INCOR: Inter-flow Network Coding based Opportunistic Routing in Wireless Mesh Networks

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***Abstract*—Both opportunistic routing and inter-flow network coding are useful mechanisms for improving the performance of wireless networks. Both of them exploit the broadcast nature of the wireless medium and the spatial diversity of multi-hop wireless networks. In this paper, we aim at incorporating inter-flow network coding into opportunistic routing for further improving the performance of wireless mesh networks (WMNs). The main issue in designing such a scheme is candidate set selection and prioritization based on a proper metric for opportunistic routing. To this end, in this paper, we first present a new metric to determine the prioritization of the forwarders in the set of candidates and then design an *Inter-flow Network Coding-based Opportunistic Routing* (INCOR) scheme using the defined metric. Our proposed INCOR scheme can integrate the characteristics of inter-flow network coding and opportunistic routing effectively to make full use of the broadcast nature of the wireless medium. We carry out extensive simulations to evaluate the effectiveness of the INCOR method. Our data shows that INCOR outperforms both opportunistic routing and inter-flow network coding schemes.**

I. INTRODUCTION

Wireless mesh networks (WMNs) have become very popular as they have been considered as a promising solution for providing high-speed broadband wireless Internet access to users. To improve the performance in WMNs, there has been growing attention regarding the broadcast nature of the wireless medium. With the benefit of this feature, opportunistic routing [1] was introduced to mitigate the impact of the unreliable wireless links. In traditional routing practices, the route from a source to a destination is determined in advance by a routing protocol whereas in opportunistic routing, a set of next-hop forwarding candidates is selected on-the-fly. From this set, one node is selected as a real relay node based on some prioritization rules. Consequently, opportunistic routing has the potential for achieving a significant performance gain over traditional routing, especially in the low-quality wireless network environment.

Inter-flow network coding [2], [3] has also been used to improve the performance in WMNs. When multiple flows cross at a node, inter-flow network coding allows data packets received from different flows to be mixed at the intersection node for further transmission. In this way, a single transmission can piggyback several different information flows to different receivers. As a result, inter-flow network coding can perform better than traditional routing in terms of throughput in high-quality wireless networks.

Although both opportunistic routing and inter-flow network coding approach the similar goal of improving the performance of WMNs by exploiting the broadcast nature of wireless links, their applicable environment is different as mentioned. To be specific, opportunistic routing is more valuable in low-quality wireless environments than high-quality environments because it improves the chance for a packet to be delivered towards the destination by leveraging a large number of potential forwarders. On the other hand, inter-flow network coding performs effectively in networks with error-free channels become there are additional coding opportunities at the intersection node under such circumstances. Hence, one research problem is raised: *how can we combine opportunistic routing and inter-flow network coding, ensuring that the integrated scheme performs better than the individual ones?*

In this paper, we devise a novel *Inter-flow Network Coding-based Opportunistic Routing* (INCOR) scheme to further reduce the number of transmitted packets and to improve the performance of WMNs. The key idea of integrating these two schemes is to fully use coding opportunities by introducing multiple potential coding nodes and selecting the best node to be the real coding node. Then, the main challenge is how to determine the candidate sets for each node and prioritize them.

The main contributions of this paper are as follows:

- We present a new metric called *Coding-based Expected Transmission Count* (CETX) to determine the priority of the forwarders in a set of candidates. The CETX metric precisely computes the expected transmission count required to deliver one packet to a destination when inter-flow network coding is incorporated.
- We design a novel INCOR protocol based on the CETX metric. Our proposed INCOR method effectively integrates the characteristics of inter-flow network coding and opportunistic routing to fully utilize the broadcast nature of the wireless medium. The INCOR scheme mainly consists of the following three components: (i) candidate selection and prioritization that selects and prioritizes the candidate set of every node to the destination; (ii) opportunistic encoding and forwarding that makes effective rules for nodes encoding and forwarding packets to their downstream nodes; and (iii) opportunistic listening that aims at finding coding opportunities for nodes.
- We perform simulations to show the effectiveness of INCOR. The data shows that INCOR outperforms both opportunistic routing and inter-flow network coding schemes. On average, INCOR achieves a perfor-

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mance gain of 1.123 and 1.168 better than inter-flow network coding and opportunistic routing in terms of the transmission count of reliable delivering a packet from source to destination, respectively.

