

Towards Constructive Relay based Cooperative Routing in MANETs

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Abstract—Frequent link breaks (due to node mobility) and quick exhaustion of energy (due to limited battery volume) are two major problems impacting on the flexibility in Mobile Ad hoc Networks (MANETs). Cooperative communication in MANETs has become an appealing topic, as it can improve system capacity and energy efficiency. In spite of such advantages of cooperative communication, some issues still remain such as the lack of a systematically designed cooperative routing scheme (including route discovery, route reply, route enhancement and cooperative data forwarding), facilitation of cooperative communication in mobility resistance, and route selection (jointly considering energy consumption, energy harvesting ability and link break probability). Driven by the above concerns, we propose a novel Constructive Relay based CoOperative Routing (CRCPR) protocol in this article. Using topological information stored and maintained in a CoOperative (COP) Table and Relay Table, CRCPR enhances resilience to mitigate the mobility issue by self-managing to construct adequate relays for data forwarding. Furthermore, assuming nodes are mostly battery-operated, CRCPR proposes a new route selection mechanism which takes into account energy consumption, energy harvesting and link break probability, to determine an appropriate route across a network. Simulation results show the robustness of CRCPR against node mobility, further with improvement for up to 60% network throughput and 40% prolonged network lifetime.

Index Terms—Mobile Ad hoc Networks, Cooperative Communication, Energy Efficiency.

I. INTRODUCTION

Currently, the most common systems which utilize wireless communication are cellular networks and Wireless Local Area Networks (WLANs). However, both of them can only traverse the “last hop” connecting the mobile device to wired infrastructure which cannot adapt to the emerging self-organized communication applications like robotic cooperation [1], driverless based on vehicle network [2] [3] [4] [5]. These scenarios require devices to organize themselves into a network, and to build routes among themselves without external additional support. Nevertheless, MANETs also face certain constraints, e.g. the limited communication range of mobile nodes, the restricted power supply and link breaks due to node mobility. In order to address these difficulties, cooperative communication has received much attention for its perceived benefits, such as lower power consumption, reduced interference and potential channel diversity gain.

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Alongside more mature Physical layer [6] [7] and MAC layer [8] [9] mechanisms to support cooperative communication, research interest has grown regarding cooperative communication at the Network layer. Authors in [10] propose a model for cooperative communication using a decode-and-forward approach, where a node which plays a role of a relay tries to decode an entire message and forwards it to the next hop. Additionally, multiple relays can cooperate at the symbol-level and forward data together, under the assumption that frame level synchronization can be achieved among nodes. Results show that Broadcast-Cooperative (BC) policies can save more than 40% energy when compared to a None Cooperative (NC) policy. Based on the framework proposed in [10], other research has further explored cooperative communication. For example, [11] provides a systematic strategy for evaluating the cooperative routing schemes and compares their pros and cons. In [12], the authors focus on the impact of cooperative routing on balancing the energy distribution among nodes, rather than how to minimize the total energy consumption from source to destination. A novel routing scheme called Energy-Balanced Cooperative Routing (EBCR) is proposed to select cooperative relay nodes and decide their transmission power for each hop.

Although [10] proposes a very useful model to support cooperative communication, the follow-up studies [11] [12] do not consider several important aspects: 1) A fundamental routing structure at the Network layer for cooperative communication is overlooked. Without that concern, contributions from Physical layer and MAC layer can not drives satisfied performance. Also, research efforts on selection of cooperative relay node at the Network layer is unable to make the practical contribution, without a complete routing structure for cooperative communication. 2) Even though the cooperative communication could contribute to energy consumed for data transmission with the help of cooperative diversity, how to reduce the link breaks via cooperative communication, still has not received much attention. 3) If the energy harvesting ability is also involved when selecting a route, the lifetime of whole network could be improved, by bringing the node energy harvesting ability for route selection.

Given above issues, a reactive fundamental cooperative routing structure, called Constructive Relay based CoOperative Routing (CRCPR) is proposed in this article, which can utilize several topological information stored in Cooperative Neighbor Table, CoOperative (COP) Table and Relay Table to implement cooperative transmission and mobility resilience. The key contributions of this work are:

- A complete systematic design at the Network layer to support the cooperative communication.

- A locally self-managed scheme for the cooperative communication based on the four-node COoPerative (COP) topology information included in COP Table.
- An innovative COP possibility detection algorithm for COP topology creation and maintenance, via information included in Cooperative Neighbor Table.
- A robust link-break handling mechanism to construct relays for data forwarding via a Relay Table.
- A novel route selection algorithm that is resilient to link breaks and provides economic energy consumption and energy harvest.

II. RELATED WORK

A. Cooperative Routing Protocol

Recently, research interest in the cooperative communication at the Network layer has grown. The authors in [13] present a novel joint clustering and routing mechanism, called “Ad-hoc On-demand Cooperative MIMO Routing” which makes the use of a relay node to expand the transmission range and further increases the throughput. In addition, two cooperative models have been proposed in [14], based on Dijkstra’s shortest path algorithm to exploit cooperative communication. A pure network layer scheme called Cooperative Opportunistic Routing in Mobile Ad hoc Network (CORMAN) is proposed in [15], which broadens the applicability of ExOR [16]. The authors explore in depth how to setup a new route in the intermediate forwarding node and how to re-transmit missing packets between two consecutive forwarding nodes. However, none of above researches does consider a systematic cooperative routing structure.

Targeting the lack of systematic cooperative routing scheme, some latest researches are being proposed. Based on cooperative communication model in [10], the authors in [17] design an energy-efficient routing protocol (CWR) for cooperative networks, based on AODV [18] protocol. Therefore, it inherits most of the features of AODV like route discovery, route link break detection, route reply, the hello message broadcast scheme etc. The key novelty of CWR is that it employs a “request-to-recruit” scheme for the transmitting and receiving nodes on the selected route to recruit neighbor nodes to assist in communication. Based on AODV scheme, CWR does not consider the factor of “recruit” ability, energy saving ability or link break probability when selecting a final route. What’s more, five control packets are used for negotiating in “request-to-recruit” scheme before forwarding data which leads to significant control overhead and transmission inefficiency. The problem of this three-node cooperative model is that it is difficult to utilize the cooperative communication for saving energy consumption during transmission.

B. Energy-aware Routing Protocol

The quick exhaustion of energy due to batter capacity leads to network lifetime limitation in MANETs. Researches focusing on energy harvesting ability in MANETs is a key interest in the long term. AODV-EHA in [19] considers the energy harvesting ability of all nodes and tries to find the route with least transmission cost by replacing “hop count”

with “energy count”. Here, energy count can be obtained by predicting the average transmission cost to forward a data packet successfully from the sending node to the receiving node. The authors later compared the AODV-EHA performance with competitor, DEHAR [20], which is another energy harvesting-based routing protocol using the concept of “energy distance” when measuring the energy status. “energy distance” is encoded from spatial distance and it makes the real distance related to the energy status (how much energy can be harvested from the surroundings) of the sending node. The route with the shortest energy distance will be selected as the final route. Nevertheless, the node mobility is overlooked in their design which can affect the performance in many ways. In [21], an approach to reduce energy consumption and to improve mobility robustness is proposed using a multi-path routing scheme. The authors try to find the routes with shortest hops, lowest energy consumption and suitable traffic loading balance in a unified way. Obviously, the problem is that multi paths typically require a more complex scheme and more control messages to be maintained than the single path routing scheme.

