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A Network Coding-Aware Routing Mechanism for Time-Sensitive Data Delivery in Multi-Hop Wireless Networks

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Abstract

The network coding mechanism has attracted much attention because of its advantage of enhanced network throughput which is a desirable characteristic especially in a multi-hop wireless network with limited link capacity such as the device-to-device (D2D) communication network of 5G. COPE proposes to use the XOR-based network coding in the two-hop wireless network topology. For multi-hop wireless networks, the Distributed Coding-Aware Routing (DCAR) mechanism was proposed, in which the coding conditions for two flows intersecting at an intermediate node are defined and the routing metric to improve the coding opportunity by preferring those routes with longer queues is designed. Because the routes with longer queues may increase the delay, DCAR is inefficient in delivering real-time multimedia traffic flows. In this paper, we propose a network coding-aware routing protocol for multi-hop wireless networks that enhances DCAR by considering traffic load distribution and link quality. From this, we can achieve higher network throughput and lower end-to-end delay at the same time for the proper delivery of time-sensitive data flow. The Qualnet-based simulation results show that our proposed scheme outperforms DCAR in terms of throughput and delay.

Keywords

Coding-Aware Routing, Link Quality, Multi-Hop Wireless Network, Network Coding, Traffic Load Distribution

1. Introduction

Device-to-device (D2D) communication is one of the capabilities of 5G and currently under process of standardization and will be included in 3GPP Release 12 [1]. D2D communication allows devices in proximity to communicate directly via a wireless link with bypassing the base station (BS). However, in disaster situations with malfunctioning BSs, D2D devices act autonomously and the coverage of D2D communication may be extended to multiple wireless hops like the mobile ad hoc network (MANET). The authors in [2] categorized D2D communication into four types and, among them, the D2D communication type of the device relaying with device controlled link establishment (DR-DC) is similar to MANET. In the case of DR-DC, source and destination devices coordinate their communication using relays between them without the involvement of the cellular network operator. Communications via multi-hop wireless links are significantly affected by limited wireless link capacity, so the mechanisms to resolve this limitation are required for the proper operation of D2D communication of the type DR-DC.

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Recently, there has been intensive research done on network coding for the improvement of network performance in multi-hop wireless networks. Network coding has the advantages of increased throughput and energy efficiency thanks to its capability of delivering more information than the traditional non-network coding based delivery mechanisms. Inter-flow network coding is the mechanism of encoding packets from multiple flows together at intermediate nodes [3-10]. Most of the inter-flow network coding-based data delivery mechanisms have considered simple network topologies such as two-hop transmissions using a relay in the middle. In this paper, we aim to improve the network performance by adopting network coding in the routing domain. Related to this, the distributed coding-aware routing (DCAR) mechanism is proposed in [7]. In DCAR, routes are established based on the dynamic source routing [11] mainly through those links with more data in outgoing queues in order to maximize the possibility of network coding. The motivation of DCAR is that the network coding possibility increases as more packets are given. Even though DCAR can increase the possibility of encoding, the end-to-end delay may increase as well because of longer queues on a route and it becomes even worse because traffic tends to concentrate on those nodes with longer queues. Therefore, DCAR may not be a good candidate for time-sensitive real-time services like real-time video. Moreover, once an intermediate node receives an encoded packet, it has to decode the packet. This may force packets to experience multiple encoding and decoding operations on the end-to-end route, resulting in increased delay.

In this paper, we extend our work in [8] where a network coding-aware routing mechanism based on DCAR is proposed to find an expedite route with a single encoding possible node for a new flow of a given source and destination pair. That is, a data packet is encoded only once on a given route and, once it is encoded, it is forwarded onto the path with less traffic (i.e., shorter queues) without being decoded at intermediate nodes for the expedite data delivery to the destination.

This paper is organized as follows. In Section 2, we briefly go through how inter-flow network coding works in two-hop and multi-hop wireless networks. Because our proposed routing mechanism is primarily based on DCAR, the detail operation of DCAR is given in Section 2. In Section 3, our coding-aware routing mechanism is described in detail. Section 4 gives the performance analysis and we conclude in Section 5.

