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Virtual Overhearing: an Effective Way to Increase Network Coding Opportunities in Wireless Ad-Hoc Networks

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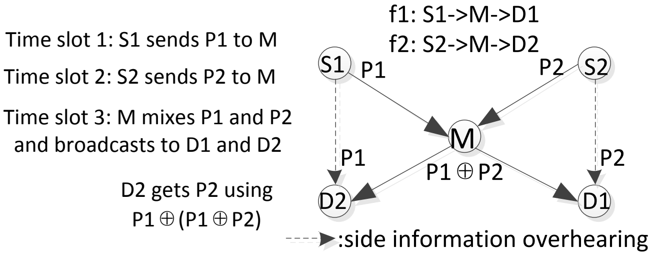
Abstract: Overhearing is of great importance to wireless network coding in that it can be exploited to obtain the side information needed for packet decoding. Recently, a new technique called virtual overhearing (VOH) was proposed to allow a node to obtain the packet sent by another node that is multiple hops away for free, which can overcome the limit of overhearing and be used to discover more coding opportunities. In this paper, we take advantage of VOH and propose two manners of usage of VOH for increasing coding opportunities in wireless ad-hoc networks. First, we make use of VOH to increase the chance of finding a route with coding opportunities for a new incoming flow. Second, and more importantly, we make use of VOH to allow a third flow to *create* coding opportunities between two established flows which are currently unmixable. Note that most previous studies only attempt to find coding opportunities rather than create them. Based on these two manners of usage of VOH, we design two routing protocols: distributed coding-aware routing with virtual overhearing (DCAR-VOH), and its enhanced version DCAR-VOH+. DCAR-VOH implements only the first manner of usage, whereas DCAR-VOH+ incorporates both manners of usage. Our extensive simulations indicate that VOH provides an effective way to discover coding opportunities, resulting in improved network performance. The positive effect of the second manner of usage stands out especially.

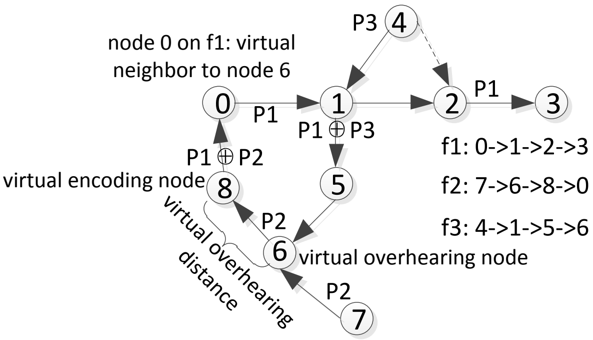
Keywords: network coding, overhearing, virtual overhearing, coding-aware routing.

1. Introduction

Overhearing is of great importance to network coding in wireless networks. In the past decade, network coding [1] emerges as a promising tool to effectively boost the wireless network capacity via packet encoding/mixing [2-4]. One important form of network coding is the inter-flow network coding [6-8], which encodes packets from different flows using XOR [6] or random linear combination [5] and serves those flows simultaneously with the coded packet(s). To decode the coded packet, some node(s) on one flow must be able to obtain the packet(s) or the side information [9] from the other flows; overhearing is generally exploited for the side information acquisition, as illustrated in Fig. 1(a). Many previous works [13-18] on inter-flow network coding exploit overhearing for network coding opportunity discovery. For example, DCAR [13] defines two conditions for an intermediate node to be an encoding node for two flows: (1) the node must be an intersection node between the two flows; and (2) with respect to the encoding node, a downstream node of each of the flows must be able to *overhear* an upstream node of the other flow.



(a) network coding with overhearing



(b) network coding with VOH

Figure 1: Inter-flow network coding examples.

Though overhearing provides an appealing way for the side information acquisition in network coding, it only takes effect in the *one-hop* neighborhood of a node and thus is restrictive in coding opportunity discovery. Fig. 1(b) presents a general scenario in multi-hop wireless ad-hoc networks to illustrate how overhearing fails to bring coding opportunities. It can be observed from the figure that all aforementioned previous works [13-18] could not find any coding opportunity at node 1, the intersection node of flow 1 (f1) and flow 3 (f3). This is because none of the downstream nodes of f3, node 5 or 6, can overhear packets of f1.

Recently, a new technique called virtual overhearing (VOH) [9] was proposed to overcome the above limit of overhearing for discovering more coding opportunities. VOH enables a node to obtain a packet sent by another node that can be *multiple* hops away for free. Thus, with VOH, a node can *virtually* overhear another node that is far away. In fact, given the establishment of f1 and f2 in Fig. 1(b), VOH can be applied to allow all upstream nodes, i.e., nodes 6 and 7, of node 8 on f2 to obtain the packet (e.g., P1) sent by node 0 on f1 at no cost, details of which will be illustrated in the next section where VOH is reviewed. Thus, with VOH in Fig. 1(b), the intersection node 1 of f1 and f3 is now enabled to encode packets from the two flows, because both node 2 on f1 and node 6 on f3 can decode the coded packet, e.g., P1 $\oplus$ P3, by node 1.

[9] mainly investigates in a simple practical network how the extra coding opportunities brought by VOH improve network performance, but it fails to consider how to make better use of VOH in a general network, e.g., in multi-hop wireless ad-hoc networks. In this paper, we take advantage of VOH and propose the following two manners of usage of VOH to increase coding opportunities. Refer to Fig. 1(b) again.

Increasing the chance of finding a route with coding opportunities for a new incoming flow: If f3 in Fig. 1(b) is the last flow to enter the network, it could be made aware of the existing VOH between node 6 on f2 and node 0 on f1, and take it into consideration in the route discovery process. By doing so, f3 could find a route with coding opportunities thanks to VOH. Actually, this routing strategy falls into network coding-aware routing [12] which aims to find coding opportunities for a new incoming flow with existing flows before its establishment. It is shown in many previous works [13-18] that coding-aware routing yields more coding opportunities and thus benefits network performance.

Allowing any new emerging of VOH (caused by new flow establishment) to create coding opportunities between two established flows which are currently unmixable: First, if f1 is the last flow to enter the network, its establishment will enable VOH between node 6 on f2 and node 0 on f1, which then *creates* coding opportunities for f1 and f3 at node 1. Second, if f2 is the last flow to be established, the situation is similar to the case above.

Note that in all previously proposed coding-aware routing protocols [13-18], if two existing flows are not mixable under real or traditional overhearing, they will never be mixable regardless of the setup of other flows. By contrast, with VOH, a third flow (e.g., f2 in Fig. 1(b)) can create coding opportunities for two unmixable existing flows. As will be seen later, this is the most attractive feature of VOH regarding new coding opportunity discovery.

To implement the above two manners of VOH usage, we propose two routing protocols in this paper: distributed coding-aware routing with virtual overhearing (DCAR-VOH) and its enhanced version DCAR-VOH+. DCAR-VOH implements the first manner of usage whereas DCAR-VOH+ implements both manners of usage. Furthermore, in this paper we conduct extensive computer simulations to study the performances of the two routing schemes in various network conditions.

The rest of this paper is organized as follows. Section 2 reviews VOH and describes the mechanism for its discovery. The designs of DCAR-VOH and DCAR-VOH+ are introduced in Sections 3 and 4, respectively. Section 5 gives the summary of the system implementation and analyzes the protocol complexity. Section 6 presents our simulation results, and Section 7 concludes this paper and discusses possible directions for future work.

2. VOH and Its Discovery

In this section, we first briefly review the conditions of VOH and illustrate how it works, and then we introduce five critical definitions related to VOH. Finally, we describe the mechanism for VOH discovery.

