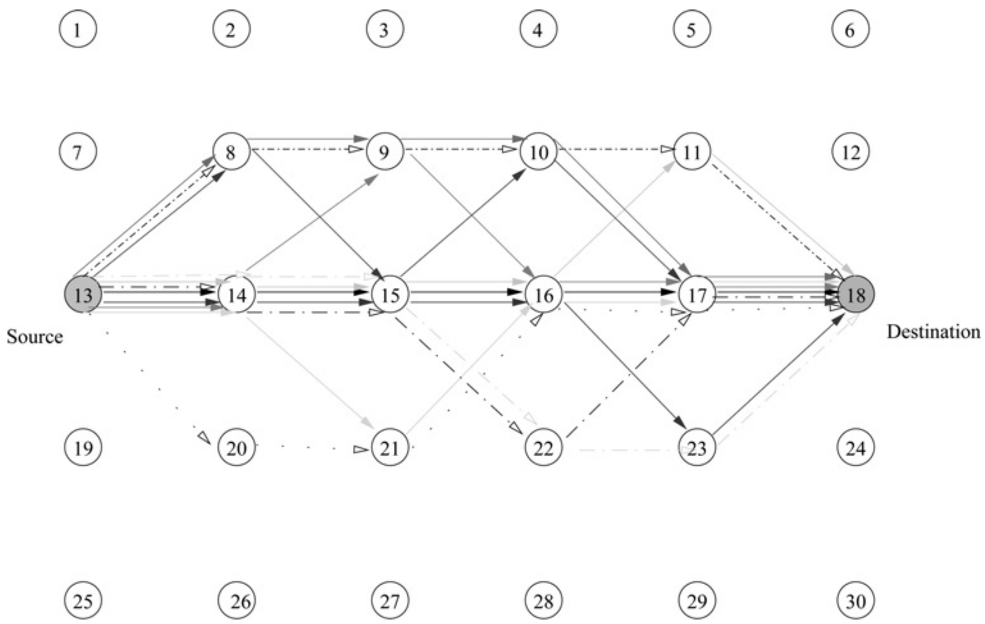

Fig. 2 *Grid wireless sensor network employing the CDSR routing protocol, where Node$_{13}$ and Node$_{18}$ are the source and destination nodes, respectively*

illustration simplicity, all the nodes are placed in a grid fashion, although the DSR protocol is directly applicable to mobile scenarios. 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, including the source and the destination, can learn routes to other nodes on the path. For route maintenance operations, the node forwarding the packet is responsible for confirming that a packet has been successfully received 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) packet indicating a broken link, which would trigger a new route discovery process. Each node forwarding the RERR packet 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 [6, 10, 20]. This is because the routing information stored in the RREP packets is exploited aggressively as mentioned above, hence the source node could have more than enough information to select the desirable cooperative paths, as exemplified in Fig. 1*a*. By contrast, MAC layer relay selection schemes [6, 10, 20] ignore this valuable information within the RREP packets and require additional control packets to select/inform the relays. Furthermore, the MAC layer schemes select relays separately for each hop, resulting in significant overhead and delay, especially when the total number of hops is large, whereas the proposed CDSR protocol selects the appropriate relays for all the nodes jointly. We will illustrate the proposed CDSR protocol in more detail and focus on the necessary modifications over the above-mentioned DSR protocol in order to accommodate cooperative transmissions.

3.1 Route discovery of CDSR

The objective of the route discovery of CDSR protocol is to discover and select adjacent routes in order to enable cooperative transmissions in contrast to a single route of the DSR [28].

More explicitly, in the standard DSR protocol [28], since all the duplicated RREQs [Duplicate RREQs are defined as RREQs having the same identification number.] 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 Fig. 2 is selected, route (13-**8**-15-16-17-18) could remain unknown to the source node. This is because $Node_{15}$ processes the RREQ from $Node_{14}$ and ignores the 'duplicated' RREQ from $Node_8$, which could be equally valuable for our cooperative transmissions. Therefore the following modification is made. Instead of discarding every duplicated RREQ, intermediate nodes will forward the RREQs whose hop counts (i) 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. In our example, Fig. 2, the RREP limit is set to 11.

Particularly, Table 1 summarises the 11 paths obtained by extracting the information from the RREPs. As mentioned in Section 2, the first step in the proposed CDSR protocol is to find the optimal solution of Fig. 1*a*, aimed at providing full cooperation. Specifically, the route selection process will try to find a pair of 'distinctive' paths [Distinctive paths are defined as routes that do not share any intermediate nodes.] at first, which can 'assist' the transmission of each other. The 'distinctive' requirement ensures the intermediate nodes to achieve cooperative diversity. Taking Fig. 2 and the associated Table 1 as an example, a pair of cooperative paths obeying the above-mentioned criterion can be selected using the following steps:

Table 1 CDSR protocol's routing table at the source node, where $Node_{13}$ and $Node_{18}$ are the source and destination nodes as seen in Fig. 2

Route no.	$i=1$	$i=2$	$i=3$	$i=4$	Cooperation metric (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	$Node_{14}$	$Node_{15}$	$Node_{16}$	$Node_{11}$	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

The RREP limit is set to 11

1. Distinctive paths can be satisfied by choosing a pair of routes from Table 1 having no shared intermediate nodes, that is, if a node is occupied in one route, it is prohibited from being appearing again in the other route. Thus, when trying all the combinations from Table 1, only three pairs 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 certain node is selected by different routes, the more direct neighbours it could have. Hence, this node has a higher possibility of achieving cooperative diversity. For example, in Table 1 with $i=1$, since $Node_{14}$ is selected seven times by route no. (1, 2, 3, 6, 7, 8, 9), it is defined to have a cooperation metric of $\lambda=7$. Similarly, $Node_{15}$ with $i=2$ has a cooperation metric of $\lambda=6$, evidenced by $Node_{15}$ appears six times on the third column of Table 1.
3. Calculating the aggregated cooperation metric λ_{total} for each route by adding the cooperation metrics of each node in Step 2, which is particularly listed in Table 1 as an indicator of the cooperation potentials.
4. The distinctive route pair having the highest aggregated cooperation metric λ_{total} is selected as the cooperative routes. In our example of Table 1, route pair (1,4) has an aggregated metric of $\lambda=26+9=35$, route pair (2,5) and (5,7) have an aggregated metric of $\lambda=32$. Therefore, route pair (1,4), having the highest cooperation metric, is selected by our CDSR protocol. If multiple route pairs share an identical aggregated cooperation metric, cross links between them will be examined as detailed in the next step.
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 $Node_8$ and $Node_{15}$ exists, which is recorded in route no_{11} of Table 1.