2. Related Work

The network coding has attracted many researchers because of its capability of network throughput improvement. The network coding allows more packets to be delivered compared with the traditional mechanism. In [3], COPE which is a new forwarding architecture adopting the network coding in the wireless network is proposed. COPE can reduce the number of transmissions, but it can be applied only to a limited network topology such as the chain topology, the X topology, the cross topology and the wheel topology. And the network coding opportunity heavily depends on the traffic pattern. Recently, inter-flow network coding mechanisms for multi-hop wireless networks have been proposed. [10] classifies inter-flow network coding mechanisms into opportunistic and deterministic routing schemes. In the opportunistic routing mechanism, every intermediate node decides whether to encode packets from multiple flows based on a given forwarding probability [4-6]. On the other hand, in the deterministic mechanism, an end-to-end route for a new flow is determined according to coding opportunities [7-10]. [9] proposes the connected dominating set (CDS)-based and flow-oriented coding-aware routing (CFCR) mechanism that selects coding capable nodes from CDS. However, the concept of CDS can be applied only to the static network such as the wireless mesh network, and CFCR operates in four steps, RREQ, RREP, RC and RC_ACK steps. [10] proposes the distributed greedy coding-aware deterministic routing (DGCDR) that allows packets from more than two flows to be encoded. Similar to CFCR, DGCDR consists of four steps, RREQ, RREP, RCON and RACK steps, for route establishment, resulting in almost twice longer route setup time than the scheme based on DSR such as [7] and [8], and requires much more information to be included in the routing-related messages.

DCAR [7] operates based on DSR and integrates route determination with network coding for two flows. DCAR checks the network coding possibility of an existing flow and a new flow during the route discovery. For this, nodes periodically exchange HELLO messages to obtain the link status of 1-hop neighbors. During the route discovery phase, the sender puts its 1-hop neighbor information and its link quality or success probability in a route request (RREQ) message. Once a node receives the RREQ message, it stores the neighbor and link quality information in the RREQ message. If a node receives an RREP message, it checks the possibility of coding opportunity by comparing the route information in the RREP message and the stored RREQ information. If a node on the route is found to be coding capable, it is marked as coding capable in the RREP message. A node c can encode packets of two flows F_1 and F_2 intersecting at c, if and only if the following conditions (C1) and (C2) are met:

(C1) There exists $d_1 \in D(c, F_1)$, such that $d_1 \in N(s_2)$, $s_2 \in U(c, F_2)$, OR $d_1 \in U(c, F_2)$.

(C2) There exists $d_2 \in D(c, F_2)$, such that $d_2 \in N(s_1)$, $s_1 \in U(c, F_1)$, OR $d_2 \in U(c, F_1)$.

where s_i and d_i are the source and the destination of F_i, respectively.

Also, in DCAR, the coding-aware routing metric (CRM) is computed and included in the RREP message. The CRM value of a link *l* is defined based on the queue lengths of itself and its neighbors:

$$CRM_l = \frac{1 + MIQ_d(l)}{1 - P_l} \tag{1}$$

where P_l is the packet loss probability and $MIQ_d(l)$ is the dynamic modified interference queue length of the transmitter on *l*. Here, $MIQ_d(l)$ corresponds to the expected number of transmissions for successfully transmitting the existing packets as well as one incoming packet for the new flow.

The node with shorter queues of itself and its neighbors has a larger CRM value. Then, the source selects the route with the smallest CRM value (i.e., the route composed of the nodes with longer queues). That is, the DCAR routing mechanism prefers the routes composed of nodes with longer queues so that the possibility of network coding can be increased. Even though this can enhance the coding opportunity, it may increase the end-to-end delay as a side effect. Besides, intermediate nodes may perform unnecessary network coding and decoding operations if there is more than one coding capable node on the route as shown in Fig. 1 (i.e., the route with two coding capable nodes may result in lower throughput).