2.1 Conditions of VOH

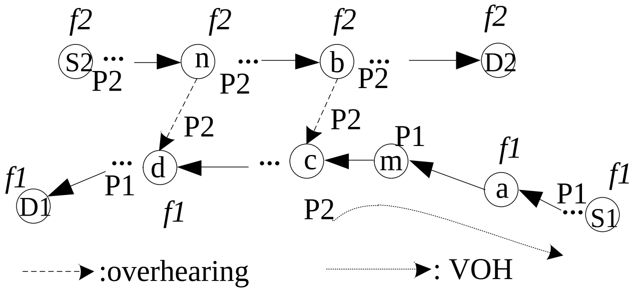


Figure 2: Conditions of VOH.

For one node, say node **a**, to virtually overhear another node, say node **b**, [9] has generalized the conditions, which are restated as follows.

1) Nodes **a** and **b** must be on the paths of two established flows, say f1 and f2, respectively.
2) There must exist one downstream node, say node **c**, of node **a** on f1 that is able to directly overhear the packet sent by node **b** on f2.
3) There must further exist one downstream node, say node **d**, of node **c** on f1 that is able to directly overhear the packet of f2.

Once the three conditions are met, node **a** on f1 can virtually overhear node **b** on f2 and obtain the packet of f2 sent by node **b** for free. Fig. 2 presents a typical scenario where node **a** on f1 virtually overhears node **b** on f2. Now let us examine how the three conditions are met in Fig. 1(b) for node 6 on f2 to virtually overhear node 0 on f1. First, given the establishment of f1 and f2, condition 1) is already met. Second, node 8, i.e., a downstream node of node 6 on f2, can directly overhear node 0 on f1, hence condition 2) is also met. Third, node 0, i.e., a downstream node of node 8 on f2, can directly overhear itself on f1 (here, we say one node can overhear itself in the sense that it knows any packet that it has sent), hence condition 3) is met. Therefore, node 6 on f2 can virtually overhear node 0 on f1.

We now illustrate in Fig. 1(b) how the packet, say P1, of f1 sent by node 0 can be obtained by node 6 for free. The idea is to allow node 8 on f2 to assist as follows. Instead of sending a packet P2 from node 7 to node 0 all the way on f2, node 8 will encode P2 with the overheard packet, P1, from f1 to form P1 $\oplus$ P2. Then node 8 broadcasts P1 $\oplus$ P2 to nodes 0 and 6. Upon receiving P1 $\oplus$ P2, node 0 could still decode P2 from P1 $\oplus$ P2 and its own native packet P1; and upon overhearing P1 $\oplus$ P2, node 6 could decode P1 from P1 $\oplus$ P2 and previously stored P2. This way, node 6 obtains or virtually overhears the packets sent by node 0 of f1, and additional coding opportunities could be discovered. In fact, similar to node 8, node 6 can also encode P1 with any packet of f2 and broadcast the coded packet to let node 7 obtain P1.

To make use of VOH in the routing protocol design, we first introduce the following five definitions related to VOH. Refer to Fig. 2 again. Node **c** is termed a *virtual encoding* node on f1, and node **d** is termed a *virtual decoding* node to node **c** on f1; node **a** is termed a *virtual overhearing* node on f1; node **b** on f2 is termed a *virtual neighbor* to node **a** on f1; and the distance (or the hop number) between nodes **a** and **c** on f1 is termed *the virtual overhearing distance* between node **a** and its virtual neighbor node **b**. Fig. 1(b) also illustrates these new terms. Obviously, VOH starts at the virtual encoding node, and the virtual decoding node is responsible for decoding the packet coded by the virtual encoding node.

2.2 Virtual Neighbor Discovery

In this subsection, we propose a *distributed* mechanism for a node on a flow to discover all potential virtual neighbors from other flows. In order to do that, two requirements are imposed.

First, every node on an existing flow records the entire path consisting of the node IDs of all of the nodes on that flow and the flow ID of that flow. Note that the flow ID is uniquely represented by the structure of (*source ID*, *flow sequence number*), where the flow sequence number is generally assigned in an increasing order to the subsequent flows generated from a source. The entire path can be directly obtained because source routing is normally adopted by network coding-aware routing [13-18]. Second, once a new flow is established, every node except the destination node on that flow broadcasts the new flow ID to its neighbors. We employ Hello message broadcast to carry this new flow ID information. Upon receiving this broadcast, each neighbor not on the same flow creates a local record in the form of (*neighbor_flow_id*, *hello_source*) where *neighbor_flow_id* is the new flow ID in the Hello message and *hello_source* is the node sending this Hello message. We refer to this record as the overhearing record (OHR). The virtual neighbor discovery procedure involves two steps:

Step 1: Reporting OHR to the upstream nodes – This step is triggered by one of the following two situations:

1) A node on some existing flow(s) creating a new OHR – If a node on some existing flow(s) creates a new OHR, then, for each existing flow, it generates a packet containing the new OHR and that existing flow ID, *my_flow_id*, and forwards that packet to all of its upstream nodes on that existing flow. Upon receiving this packet, each upstream node extracts and stores the information locally in the form of (*neighbor_flow_id*, *my_flow_id*, *hello_source, downstream_node*) where the *downstream_node* is the node sending this packet. We refer to this as the reported overhearing record (ROHR). Note that the step in this situation will allow a node on some existing flow(s) to find some virtual neighbors from a newly established flow.

2) A node with some previously stored OHRs appearing on a newly established flow – If a node on a newly established flow has previously stored OHRs, it creates a packet to contain all of those OHRs together with the new flow ID and forwards this packet to its upstream nodes along the new flow. Upon receiving that packet, each upstream node creates an ROHR for each OHR contained in the packet. The step in this situation will allow a node on a newly established flow to discover some virtual neighbors from existing flows.

Step 2: Extracting virtual neighbors from ROHRs – After Step 1, a node may have stored some ROHRs. Then, it tries to find some virtual neighbors from those ROHRs. Among those ROHRs, if there are two records with the same first two elements, i.e., *neighbor_flow_id* and *my_flow_id*, a new virtual neighbor is found according to the VOH conditions and the definition in Section 2.1. The newly found virtual neighbor is locally stored as the virtual neighbor record (VNR) in the form of (*neighbor_flow_id, my_flow_id, VN_id*) where the *VN_id* is the virtual neighbor's ID, i.e., the *hello_source* stored in one of the two ROHRs.

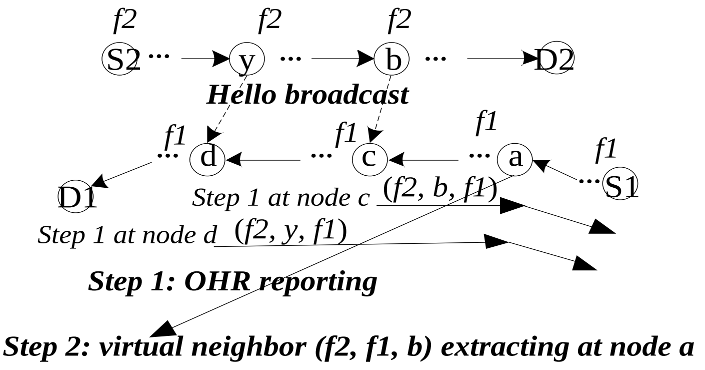


Figure 3: Virtual neighbor discovery.

Fig. 3 shows an example of the virtual neighbor discovery process in the first situation. Suppose f2 is a newly established flow. Then, after nodes **c** and **d** on f1 receive Hello messages from nodes **b** and **y** on f2, respectively, each of them creates a new OHR locally and forwards that OHR to the upstream nodes on f1. After node **a** on f1 receives two OHRs from its downstream nodes, it creates two ROHRs, (*f2, f1, b, c*) and (*f2, f1, y, d*). With these two

ROHRs, node **a** knows that node **b** on f2 is a new virtual neighbor and records it as a new VNR in the form of (*f2, f1, b*) locally.