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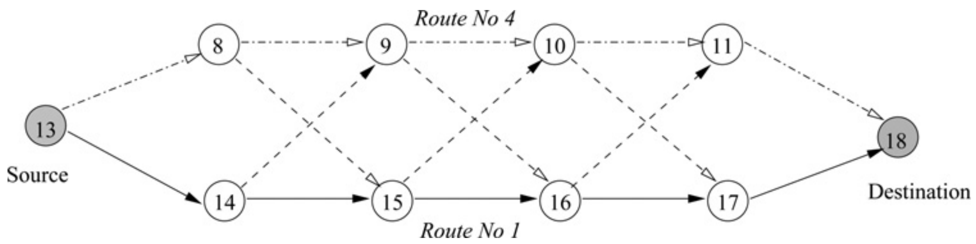

Fig. 3 *Distinctive routes that can assist the transmission of each other, which are selected using the proposed CDSR protocol for the wireless sensor network example of Fig. 2*

Finally, Fig. 3 demonstrates the distinctive routes that can assist the transmission of each other, which are created using the proposed CDSR protocol for the wireless sensor network example of Fig. 2. Again, the linkage between route pairs 1 and 4 is guaranteed by the above-mentioned cross path examination technique. Note that the data transmission becomes multi-cast (see Fig. 3), instead of uni-cast in the standard DSR protocol. Therefore, the 'source route option' header in [28] is modified to contain a pair of cooperative routes selected by the CDSR protocol, instead of a single path in the standard DSR protocol.

However, in some cases the optimal solution in Fig. 1*a* is not achievable, which means that a pair of 'distinctive' paths cannot be obtained. Then, the suboptimal solution of Fig. 1*b* will be used to achieve partial diversity, where a pair of paths that have the same hop count and share one or more intermediate nodes can be selected to transmit data packets. Note that our route selection criterion intends to maximise the achievable node-level cooperative diversity based on the information extracted from the RREPs. The suboptimal cooperative paths can be selected by using similar steps as in the optimal solution. The algorithm of the proposed CDSR protocol can be summarised as follows:

1. Calculating the aggregated cooperation metric λ_{total} for each route as shown in Fig. 2 and the associated Table 1.
2. The cooperative paths with the fewest shared intermediate nodes have the highest priority for selection.
3. If there are two or more pairs of paths with the fewest shared intermediate nodes, the pair having the highest aggregated cooperation metric λ_{total} will be selected.
4. The cross links between the selected pair will be examined to ensure that the route pair is indeed capable of assisting each other, as in the optimal solution.

The complexity of our algorithm to select the best pair is in the order of $O[n^2]$, where n is the number of the available routes in the source node's route table. An RREP limit is imposed at the destination node in order to avoid excess network overhead. This will also limit the number of routes in the source nodes route table and this will consequently reduce the complexity of the algorithm. Note that this algorithm is applied only once after a route discovery process. This process is triggered only when there is no path available in the source node's route table. Since this does not occur frequently, the complexity imposed by the algorithm to the entire network is negligible. Although there is no minimum requirement for λ_{total} in this algorithm, the CDSR protocol always chooses the pair of routes with the top λ_{total} value. The results in Section 6 confirm that the pair of routes with the top λ_{total} value is the best pair to maintain cooperative diversity.

3.2 Route maintenance of CDSR

Let's briefly review the route maintenance process in the standard DSR protocol using 802.11 DCF in the MAC layer. When a transmitter fails to receive the correct ACK packet (denoted as 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 communication link, followed by the retransmission of the original data packet. This process can be visualised as Fig. 4

Note that both the 'retransmission' and the additional route discovery processes triggered by the RERR packet are major factors in contributing to transmission delays of the DSR protocol.

By contrast, our CDSR protocol is capable of reducing the system delay significantly. More explicitly, the probability of packet failures owing to channel impairments is greatly reduced as compared with DSR protocol, 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 other words, any single link breakage would NOT terminate the ongoing data transmission, thanks to the multi-path capability of the CDSR protocol.

More explicitly, the flow chart of the CDSR protocol is given by in Fig. 5

In the ideal case, both cooperative transmitters, that is, in Fig. 3, 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 < 2), the corresponding retransmission counters are checked. Only when both transmitters reach their retransmission limit, will a RERR packet be sent to the source node [A newly introduced not-to-send (NTS) packet will be used by the cooperative node to notify the other not to send RERR before reaching its retransmission limit. The RERR packet transmission process is the same as the standard DSR protocol as no cooperation transmission techniques are employed.]. Otherwise, a RTS packet is

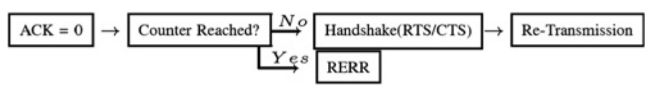

Fig. 4 *RTS/CTS handshake*

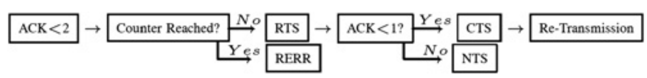

Fig. 5 *CDSR protocol*

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 (PSN), in order to identify the undelivered packet as well as to synchronise the cooperative transmitters. When the source node receives the RERR, it will remove the current pair of paths from its route table and re-select the best pair of paths from the remaining routes to transmit packets, by using the proposed CDSR protocol in Section 3.1. If no routes available, a new route discovery process will be triggered by the source node. A detailed description of the synchronous transmission process using the modified RTS/CTS packets is provided in Section 4 and illustrated later in Fig. 6. At the moment, we focus on the route maintenance process of the CDSR protocol.