Therefore, in this paper, we propose a coding-aware routing mechanism for multi-hop wireless networks which allows a low delay route for a new flow with only one coding capable node.

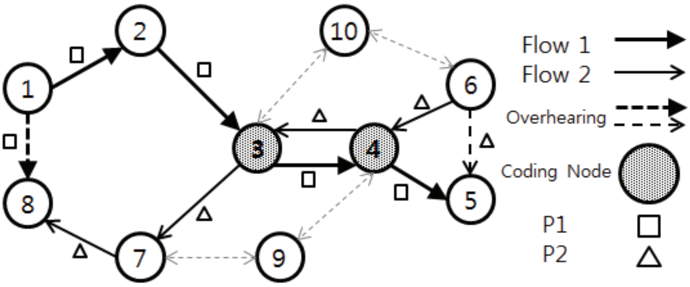


Fig. 1. DCAR routing in a topology with two coding capable nodes.

3. Delay-Throughput Coding-Aware Routing Mechanism

Our proposed mechanism aims to minimize the delay and, at the same time, maximize the throughput by adopting the routes composed of high quality links with only one network coding capable intermediate node. The routing metric used in our routing mechanism is the same as that of DCAR, i.e., CRM, and the route discovery is composed of two phases, the RREQ broadcast phase and the RREP unicast phase. Each node maintains two tables, the neighbor status table and the candidate route table. The neighbor status table consists of entries for 1-hop neighbors and their corresponding link quality (represented in the delivery success ratio). The candidate route table contains the partial routes from a source to itself which are discovered during the RREQ broadcast phase.

The RREQ broadcast phase is performed as follows. When a new flow is created by the source node, the source broadcasts the RREQ message with its neighbor status information. If an intermediate node receives an RREQ message, it stores the discovered candidate route in its candidate route table and adds its own neighbor status in the forwarded RREQ message. In order to prevent the number of RREQ messages from being exponentially increased, the number of candidate route information in the RREQ message can be limited to a specific number. During the RREQ broadcast phase, each node can obtain the candidate routes from the source to itself and the corresponding link status of those nodes on the routes.

Fig. 2 shows how nodes get the neighbor status information of the other nodes on the partial routes throughout the RREQ broadcast phase for the example of Fig. 1. The nodes 10 and 4 can have the neighbor status information of the node 6, the source of the new flow F2. Here, ‘x↔y: c’ implies that the quality of the link between the nodes x and y is c. For example, the node 4 forwards the RREQ message with including its own neighbor status information, 4↔3: 0.7, 4↔5: 0.8, 4↔6: 0.8 and 4↔9: 0.7.

The example of candidate routes obtained during the RREQ broadcast phase is shown in Fig. 3. For example, the node 7 has three candidate routes, 8↔7↔3↔10↔6, 8↔7↔3↔4↔6 and 8↔7↔9↔4↔6.

Once the destination receives the RREQ message via the shortest route, it waits for a given amount of time for other RREQs to arrive. Among the routes collected from the received RREQ messages, the destination sends back the RREP message via the shortest route with the minimum cost route information. The node receiving the RREP message directly from the destination includes the candidate routes for the new flow in the RREP message before forwarding the RREP message. And, with each of the candidate routes, only the smallest link quality value is associated in order to reduce the overhead of the RREP message.