3. DCAR-VOH

In this section, we describe how DCAR-VOH makes use of VOH during the establishment of a new incoming flow to find a route with coding opportunities. The route discovery, the route selection, and the VOH initiation are three main steps in DCAR-VOH.

3.1 Route Discovery

When a source intends to set up a flow to a destination, it needs to collect all possible paths to the destination and select the best one among them.

First, to collect those paths, the source broadcasts a route request (RREQ) packet. The RREQ packet consists of the source ID, the destination ID, and a flow sequence number.

Next, upon receiving an RREQ, if a node is not the destination and the sequence number in that RREQ is larger than the one it previously received from this source, the node then updates its local record of the sequence number for this source and further broadcasts this RREQ. Before broadcasting, the node appends its ID in the RREQ packet so as to eventually form the entire path. It also appends all of its 1-hop neighbors and VNRs in this packet. The 1-hop neighbor is directly obtained from the Hello message and the VNRs are obtained from the mechanism in Section 2.2.

Once this RREQ eventually reaches its destination, the destination then sends the route reply (RREP) packet back to the source along the opposite path recorded in the RREQ packet header.

During the forwarding of the RREP packet back to the source, each intermediate node needs to execute the following two tasks.

(1) Coding opportunity identification. If this intermediate node is on some existing flows, it needs to identify whether it could be an encoding node between the new incoming flow

and any of those existing flows. Here we treat the virtual neighbor in the same way as the 1-hop neighbor. Thus, we adopt the same two conditions as in DCAR mentioned in Section 1 to identify the coding opportunity between two flows. However, a higher priority is given to *direct* overhearing than to VOH. This means that if the network coding between two flows can be simultaneously supported by direct overhearing and VOH, direct overhearing will be used. This is because network coding with VOH has more complicated procedures, e.g., the VOH initiation, as will be shown below.

(2) Channel congestion state (CCS) report. Each intermediate node is required to report its channel congestion state [13] in the RREP so that the source can evaluate the returned routes and choose the best route. We adopt the same metric, the modified interface queue length (MIQ), defined in DCAR to reflect the channel congestion state. The MIQ length at one node is the required number of transmissions for that node to send all packets in the interface queue, and this can be calculated based on the coding graph [13]. This coding graph is built based on the coding opportunities identified from (1) for two flows. Details of the calculation of the MIQ length can be found in [13]. Then, the channel congestion state of one node is simply the sum of the MIQ length at this node and all of its neighbors. In order to know the up-to-date MIQ length values of all neighbors, every node is required to contain its current calculated MIQ length in the Hello message.

3.2 Route Selection

Once all RREP packets are returned, the source first evaluates each route by summing up the recorded MIQ length values of all intermediate nodes in the reply. Then, it chooses the route with the smallest sum for the new incoming flow. During the packet transmission process, this route path will be appended in the packet header.

3.3 VOH Initiation

Once an intermediate node knows that it is an encoding node for a new flow and the network coding is supported by VOH, the intermediate node needs to initiate the VOH. This initiation will be executed once this encoding node receives the first packet from the source of this new flow. For example, in Fig. 1(b), once node 1 receives a packet from f3 for the first time, it will inform node 8 on f2 to start mixing the overheard packet from f1 and the packet from f2 so that the decoding node of f3, node 6, can get the packet from f1 later.

Two steps are involved in the VOH initiation as shown in Fig. 4.

Step 1: *Encoding node informing the decoding node about the virtual neighbor record.* In the previous coding opportunity identification, the encoding node came to know the decoding node of the new flow and its virtual neighbor. Now, the encoding node starts sending a packet carrying this VNR to this decoding node. In Fig. 1(b), for example, node 1 knows that node 6 is the decoding node of f3 and node 0 is its virtual neighbor from the VNR (*f1, f2, 0*) contained in the RREP. Then, node 1 sends this VNR to node 6 once it receives the first packet from f3.

Step 2: *Start of VOH*. Upon receiving the VNR, (*neighbor_flow_id, my_flow_id, VN_id*), in Step 1, the decoding node then needs to inform the corresponding virtual encoding node on flow, *my_flow_id,* to start mixing the overheard packet from flow, *neighboring_flow_id.* The process works as follows. The decoding node sends a packet containing the information of *neighbor_flow_id* and *VN_id* to its first downstream node of flow, *my_flow_id.* Then, this packet will be continuously forwarded to the virtual encoding node which can directly overhear the node, *VN_id*, on the flow *neighbor_flow_id*. Then, this virtual encoding node will start mixing the overheard packets from flow *neighbor_flow_id*. All nodes on flow *my_flow_id* between the virtual encoding node and the decoding node of the new flow will further mix the packets from flow *neighbor_flow_id* so that those packets can finally reach the decoding node.

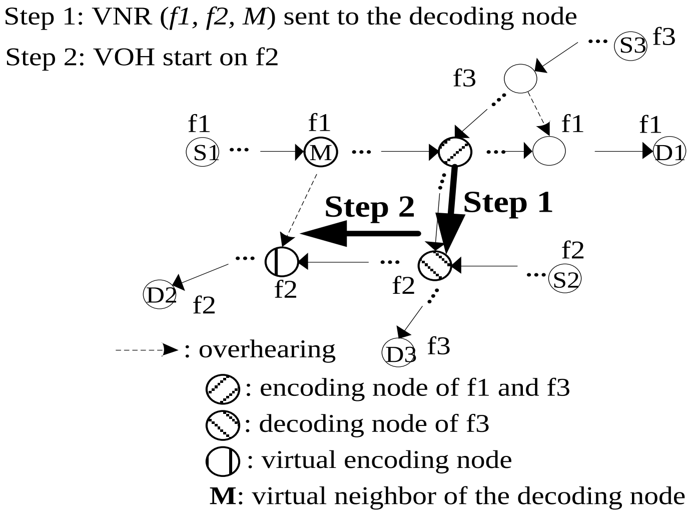


Figure 4: VOH initiation.

Note that the virtual encoding node only mixes the packets that are overheard after it receives the VOH ‘start’ command in Step 2 above. Meanwhile, we introduce a simple mechanism termed ‘*the selective VOH*’ to assist the virtual encoding node in selecting packets for mixing. If the decoding node mentioned in Step 2 lacks a certain packet, say P1, for decoding a received coded packet, it can piggyback P1’s ID onto the packets of flow *my_flow_id* to inform the virtual encoding node to choose P1 for mixing. In Fig. 1(b), for example, if node 6 receives P1 ⊕ P3 before it virtually overhears P1, it can append the ID of P1 to f2’s packets (e.g., P2) to let the virtual encoding node 8 first choose P1 to mix.

4. DCAR-VOH+

In this section, we introduce the enhanced routing scheme, DCAR-VOH+, which is designed on top of DCAR-VOH and allows any new emerging of VOH to create coding opportunities for two *unmixable* established flows.

We first present an example in Fig. 5 to show the advantage of the second manner of usage of VOH. As will be seen from the simulation study, this example is actually typical under some practical network settings. In Fig. 5 three flows form a symmetric structure, and among them f3 is the last flow entering the network. Obviously, with the first manner of usage (or in DCAR-VOH), only node 3 is identified as an encoding node for f1 and f3. If we further apply the second manner of usage, nodes 1 and 2 will be also identified as encoding nodes. Specifically, the setup of f3 enables nodes 1 and 3 to virtually overhear node 3 on f3 and node 2 on f2, respectively, which then create coding opportunities between f2 and f3 at node 2 and between f1 and f2 at node 1, respectively. Hence, in order to benefit from the second manner of usage, DCAR-VOH+ is proposed.