C. Our Contribution

Though various routing schemes for MANETs are actively discussed in terms of cooperative communication and energy awareness, a fundamental routing structure for cooperative communication is overlooked. What is more, how to improve the robustness against mobility and energy efficiency especially with comparative communication is still rare. CRCPR provides a complete systematic cooperative routing scheme including cooperative route discovery, route reply, route enhancement, route selection, cooperative data forwarding. Also, a new route selection criteria which considers energy consumption, energy harvesting and link break probability contributes to find a final route with economic energy consumption and high robustness resulting from mobility induced link breaks.

III. CRCPR DESIGN

CRCPR is a reactive routing protocol with proactive local enhancements. It is reactive in the sense that a route is built only when data needs to be sent, and proactive in the sense that the COP topology is set up in advance for all source-destination pairs and can be locally self-managed. The fundamental cooperative model of CRCPR could be referred to [11], whereas 6 new phases are designed to support the designed functions of CRCPR:

- **Neighbor Discovery:** The establishment of the COP Table and Relay Table, which play a fundamental role in the protocol, are introduced in the Neighbor Discovery section.
- **Route Discovery:** The route discovery procedure, concerning how the COP topology information is carried via route discovery packets, is considered in the Route Discovery section.
- **Route Reply:** The route reply procedure, explaining how route request packets are replied, is addressed in the Route Reply section.

- **Route Enhancement:** In the Route Enhancement section, the means which CRCPR can improve robustness against mobility are illustrated.
- **Route Selection Criteria:** The routing selection algorithm which uses COP topology information to find a more stable route is described in the Route Selection Criteria section.
- **Data Forwarding:** Finally, after the route is established, how data is forwarded considering the COP topology is introduced in the Data Forwarding section.

A. CRCPR Framework

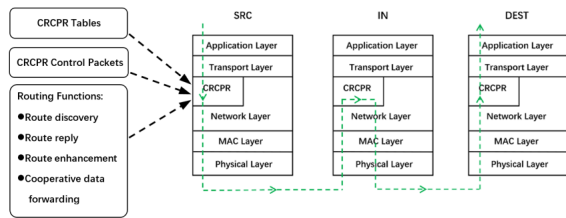


Fig. 1. CRCPR Framework

Figure 1 illustrates the CRCPR framework. CRCPR is a sub-layer within the Network Layer. The reason is that the sub-layer design will not affect the original architecture and functions of the Open Systems Interconnection (OSI) model. If the function of CRCPR is required, it can be activated to support multi-hop ad hoc mobile communication. Otherwise, it can still support regular IP traffic over other wired or one-hop wireless networks. Inside the CRCPR framework, it consists of three parts: CRCPR tables, CRCPR Control Packets and Routing functions.

- **CRCPR Tables:** the COP Table, Relay Table and Cooperative Neighbour Table.
- **CRCPR Control Packets:** Cooperative Hello (CHLO) Packet, Cooperative Route Request (CREQ) Packet, Cooperative Route Reply (CREP) Packet and Cooperative Confirm (CCON) Packet.
- **Routing Functions:** Routing Discovery, Route Reply, Route Enhancement and Cooperative Data Forwarding

B. Neighbor Discovery

1) *Cooperative Neighbor Table Creation:* Once a node receives a Cooperative Hello (CHLO) packet from its neighbors, the Cooperative Neighbor Table can be built based on the collected information as shown in Figure 2. Two new items are included in the Cooperative Neighbor Table compared with the traditional Neighbor Table: the *NSN Addr List* field and the *B/U* field.

Each neighbor's neighbors are attached to the corresponding *NSN Addr List* field, which facilitates building the COP table and maintaining the COP topology. *B/U* marks whether an incoming CHLO, which updates a given entry, was received via a broadcast or unicast packet. Similar to most classic MANETs routing protocols, broadcasting is the common transmission

method for hello packets, whilst unicast is only employed by cooperative nodes and relay nodes when the COP and Relay Tables are being created in CRCPR. Further details are provided in the Route Enhancement section.

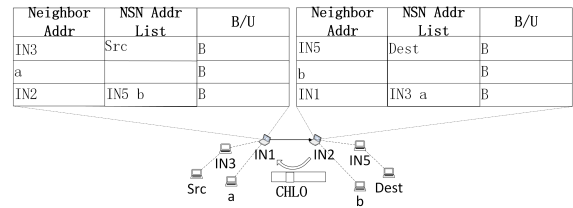


Fig. 2. Cooperative Neighbor Table Creation

2) *COP Table Creation:* As long as a node learns through its Cooperative Neighbor Table (with the help of the *Neighbor Addr* and *NSN Addr List* fields) that there exist two neighbor nodes that are also a common neighbor to another node via the COP Possibility Detection Algorithm shown in Algorithm 1, a four-node COP topology is formed as illustrated in Figure 3. Although a COP topology with more than four nodes may lead to better performance, choosing a four-node arrangement to form the COP topology is a compromise between algorithm complexity and network performance in MANETs. For a three-node topology, it is not easy to utilize the transmission diversity to save transmission energy. For four-node topology, the algorithm to create and maintain this topology is not very difficult but it can provide promising performance in terms of link break reduction and energy saving. For topologies with more than four nodes, the algorithm to create and maintain this topology becomes more difficult and complex. It is not realistic to design and implement such an algorithm in dynamic MANETs. In addition, the lower layer mechanism for this form of cooperative transmission is well understood and the technological challenges regarding frame synchronization for cooperative communication are studied fully. Furthermore, this approach is not restrictive, as many four-node COP topologies can coexist within the MANETs. This provides ample opportunity to save energy and improve robustness.

Along the route, the first node within the COP topology receiving valid data will be regarded as the COP Source (Src) and the Intermediate Nodes (INs) will be assigned roles according to the COP Table of the COP Src via a Cooperative Confirm (CCON) packet.

More precisely: Firstly, before the COP Src forwards data, it chooses a suitable entry from its COP Table list and places this entry in a CCON packet. Secondly, CCON packet is sent to notify both the suitable Cooperative (C) nodes to be ready to transmit data cooperatively and the appropriate COP Destination (Dest) to combine the cooperative data signal. Thirdly, after the COP Table is confirmed across the four INs in the COP topology, the data forwarding procedure commences.

The details about data forwarding via COP Table are covered in Data Forwarding section. Sometimes, several COP topologies can co-exist between two hops along a route. Only

the COP topology activated via the COP Table will participate in cooperative communication and the others remain “silent”. A CCON packet will not be sent to trigger activation of a “silent” COP topology until the previously activated one ceases.