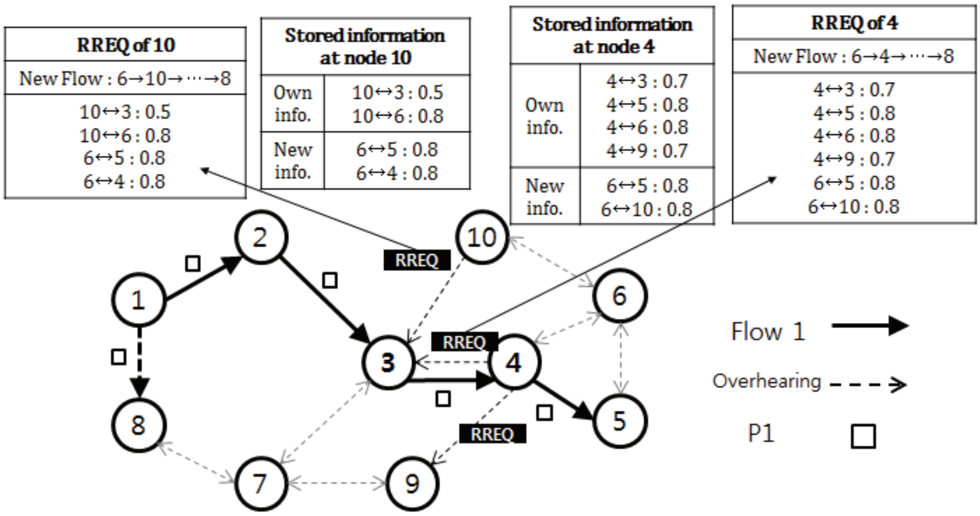


Fig. 2. The RREQ broadcast phase.

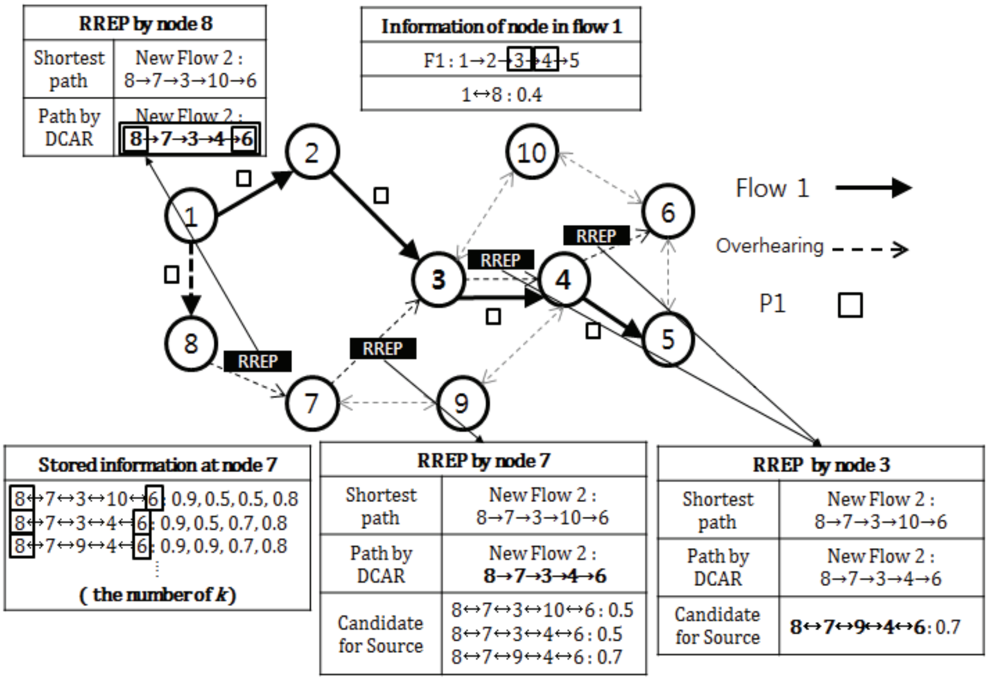
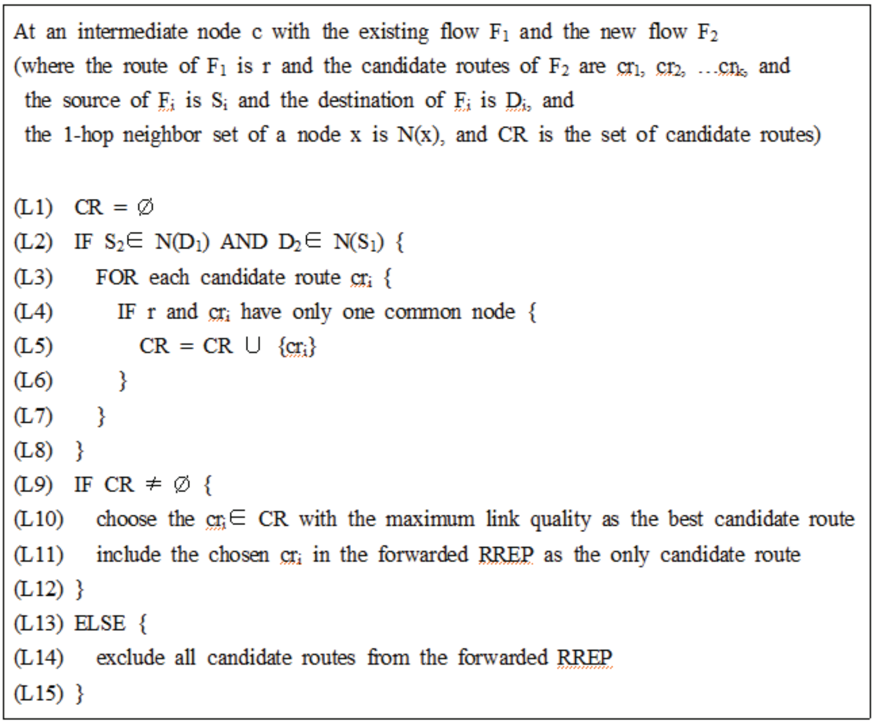