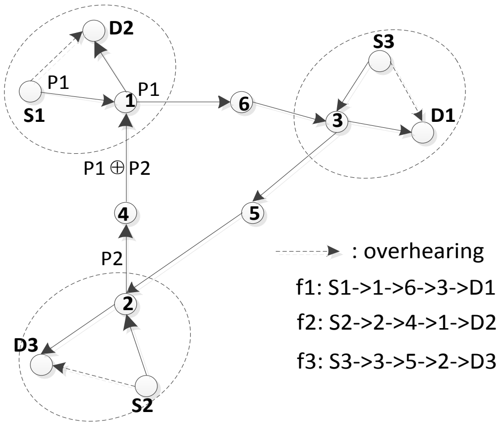


Figure 5: Coding opportunity creation in DCAR-VOH+.

DCAR-VOH+ is based on DCAR-VOH, but incorporates the following two mechanisms.

(1) *Flow overhearing status recording at the non-encoding intersection node*: For each non-encoding intersection node of two flows, say f1 and f2, if all downstream nodes of f1 (f2) can neither directly nor virtually overhear the upstream node(s) of f2 (f1), this intersection node is required to record this situation. This kind of information is referred to as the flow overhearing status, and it can be obtained during the route discovery for a new flow in DCAR-VOH when the coding opportunity identification is executed by the intersection node. In Fig. 1(b), for example, in the absence of f2,

the intersection node of f1 and f3, i.e., node 1, will make a record that none of the downstream nodes of f3 could directly or virtually overhear the upstream nodes of f1.

(2) *New VNR reporting*: As mentioned earlier, with the virtual neighbor discovery mechanism, each node may create some new VNRs after a new incoming flow is established. A new VNR creation means that the abovementioned flow overhearing status might be changed. In DCAR-VOH+, once a node on some existing flow(s) creates a new VNR, it sends a packet to report that VNR to the upstream nodes of each existing flow. This packet carries the existing flow ID, this node ID, and the new VNR, (*neighbor_flow_id, my_flow_id, VN_id*). Consider the case in Fig. 1(b) that f2 or f3 is the last established flow. After the establishment of f2 or f3, node 0 on f1 is detected by node 6 on f2 as a new virtual neighbor. Then, node 6 reports this new VNR (*f1, f2, 0*) to all of its upstream nodes on f3, including node 1.

Upon receiving the reported VNR from (2), a node knows that some downstream node of the existing flow indicated in the packet can virtually overhear some upstream node of flow *neighbor_flow_id* contained in VNR. Hence, with the acquisition of this information, a non-encoding intersection node of two flows may update its recorded flow overhearing status between the two flows, and then determine whether new coding opportunities arise between the two flows. Let us continue with the example in (2). Once node 1 receives the newly reported VNR (*f1, f2, 0*) from node 6, node 1 knows that some downstream node of f3 now can virtually overhear node 0 on f1, i.e., one of its upstream nodes on f1, and that the flow overhearing status between f1 and f3 can be updated. Thus, node 1 finally knows that it now becomes an encoding node of f1 and f3. Similarly, with the two mechanisms above, the encoding nodes, nodes 1 and 2 in Fig. 5, will be additionally found in DCAR-VOH+.

5. System Implementation and Complexity of DCAR-VOH+

We here present the system implementation of DCAR-VOH+ in NS-2. Fig. 6 shows how DCAR-VOH+ is implemented at each node. Four modules are closely related to DCAR-VOH+: the routing module, the hello broadcast module, the decoding module, and the interface queue module.

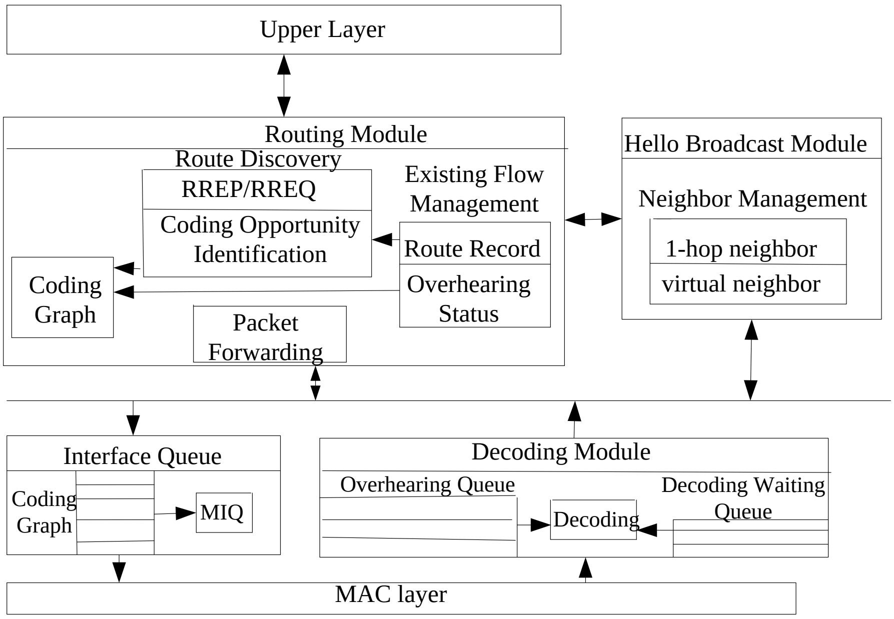


Figure 6: The architecture of DCAR-VOH+.

First, it can be seen from Fig. 6 that the routing module is to manage all flows via one node, mainly responsible for the packet forwarding, the flow route discovery, the coding opportunity identification, and the overhearing status recording between any two established flows. Second, the hello broadcast module is to manage the neighbor information, including the 1-hop neighbor and the virtual neighbor. Third, two queues reside in the decoding module: the overhearing queue and the decoding waiting queue. The former is used to store both directly overheard packets and virtually overheard packets. The latter is uniquely used in DCAR-VOH+ for storing those encoded packets, of which the decoding is supported by VOH, because it is possible in DCAR-VOH+ for the encoded packet to arrive at its decoding node earlier than the packet to be virtually overheard for decoding. For example, in Fig. 1(b), if node 8 is congested, packet P1, which needs to be virtually overheard by node 6, may arrive at node 6 later than the coded packet P1 $\oplus$ P2. Hence, with this decoding waiting queue, an coded packet in DCAR-VOH+ could be decoded later, and we refer to the waiting time for this packet to be decoded as the decoding delay for this packet. Lastly, the interface queue module is used to store those packets waiting for a free channel. Each time the interface queue module is about to send a data packet to the MAC layer, it refers to the coding graph maintained by the routing module to see whether any other queued packet can be mixed with that data packet.

We now analyze the communication complexity of DCAR-VOH+ in terms of the number of control messages. We find that DCAR-VOH+ has the same communication complexity as DCAR. The reasons are given as follows.

First, the virtual neighbor discovery in DCAR-VOH+ can be performed without incurring any new control packet. On one hand, the Hello message is used in both DCAR and DCAR-VOH+, and the broadcast of a new flow ID in DCAR-VOH+ is carried out in the Hello message transmission. On the other hand, a new created OHR can be piggybacked onto the data packet and then overheard by the upstream nodes of a flow. In Fig. 3, when node **c** sends f1's packets, it can piggyback the new created OHR onto f1's packets, and let its upstream node on f1 overhear the OHR. Later, node **c**'s upstream node(s) that overhears the new OHR can further do the same to let all node **c**'s upstream nodes on f1 be informed of this OHR. Second, the communication complexity of the flow route discovery in DCAR-VOH+ is actually the same as that in DCAR. Both DCAR-VOH+ and DCAR adopt the same route request and route reply as DSR. Third, the VOH initiation in DCAR-VOH+ also does not need any new control packet. In Fig. 4, the information carried in the two steps can actually be piggybacked onto the data packets, e.g., the VNR information in Step 1 can be piggybacked onto f3's packets. Therefore, the above three reasons show that DCAR-VOH+ has the same communication complexity as DCAR in terms of the number of the control packet.