If both cooperative transmitters receive no ACKs (ACK = 0 < 1), 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 NTS packet in order to notify the other transmitter that 'retransmission is not necessary and transmit the next packet'. The NTS packet is also used to notify the other cooperative node not to send RERR before the current transmitting node meets its maximum retransmission limit. 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). We make sure that VSIFS is shorter than short inter-frame space (SIFS). The cooperative (re)transmission process will be discussed in detail in Section 4 and the modified RTS/CTS, together with the NTS packet formats, will be demonstrated in Fig. 6.

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 Fig. 1*a*, 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, although it is not guaranteed by the route discovery process. The simulation results in Section 6 will show that the CDSR protocol's cooperative routes are usually close to each other and the transmission delay is indeed reduced significantly, compared with the DSR protocol. In the unlikely event that no communication link exists between the transmitters, a single link's failure would trigger the RERR packet.

4 MAC layer

In the MAC layer of our design framework, the 802.11DCF is improved in a way that cooperative nodes are scheduled to transmit simultaneously, while keeping the macroscopic asynchronous nature of wireless sensor networks. In other words, the issue of local synchronous transmission is addressed in the MAC layer. Again, the phrase 'local synchronous transmission' indicates that cooperative nodes within each hop transmit simultaneously, whereas nodes belonging to separate hops remain within the rules of the CSMA/CA protocol. By contrast, schemes [5, 11] based on the standard 802.11 DCF can only achieve partial advantage of the VMIMO structure.

In addition to its original functionality, the RTS/CTS and ACK packets in 802.11 DCF are modified in order to achieve local synchronous transmission. Furthermore, the NTS packet is introduced by the route maintenance process of Section 3.2 in order to handle link breakage more wisely. The frame formats for the cooperation-oriented RTS, CTS, NTS and ACK are depicted in Fig. 7. For the RTS, CTS and ACK packets, the addresses of the cooperative nodes are incorporated, since they are intend to communicate with

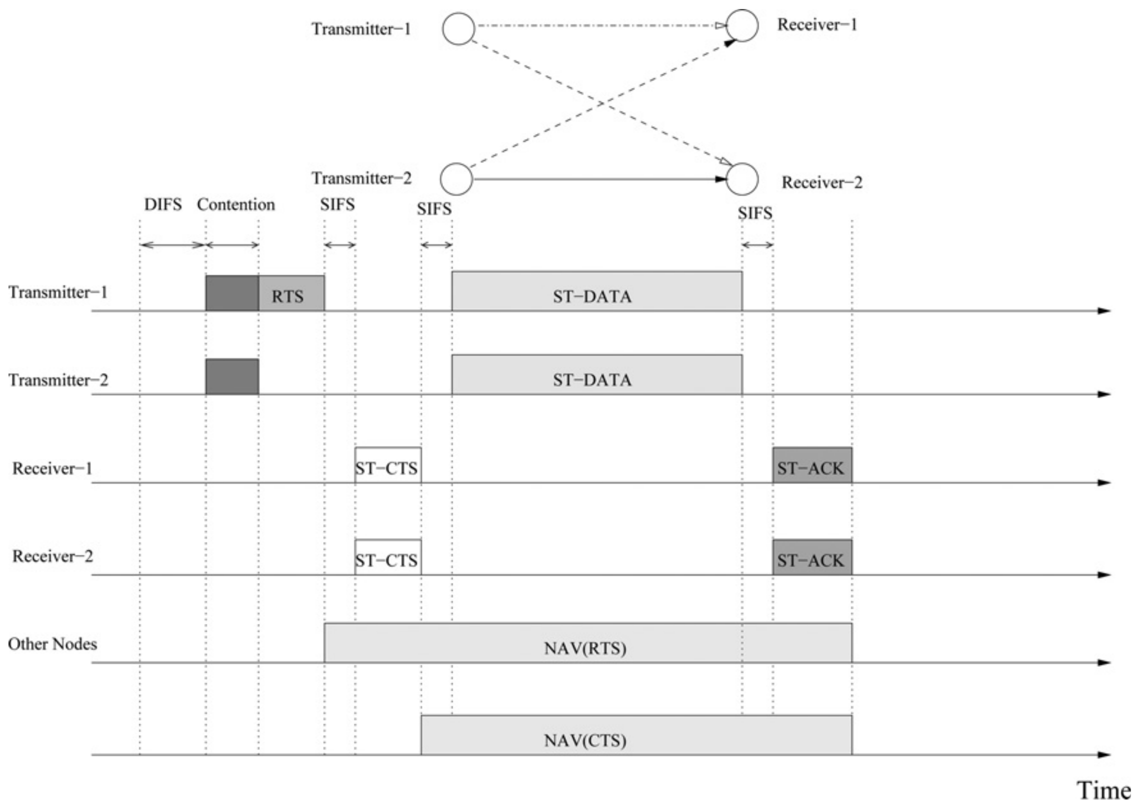

Fig. 6 *MAC layer: the sequence of packet transmissions over a VMIMO link*

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Request To Send (RTS) frame format

Frame Control	Duration	RA−1	RA−2	TA−1	TA−2	FCS	PSN
2 bytes	2 bytes	6 bytes	6 bytes	6 bytes	6 bytes	4 bytes	2 bytes

Clear To Send (CTS) frame format

Frame Control	Duration	RA−1	RA−2	FCS
2 bytes	2 bytes	6 bytes	6 bytes	4 bytes

Acknowledgement (ACK) frame format

Frame Control	Duration	RA−1	RA−2	FCS
2 bytes	2 bytes	6 bytes	6 bytes	4 bytes

Not To Send (NTS) frame format

Frame Control	Duration	RA	FCS
2 bytes	2 bytes	6 bytes	4 bytes

RA: Receiver Address

TA: Transmitter Address

FCS: Frame Check Sequence

PSN: Packet Sequence Number

Fig. 7 *Modified RTS, CTS and ACK frame formats for the cooperative wireless sensor networks, as well as the frame format for the NTS packet of Section 3.2*

both cooperative nodes. On the other hand, the NTS packet described in Section 3.2 is only used when a node needs to communicate with its cooperation partner, therefore it has a simple frame structure as seen in Fig. 7. More importantly, the RTS packet contains one additional field, namely 'packet sequence number' (PSN) seen in Fig. 7, which contains the identification of the current data packet. Thus, in the case of retransmission, the cooperative transmitter would know which packet to retransmit by extracting data packet identification from the RTS packet.