The rest of the paper is organized as follows. In Section II, we introduce existing research efforts relevant to our research. In Section III, we present our proposed INCOR scheme in detail. In Section IV, we show a performance evaluation of INCOR through simulations using different topologies. Finally, we conclude the paper in Section V.

II. Related Work

In this section, we conduct a literature review of existing research efforts that are related to network coding and opportunistic routing. For opportunistic routing, there have been a number of research efforts. For example, Biswas and Morris in [1] proposed a new opportunistic routing protocol, called ExOR, for wireless networks. MAC-independent Opportunistic Routing and Encoding Protocol (MORE) [4] is an enhancement of ExOR. By incorporating intra-flow random linear network coding and opportunistic routing, MORE does not need a highly structured MAC scheduler and can run directly on top of 802.11, achieving a better throughput than ExOR.

Inter-flow network coding was initially implemented in the COPE protocol [3]. By identifying coding opportunities and then forwarding multiple packets in a single transmission, COPE leads to larger bandwidth savings than traditional routing schemes. DCAR [5] adopts a more generalized coding scheme by eliminating the two-hop limitation in COPE. As a result, it can identify more coding opportunities to improve performance. I^{2}NC [6] is another enhancement on COPE. By introducing redundancy through intra-flow network coding, I^{2}NC is resilient to packet loss and it does not need to rely on the exact knowledge of the states of the nodes' neighbors.

To further improve the performance of WMNs, there have been some research efforts on integrating inter-flow network coding and opportunistic routing [7]–[10]. For example, XCOR [7] is a protocol which integrates both opportunistic routing and inter-flow network coding. Nonetheless, only two simple topologies were considered in the evaluation of XCOR. CAOR [8] is a protocol that takes advantage of both intra-flow-based opportunistic routing and inter-flow network coding for lossy wireless networks. CAOR aims at integrating inter-flow network coding into the MORE protocol by focusing on creating linear combinations of packet sets rather than employing candidate set selection and prioritization. CORE [9] is a protocol that allows the next-hop node with the most coding gain to continue forwarding packets through opportunistic forwarding and attempts to maximize the number of packets which can be carried in a single transmission through localized network coding. Nonetheless, the forwarder set selection and prioritization as well as coding opportunity computation remain as open problems. In [10], using dynamic programming techniques, the authors proposed an optimal forwarding scheme to minimize the expected transmission count of bidirectional flows for opportunistic network coding. Nonetheless, the network model used is simple and consists of only two nodes that transmit packets to each other and some common neighbor nodes of the two transmitting nodes.

Note that one of the key issues of opportunistic routing is candidate set selection and prioritization based on proper metrics for specific scenarios [11], [12]. For example, the authors of [12] developed the EATT metric and designed the corresponding candidate set selection algorithm for multirate anypath routing. In addition, some other problems of opportunistic routing have been addressed in a similar way, including energy efficiency [13], congestion control [14], etc. Nonetheless, little work has been conducted to effectively incorporate inter-flow network coding into opportunistic routing. To fulfill this gap, in this paper, we design an inter-flow network coding-based opportunistic routing scheme by using the coding-based expected transmission count.

III. INCOR: Inter-flow Network Coding based Opportunistic Routing

In this section, we first present the system model and the design rationale of INCOR. Afterwards, we present the key metrics and the detailed design of INCOR.