6. Simulation Results and Discussion

This section evaluates the performances of the two proposed routing protocols, DCAR-VOH and DCAR-VOH+, in different network scenarios by simulation in NS-2. The two well-known network coding schemes, COPE [6] and DCAR [13], are used for comparison. In all simulations, IEEE 802.11 standard is adopted as the MAC layer, and the data transmission rate is fixed at 1Mbps. The radio transmission range is 100 meters, and the carrier sensing range is 250 meters. The lengths of the interface queue, the overhearing queue, and the decoding waiting queue are set at 50 packets, 500 packets, and 1500 packets, respectively. The Hello broadcast interval is 1 second. The User Datagram Protocol (UDP) is used for each flow.

6.1 Performance of DCAR-VOH in the Illustrative Network Topology

This subsection studies how DCAR-VOH responds to several important network parameters, including the traffic type, the flow rate, the link quality, and the virtual overhearing distance, in the illustrative topology of Fig. 1(b). To identify node 1 as an encoding node in DCAR-VOH, we assume in the simulation that f3 is the last flow entering the network.

A. Impact of the Traffic Type

We first study the impact of the traffic type on DCAR-VOH. Both the constant-bit-rate (CBR) traffic and the bursty traffic are considered for the source nodes in Fig. 1(b).

Case of CBR traffic: For this study, we assume all the three flows have the same flow rate. Fig. 7 shows the throughput of each flow in DCAR-VOH and DCAR at different flow rates. First, we see from Fig. 7 that at a high flow rate of 90kbps to 120kbps, the throughput of f1 and f3 in DCAR-VOH is about 21% and 26% higher than that in DCAR, respectively. Supported by VOH, network coding at node 1 between f1 and f3 improves the throughput of both f1 and f3 in DCAR-VOH. Especially, we find in this study that most encoded packets of f3 are successfully decoded at the decoding node 6. By contrast, DCAR cannot find any coding opportunity in Fig. 1(b), thus resulting in a lower throughput. Second, at a low flow rate (< 70 kbps), DCAR and DCAR-VOH perform at the same level for the throughput of f1 and f3 because both can handle the light traffic. Third, at all flow rates, the throughput of f2 in DCAR-VOH remains essentially the same as in DCAR. This shows that VOH does not affect the throughput of f2, similar to the observation in [9]. Therefore, regarding the overall network throughput, we see that DCAR-VOH improves DCAR at a high flow rate by about 15%.

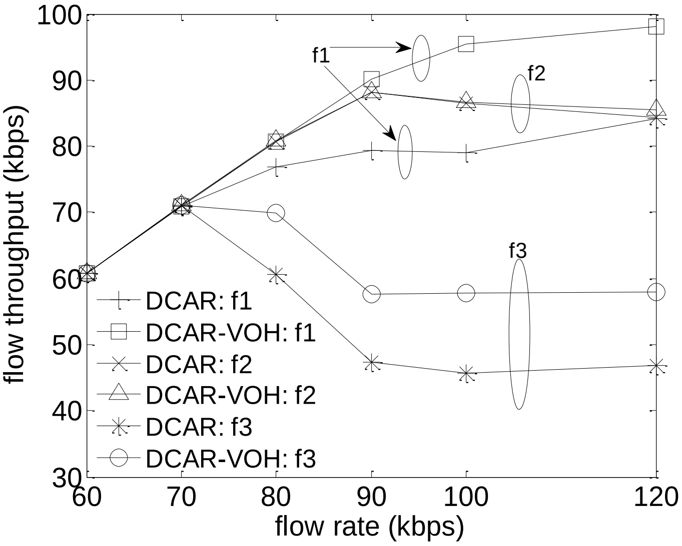


Figure 7: Flow throughput under CBR traffic.

Case of bursty traffic: we here consider Pareto On/Off (POO) traffic [10] as the bursty traffic to study the performance of DCAR-VOH. The key parameters in POO traffic are set as follows. The Pareto shape parameter is set 1.5, and both the average "On" time and the average "Off" time are set 500ms. In this study, we also assume all the three flows have the same rate during burst. After a number of simulations, we find that at medium to high flow rates during burst, DCAR-VOH still outperforms DCAR, similar to the case under CBR traffic. For example, Fig. 8 shows the overall throughput of DCAR-VOH and DCAR at different average flow rates, from which we see that DCAR-VOH outperforms DCAR by about 9% at a high average flow rate of 100kbps. Note that in our POO traffic the average flow rate equals a half of the flow rate during burst. This throughput improvement, however, is not as high as that under CBR traffic, where the improvement is about 15% at the flow rate of 100kbps. The reason is as follows. Given a short time interval, the possibility that nodes 0 and 4, i.e., the source nodes of f1 and f3, send packets at the same time under bursty traffic is low, whereas the two nodes always send packets simultaneously under CBR traffic. Consequently, the chance for the encoding node 1 of f1 and f3 to perform network coding during that time interval is lower under bursty traffic. Indeed, we find from the simulation that at the average flow rate of 100kbps, the encoded packet number per second at node 1 is 11 on average under bursty traffic, whereas it is 14 under CBR traffic. Evidently, the lower improvement in DCAR-VOH under bursty traffic results from the reduced coding opportunities at node 1.

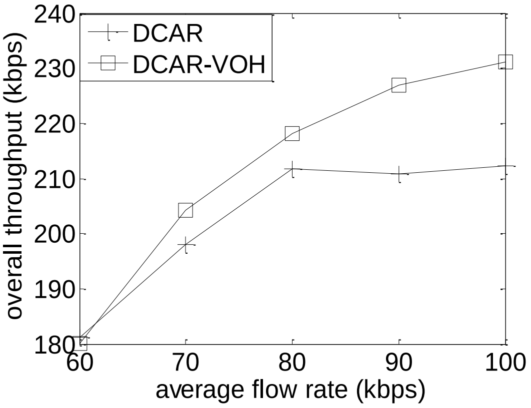


Figure 8: Overall throughput under bursty traffic.

Hence, from the studies above, we see that the coding opportunities brought by VOH can be translated into performance gains under both CBR and bursty traffic and particularly, more performance gains can be attained under CBR traffic. Hereafter, all our simulation studies below are based on CBR traffic.

B. Impact of the Flow Rate of f2

We now study how the flow rate of f2 affects the performance of DCAR-VOH in Fig. 1(b). Both f1 and f3 are fixed at a high flow rate, 110kbps, to enable plenty of coding opportunities at node 1, and the flow rate of f2 varies from 20kbps to 100kbps.