Ideally, every stage of transmissions of Fig. 1*a* should form a (2 × 2) VMIMO structure having two transmitters and two receivers, selected by the CDSR protocol of Section 3. Note that a (2 × 1) or (1 × 2) VMIMO structure may be formed in some cases (i.e. the suboptimal solution of Fig. 1*b*), which can also improve the performance. Furthermore, Fig. 6 depicts the synchronous transmission process, which is explained step-by-step as follows:

1. *Contention*: The cooperative transmitters compete for the right to initialise the transmission as described in the contention process of 802.11 DCF (see Fig. 6).

2. *Sending RTS packet*: After waiting for a distributed inter-frame space (DIFS), the transmitter that wins the contention will multi-cast the RTS packet to the two receivers. The other cooperative transmitter also expects to receive the CTS packet, hence it will not set the network allocation vector. Note that there is a potential hidden terminal problem for this node because it did not initiate sending the RTS packet. Also, the revised RTS packet can be used to synchronise the transmission and reception of the cooperative nodes. Once the synchronisation is established, the data and ACK transmission are all synchronised.

3. Sending the space-time coded CTS (ST-CTS) packets simultaneously upon successfully receiving the RTS packet. The receiving nodes encode the CTS packet using the ST technique detailed in Section 5, 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 Fig. 7, which is listed in Table 2. Above all, we state that if one of the receivers of Fig. 6 is capable of decoding the RTS packet, then at least one of the cooperative transmitters of Fig. 6

Table 2 All the possible VMIMO structures formed using the RTS/ST-CTS handshaking

No. of receivers decode RTS	No. of transmitters decode 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 3.2				

will successfully decode the ST-CTS packet. That is because the length of the ST-CTS packet (20 bytes) is less than that of the RTS packet (34 bytes). Hence, lower packet error rate is expected, provided that the channels' fluctuation is trivial within this short period of time. Based on the discussion above, a total number of five possible VMIMO systems can be formed, as listed in Table 2.

More explicitly, when 'both' of the cooperative transmitters of Fig. 6 hear the ST-CTS packet, a cooperative transmit diversity of $D_{tx} = 2$ can be achieved, namely, we have either a (2×2) or (2×1) VMIMO system; On the other hand, when 'only one' of the cooperative transmitters of Fig. 6 gets the ST-CTS packet, the cooperative transmit diversity drops to $D_{tx} = 1$, that is a (1×2) or (1×1) VMIMO system is formed; The worse case scenario is that none of the receivers hears the RTS packet, which triggers the route maintenance process described in Section 3.2.

5. Transmitting the ST-coded data packets over the VMIMO link of Table 2.
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 Fig. 6, where the packets' formats are given in Fig. 7. Furthermore, the data packets as well as the CTS/ACK packets, are ST-coded and protected by the cooperative diversity when the hop have cooperation nodes to assist the transmission, which greatly enhances the reliability of the wireless links. However, it is unnecessary to have cooperation for all data packets and the CTS/ACK packets. Even only one cooperation is available, it can improve the performance. Finally, a simply NTS packet is introduced in order 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. Again, this process has been detailed in the route maintenance process of Section 3.2.

The main challenge in cooperative transmission is handling the ISI incurred by the frequency-selective fading subject to high-speed data transmission. In our scheme, this is taken care of by the TR-STBC [25, 27] in the PHY layer. It is capable of ensuring full cooperative diversity, even in the presence of ISI incurred by multi-path propagation in frequency-selective channels.

5 PHY layer

We will consider a single-hop scenario having two transmit antennas and one receive antenna with $(L+1)$-path frequency-selective channels, where the TR-STBC scheme [25] is adopted. Suppose that a block of information signal symbols $\boldsymbol{B} = [\boldsymbol{b}_1, \boldsymbol{b}_2, \ldots, \boldsymbol{b}_T]$ is composed of T information vectors with each vector having two information symbols, and $\boldsymbol{b}_t^{\mathrm{T}} = [b_{t1},\ b_{t2}]$. According to the $\mathcal{G}_2$ arrangement, one STBC codeword is divided into two symbol intervals and the tth STBC codeword can be specified as

$$\boldsymbol{S}_t = \left[\boldsymbol{s}_1^{(t)} \quad \boldsymbol{s}_2^{(t)}\right] = \begin{bmatrix} b_{t1} & -b_{t2}^* \\ b_{t2} & b_{t1}^* \end{bmatrix} \tag{1}$$

As for the TR-STBC scheme, a block of symbols $\boldsymbol{S}_t$ can be divided into two blocks, $\boldsymbol{s}_1^{(t)}$ and $\boldsymbol{s}_2^{(t)}$, $\forall = 1, \ldots, T$. The transmission frame will also be divided into two halves. During the $\bar{t}$ = first half of the frame, b_{t1} and b_{t2} will be transmitted from antenna one and two, respectively, in the order of $t = 1, 2, \ldots, T$. During the $\bar{t}$ = second half of the frame, $-b_{t2}^*$ and b_{t1}^* will be transmitted from antenna one and two in a time-reversed order, that is, in the order of $t = T, T-1, \ldots, 1$. More quantitatively, we can write the $(T \times 1)$-element signal vector received at the $\bar{t}$th frame in the following form

$$\boldsymbol{r}_{\bar{t}}^{\mathrm{T}} = \boldsymbol{h}^{\mathrm{T}} \boldsymbol{A} \bar{\boldsymbol{S}}_{\bar{t}} + \sum_{i \in \mathbb{I}} \tilde{\boldsymbol{h}}_i^{\mathrm{T}} \tilde{\boldsymbol{A}}_i \tilde{\boldsymbol{S}}_{\bar{t}i} + \boldsymbol{n}_{\bar{t}}^{\mathrm{T}}, \quad \forall \bar{t} = 1,\ 2,\ \ldots,\ \bar{T} \tag{2}$$

where the $(2 \times T)$ vector $\bar{\boldsymbol{S}}_{\bar{t}}$ with $\bar{t} \in \{1,\ 2\}$ in (2) can be epitomised as

$$\begin{aligned} \bar{\boldsymbol{S}}_1 &= \left[\boldsymbol{s}_1^{(1)} \quad \boldsymbol{s}_1^{(2)} \quad \cdots \quad \boldsymbol{s}_1^{(T)}\right] \\ \bar{\boldsymbol{S}}_2 &= \left[\boldsymbol{s}_2^{(T)} \quad \boldsymbol{s}_2^{(T-1)} \quad \cdots \quad \boldsymbol{s}_2^{(1)}\right] \end{aligned} \tag{3}$$