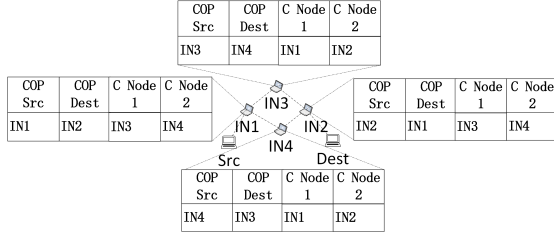


Fig. 3. COP Table Creation

Algorithm 1 COP Possibility Detection Algorithm

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1: Let  $NA_i$  be neighbor addresses in each IN
2: Let  $NSN_j$  be each list of neighbors' neighbor addresses
3: Let  $L_{(i,j)}$  be each neighbors' neighbor addresses in one  $NSN_j$ 
4: for each  $i$  in  $NA_i$  do
5:   for each  $j$  in  $NSN_j$  do
6:     *Find neighbors' neighbor address*
7:     Obtain  $L_{(i,j)}$ 
8:     for each  $i+1$  in  $NA_i$  do
9:       for each  $k$  in  $NSN_j$  do
10:        *Find neighbors' neighbor address*
11:        Obtain  $L_{(i+1,k)}$ 
12:        *Compare neighbors' neighbor address*
13:        if  $L_{(i,j)} == L_{(i+1,k)}$  then
14:          *Insert a new entry in COP Table*
15:          Add own IP address in COP Src
16:          Add  $L_{(i,j)}$  or  $L_{(i+1,k)}$  in COP Dest
17:          Add two  $NA_i$  in C Node
18:        else if  $L_{(i,j)} \neq L_{(i+1,k)}$  then
19:          *Start the next loop*
20:          continue
21:        end if
22:      end for
23:    end for
24:  end for
25: end for

```

3) *Relay Table Creation*: When the Cooperative Neighbor Table is updated by a CHLO packet, every IN runs the COP Possibility Detection Algorithm to update the COP Table or delete invalid entries if the COP topology no longer exists. If an entry is deleted from the COP Table but the C nodes in this entry remain neighbors, a Relay Table will be built. The elements in the Relay Table: Relay Neighbor 1 and 2 are the IP addresses IN1 and IN2, respectively. An example considering the Relay Table creation of IN2 and IN4 is given in Figure 4.

C. Route Discovery

When a node requires a route to a destination it must broadcast a Cooperative Route Request (CREQ) packet to seek a route across the MANETs. A new CREQ packet handling procedure (including broadcasting across normal and COP topologies shown in Algorithm 2) is designed to allow COP topology information, if any, to be carried in a CREQ packet to the destination therefore contributing to the final route selection strategy.

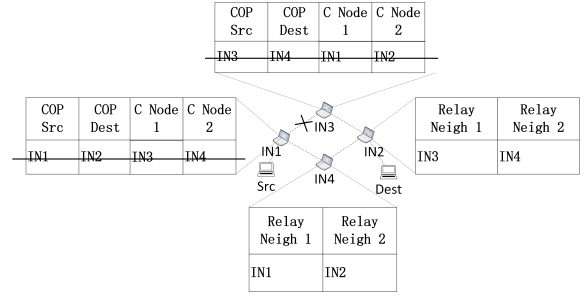


Fig. 4. Relay Table Creation

Algorithm 2 CREQ Handle

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1: Let  $N_i$  be the number of entries in the COP Table of one node
2: if  $N_i == 0$  then
3:   *Broadcast CREQ based on non-cop topology broadcasting principle*
4: else if  $N_i \neq 0$  then
5:   for each  $i$  in  $NSN_i$  do
6:     if COP Dest is the second last hop then
7:       if COP topology set in RMV by the second last hop then
8:         if Two C nodes of COP Table in the current receiving node
           are NOT the same with the two C nodes set in RMV then
9:           *Replace old RMV*
10:          *Replace last hop IP with its own IP*
11:         end if
12:       end if
13:     end if
14:     if COP Dest is last hop then
15:       if COP topology set in RMV by last hop then
16:         if Two nodes in new COP topology are NOT the same with
           two nodes in old COP topology set by last hop then
17:           *Set new RMV*
18:         end if
19:       end if
20:     end if
21:     *Broadcast CREQ*
22:   end for
23: end if

```

As CREQ handling in a normal topology is similar to AODV, we focus here on the COP topology case.

In the COP topology, once an IN receives a CREQ packet and finds that the immediate upstream node of the last hop is the COP Dest in its COP Table, it performs “last hop replacement”; that is the IN replaces last hops IP address in the CREQ packet IP list with its own IP address which can make the location of COP Dest closer to the destination and reduce the total hops in the final route.

Furthermore, the “last hop replacement” leads to the C nodes invisibility if this COP topology is selected in the final route. The invisibility of C nodes actually results in a virtual point-to-point connection diagonally within the COP topology even though the COP Src and COP Dest may not be within each other’s direct transmission range. This virtual point-to-point connection does not only contribute to saving energy via cooperative communication, but improves the robustness against mobility. This is because if any one of the C nodes moves away from the COP topology, a Relay Table will be built to maintain the connection between COP Src and COP dest. If more COP topologies are involved in the final route, this leads to greater robustness against mobility and improved energy savings through cooperative transmissions.

As CRCPR exploits a cross-layer design which can utilize

the information from the Physical layer and MAC layer called Routing Matrix Values (RMV) up to IP Layer as important factors contributing to the final route decision so, during the CREQ packet handling procedure, RMV need to be carried in the CREQ packet to the destination. In Figure 5, we illustrate the RMV appending process in CREQ. When the IP address is added to the CREQ packet, the RMV of the current node are also included. This case is also suitable for the “last hop replacement” scheme, which means when the IP address of one node is replaced, its RMV in the CREQ packet will also be replaced. How to utilize RMV such as battery capacity, energy accumulation rate, real-time residual energy and link break probability are explained in Route Selection Criteria section. Furthermore, the RMV appending process can be easily extended to other route protocols which may employ different types of RMV within the route selection process.

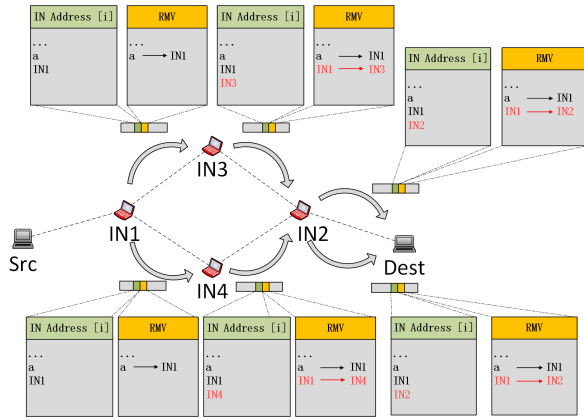


Fig. 5. RMV Appending in CREQ

In CRCPR, we use a “source-dest triplet $\langle Src, Sequence_Number, Dest \rangle$ ” to prevent the “broadcast storm problem. More specifically, there is a sequence number in each broadcasting route request packet. When a route request packet reaches a node, this sequence number with the source node IP address and destination node IP address will be saved as a triplet $\langle Src, Sequence_Number, Dest \rangle$ in this receiving node. In a route request process for the same source node and destination node, only the route request packet with the same or newer sequence number compared with the triplet will be rebroadcast and any old one is discarded to prevent a “broadcast storm. In a route request process for the same source node and destination node, if a route request packet with a newer sequence number reaches a node, this node will update the sequence number in its corresponding triplet $\langle Src, Sequence_Number, Dest \rangle$ to prevent the older route request packet broadcasting in the network.

D. Route Reply

After receiving the first CREQ packet, the destination node waits for a period of time to allow collecting all possible CREQ packets originating from the same source via different routes. A Cooperative Route Reply (CREP) packet is then generated with the output of route selection introduced in

Route Selection Criteria section. This CREP packet contains the IP list of the reverse selected route and is unicast back to the source. When the CREP packet comes to the C nodes in COP topology, if the connectivity does not exist between the COP Dest and COP Src (the connectivity can be obtained with the help of the *Neighbor Addr in CHLO* and *NSN Addr List* fields), it unicasts the CREP packet to the COP Src.