A. System Model

In our study, we consider a wireless mesh backbone network, consisting of multiple mesh routers. The network can be modeled as a graph $G(V, E)$, where V is the set of nodes and E is the set of links in the network. Each node i in the network can transmit packets to its neighbor nodes $j \in N(i)$ with a certain probability. The data transmission can be overheard by neighboring nodes. Denote $p_{i,j}$ as the probability that the packet transmitted by node i is successfully received by node j, which is also defined as the link delivery probability from node i to j. Without loss of generality, similar to the existing work found in [10], we also assume that the links are symmetrical in both directions (i.e. $p_{i,j} = p_{j,i}$).

We define the potential downstream nodes to receive and relay the packet transmitted by node i as the set of forwarding candidates of node i, denoted as $\mathcal{F}_i$. Note that $\mathcal{F}_i$ is a nonempty set, which consists of neighboring nodes selected to forward the packet opportunistically according to a specific selection strategy. Meanwhile, $\mathcal{F}_i$ is an ordered set, where the order of the candidates corresponds to the candidate priority in forwarding the packet. Hence, under the assumption that the link delivery probability is independent, the probability that a packet transmitted from node i is successfully received by at least one node in $\mathcal{F}_i$ is $1 - \prod_{j \in \mathcal{F}_i}(1 - p_{i,j})$.

B. Design Rationale

Our INCOR is a *inter-flow network coding-based opportunistic routing* scheme that aims to improve the performance in WMNs. It effectively combines opportunistic routing and inter-flow network coding to make full use of the broadcast nature of the wireless medium. With network coding, when a coding opportunity arises, two or more packets can be transmitted in a single transmission. In addition, with opportunistic forwarding, other low-quality links rather than the best link can be used to deliver packets. As a result, the total packet transmission count can be reduced, leading to a significant performance gain in terms of throughput.

To illustrate the basic idea of INCOR, we will first introduce an example to motivate our study. Consider the scenario in Fig. 1, where nodes A and B need to exchange a pair of packets P_a and P_b to each other. Because A and B are out of each other's transmission range, several relay nodes are responsible for forwarding these packets. In traditional routing, nodes A and B first select the best relay node, using a predetermined metric such as ETX [15], and then retransmit the packet until an ACK is returned. In opportunistic routing, nodes A and B continuously retransmit the packets until one copy is received by any one of the relay nodes. Then, the relay node that receives the packet takes the responsibility of transmitting the packet to the destination.

Similar to traditional routing, in inter-flow network coding, after nodes A and B choose the same relay node as the best forwarder in advance, the relay node can simply transmit the bitwise XOR of packets $P_{ab} = P_a \oplus P_b$ and node B can decode P_a by performing the bitwise XOR of P_{ab} and P_b, which is $P_a = P_{ab} \oplus P_b$. Note that node A can decode P_b in a similar fashion. Nonetheless, if either packet P_a or P_b is lost during transmission due to an unreliable wireless link, the coding opportunity is wasted. Utilizing this fact, INCOR employs a different method from network coding and selects relay nodes on-the-fly rather than in a pre-determined manner. As long as there exists a relay node that successfully receives both P_a and P_b, it will be selected as the forwarder. In this way, the broadcast nature of wireless communication can be fully utilized.

The essential issue of opportunistic routing is how to choose the selection metric and how to determine and prioritize the forwarding candidates using the selected metric [11]. For example, in ExOR [1], the candidate priority is simply selected based on the cost of delivering a packet from each node to the destination. In EAX [16], the candidate priority is based on the expected any-path transmissions, which further captures the characteristics of opportunistic routing. In this paper, by considering that inter-flow network coding can reduce the transmission cost much further if multiple information flows cross at some nodes, we define and analyze the metric of *Coding-based Expected Transmission Count* (CETX) under opportunistic routing.