Then, the $(2 \times T)$ vector $\tilde{\boldsymbol{S}}_{\bar{t}i}$ in (2) that precurs the ith ISI component to the tth received signal can be epitomised as:

$$\begin{aligned} \tilde{\boldsymbol{S}}_{1i} &= \left[\boldsymbol{0}_{2\times i} \quad \boldsymbol{S}_1^{(1)} \quad \cdots \quad \boldsymbol{S}_1^{(T-i)}\right] \\ \tilde{\boldsymbol{S}}_{2i} &= \left[\boldsymbol{0}_{2\times i} \quad \boldsymbol{S}_2^{(T)} \quad \cdots \quad \boldsymbol{S}_2^{(i+1)}\right] \end{aligned} \tag{4}$$

where $\boldsymbol{0}_{2 \times i}$ is a $(2 \times i)$-dimensional all-zero matrix.

The $(L+1)$-tap frequency-selective channel will be represented as a polynominal having an order of L. The discrete-time model of an L-delay-tap channel with two transmit antennas and one receive antenna can be quantified as

$$\begin{aligned} r_t &= h_1(q^{-1}) b_{t1} + h_2(q^{-1}) b_{t2} + n_t \\ &= h_{10} b_{t1} + h_{11} b_{(t-1)1} + \cdots + h_{1L} b_{(t-L)1} \\ &\quad + h_{20} b_{t2} + h_{21} b_{(t-1)2} + \cdots + h_{2L} b_{(t-L)2} + n_t \end{aligned} \tag{5}$$

The (2×1) vector $\boldsymbol{h}$ in (2) contains the first taps of the two independent frequency-selective channels, which can be further detailed as $\boldsymbol{h} = [h_{10},\ h_{20}]^{\mathrm{T}}$. Correspondingly, the ith tap of the polynomial model characterising the channel with delay spread, as represented by $\tilde{\boldsymbol{h}}_i$ in (2), can be further detailed as $\tilde{\boldsymbol{h}}_i = \left[h_{1i},\ h_{2i}\right]^{\mathrm{T}}$. The two amplitude matrices in (2) can be epitomised as $\boldsymbol{A} = 1/\sqrt{2}\boldsymbol{I}_2$ and $\tilde{\boldsymbol{A}}_i = 1/\sqrt{2}\boldsymbol{I}_2$, respectively, where $\boldsymbol{I}_2$ is the (2×2)-element identity matrix. The $(T \times 1)$ AWGN vector in (2) can be finalised as $\boldsymbol{n}_{\bar{t}} = \left[n_{1\bar{t}},\ n_{2\bar{t}},\ \ldots n_{T\bar{t}}\right]^{\mathrm{T}}$.

On the receive side, the pre-process applied to the received signal before being fed into the sphere decoding (SD)-based decoder can be decomposed into two parts. Firstly, the signal vector $\boldsymbol{r}_2$ containing the T samples collected during the second half frame have to be complex conjugated and time reversed in order to form the $(T \times 1)$-vector $\bar{\boldsymbol{r}}_2 = \left[\bar{r}_{12},\ \ldots,\ \bar{r}_{T2}\right]$, where $\bar{r}_{t2} = r_{(T+1-t)2}^*$. Thus, the resultant matrix of the first part can be represented by $\bar{\boldsymbol{r}} = \left[\boldsymbol{r}_1^{\mathrm{T}} \quad \bar{\boldsymbol{r}}_2^{\mathrm{T}}\right]^{\mathrm{T}}$. Then, the output matrix $\bar{\boldsymbol{r}}$ will be filtered

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with the matched filter $\boldsymbol{H}^{\mathrm{H}}$ to generate the detection input

$$\boldsymbol{z} = \begin{bmatrix} z_{11} & \cdots & z_{t1} & \cdots & z_{T1} \\ z_{12} & \cdots & z_{t2} & \cdots & z_{T2} \end{bmatrix} = \frac{1}{\sqrt{2}} \boldsymbol{H}^{\mathrm{H}} \bar{\boldsymbol{r}}$$

$$= \frac{1}{\sqrt{2}} \begin{bmatrix} h_1^*(q) & h_2(q^{-1}) \\ h_2^*(q) & -h_1(q^{-1}) \end{bmatrix} \begin{bmatrix} \boldsymbol{r}_1 \\ \bar{\boldsymbol{r}}_2 \end{bmatrix}$$

$$\boldsymbol{z}_t = \begin{bmatrix} \frac{1}{\sqrt{2}} \sum_{i=0}^{L} h_{1i}^* r_{(t+i)1} + \frac{1}{\sqrt{2}} \sum_{i=0}^{L} h_{2i} \bar{r}_{(t-i)2} \\ \frac{1}{\sqrt{2}} \sum_{i=0}^{L} h_{2i}^* r_{(t+i)1} - \frac{1}{\sqrt{2}} \sum_{i=0}^{L} h_{1i} \bar{r}_{(t-i)2} \end{bmatrix} \quad (6)$$

Further deriving the above formula, we can obtain the detection input $\boldsymbol{z}_t$ in the following form

$$\boldsymbol{z}_t = \boldsymbol{X}\bar{\boldsymbol{b}}_t + \sum_{i \in \mathbb{I}} \tilde{\boldsymbol{X}}_i \tilde{\boldsymbol{b}}_{ti} + \bar{\boldsymbol{n}}_t, \quad \forall t = 1, 2, \ldots, T \quad (7)$$

where $\boldsymbol{z}_t^{\mathrm{T}} = [z_{t1}, z_{t2}]$. More exactly, as for the desired signal in (7), we have

$$\bar{\boldsymbol{b}}_t = [b_{t1}, b_{t2}]^{\mathrm{T}} \text{ and } \boldsymbol{X} = x\boldsymbol{I}_2, \text{ with}$$
$$x = \frac{1}{2} \sum_{k=1}^{2} \sum_{i=0}^{L} |h_{ki}|^2 \quad (8)$$