Fig. 9 shows the throughput of the three flows under DCAR-VOH and DCAR. First, it can be seen that regardless of the flow rate of f2, the throughput of f1 in DCAR-VOH is higher than that in DCAR by about 23%. This is because with network coding at node 1 in DCAR-VOH, whenever the channel is occupied by node 1, the packets from f1 can be transmitted immediately, whereas in DCAR those packets from f1 cannot be sent immediately because they need to compete with packets from f3 at node 1. Second, similar to Fig. 8, VOH has no impact on the throughput of f2**.** Third, interestingly, we see that (1) at a low flow rate of f2 the throughput of f3 in DCAR is higher than that in DCAR-VOH; (2) but at a high flow rate of f2 the situation is just the opposite. The reasons are as follows. Due to high flow rates of f1 and f3, most packets of f3 received at node 6 in DCAR-VOH are encoded packets, the decoding of which need the packets of f1 to be virtually overheard at node 6. Unfortunately, many encoded packets cannot be decoded at node 6 at a low flow rate of f2, because fewer packets of f1 are virtually overheard by node 6. Table 1 shows that up to 70% of the encoded packets of f3 cannot be decoded at the low flow rate of f2, 20kbps. Thus, the decoding failure decreases the throughput of f3 in DCAR-VOH. By contrast, at a high flow rate of f2, as shown in Table 1, node 6 can decode most of the encoded packets of f3 because node 6 can virtually overhear the packets of f1 quickly when the flow rate of f2 is high. Hence, at a high flow rate of f2, the throughput of f3 in DCAR-VOH benefits from the coding opportunities at node 1.

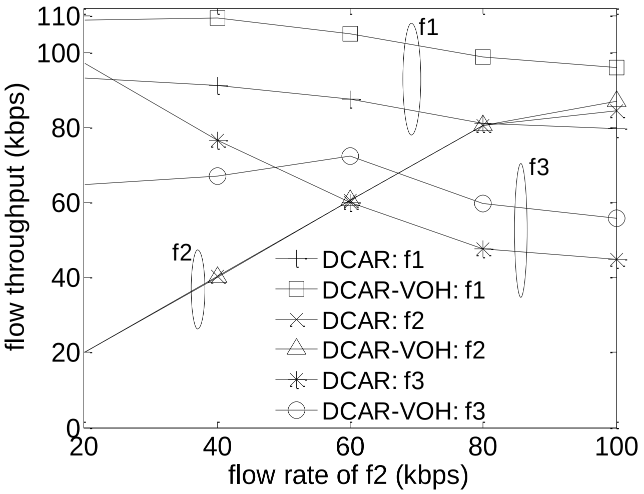


Figure 9: Flow throughput at different flow rates of f2.

Table 1: The statistics of the packet decoding at node 6 on f3

Flow rate of f2	Flow rate of f1 = Flow rate of f3 = 110kbps; Simulation time = 250s			
	Undecoded packet ratio†	Average decoding delay	Average packet delivery delay	Required Decoding waiting queue size
20kbps	2871 / 4130 = 70%	0.46s	1.16s	2871 packets
40kbps	1457 / 3965 = 37%	0.52s	1.56s	1457 packets
60kbps	106 / 3662 = 3%	0.68s	1.84s	132 packets
80kbps	11 / 3378 = 0.3%	0.2s	1.99s	20 packets
100kbps	19 / 3289 = 0.5%	0.2s	3.31s	23 packets

†undecoded packet ratio = the undecoded packet number over the total encoded packet number

Table 1 also shows the size requirement of the decoding waiting queue and the average decoding delay for the decoded packets at different flow rates of f2. Not surprisingly, it can be seen from the table that a higher flow rate of f2 speeds up both the VOH process and the packet decoding at node 6, yielding a relatively low average decoding delay, and a low requirement for the decoding waiting queue size as well. Especially, we can find that at a high flow rate of f2 (from 80kbps to 100kbps) the average decoding delay is rather limited as compared to the average packet delivery delay in DCAR-VOH. Hence, this study shows that to ensure a quick VOH process is critical for DCAR-VOH to succeed, which is also observed in [9].

C. *Impact of the Virtual Overhearing Distance*

Now we study how the virtual overhearing distance impacts the performance of DCAR-VOH in Fig. 1(b). Note that in Fig. 1(b) the virtual overhearing distance between node 6 and node 0 on f1 is 1 hop. To have different virtual overhearing distances for our study, we first properly move node 7 upward to let it be a neighbor of node 5, and then we choose node 7 as the destination node of f3 to have a 2-hop virtual overhearing distance. Intuitively, a longer virtual overhearing distance incurs a longer decoding delay for the packet decoding, thus decreasing the performance of DCAR-VOH. However, the study below shows that the impact on DCAR-VOH from increasing the virtual overhearing distance is actually very limited.

We evaluate the performance of DCAR-VOH under the above two virtual overhearing distances with the following network settings. We fix f1 and f3 at a high flow rate, 110kbps, and vary the flow rate of f2 from low to high values. Fig. 10 shows the flow throughput of DCAR-VOH for this study, from which we see that the throughput of f1, f2, or f3 basically keeps the same under the two virtual overhearing distances. Let us focus on explaining why f3 achieves the same throughput under different virtual overhearing distances in Fig. 1(b).

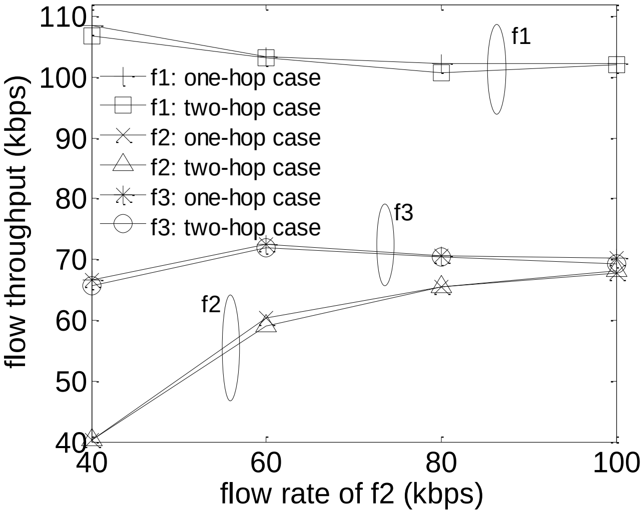


Figure 10: Flow throughput under different virtual overhearing distances.

Table 2 compares the statistics of the packet decoding in DCAR-VOH under the above two virtual overhearing distances. At any given flow rate of f2, it can be seen from the table that the average decoding delay incurred under the 2-hop virtual overhearing distance is always larger than that under the 1-hop case. Nonetheless, the impact of this longer delay is very limited in DCAR-VOH, because the undecoded packet ratio, a parameter that is critical to the performance of DCAR-VOH, in the two cases are very close. In addition, we also see that the size requirement of the decoding waiting queue in the 2-hop case increases limitedly compared with the 1-hop case. Hence, Table 2 shows that overall speacking, increasing the virtual overhearing distance has very limited impact on DCAR-VOH.

Table 2: The statistics of the packet decoding at node 6 under different virtual overhearing distances

Flow rate of f2	Flow rate of f1 = flow rate of f3 = 110kbps; Simulation time = 250s					
	Undecoded packet ratio		Average decoding delay		Required decoding waiting queue size	
	one-hop case	two-hop case	one-hop case	two-hop case	one-hop case	two-hop case
40kbps	38.2%	40.4%	0.51s	0.84s	1515 packets	1648 packets
60kbps	6.8%	7.0%	1.15s	1.5s	271 packets	303 packets
80kbps	3.5%	5.7%	0.77s	1.68s	135 packets	240 packets
100kbps	1.3%	1.4%	0.58s	0.95s	57 packets	70 packets

D. Impact of the Link Quality

Lastly, we study how DCAR-VOH responds to the link quality in Fig. 1(b). The simulation is configured as follows. By default, node 6 is chosen as the destination node for f3. Both the flow rates of f1 and f3 are fixed at a high value, 100kbps, and the flow rate of f2 is also fixed at a relatively high value, 80kbps. For simplicity, all links in this study are assumed to have the same packet delivery probability (PDP).