Fig. 3. The RREP unicast phase.

For example, in Fig. 3, the destination node 8 includes the minimum cost path (indicated as 'Path by DCAR') in the RREP message and sends this message via the shortest path 8↔7↔3↔10↔6. When the node 7 receives this RREP message, it forwards the message with the candidate paths (indicated as 'Candidate for Source').

Each intermediate node on the shortest route compares the candidate route information in the received RREP message with the route information of the existing flow in order to figure out whether it can be the coding capable node or not for the new and the existing flows, and chooses the best candidate route. The procedure for selecting the best candidate route is shown in Fig. 4. In the procedure, F1 is the existing flow and F2 is the new flow. Only the candidate routes of F2 satisfying the condition in (L2) and with only one coding capable node for F1 and F2 (in (L5)) can be considered in selecting the best candidate route of F2 (in (L10) to (L11)).

For example, in Fig. 3, because F1 and F2 satisfy the condition in (L2), the node 3 can select the best candidate route for F2. Thus, in (L3) to (L6), the node 3 compares the route of the existing flow F1, 1↔2↔3↔4↔5, with the candidate routes for F2 in the RREP message. Among the candidate routes, 8↔7↔9↔4↔6 and 8↔7↔3↔10↔6 are taken into considerations because they have a single coding capable node 4 and 3, respectively. That is, in (L9), 8↔7↔9↔4↔6 and 8↔7↔3↔10↔6 are in the set CR. Then, in (L10) to (L11), the node 3 chooses 8↔7↔9↔4↔6 as the best candidate route because it has a higher link quality value of 0.7 than 0.5 of 8↔7↔3↔10↔6, and includes only 8↔7↔9↔4↔6 in the forwarded RREP message.



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At an intermediate node c with the existing flow $F_1$ and the new flow $F_2$
(where the route of $F_1$ is r and the candidate routes of $F_2$ are $cr_1$, $cr_2$, ...$cr_k$, and
 the source of $F_i$ is $S_i$ and the destination of $F_i$ is $D_i$, and
 the 1-hop neighbor set of a node x is N(x), and CR is the set of candidate routes)

(L1)  CR = $\emptyset$
(L2)  IF $S_2 \in N(D_1)$ AND $D_2 \in N(S_1)$ {
(L3)      FOR each candidate route $cr_i$ {
(L4)          IF r and $cr_i$ have only one common node {
(L5)              CR = CR $\cup$ {$cr_i$}
(L6)          }
(L7)      }
(L8)  }
(L9)  IF CR $\neq \emptyset$ {
(L10)     choose the $cr_i \in$ CR with the maximum link quality as the best candidate route
(L11)     include the chosen $cr_i$ in the forwarded RREP as the only candidate route
(L12) }
(L13) ELSE {
(L14)     exclude all candidate routes from the forwarded RREP
(L15) }
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Fig. 4. The procedure for selecting the best candidate route.