As for the ISI components in (7), we will have $\tilde{\boldsymbol{b}}_{ti} = \left[b_{(t-i)1}, b_{(t-i)2}\right]^{\mathrm{T}}$, and the dynamic range for i can be divided into two closed integer areas which are [–L, –1] and [1, L], respectively. Correspondingly we will have

$$\tilde{\boldsymbol{X}}_i = \tilde{x}_i \boldsymbol{I}_2, \text{ with } \tilde{x}_i = \frac{1}{2} \sum_{i=1}^{L} \sum_{k=1}^{2} \sum_{j=0}^{L-i} h_{kj}^* h_{k(j+i)}, \quad i = 1, \ldots, L; \text{ and}$$

$$\tilde{x}_i = \frac{1}{2} \sum_{i=-L}^{-1} \sum_{k=1}^{2} \sum_{j=0}^{L+i} h_{k(j-i)}^* h_{kj}, \quad i = -L, \ldots, -1 \quad (9)$$

The AWGN components in (7) can be finalised as $\bar{\boldsymbol{n}}_t = [\bar{n}_{t1}, \bar{n}_{t2}]^{\mathrm{T}}$, where

$$\bar{n}_{t1} = 1/\sqrt{2} \left(\sum_{i=0}^{L} h_{1i}^* n_{(t+i)1} + \sum_{i=0}^{L} h_{2i} n_{(T+1-t+i)2}^* \right)$$
$$\bar{n}_{t2} = 1/\sqrt{2} \left(\sum_{i=0}^{L} h_{2i}^* n_{(t+i)1} - \sum_{i=0}^{L} h_{1i} n_{(T+1-t+i)2}^* \right) \quad (10)$$

Then we can feed z_{t1} and z_{t2} into two parallel SD-based decoders [29–31], with $t = 1, 2, \ldots, T$. The decoder output, that is, the estimation of the transmitted signal vector $\hat{\boldsymbol{b}}_1$ or $\hat{\boldsymbol{b}}_2$ can be obtained by solving

$$\hat{\boldsymbol{b}}_{\bar{t}} = \arg_{\dot{\boldsymbol{b}} \in \mathbb{B}_T} \min \sum_{t=1}^{T} \| z_{t\bar{t}} - x\dot{\bar{b}}_t - \sum_{i \in \mathbb{I}} \tilde{x}_i \dot{\tilde{b}}_{ti} \|^2,$$
$$\forall \bar{t} = 1 \text{ or } 2 \quad (11)$$

where $\mathbb{B}_T$ is the full-set containing all the $\mathcal{M}^{\mathrm{T}}$ candidate solutions, when an $\mathcal{M}$-ary modulation scheme is employed. In (11), $\dot{\boldsymbol{b}}$ represents an arbitrary candidate solution from set $\mathbb{B}_T$, which may be expanded as $\dot{\boldsymbol{b}} = [\dot{b}_1, \dot{b}_2, \ldots, \dot{b}_T]$. The desired signal and the interfered signal in (11) can be quantified as $\dot{\bar{b}}_t = \dot{b}_t$ and $\dot{\tilde{b}}_{ti} = \dot{b}_{(t-i)}$, respectively. Hence, we need to insert L zero-vectors before and after any transmitted signal block $\boldsymbol{B}$. Besides, we also need to insert L zero-elements before and after the trial vector $\dot{\boldsymbol{b}}$. Both of the zero-vectors or the zero-elements are served as the guard intervals. The SD-based algorithm [29–32] will solve (11) by only searching the candidate vectors lying inside a radius, which can be gradually reduced during the detection process. As a result, the SD-based algorithm will save lots of complexity compared with the exhaustive search algorithms such as the ML detector.

6 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 is invoked. In the simulations, the input data generated at a Constant Bit Rate, is encapsulated into fixed 500 bytes user datagram protocol (UDP) packets. In the PHY layer, the IEEE 802.11b data rate is 2 Mbps and the noise factor is 10.0. Frequency-selective fading with three paths is employed in our simulation. The system parameters for the employed TR-STBC scheme are listed in Table 3. In the proposed CDSR, the transmit power of cooperative intermediate nodes is set as half of those in the standard DSR, whereas the source, the destination and the shared intermediate nodes' transmit power is set as the same as those in the standard DSR. In this way, the total energy consumption of the DSR and CDSR protocols remains the same.

In Figs. 8 and 9, the CDSR scheme using the MAC scheme with RTS/CTS described in Section 4 is compared with the standard DSR with or without RTS/CTS. Note that the retransmission process is activated in these scenarios. In the proposed CDSR scheme, nodes will refresh 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 × 1500 m area. Specifically, in Fig. 8, 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 Fig. 9, where three and five retransmissions are employed. As shown in Figs. 8 and 9, the proposed CDSR scheme is capable of attaining a better performance than the standard 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 fresh their buffers

Table 3 System parameters for TR-STBC schemes

number of channel uses per block	2
number of symbols per information vector	2
length of a decoding block	8
length of the guard interval	2
number of paths per channel	3
channel constant for	ten codewords
modulation	BPSK