However, if connectivity exists, it will destroy the CREP packet. The reason for this is that due to connectivity between COP Dest and COP Src, the CREP packet from the COP Dest can be received directly by the COP Src and sending it again via C nodes would be redundant. The same procedure arises when the CREP packet comes to a node with a Relay Table. The only difference is that the node needs to check whether connectivity exists between its preceding and succeeding Relay Neighbors. For a COP Src, valid CREP packets are unicast to the next hop. However, if any repeated CREP packets arrive from different C nodes, they are discarded. Once the CREP packet successfully arrives at the source node, data forwarding can commence.

E. Route Enhancement

If a valid next hop in the Route Table does not exist in the Neighbor Table, the route will be removed. The CHLO unicast scheme can enhance the neighbor relationship between C nodes in the COP Table and relay neighbors in the Relay Table which means both broadcast and unicast neighbors can be regarded as valid when they are used to verify the next hop validity in the Route Table and increase the possibility of a valid route being identified. The CHLO unicast scheme operates as follows: When one node receives a CHLO packet from one of its C nodes in the COP Table or relay neighbor in the Relay Table, it unicasts this CHLO to the other C node or relay neighbor.

In order to utilize this enhanced neighbor relationship during data transmission to improve route robustness, the relay manner of forwarding data introduced in Data Forwarding section is involved. Figure 6 provides more detail about route enhancement.

Scenario (a) assumes that there is no connectivity between the COP Src and COP Dest. Only when the two cooperative nodes (C node 1 and 2) move out of range at the same time, will the route be broken. This is because if only one cooperative node leaves, the other cooperative node will establish a Relay Table, which allows data to be relayed from the COP Src to COP Dest in relay way, maintaining the route.

Scenario (b) assumes there is connectivity between the COP Src and COP Dest. Due to mobility, if the connectivity is lost, the link between COP Src and COP Dest is also stable due to cooperative communication via two cooperative nodes. At this moment, if one cooperative node moves away, the other cooperative node will establish a Relay Table and perform the relay function, which is the same with scenario (a).

Scenario (c) shows the case that if only the COP Src and COP Dest are involved initially, and subsequently two C nodes (Joining N nodes) move into the range to build a COP topology. At this moment, the enhanced performance will be the same as for scenario (b).

The above three cases assume there is only one COP topology between a pair of COP Src and COP Dest. If more than one COP topologies exist as mentioned in COP Table Creation Section and two activated C nodes moves out of the current COP topology, the link between the COP Src and COP Dest is still stable. The reason is that the COP Src can manage locally to trigger another COP topology to implement cooperatively sending the data to COP Dest.

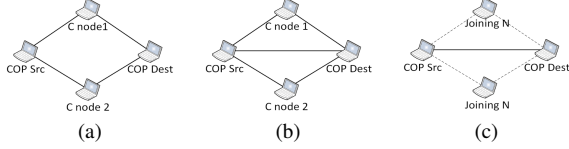


Fig. 6. Route Enhancement Scenarios

To summarize, only when all the links between the COP Src and COP Dest are lost is the route indeed broken. Therefore, CRCPR constructs a robust, energy-efficient route by employing a COP Table, Relay Table and CHLO unicast scheme.

F. Route Selection Criteria

TABLE I
LIST OF NOTATION

H_i	Energy harvest degree
C_e	Energy conversion efficiency
K_i	Energy harvest contribution
C_a	Battery capacity
R_i	Energy accumulation rate
E_i	Real-time residual energy degree
a_i	Energy drain rate coefficient
L_i	Link break degree
p_i	Link break probability
Q	Route performance coefficient

In CRCPR, in order to obtain the final route with highest route performance coefficient Q , we need the information defined in Table I:

1) Energy Harvest Degree:

$$H_i = C_e \left(-e^{-\frac{K_i}{n}} + 1 \right) \quad (1)$$

From Equation (1), the energy harvest degree of node i with constant value n is relate to energy conversion efficiency C_e and energy harvest contribution K_i , where K_i is determined by battery capacity C_{a_i} and energy accumulation rate R_i in Equation (2)

$$K_i = \frac{R_i}{C_{a_i}} \quad (2)$$

Generally, battery capacity C_{a_i} is fixed for each device but energy accumulation rate R_i is different according to the energy source like radio waves [22] or solar [23]. In this paper, we choose the more mature energy harvest technology solar energy harvester and more details can be referred to [23].

2) Real-time Residual Energy Degree:

$$E_i = \left(-e^{-E_i^r(1+H_i)/n_1} + 1 \right)^{n_2} \quad (3)$$

E_i^r is the real-time residual energy of node i and $E_i^r \geq 0$. H_i is the Energy Harvest Degree. n_1 and n_2 are the constant value. Equation (3) guarantees E_i is within the range of [0, 1].

3) *Energy Drain Rate Coefficient*: Energy Drain Rate can be used to reflect the energy consuming rate of one node. Although one node has high residual energy, its lifetime could not be long if it also has a high energy consuming rate. Therefore, we define a Energy Drain Rate Coefficient to describe this property in the Equation (4), where E_i is the Real-time Residual Energy Degree and R_i is the energy drain rate defined in [24] as Equation (5). R_{thr} is a scenario-selectable parameters. The value of Energy Drain Rate Coefficient a_i could be used in the final route selection scheme to exclude the node with high energy drain rate.

$$a_i = \begin{cases} 1 & \frac{R_i}{E_i} < R_{thr} \\ 0.1 & \frac{R_i}{E_i} \geq R_{thr} \end{cases} \quad (4)$$

$$R_i = \frac{1}{N-1} \sum_{k=i-N+1}^l R_k(t) \quad (5)$$

4) *Link Break Degree*: Link Break Degree L_i is utilized to reflect the stability of each link on the route which can be calculated based on Equation (6)

$$L_i = \frac{1}{(1 + e^{-10(p_i - p_0)})} \quad (6)$$

where p_i is the different link probabilities in CRCPR which will be introduced later and p_0 is a scenario-selectable parameter and make our final selected route more stable. More specifically, one pivotal target of CRCPR is to enhance resilience in the network as described in Route Enhancement section. After deploying this design into the network, the link break probabilities of some specific nodes are still higher than a scenario-selectable threshold p_0 , we will regard these links as “extremely unstable” nodes. On the contrary, the links with lower link break probabilities than p_0 should have more chance to be selected. Therefore, Equation (6) can implement this design by make the link break probability higher than p_0 more favorable and lower than p_0 less favorable. Finally, it is more likely to make the “extremely unstable” nodes not involved in the final route and enhance resilience in the network.