C. Coding-based Expected Transmission Count

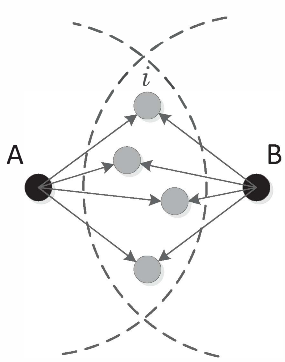

Fig. 1. A simplified network topology of bidirectional communication

We define the CETX to be the expected number of transmissions of a packet from a node to the destination through a set of candidates when inter-flow network coding is incorporated. We will begin with a simplified case and then extend it to a generic case. Consider the topology shown in Fig. 1 and that node A and node B transmit a stream of packets to each other. Because A and B are out of each other's transmission range, several relay nodes (say the number of relay nodes is N) are responsible for forwarding the packets. For relay node i, denote $p_{i,A}$ and $p_{i,B}$ as the link delivery probability of node i to nodes A and B, respectively. Assume that the sets of forwarding candidates of nodes A and B are $\mathcal{F}_A = \{r_{A_1}, r_{A_2}, \ldots, r_{A_N}\}$ and $\mathcal{F}_B = \{r_{B_1}, r_{B_2}, \ldots, r_{B_N}\}$, with priorities $r_{A_1} > r_{A_2} > \cdots > r_{A_N}$ and $r_{B_1} > r_{B_2} > \cdots > r_{B_N}$, respectively. Then, we can derive the expected transmission count of node A delivering one packet to node B (denoted as C_A) as follows:

$$C_A = d_{A,\mathcal{F}_A} + C_{\mathcal{F}_A}, \tag{1}$$

where $d_{A,\mathcal{F}_A}$ is the expected transmission count from node A to its candidate set $\mathcal{F}_A$ and $C_{\mathcal{F}_A}$ is the expected transmission count from the candidate set to node B.

Similar to computing EAX [16], we have

$$d_{A,\mathcal{F}_A} = \frac{1}{1 - \prod_{i \in \mathcal{F}_A}(1 - p_{i,A})}, \tag{2}$$

and

$$C_{\mathcal{F}_A} = \frac{\sum_{j=1}^{N} p_{j,A} \prod_{k=1}^{j-1}(1 - p_{k,A}) C_j}{1 - \prod_{i \in \mathcal{F}_A}(1 - p_{i,A})}. \tag{3}$$

Note that Equation (3) is the conditional probability that any candidate relays the packet only if any other candidates with a higher priority does not receive the packet, given that at least one of the candidates receives the packet.

Then, C_A and C_B can be derived as follows:

$$C_A = \frac{1 + \sum_{j=1}^{N} p_{j,A} \prod_{k=1}^{j-1}(1 - p_{k,A}) C_j}{1 - \prod_{i \in \mathcal{F}_A}(1 - p_{i,A})}, \tag{4}$$

and

$$C_B = \frac{1 + \sum_{j=1}^{N} p_{j,B} \prod_{k=1}^{j-1}(1 - p_{k,B}) C_j}{1 - \prod_{i \in \mathcal{F}_B}(1 - p_{i,B})}. \tag{5}$$

When inter-flow network coding is introduced, the expected number of transmission for nodes A and B for exchanging a pair of packets can be further reduced. Assume that a coding opportunity arises at node i. That is to say, node i receives packets from both nodes A and B. Then, the $\frac{1}{1-(1-p_{i,A})(1-p_{i,B})}$ transmissions at node i can be reduced because only if neither of nodes A or B receives the coding packet, the number of retransmissions at node i is the same as in the traditional routing case. In addition, similar to opportunistic routing, the event that node i becomes a coding relay node occurs with the conditional probability that the other candidates with a higher priority do not receive both packets (i.e., $\prod_{j=1}^{i}(1 - p_{j,A}p_{j,B})$) given that at least one of the candidates receives both the packets (i.e., $[1 - \prod_{i \in \mathcal{F}_A}(1 - p_{i,A})][1 - \prod_{i \in \mathcal{F}_B}(1 - p_{i,B})]$). Hence, the reduced total number of transmission Δ_{AB} can be derived as follows:

$$\Delta_{AB} = \frac{\sum_i \frac{1}{1-(1-p_{i,A})(1-p_{i,B})} p_{i,A} p_{i,B} \prod_{j=1}^{i}(1 - p_{j,A}p_{j,B})}{[1 - \prod_{i \in \mathcal{F}_A}(1 - p_{i,A})][1 - \prod_{i \in \mathcal{F}_B}(1 - p_{i,B})]}. \tag{6}$$