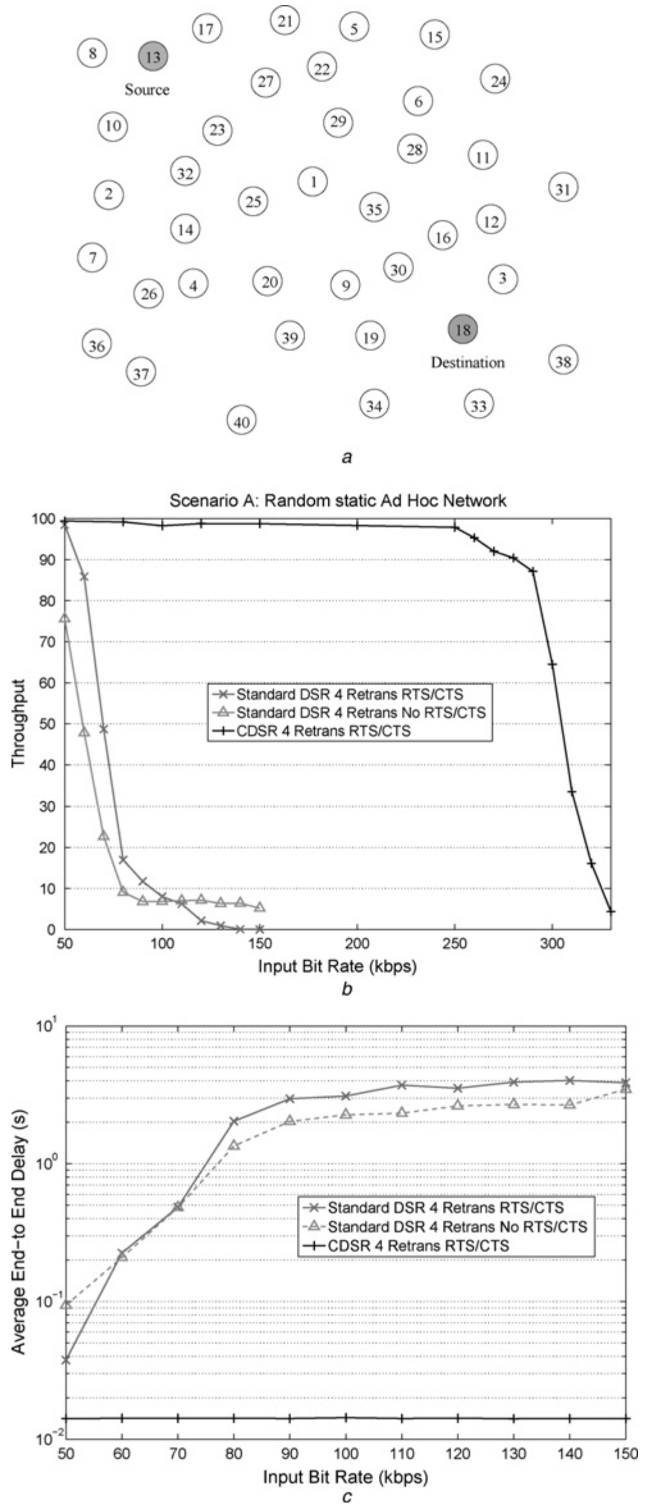

Fig. 8 *Scenario A: random static wireless sensor network The proposed CDSR scheme is capable of attaining a better performance than the standard DSR, not only in throughput but also in average end-to-end delay*

a 40 nodes are placed randomly in a 1500m × 1500m area
b Throughput performance
c Average end-to-end delay performance

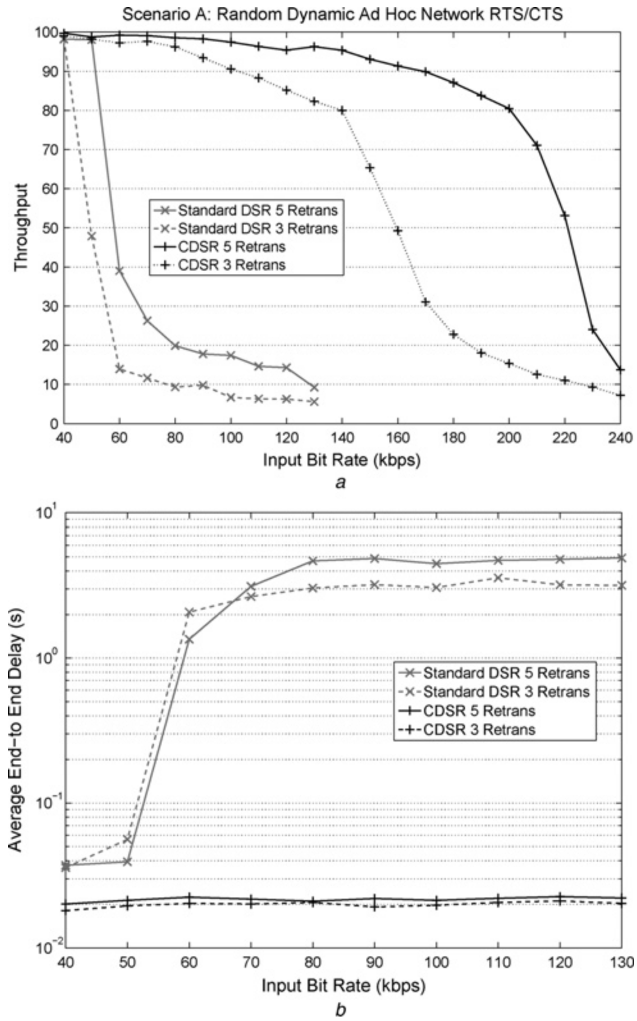

Fig. 9 *Scenario A: comparing the performance of the standard DSR with the proposed CDSR scheme based on a random dynamic wireless sensor network that is robust in resisting network topology variation caused by nodes' mobility*

a Throughput performance
b Average end-to-end delay performance

when link break happens or RERR message is received. Consequently, the average end-to-end delay is significantly reduced as demonstrated in Figs. 8 and 9. Furthermore, because of the achievable cooperative diversity, fewer retransmissions are required for data packets to be delivered from the source to the destination. It can be seen from Fig. 8 that the CDSR with RTS/CTS outperforms the standard DSR without RTS/CTS in terms of throughput and average end-to-end delay. The results in this figure also verify that the standard DSR with RTS/CTS outperforms the standard DSR without RTS/CTS in terms of throughput performance. This is mainly because of more overhead used for RTS/CTS. [In the IEEE 802.11, at the expense of more overhead, the optional RTS and CTS provide a handshake control over the CSMA/CA environment. These short packets aim at minimising collisions among hidden nodes when two nodes, that do not sense each other, attempt to send a packet to the third node located within their transmission reach.] However, it is outweighed by the latter in terms of the average end-to-end delay.