5) *Link Break Probability p_i in CRCPR*: For CRCPR, p_i consists of three different link break probabilities according to three types of links: a normal link p_n (two nodes can communicate with each other directly), a connected COP link p_c (i.e. a link exists between IN1 and IN2) and an unconnected COP link p_{nc} (i.e. a link does not exist between IN1 and IN2) as shown in Figure 7 from (a) to (c). As details for calculating the link break probability of a normal link like (a) in Figure 7 have been presented in [25], we only refer to the conclusion

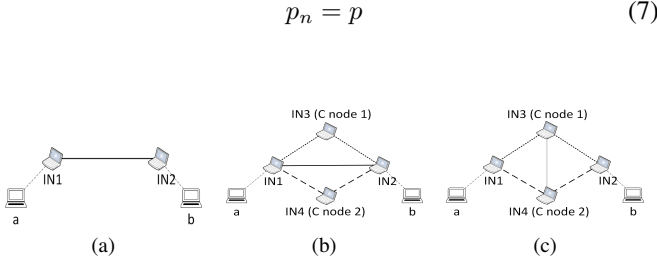


Fig. 7. COP Topology Links

For a connected COP link like (b), we have the dotted “link” L_{dotted} , solid “link” L_{solid} and dashed “link” L_{dashed} . For an unconnected COP link like (c), we have the dotted “link” L_{dotted} and dashed “link” L_{dashed} . The link break probability of the dotted “link”, solid “link” and dashed “link” are obtained by the property of mutually exclusive events.

$$P(L_{dotted}) = 1 - (1 - p_n)^2 = 2p - p^2 \quad (8)$$

$$P(L_{solid}) = p_n = p \quad (9)$$

$$P(L_{dashed}) = 1 - (1 - p_n)^2 = 2p - p^2 \quad (10)$$

We can then obtain the link break probabilities for the connected and unconnected COP link cases from Equation (11) and (12), respectively.

$$p_c = P(L_{dotted}) \times P(L_{solid}) \times P(L_{dashed}) = p^5 - 4p^4 + 4p^3 \quad (11)$$

$$p_{nc} = P(L_{dotted}) \times P(L_{dashed}) = p^4 - 4p^3 + 4p^2 \quad (12)$$

After we get all these three link break probabilities in CRCPR, the Link Break Degree L_i can be calculated based on Equation (6).

6) *Route Selection Strategy*: Due to mobility and limited node energy in MANETs, a route selection scheme should reduce the link break probability and minimize the energy consumption. The ability to harvest energy is also a key factor for improving the network lifetime. Therefore, based on the above conditions, a route selection strategy considering the lowest route break probability and the highest network lifetime is modeled in the following equation, where Q indicates the route performance coefficient.

$$Q = \min_{1 \leq i \leq n} \left[\frac{E_i}{e^{\frac{routeEntry}{2}}} \right] \times \prod_{i=1}^n (e^{a_i + 1 - L_i}) \quad (13)$$

where i indicates the hop numbers in the total route, $routeEntry$ indicates the amount of route table entries at node i , E_i is Real-time Residual Energy Degree, L_i is Link Break Degree and a_i is Drain Rate Coefficient. $E_i / e^{\frac{routeEntry}{2}}$ is designed to avoid choosing the node in the final route with much heavy payload which may lead to fast energy consumption even transmission collision. As CRCPR is a cross-layer design, it can utilize the RMV passed from Physical layer and MAC layer up to IP Layer, such as battery capacity, energy accumulation rate, real-time residual energy, link break probability

and so on. All these data can be carried by CREQ packet to the destination and contribute to the Route Selection Strategy. Assuming ε CREQ packets are received during CREQ_WAIT period, the sequence of CREQ packets can be denoted by $\{C_{pkt_1}, C_{pkt_2}, \dots, C_{pkt_\varepsilon}\}$. $Q(C_{pkt_\varepsilon})$ represents each Route Selection Strategy value for each C_{pkt_ε} . Finally, a route with the maximum value of $Q(C_{pkt_\varepsilon})$ is chosen and the corresponding $Q(C_{pkt_\varepsilon})$ will be inserted into CREP before unicasting back to source node.

$$Q_{final} = \max[Q(C_{pkt_1}), Q(C_{pkt_2}), \dots, Q(C_{pkt_\varepsilon})] \quad (14)$$

G. Data Forwarding

After the final route is confirmed and a data packet is about to be sent, for CRCPR, there are three different methods of forwarding data: normal manner, cooperative manner and relay manner. For normal manner, when data is received, it will only be processed if the Next Hop field of the packet matches its own. The cooperative manner is used when data reaches the Cooperative (C) nodes in a COP topology. In a COP topology, we have four INs with their corresponding COP tables in Figure 3. As mentioned in the COP Table Creation section, once a CCON sent by the COP Src node has confirmed two activated C nodes across the four INs of the COP topology, the specific roles for the four INs are confirmed as one COP Src node, two C nodes and one COP Dest node. Then, cooperative data forwarding commences: two C nodes cooperatively transmit the data to the COP Dest node, which is similar to the “Typical Model for Cooperative Communication” in [10]. The relay manner of forwarding data is employed in a node which has a Relay Table (In Figure 3, relay manner happens in the node IN4). If a data packet is received by a node with the Relay Table and this data comes from one Relay Neighbour node indicated in the Relay Table, this node will relay the data packet to the other Relay Neighbour node after confirming there is no direct connection between these two Relay Neighbours. In summary, the relay manner means a node with the Relay Table relays the data from one Relay Neighbour to the other Relay Neighbour. In CRCPR, different roles of the nodes perform different data forwarding methods and Figure 8 illustrates data process flows for different roles of the node in CRCPR.

Firstly, the COP Src sends the data in the normal manner. Secondly, due to the phenomenon of overhearing transmissions in wireless communication, two activated C nodes can hear this data packet and then both C nodes will beam-form this data to the appropriate COP Dest in a cooperative manner. This can provide lower power consumption via cooperative communication. Thirdly, after the COP Dest combines the cooperative data and recovery it successfully, it continues to forward this data. If the COP Dest plays the role of a COP Src in the next COP topology along the route, the above procedure is repeated.

This cooperative data forwarding procedure in CRCPR differs from the “request-to-recruit” phase in CWR [17] because activated C nodes in the proactive COP Table can perform cooperative transmission without the need to recruit relay neighbors after each data packet is sent. This greatly reduces

the control overhead by avoiding the complex “request-to-recruit” mechanism in CWR.

When data arrives at a relay node with a Relay Table, it is relayed from one relay neighbor to another in relay manner if no direct connectivity exists between these two relay neighbors (The connectivity existence can be implemented via the Cooperative Neighbour Table). If there is a direct connectivity, the relay node simply discards this data to avoid repeated transmissions between relay neighbors. Both the cooperative and relay manners of forwarding data via the COP Table and Relay Table, respectively, contribute to improving robustness against mobility in CRCPR.

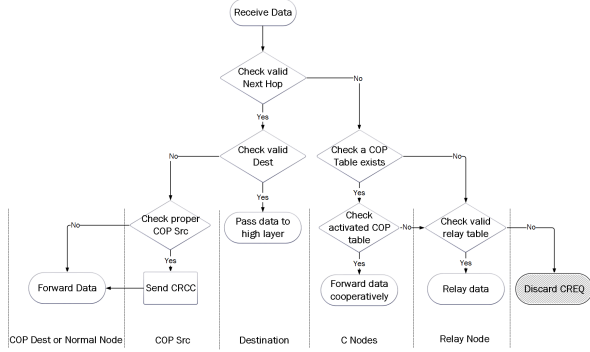


Fig. 8. Flow chart of forwarding data for different roles in CRCPR

IV. ANALYTICAL COMPARISON AND SIMULATION RESULTS

A. Mobility Extension Area

In the CRCPR Design section, we have described all the procedures about CRCPR and explained how CRCPR is able to improve robustness against mobility. In this section, we mathematically demonstrate the benefit with the help of a new concept called the Mobility Extension Area (MEA) and the simulation is carried out in MATLAB. In order to compare a normal MANET and a MANET with the COP topology, we use the same node names for the nodes located in the same position in these two types of MANETs as shown in Figure 10 and Figure 11. And we use Figure 10 as an example to demonstrate the MEA for COP Dest. First, the concept of ultimate area direction is proposed to help define the MEA, which is the direction of the line connections from the source node to the destination node. Then, we fix the last hop of COP Src, COP Src and next hop of COP Dest respectively along the ultimate area direction. The shadow area in Figure 10 is the MEA for COP dest. As we can see, if the larger of the MEA between two adjacent nodes is, the greater the mobility that can be supported.