We focus on the throughput of f2 and f3 in DCAR-VOH in this study. We find from the simulation results (not shown as figures here) that (1) at any PDP, VOH does not impact f2, i.e., f2 achieves the same throughput in both DCAR-VOH and DCAR, and (2) DCAR-VOH improves the throughput of f3 in DCAR limitedly as PDP becomes lower. The reason for (2) is that at a lower PDP, more coded packets of f3 in DCAR-VOH cannot be decoded at node 6 due to the loss of the side information, as shown in Table 3. In particular, the side information loss can occur when node 8 fails to overhear the packet sent by node 0 on f1 or when node 6 fails to overhear the coded packet sent by node 8. The loss in the former case is termed the overhearing loss, and the loss in the latter case is termed the VOH loss. Table 3 shows that the overhearing loss is the major cause for (2). This is because if node 8 fails to overhear the packet of f1, it will miss it forever; whereas if node 6 fails to overhear a coded packet, e.g., P1 $\oplus$ P2 in Fig. 1(b), from node 8, it can keep informing node 8 to mix the packet P1 of f1 until it obtains P1, thanks to ‘the selective VOH’ mechanism introduced in Section 3. Hence, to improve DCAR-VOH under lossy links, we may only need to improve the reliability of direct overhearing, e.g., from node 0 to node 8 in Fig. 1(b), which is actually a common problem to traditional network coding schemes [11]. [9] actually has made the similar observations to (1) and (2) above.

Table 3: Statistics related to the performance of f3 in DCAR-VOH under lossy links

PDP	Simulation time = 250s		
	Encoded packet number	Undecoded packet number at node 6	
		Overhearing loss	VOH loss
0.95	1553	74	36
0.90	1445	144	34
0.85	1480	268	40

6.2 DCAR-VOH+ in the Illustrative Network Topology

In this simulation, we study how DCAR-VOH+ can further improve DCAR-VOH in the scenario of Fig. 5. The three flows in Fig. 5 are randomly generated at different times with the same flow rate. We assume all links in Fig. 5 are reliable.

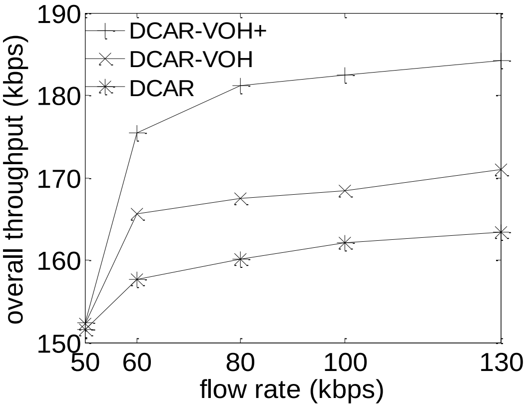


Figure 11: Overall throughput of the three flows in Fig. 5.

Fig. 11 shows the overall throughput of DCAR-VOH+, DCAR-VOH, and DCAR. Not surprisingly, DCAR-VOH+ is the best performer among them. At a high flow rate (i.e., > 80 kbps), DCAR-VOH+ could improve the overall throughput over DCAR and DCAR-VOH by 14% and 9%, respectively. The main reason for this is that as explained earlier, all three intersection nodes in the figure, i.e., nodes 1, 2, and 3, are identified as the encoding nodes in DCAR-VOH+, whereas only ONE node (node 1, 2 or 3, depending on the establishment order of the three flows) can be the encoding node in DCAR-VOH and no encoding node is identified in DCAR. Hence, DCAR-VOH+ benefits from the higher number of coding opportunities that are identified.

In fact, VOH increases coding opportunities without incurring additional costs, e.g., energy consumption. Fig. 12 plots the energy consumption of these three protocols in terms of the average needed physical transmission times for each successfully delivered packet. The average transmission times, N_t, is defined as the ratio of the total number of data packet transmissions over the total number of received data packets at the destinations. Fig. 12 shows that the N_t values for DCAR, DCAR-VOH, and DCAR-VOH+ are about 4.3, 4.1, and 3.8, respectively. With three encoding nodes, 1, 2, and 3, DCAR-VOH+ achieve a $N_t < 4$ (i.e., the number of hops for each flow in Fig. 5). The reason for $N_t > 4$ in DCAR at high flow rates is that no coding opportunity is identified there, and there are some wasted transmissions contributed by the packets dropped at the interface queue of some intermediate nodes.

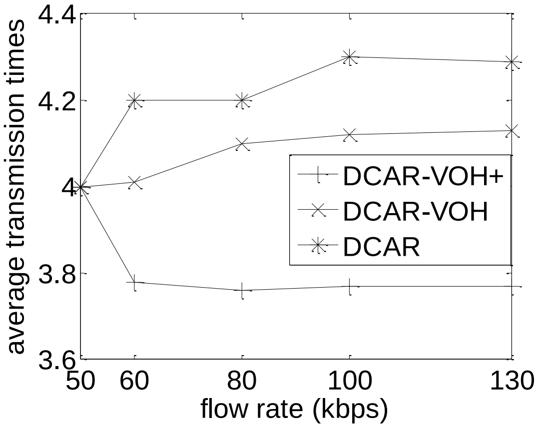


Figure 12: The average transmission times for each delivered packet.

6.3 DCAR-VOH+ in Random Networks with Random Traffic

In this simulation, we are interested in studying how DCAR-VOH+ can improve DCAR-VOH and DCAR under random traffic in a random topology. Thirty nodes are randomly placed in a 400m x 400m network, and six flows are randomly generated at different times. All flows are injected to the network at an equal flow rate.

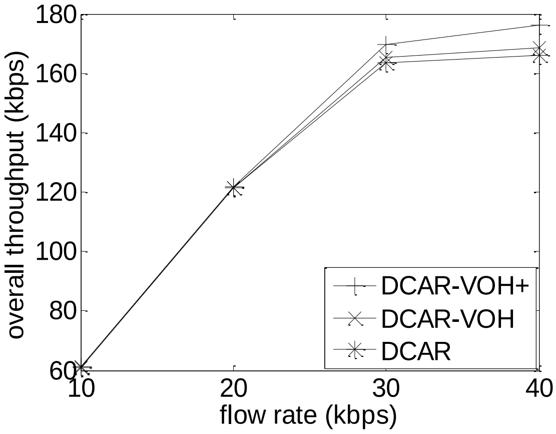


Figure 13: Overall throughput in the random network.

Fig. 13 plots the overall throughput of these three schemes, where we see that DCAR-VOH+ outperforms the other two schemes and improves the performance of DCAR by about 6% at high flow rates. Due to the second manner of VOH usage, DCAR-VOH+ can find the most coding opportunities, thus improving network performance. By contrast, the first manner of VOH usage in DCAR-VOH finds very few extra coding opportunities in a random network compared with DCAR, yielding essentially the same performance level as DCAR.

6.4 DCAR-VOH+ under Traffic with Certain Patterns

Apart from the study under random traffic flows above, here we present two typical traffic patterns, the inter-cluster traffic and the three-node cyclical traffic, which will favor both DCAR-VOH and DCAR-VOH+.

Case of the inter-cluster traffic: This traffic pattern assumes in a network that 1) there are a number of separate clusters, with each being formed by some nearby nodes, and 2) the source and the destination of each flow are selected from two different clusters. Fig. 5 actually shows an example of the inter-cluster traffic. The nodes in each dashed circle in Fig. 5 form a cluster, and each flow is established from one cluster to another. We consider the inter-cluster traffic in the random network to study DCAR-VOH+ and DCAR-VOH. The network is configured as follows. In a 400m x 400m random network, four cluster regions are formed at four corners of the network area. We assume that each cluster has a relatively small region, a 150m x 150m square, to represent some traffic hotspot, and that any two cluster regions are beyond one hop, similar to the case in Fig. 5. A total of 30 nodes are uniformly distributed in the network and the nodes located in one cluster region form a cluster. Then, six inter-cluster flows are randomly generated in the network at different times. Fig. 14 shows a comparison of the overall throughput of the four protocols including COPE.