Fig. 9 demonstrates the CDSR scheme's robust resistance to network topology variation caused by nodes mobility. Since the proposed 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 Fig. 9 that increasing the retransmission numbers is helpful for both the CDSR and the standard

DSR to achieve a better throughput performance, at the expense of a longer delay performance.

Finally, the CDSR scheme using the MAC scheme with RTS/CTS and the standard DSR with RTS/CTS are evaluated in the multi-session scenario shown in Fig. 10*a*, where node 13 sends data to node 18, while node 1 transmits packets to node 10 and node 24 sends data to node 16. In this scenario, 24 nodes are placed randomly in a 1500 m × 1500 m area and move randomly at a speed of 2 mps. In comparison with the previous networks used in Figs. 8 and 9, this can be treated as a low-density wireless sensor network. As indicated in Fig. 10, the proposed CDSR scheme has a considerable advantage over the standard DSR in a multi-session scenario and in a low-density wireless sensor network. In addition, it further verifies that the proposed CDSR, by limiting the destination nodes' RREP number, is capable of avoiding excess overhead. Furthermore, by fully exploiting the concept behind the cooperative diversity, the proposed CDSR scheme will improve the transmission success ratio and thereby reduce the number of retransmissions. This, in turn, will cause reduction in the delay performance, as shown in Fig. 10.

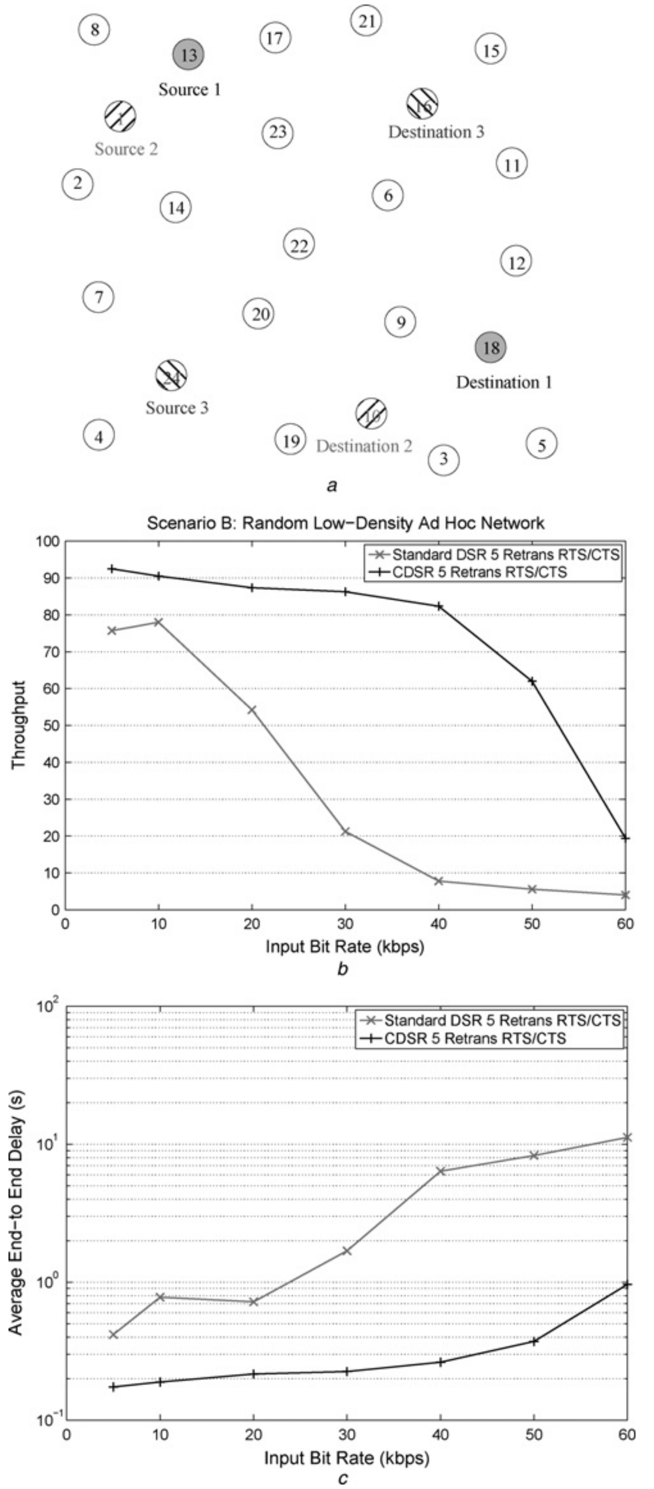

Fig. 10 *Scenario B: a multi-session scenario in a low-density wireless sensor network The proposed CDSR scheme is capable of achieving partial cooperative diversity and improving the performance*

a 24 nodes are placed randomly in a 1500m × 1500m area
b Throughput performance
c Average end-to-end delay performance

7 Conclusions

In this paper, we proposed a novel design framework, integrating cooperative diversity seamlessly into wireless sensor networks. The core feature of this architecture is that cooperative routes can assist the transmission of each other and hence enhance the reliability of all the wireless links. As a result, 'the link breakage probability is significantly reduced and the system delay is improved'. More specifically, in the network layer multiple routes are selected based on their ability of cooperating with others. In the MAC layer, the modified RTS/CTS packets are employed to achieve synchronous transmission in a wireless sensor network, whereas the NTS packet is introduced in order to allow the route maintenance process and to benefit from cooperative diversity. We also demonstrated that cooperative diversity can be achieved, when employing the MAC layer scheme without an RTS/CTS handshake.

In the PHY layer, the TR-STBC transmission scheme in combination of SD-based decoding algorithm are employed in order to achieve full cooperative diversity, even under frequency-selective channels. Please note that the overhead of the proposed CDSR protocol is very limited. First of all, the source nodes need to process the reply information in the RREPs and therefore no additional signalling is required by the proposed CDSR protocol. In the MAC layer, besides the control packets defined in 802.11DCF, the NTS packet is required in order to handle the route maintenance process efficiently and, since the burden of synchronisation has been taken off by the MAC layer, there is no extra overhead in the PHY layer. The simulation results demonstrated substantial improvement over packet delivery ratio and reduced system delay in both static and wireless sensor networks at the expense of higher complexity caused by the employed cooperative TR-STBC scheme.

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