The MEA in normal Ad hoc network and the Ad hoc network with COP topology can be modeled as a mathematical problem of the intersection of circles. For the normal Ad hoc network, the MEA is an intersection of two circles as illustrated in (a) of Figure 9. We define r_1 and r_2 as the radius of these two circles and θ_1 and θ_2 as the angle subtended by the segment at the center. The area of the circular segments is obtained from Equation 15:

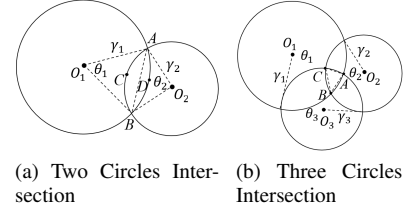


Fig. 9. Intersection of Circles

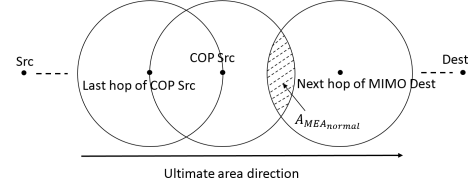


Fig. 10. MEA in Normal MANETs

$$\begin{aligned} A_{Segment_{ADB}} &= A_{Sector_{AO_1B}} - A_{Triangle_{AO_1B}} \\ &= \int_0^\theta \int_0^r \tilde{r} d\tilde{r} d\tilde{\theta} - \frac{1}{2} AO_1 BO_1 \sin \theta \\ &= r^2/2(\theta - \sin^{-1}\theta) \end{aligned} \quad (15)$$

Applying the above result to our case, we obtain

$$A_{MEA} = r_1^2/2(\theta_1 - \sin \theta_1) + r_2^2/2(\theta_2 - \sin \theta_2) \quad (16)$$

As $r_1 = r_2 = r$ and $\theta_1 = \theta_2 = \theta$, we get

$$A_{MEA_{normal}} = r^2(\theta - \sin \theta) \quad (17)$$

The MEA for the MANETs with a COP topology is shown in Figure 11 and it is the sum of $A_{MEA_{normal}}$ and $A_{MEA_{diff}}$, where $A_{MEA_{diff}}$ can be obtained by using the intersection area of two circles around cooperative nodes 1 and 2 (ie. N_{c_one} and N_{c_two}) and subtracting the intersection area of the three circles: Circle N_{c_one} , Circle N_{c_two} and Circle COP Src. The intersection area of three circles is illustrated in (b) of Figure 9. The angle Φ in Figure 11 will change from 0 to π , so we can calculate the MEA mathematically as:

$$A_{MEA_{cop}} = \begin{cases} A_{MEA_{normal}} + A_{diff}, & 0 < \Phi < \frac{2}{3}\pi \\ A_{MEA_{normal}}, & \frac{2}{3}\pi < \Phi < \pi \end{cases} \quad (18)$$

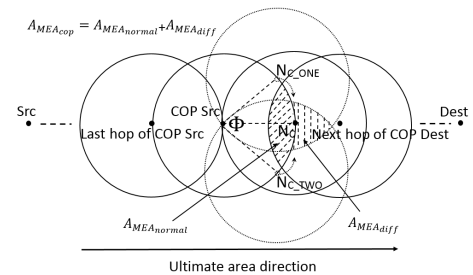


Fig. 11. MEA in MANETs with COP Topology

$$A_{MEA_{normal}} = r^2 \left(\frac{2\pi}{3} - \sin \frac{2\pi}{3} \right) \quad (19)$$

$$A_{MEA_{diff}} = r^2 \left[(\pi - \Phi) - \sin(\pi - \Phi) \right] - \frac{1}{4} \times 2r \times \sin\left(\frac{\pi}{3} - \frac{\Phi}{2}\right) \times \sqrt{4r^2 - [2r \times \sin\left(\frac{\pi}{3} - \frac{\Phi}{2}\right)]^2} - 2 \times \left(r^2 \sin^{-1} \frac{1}{2} - \frac{r}{4} \sqrt{3r^2} \right) - r^2 \sin^{-1} \frac{2r \times \sin\left(\frac{\pi}{3} - \frac{\Phi}{2}\right)}{2r} + \frac{2r \times \sin\left(\frac{\pi}{3} - \frac{\Phi}{2}\right)}{4} \sqrt{4r^2 - [2r \times \sin\left(\frac{\pi}{3} - \frac{\Phi}{2}\right)]^2} \quad (20)$$

In Figure 12, for a given transmission range, the smaller the angle Φ is, the larger the MEA (Mobility Extension Area) for the MANETs with COP topologies will be. The reason is that when the angle Φ is becoming smaller, two Cooperative nodes in the COP topology are moving to positions which are closer to the destination node and their transmission coverages along the direction from the source node to the destination node becomes larger. Therefore, the larger transmission coverage provided by Cooperative nodes in the MANETs with COP topologies allows us to accommodate more mobility without detriment for the COP Dest in the COP topology than a normal MANET. Furthermore, as the transmission range becomes larger, the MEA of the COP case is more than 3 times larger than the normal case which means the COP case has much more resilience to mobility induced link breaks. We illustrate this further in the following sections by comparing the performance among AODV [18], DSR [26] and CRCPR.

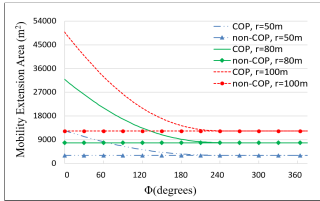


Fig. 12. MEA with Different Coverages

B. CRCPR versus AODV and DSR

In order to investigate the performance of CRRP, several scenarios are explored using an OpNET simulation platform. As with [15], AODV is chosen as one of our baselines because AODV is widely adopted and its operation is well understood by the research community. Furthermore, DSR is selected as the other baseline as DSR caches back-up routes against link breaks due to mobility, which is similar to CRCPR in terms of route robustness.

1) *Scenario*: A simulation environment is configured as an area of size 1000 meters by 1000 meters. In order to estimate the link break probability we employ the same Random Walk Mobility Model as proposed in [25]. The random trajectories are recorded for each node providing repeatability to ensure comparisons are fair. As a typical MANET comprises less than 100 nodes [15], two network sizes are considered: a 25-node and 50-node case. In the 25-node scenario, we have one call with the number of random mobile nodes increasing from one to five. In the 50-node scenario, two simultaneous calls are set up with the number of random mobile nodes increasing

from one to eight. The speed distribution for each mobile node in both scenarios is uniform [0,10] (m/s). Each scenario runs for 20 minutes simulation time with 10 random seeds to avoid the influence of correlation effects. Figure 13 gives one example scenario for 50 nodes with eight mobile nodes. The source node is N_2, N_3 and the destination node is N_{11}, N_{10} . The differently colored-label nodes represent the mobile nodes and each mobile node is randomly chosen to run within its corresponding blue rectangular region which is randomly decided as well.