Thus, in the simplified case where there is an intersection between the candidate set of nodes A and B, the CETX of nodes A and B when exchanging packets to each other can be expressed as $X_{AB} = C_A + C_B - \Delta_{AB}$. In addition, as we assume that the links in the network are symmetrical, the approximate CETX of node A transmitting packets to node B can be expressed as $X_{A,B} = \frac{X_{AB}}{2}$.

In a generalized case where the candidate set of two transmitting nodes S and D has no intersection, given the candidate set of each node, the CETX of node S when transmitting packets to node D can be derived in a similar way as Equation (3), which is given by

$$X_{S,D} = \frac{1 + \sum_{j=1}^{M} p_{j,S} \prod_{k=1}^{j-1} (1 - p_{k,S}) X_{i,D}}{1 - \prod_{i \in \mathcal{F}_S} (1 - p_{i,A})}, \qquad (7)$$

where M is the number of candidate sets of S.

When the intersection of the candidate sets of the nodes does not exist or a coding opportunity does not exist, the XOR-ed packets cannot be decoded and our INCOR becomes the opportunistic routing described in EAX [16]. Further, note that when there is only one candidate set for all nodes along a path, INCOR translates to the COPE [3] protocol. If coding is not allowed, INCOR can be viewed as traditional routing in a wireless network.

D. The Design of INCOR

In the following, we present the detailed design of the INCOR protocol. Because the prerequisite for computing the CETX is to determine the candidate sets of the nodes and their corresponding prioritization, we first present the candidates selection and prioritization algorithm. Then, in order to code the appropriate packets together in the presence of opportunistic forwarding, we introduce our opportunistic encoding and forwarding mechanism. Finally, to identify coding opportunities, we present an opportunistic listening mechanism.

1) Candidates Selection and Prioritization: Based on the CETX metric, INCOR selects and prioritizes the candidate sets for each node. The general idea of INCOR is that for node i, adding the nearer neighbor nodes and their candidate sets (in term of CETX) to the candidate sets of node i can reduce the CETX of i. In addition, the candidate set with a lower CETX will be given a high priority in relaying packets. To achieve this, we develop the candidate set selection and prioritization algorithm in INCOR by using an algorithm similar to Dijkstra's algorithm. Algorithm 1 shows the detailed procedure.

Algorithm 1 Candidates selection and prioritization algorithm

1: **for** each node i in V **do**
2: $\quad X_i \leftarrow \infty$;
3: $\quad \mathcal{F}_i \leftarrow \varnothing$;
4: **end for**
5: $X_d \leftarrow 0$;
6: $\mathcal{F}_d \leftarrow \varnothing$;
7: $S \leftarrow \varnothing$;
8: **for** each node i in V **do**
9: $\quad$ INSERT(Q, i);
10: **end for**
11: **while** $Q \neq \varnothing$ **do**
12: $\quad j \leftarrow$ EXTRACT-MIN(Q);
13: $\quad S = S \cup \{j\}$;
14: $\quad$ **for** each edge (i, j) in E **do**
15: $\quad\quad$ **if** $i \in S$ **then**
16: $\quad\quad\quad \mathcal{F}_i = \mathcal{F}_i \cup \{j\} \cup (\mathcal{F}_j \cap N(i))$;
17: $\quad\quad\quad \triangleright$ $N(i)$ returns the neighbor nodes of node i;
18: $\quad\quad\quad$ prioritize the candidates in $\mathcal{F}_i$ based on X value;
19: $\quad\quad\quad$ calculate X_i with Equation 7;
20: $\quad\quad$ **end if**
21: $\quad$ **end for**
22: $\quad$ **for** each node i in V **do**
23: $\quad\quad$ DECREASE-KEY(Q, i, X_i);
24: $\quad$ **end for**
25: **end while**
26: **return** $X_i, \mathcal{F}_i$