Now, the source of the new flow has the flexibility of selecting a route according to the QoS requirements of the new flow. The shortest route is the route with the minimum delay and the minimum cost route is the route with the highest network coding opportunities. And the best candidate route is the route that can satisfy both the delay and the throughput requirements.

Once a packet is coded with another packet at an intermediate node, the coded packet must be decoded only at the destination.

4. Performance Evaluation

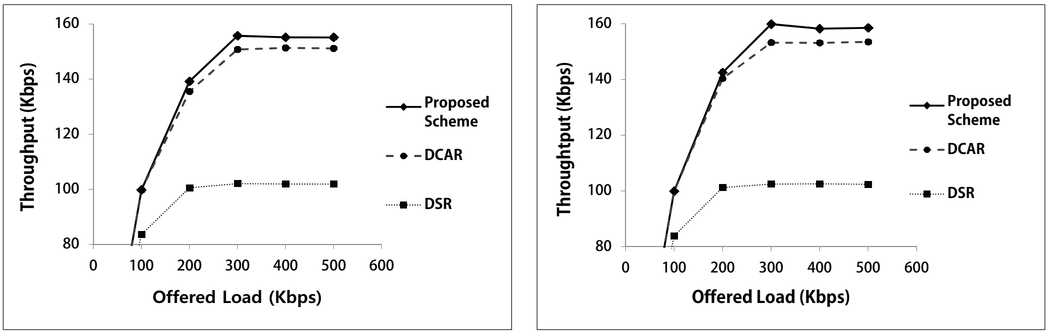
For the performance analysis of the proposed mechanism, we have carried out simulations based on Qualnet [12] and compared ours with DCAR and DSR without network coding capability. The simulation network is set to the topology in Fig. 1. In the network, the existing flow, F1, is from the node 1 to 5 via 2, 3 and 4. The new flow, F2, is from 6 to 8 via 4, 3 and 7 in DCAR, and via 4, 9 and 7 in our mechanism. The coding nodes are 3 and 4 in DCAR, and only 4 in ours. We have used the IEEE 802.11b as the MAC protocol and the maximum queue size of 50,000 bytes and the constant bit rate (CBR) sources. Table 1 gives the list of simulation parameters.

Table 1. Simulation parameters

Parameter	Value
Network size (m)	1000 × 1500
Simulation time (s)	180
Channel frequency (GHz)	2.4
MAC protocol	IEEE 802.11b
Physical layer data rate (Mbps)	2
Source-destination pairs	2
Queue size (byte)	50,000
Traffic model	CBR
Packet size (byte)	512
Offered load (kbps)	100–500

The performance factors considered for the evaluation are the average transmission delay and the throughput. The average transmission delay is the average of the delays of all the packets transmitted and the throughput is the average bits per second delivered to each destination.