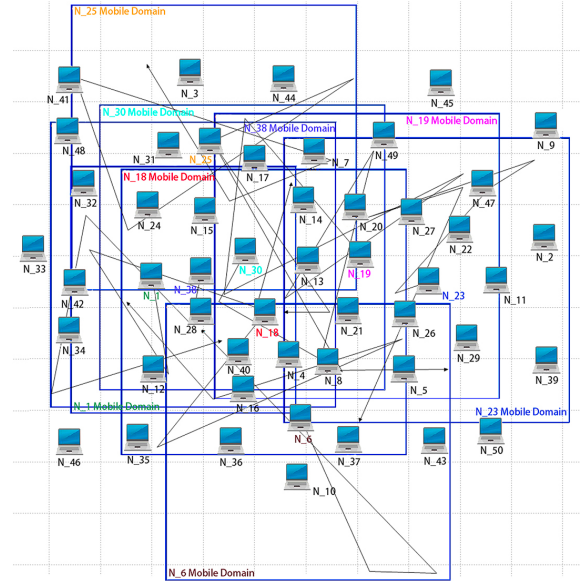


Fig. 13. Scenario for 50 Nodes

2) *Number of Link Breaks*: The results of (a) in Figure 14 show the link break frequency of the three protocols in the 50-node scenario. As DSR has a route cache scheme during the route discovery process, it costs a lot of memory to save many back-up routes in the nodes. Once the current route is broken, it will divert to a new route according the cached route. Therefore, with increasing numbers of mobile nodes, the cached routes can lead to a smaller link break frequency. For AODV, it has no specific scheme to avoid link breaks, so the link break frequency will increase quickly when the number of mobile nodes becomes larger. In CRCPR, it enhances the resilience to mitigate the mobility issue via the COP Table and Relay Table. Therefore, when the number of random mobile nodes increases from 1 to 5, CRCPR has the same performance as AODV. With 6, 7 and 8 random mobile nodes, the frequency of link breaks for CRCPR remains much lower than AODV.

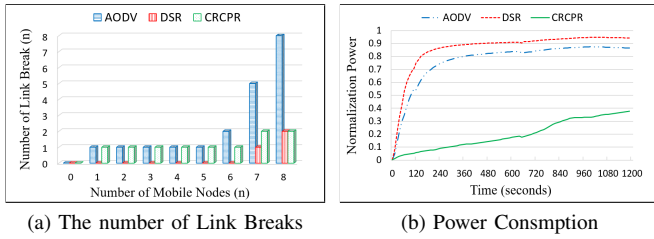


Fig. 14. Results of CRCPR versus AODV and DSR in 50-nodes Scenario

3) *Power Consumption*: All the results for power consumption are normalized according to the Equation 21, where pp is the packet *Processing Power* per bit, t_p is the *Transmission Power* per bit, b_{total} is the total bits including the data from the Application layer, control packets from the Network and MAC layers, as well as the packet header of data packet added by the Network and MAC layers, b_{data} is only the data bits from the Application layer and con is a selectable scaling coefficient to ensure our results are shown within a reasonable range.

$$P_n = \frac{2}{\pi} \times \arctan \left[con \times e^{\left(\frac{t_p \times b_{total} + pp \times b_{total}}{t_p \times b_{data} + pp \times b_{data}} \right)} \right] \quad (21)$$

From (b) of Figure 14, CRCPR has the best performance whilst DSR has the worst. The reason is that once a COP topology is selected for a route or a COP topology is formed locally during the transmission, the power will be saved more than 40% relative to the non-cooperative transmission case according to [10]. DSR consumes much energy due to the retransmission mechanism.

4) *End-to-End Delay*: As we can see from Figure 15, when more mobile nodes are involved in the scenario, the end-to-end delay of all three of these protocols increases. DSR has the worst performance. The reason is that DSR has a data cache scheme to make sure the data can be transmitted to the destination. As more link breaks happen, the longer will be the time the data will be buffered and this leads to higher end-to-end delay. As there is no specific data cache scheme in AODV and CRCPR, the end-to-end delay performance is better than DSR. More specifically, due to the link break reduction in CRCPR, the end-to-end delay for CRCPR is more stable compared with AODV when the number of mobile nodes increases and provides the best performance.

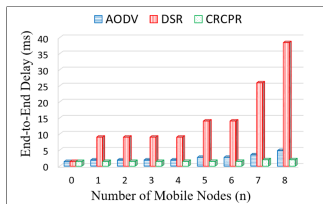


Fig. 15. End-to-End Delay

C. CRCPR versus CWR

CRCPR utilizes several data structures, namely: the Cooperative Neighbor Table, the COP Table and Relay Table to replace the “request-to-recruit” scheme in CWR [17] to reduce the control overhead and enhance resilience to mobility

induced link breaks. In order to investigate the mobility resilience of CWR and CRCPR, two simulation parameters, throughput and the number of link breaks, are explored.

As described in the Route Selection Criteria section, CRCPR includes a new route selection algorithm which can utilize RMV to estimate the energy and link break probability at the same time when it decides a particular route. In order to assess the performance of the route selection scheme in CRCPR, network lifetime is also considered. The Cooperative Neighbor Table, COP Table and Relay Table data structures in CRCPR require hello messages to be relayed except for normal broadcasting. Also, some additional information like the *NSN Addr List* field needs to be carried compared to a traditional routing protocol. Therefore, we also propose a new hello message mechanism called the Adaptive Classified Hello Scheme (ACHS) [27] to reduce unnecessary hello packet transmission in CRCPR. The hello message overhead of CWR versus CRCPR is thus explored as well.

1) *Scenario*: Two sets of experiments are run to compare CWR with CRCPR. The first set is used to compare mobility resilience and network lifetime. In order to make the comparison more reasonable, we use a similar scenario to that given in [17] regarding CWR to observe the performance. The only difference is that we change the network scale from 7 rows \times 21 columns of nodes to 3 rows \times 7 columns. This is reasonable as for our mobility resilience investigations, it is not necessary to involve a large network but only the ratio of mobile nodes to fixed ones. The straight-line distance between two adjacent fixed nodes is 20m and transmission range of each node is 30m. The source node is located in the first column of the middle row and the destination node is located in the same row, which means the final route consists of 5 hops. The number of mobile nodes in the simulation scenario increases from 4 to 8 in five simulation cases. In each simulation case, we run 30 trials for a given number of mobile nodes. The mobile nodes are deployed randomly. The second set of experiments explores the number of hello messages in CWR and CRCPR according to the network density. All the nodes are randomly deployed in an area of size of 300 meters by 300 meters. In order to realize different network densities, we will increase the number of nodes in this fixed area from 15 to 55 in 5 steps, giving five simulation cases. For each simulation case, we repeat the experiment 30 times with different random node-deployment seeds. The transmission range is also 30m. The hello message interval for CWR and CRCPR is set to 1s which is the same as AODV. For these two sets of experiments, the simulation time is set to 20 minutes.