In Algorithm 1, two data structures S and Q are maintained. S is the set of nodes whose final CETX to the destination node has been determined. The algorithm repeatedly selects the node $j, j \in V - S$ with the minimum CETX and adds j to S (line 13). Here, Q, which is a min-priority queue of nodes keyed by their CETX values, is maintained by using three priority-queue operations: INSERT (inserts element to the set), EXTRACT-MIN (returns the element with the minimum key), and DECREASE-KEY (decreases the value of an element to a new value). Lines 1-6 initialize all the $X_i, \mathcal{F}_i$ values, Line 7 initializes the data structure S to an empty set, and Lines 8-10 initializes the priority-queue Q to contain all the nodes in V. Each time through the **while** loop of lines 11-25, lines 12-13 extract the node j with the minimum X from Q and add it to S. Then, the **for** loop of lines 14-21 finds the upstream neighbor nodes of j, adds j and its candidates set to the candidate set of the neighboring nodes, and calculates the corresponding X value. The time complexity of Algorithm 1 is the same as that of Dijkstra's algorithm, which can achieve a running time of $O(V \lg V + E)$ if Q is implemented with a Fibonacci heap.

2) Opportunistic Encoding and Forwarding: Opportunistic packet forwarding in INCOR is different from the classical opportunistic routing protocol because of the existence of inter-flow network coding. When making a decision on choosing the appropriate packets to be coded with native packet P and candidate set C, the node will choose the next k packets from the output queue and check: (i) whether the previous hop of these packets is in C. and (ii) if the candidate set of the k packets contains at least one node that stores a copy of packet P based on the received reception reports. If these conditions hold, the node chooses the top packet to code with packet P.

Fig. 2 is an example to illustrate the opportunistic forwarding and listening in INCOR. Node C in Fig. 2(a) has three packets to deliver, where the previous hop and candidate set is shown in Fig. 2(b). The packets that are stored in the neighboring nodes of C are shown in Fig. 2(a). Node E overhears the transmission of packet P_1 from D to C, meaning that packet P_1 is also in E's packet pool. When making the decision on choosing the packet to be coded with P, node C checks the previous hop and the candidate set of P_1 and P_2. As packet P_1's candidate set does not contain a node that stores P, if P and P_1 are XOR-ed, the coded packet cannot be decoded by A. If P and P_2 are coded, it satisfies the coding condition and P_2 can be decoded by any of the candidates in this scenario.

On the sending side, when a node has a chance to transmit a packet, it first decides whether the packet can be encoded and which packets can be used in encoding. If the packets cannot be encoded, the node sends out the packet, including

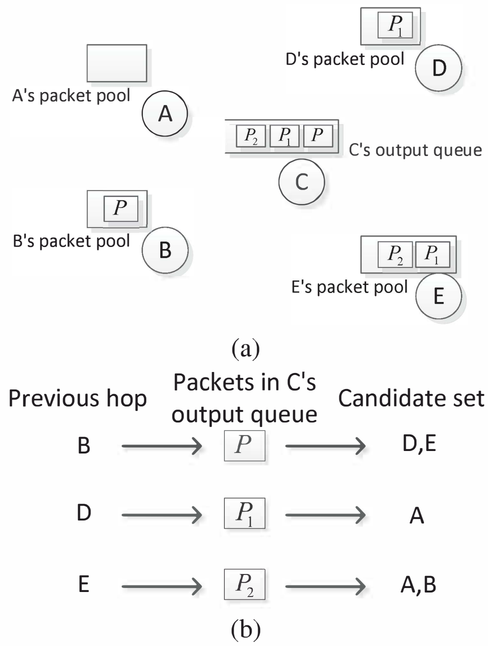

Fig. 2. An Example of INCOR: node C in (a) has three packets to deliver, where the previous hop and candidate set is shown in (b) and the packets stored in the neighboring nodes of C are shown in (a)