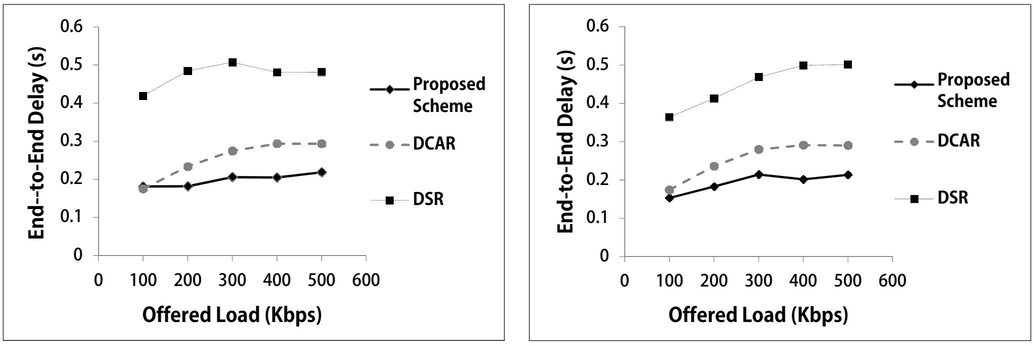
Fig. 5 depicts the simulation results in terms of the average throughput of each flow for various offered loads. As the graph shows, our mechanism slightly outperforms DCAR in terms of the average throughput because of the load balancing effect of ours. DSR without network coding gives the lowest throughput which is almost 2/3 of ours and DCAR. In all the mechanisms, if the offered traffic load is larger than 300 kbps, the average throughput is kept almost the same. This is due to collisions and interference caused by multi-hop wireless transmissions.



(a) (b)

Fig. 5. Average throughput vs. offered load for F1 (a), for F2 (b).

Fig. 6 shows the average source-to-destination delay of each flow for various offered traffic loads. As shown in Fig. 6, our mechanism significantly outperforms DCAR and DSR, which indicates that our mechanism is more appropriate for time-sensitive data delivery than DCAR and DSR.



(a) (b)

Fig. 6. Average end-to-end delay vs. offered load for F1 (a), for F2 (b).

Fig. 7 shows the average number of packets in a node queue. Our proposed mechanism gives the smallest queue size compared with DCAR and DSR. From this, we can observe that ours works the best from the perspective of load balancing and DCAR the worst.

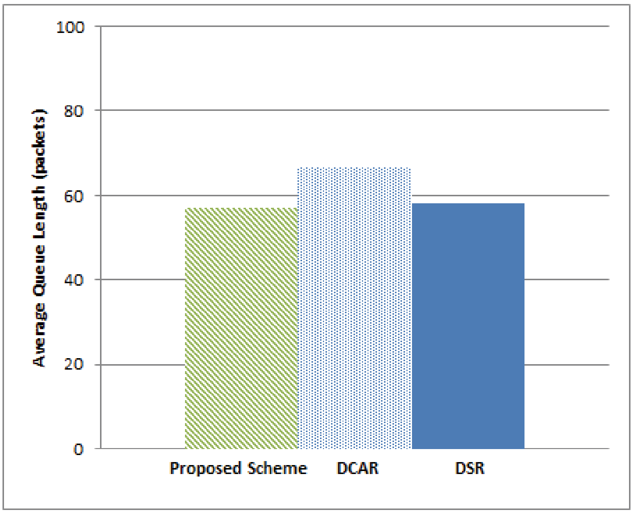


Fig. 7. Average queue length for each mechanism.

As a summary, our network coding-aware routing mechanism gives higher throughput by balancing the traffic load and lower delay by avoiding longer queues and network coding-related overhead. Intuitively, we know that throughput and delay are tightly correlated, and we have observed this from our simulation results. Finally, we can assert that our proposed mechanism is more appropriate for time-sensitive data delivery than DCAR.

5. Conclusions

One of the major issues of the network coding–aware routing mechanisms for multi-hop wireless networks is how to figure out routes with high coding opportunities for the improved network throughput. DCAR is a coding aware routing mechanism that finds source-to-destination routes based on DSR with high coding opportunities by selecting routes composed of nodes with more packets in their queues. Even though DCAR can enhance the throughput, it may not perform well in terms of delay due to larger queuing delay, possibly more hops and larger coding/decoding overhead. Therefore, in this paper, we proposed a coding-aware routing mechanism that overcomes the defect of DCAR by finding routes with only a single coding capable node for lower coding overhead and higher traffic load balancing, and with high link quality for higher reliability. Accordingly, our proposed mechanism achieves slightly better throughput and much lower delay compared with DCAR, so ours can accomplish time-sensitive data delivery.

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