2) *Resilience to Mobility*: We provide the 95% confidence intervals when showing the results. From (a) of Figure 16, we can see the throughput of CWR decreases with increasing mobile nodes, but the performance of CRCPR is more stable. The better performance of CRCPR is because it can utilize the COP topology to improve the robustness against node mobility. If one C node in the COP topology is selected as a mobile node, it does not lead to a link break as explained in the Route Enhancement section. Furthermore, if possible, the route selection criteria of CRCPR will avoid choosing a node with high link break probability in the final route, so a more stable

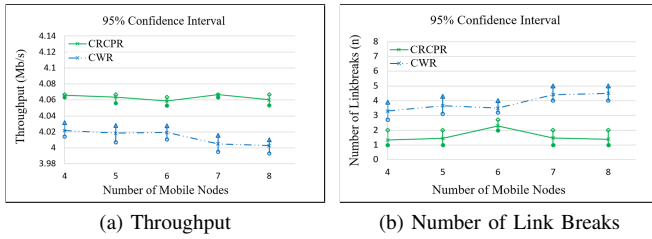


Fig. 16. Resilience to Mobility of CWR and CRCPR

route will be selected in CRCPR than the “shortest path” route selected in CWR. The resilience of CRCPR can also be seen in regard to the number of link breaks in (b) of Figure 16. As the number of mobile nodes increases, the number of link breaks with CRCPR remains lower than for CWR, which results in the route recovery process being invoked less frequently and improves the network throughput.

3) *Network Life Time*: Network lifetime is defined as the network duration when the first node along the route experiences energy drain out. For CWR, none of the nodes possess a energy harvesting (EH) capability. Therefore, in order to make the comparison fairer, we deactivate the EH function of CRCPR. The same simulation setup used for assessing the mobility resilience is implemented to investigate the route selection performance of CWR and CRCPR. More precisely, similar to the mobile node deployment approach, we only change the role of mobile nodes to energy restricted (ER), which assigns them lower energy than the normal nodes. In (a) of Figure 18, with increasing ER nodes, network lifetime of both CWR and CRCPR decreases. However, when the number of ER nodes is lower than 3, the performance of CRCPR is almost unchanged. The reason is the route selection scheme in CRCPR avoids choosing ER nodes along the final route, where possible, and leads to higher lifetime performance. When the number of ER nodes becomes larger, like 6 ER nodes in the scenario, CWR and CRCPR exhibit similar network lifetime. This is because when more ER nodes are present in the scenario, it becomes much harder for the CRCPR route selection scheme to find a route without ER nodes. Therefore, both CWR and CRCPR show the similar lifetime performance.

4) *Hello Message Enhancement*: From (a) of Figure 17, if the network scale becomes larger, the number of hello messages will increase no matter whether broadcast hello messages or relay hello messages (unicast hello messages) are employed. More nodes in the scenario leads to more hello messages being sent to maintain the neighbor relationships. For CRCPR, the number of broadcast hello messages will increase from 200 to 800 and the number of relay hello messages will increase from 100 to 1400 on average. For CWR, the number of broadcast hello messages will increase from 700 to 2700. The increment of the number of hello messages in both protocols is because more nodes in the scenario leads to more hello messages being sent to maintain the neighbour relationships. However, the broadcast hello message quantity of CRCPR is much lower than CWR. Even if relay hello messages are included, the total number of hello messages in CRCPR is still less. The trend with relay hellos is caused by the number of COP topologies in CRCPR which

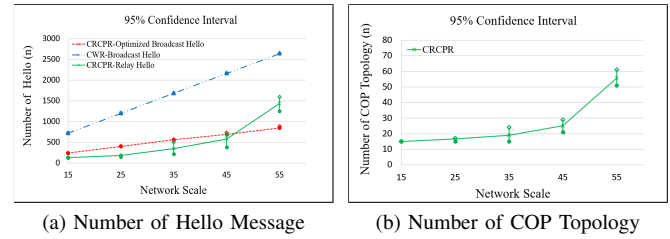


Fig. 17. Hello Message Enhancement

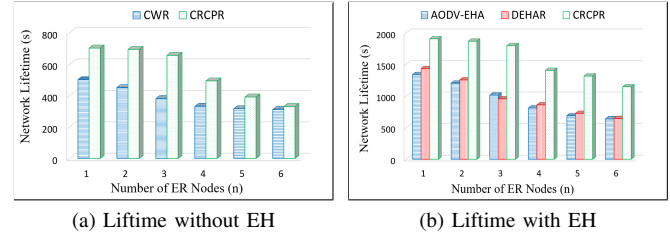


Fig. 18. Network Lifetime

is illustrated in (b) of Figure. With relay hellos, CRCPR may result in more control overhead than CWR if the network size becomes very large. However, a typical MANET, comprises fewer than 100 nodes [15]. Therefore, we can conclude that although the Cooperative Neighbor Table, COP Table and Relay Table increase the overhead of CRCPR in terms of hello message transmissions, the ACHS scheme can ameliorate this problem and reduce the number of hello messages without impacting on the overall network performance.

D. CRCPR versus DEHAR and AODV-EHA

As CWR does not consider the energy harvest capability of nodes, in order to make the comparison more appropriate, we employ two other routing protocols that account for the energy harvesting property: DEHAR [20] and AODV-EHA [19]. The features of these two protocols have been introduced in the Related Work section

1) *Scenario*: The same scenario used in the first set of experiments when investigating CWR and CRCPR is employed in this simulation. At the beginning of the simulation, all the ER nodes are set with the same energy. This scenario does not only reflect the different performance of CRCPR, DEHAR and AODV-EHA in terms of network lifetime, but also confirms the energy saving ability of cooperative communication in CRCPR.

2) *Network Life Time*: As shown in (b) of Figure 18, the overall lifetime performance is better than (a) of Figure 18, which proves that energy harvesting can increase the lifetime of the network. With increasing of ER nodes, the lifetime of all three protocols becomes shorter. But when the number of ER nodes is less than 3, CRCPR has the best performance and remains stable due to its route selection criteria which avoids choosing energy-restricted nodes in the final route. When the number of ER nodes becomes larger, although CRCPR cannot avoid the ER nodes in the final route (the same conclusion when comparing CRCPR and CWR), the lifetime is still much longer than the other two energy harvesting protocols. The reason is that CRCPR can utilize cooperative communication to save energy during transmissions.

E. Summary of Results

According to all the above simulation results, several advantages of the design in this article have been proved. Firstly, with help of topological information stored in Cooperative Neighbor Table, COP Table and Relay Table, the resilience to mobility of CRCPR is improved greatly. Secondly, the Adaptive Classified Hello Scheme can reduce the control overhead without influencing the overall network performance. Thirdly, considering the energy factors (EH and ER) when selecting the final route, the network lifetime is prolonged apparently.

V. CONCLUSIONS

In this work, we have introduced a novel routing protocol called “Constructive Relay based Cooperative Routing” based on cooperative communication to support emerging environments in MANETs. By exploiting cooperative communication with the help of a COP Table data structure, energy consumption during transmissions can be significantly reduced. Additionally, by employing a relay principle based on a Relay Table, CRCPR provides greater robustness against node mobility induced link breaks. A new route selection scheme utilizes Routing Matrix Values (RMV) from the Physical/MAC layer such as the residual energy, energy harvesting ability and link break probability to help determine the final route. The overall network performance is improved significantly. Our Network layer framework explicitly covers cooperative route discovery, route reply and route enhancement and cooperative data forwarding. This framework can be readily integrated with existing lower layer mechanisms to improve the performance of MANETs.

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