its forwarding candidates with the priority order. Otherwise, the node raises the priority of the candidate nodes, which are the potential next hops of the XOR-ed packets and then sends out the packet with the candidates list and nexthops list. On the receiving side, if a native packet is received, the node first checks whether it is in the candidates list. If so, it waits for a certain amount of time determined by its priority for an ACK, which is sent from another higher priority node. Once a timer expires, meaning that no other higher priority nodes have received the packet, it will forward the packet to its candidate set and send out an ACK. On the other hand, if the packet is encoded and the node is in the nexthop list, the node will decode the packet, send an ACK to the sending node, and continue forwarding the decoded packet.

3) Opportunistic Listening: Opportunistic listening in the INCOR protocol is similar to the COPE protocol. That is, all the nodes in the network overhear the packet transmissions to neighboring nodes and store the overheard packets for a limited period of time. In addition, the nodes in the network shall broadcast reception reports to its neighbors to inform them of packets being stored. Reception reports are transmitted in the data packets sent by the node. If a node has no data packet to transmit in a time period, it will also periodically send reception reports. Nonetheless, to ensure the ability to be decoded, coding decisions are made strictly based on reception reports rather than additional intelligent guessing techniques used in COPE.

IV. Performance Evaluation

In this section, we evaluate the performance of INCOR using two topologies. The first topology is a 5×5 grid topology network. Here, we take the link quality as the variable to investigate its effect. The second topology is a real-world link-level measurement of Roofnet [17], which is an experimental 802.11b/g wireless mesh network developed by MIT, and consists of 35 nodes. In our simulation, the data rate is 2Mbps.

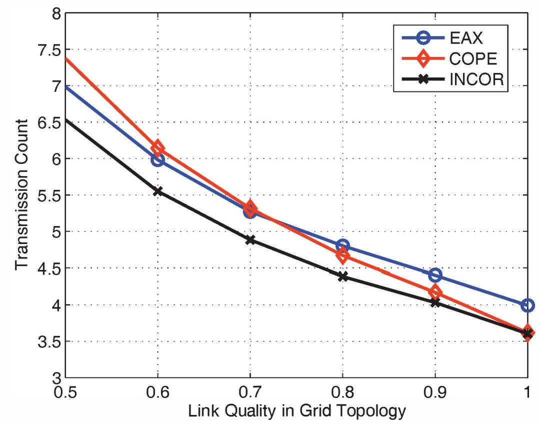

Fig. 3. The transmission count of INCOR, COPE, and EAX in different grid topologies

In the simulation for the grid topology network, we first randomly choose a pair of nodes. We then apply the candidate selection and prioritization algorithm to obtain the candidates for each node. Subsequently, we generate a series of random numbers, which are uniformly distributed in an interval of $[0, 1]$ for each transmission. If the random number of a transmission is smaller than the link quality, the transmission is successful. Based on the random numbers, we can obtain the transmission count of packets exchanged between the two nodes. Each simulation is repeated 1000 times and the results are averaged as illustrated below.

Fig. 3 shows the relationship between the average transmission count and link quality for INCOR, COPE, and EAX. As we can see, when the link qualities in the network are low, opportunistic routing performs better than network coding. When the link qualities approach 1, the performance of network coding is higher. This result matches with the theoretical analysis shown in Section III. Furthermore, in all the conditions, INCOR always achieves a better performance gain than the other two schemes.