First, Fig. 14 shows that DCAR outperforms COPE by 3% and DCAR-VOH outperforms DCAR by 5%. Obviously, the reason for this is that VOH enables DCAR-VOH to identify more coding opportunities than DCAR in the inter-cluster traffic. To see how DCAR-VOH can find more coding opportunities, we refer to the representative example of the inter-cluster traffic in Fig. 5 where three inter-cluster flows are generated. Two features exist in this traffic pattern: (1) for two nodes within one cluster on two flows, the possibility that one can directly overhear the other is high due to the small area; and (2) for two nodes in different clusters on two flows, the possibility that one can directly overhear the other becomes low. Referring to the aforementioned network coding conditions in DCAR, we see that it is difficult in this scenario to meet these conditions due to feature (2), as shown in Fig. 5. By contrast, with VOH existing between any two intersecting flows in Fig. 5, it is highly possible that DCAR-VOH can find coding opportunities under this inter-cluster traffic. For example, as illustrated earlier, if f1 and f2 are the first two established flows, then, f3, during its establishment, will find coding opportunities at node 3 with f1. Therefore, the inter-cluster traffic favors DCAR-VOH in identifying coding opportunities, and thus DCAR-VOH outperforms DCAR.

Second, Fig. 14 shows that DCAR-VOH+ improves the performance over DCAR by 10%. As illustrated earlier in Fig. 5, all the three intersection nodes are encoding nodes in DCAR-

VOH+ whereas only one among the three is identified as an encoding node in DCAR-VOH. Hence, the inter-cluster traffic favors DCAR-VOH+ more than DCAR-VOH.

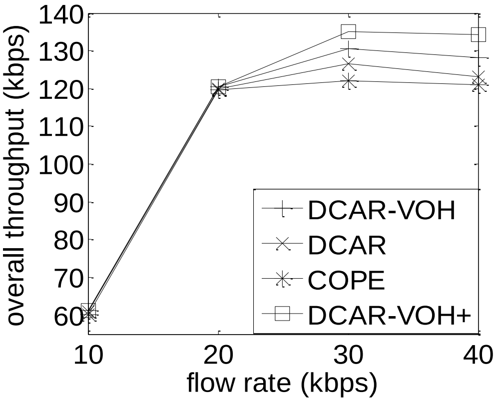


Figure 14: Overall throughput in the random network with inter-cluster traffic.

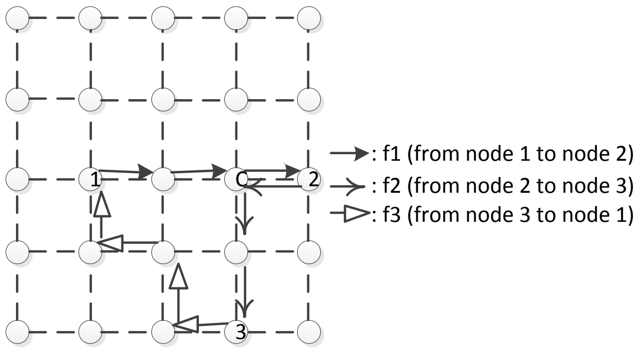


Figure 15: 5 x 5 grid topology.

Case of the three-node cyclical traffic: This traffic pattern considers three nodes sending packets in a cyclical form. Suppose the three nodes are nodes A, B, and C, then, a cyclical traffic pattern is formed when packets are sent from node A to node B, from node B to node C, and from node C to node A. Here, these three nodes form a cyclical traffic set. To study the performance of DCAR-VOH+ and DCAR, we consider this cyclical traffic in a 5 x 5 grid topology as shown in Fig. 15. Each node in this topology can directly communicate with only its eastern, southern, western, and northern neighbors, if any. We will randomly choose three nodes in Fig. 15 to form a cyclical traffic set, and different numbers of cyclical traffic sets will be formed to study the scalability of DCAR-VOH+.

Table 4: Overall throughput of DCAR-VOH+ at different numbers of cyclical traffic sets

Cyclical traffic set number	DCAR	DCAR-VOH+	Improvement
1	227.5kbps	255.8kbps	12.4%
2	203.6kbps	219.1kbps	7.6%
3	194.1kbps	205.4kbps	5.8%

Table 4 compares the overall throughput between DCAR-VOH+ and DCAR. First, DCAR-VOH+ improves the performance of DCAR at any number of cyclical traffic sets. This is because DCAR-VOH+ normally can find more coding opportunities under the 3-node cyclical traffic. Especially, if there exists an intermediate node relaying traffic for any two nodes in a cyclical traffic set, then it must be an encoding node in DCAR-VOH+. Consider a scenario in Fig. 15 that there exists an intermediate node, say node C, as a relay node for both the source nodes 1 and 2. In DCAR, node C may not be an encoding node. However, node C must be an encoding node in DCAR-VOH+: with the flow established from node 3 to node 1, node 3 can virtually overhear node 1 and thus, node C is allowed to mix the packets from nodes 1 and 2. This is why the cyclical traffic favors DCAR-VOH+. Second, as the number of cyclical traffic sets (or simply the flow number) increases, the performance improvement of DCAR-VOH+ over DCAR decreases. In fact, this trend has been shown in COPE [6], and the reason is that as the network gets more congested, the coding opportunity amount is reduced and thus, the positive effect of network coding diminishes.

7. Conclusions and Areas for Future Improvement

In this paper, we take advantage of a recently proposed new technique called virtual overhearing (VOH) to benefit the routing performance in multi-hop wireless ad-hoc networks. VOH increases network coding opportunities by enabling a node to obtain the side information from another node beyond one hop for free. We presented two manners of utilizing VOH and designed two network coding-aware routing protocols in this paper. The first protocol, DCAR-VOH, makes a new incoming flow be aware of the existing VOH during the route discovery and allows it to find a route with coding opportunities. The second protocol, DCAR-VOH+, makes further use of VOH to *create* coding opportunities between two established flows which are currently unmixable. As a result, there are many more coding opportunities in DCAR-VOH+ as compared to DCAR-VOH.

Extensive simulation results show that in many different network scenarios both DCAR-VOH and DCAR-VOH+ can discover or create extra coding opportunities compared with the two well-known network coding schemes, DCAR and COPE, which results in improved network performance. In particular, the network with either the inter-cluster traffic or the three-node cyclical traffic favors both DCAR-VOH+ and DCAR-VOH, and with the two manners of VOH usage implemented, DCAR-VOH+ outperforms DCAR-VOH, especially in random networks with random traffic.

However, our simulation studies also show one critical problem in DCAR-VOH and DCAR-VOH+, that is, both suffer from a slow VOH process. As observed in the simulation, one possible reason for this is a low rate of the flow, e.g., f2 in Fig. 1(b), on which VOH relies. In fact, we find that even if all flows have an equal flow rate, some other factors could also slow down the VOH process. In Fig. 1(b), for example, if a new flow is generated at node 8 and makes node 8 become congested, then node 6 will virtually overhear the side information slowly. To tentatively solve this problem, we may let a virtual encoding node, e.g., node 8 in Fig. 1(b), additionally forward some overheard packets to a decoding node, e.g., node 6 in Fig. 1(b), to ensure the decoding of the coded packets. Obviously, this is achieved at the expense of *additional* traffic injected to the network. We can expect that this tentative solution can work effectively in the situation where the *additional* injected traffic does not compete with existing flows for the use of network resources. However, more investigations are needed for this tentative solution, and we leave it as our future work.

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