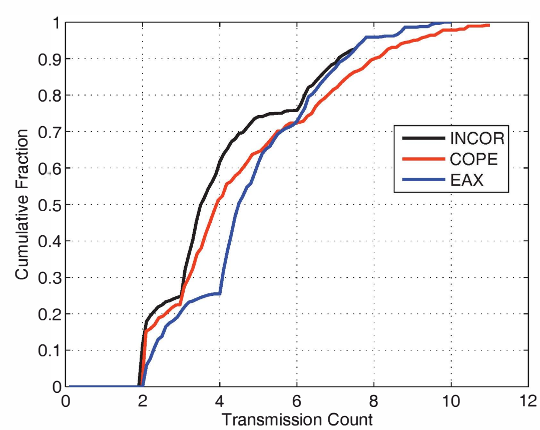

Fig. 4. CDF of transmission count of INCOR, COPE, and EAX

The procedure for simulating the ROOFNET topology network is similar with that of the grid network. Fig. 4 shows the Cumulative Distribution Function (CDF) of the transmission count of exchanging a pair of packets of INCOR, COPE, and EAX, measured over 1000 different runs. The source nodes and destination nodes in each run are randomly selected. The maximum number of candidate sets is 3. As we can see, INCOR consistently performs better than COPE and EAX. The average value of expected transmission count over 1000 runs for these three methods is 4.0835, 4.5838 and 4.7694, respectively. This indicates that INCOR achieves an average performance gain of 1.123 and 1.168 better than COPE and EAX, respectively. In addition, the maximum gain is 1.719 and 1.983 better than COPE and EAX, respectively.

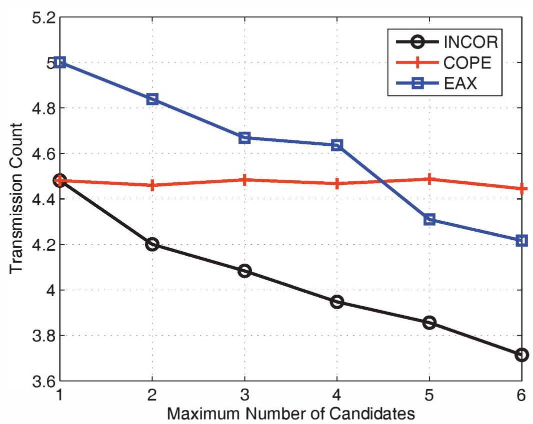

Fig. 5. The transmission count of INCOR, COPE, and EAX with different maximum numbers of candidates

Fig. 5 shows the relationship between the average transmission count and maximum number of candidates for INCOR, COPE, and EAX. As we can see, the average transmission count declines as the maximum number of candidates increases for INCOR and EAX. Nonetheless, it changes little for COPE as there is no candidate selection in the COPE protocol. Recall that when the maximum number of candidates is 1, INCOR becomes COPE, leading to the same performance in this case. We observe that if the maximum number of candidates is no bigger than 5, COPE outperforms EAX.

V. Final Remarks

In this paper, we proposed a novel INCOR protocol that integrates the characteristics of inter-flow network coding and opportunistic routing. In INCOR, we analyzed the coding-based expected transmission count based on the probabilities of link delivery, the sets of forwarding candidates, and the priority of nodes. We also developed an algorithm for candidate selections and prioritization along with opportunistic encoding and forwarding. Through a performance evaluation, our data shows that INCOR outperforms inter-flow network coding and opportunistic routing.

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References

[1] S. Biswas and R. Morris, "Exor: Opportunistic multi-hop routing for wireless networks," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 35, pp. 133–144, Aug. 2005.

[2] R. Ahlswede, N. Cai, S.-Y. Li, and R. Yeung, "Network information flow," *IEEE Transactions on Information Theory*, vol. 46, pp. 1204 – 1216, July 2000.

[3] S. Katti, H. Rahul, W. Hu, D. Katabi, M. Médard, and J. Crowcroft, "Xors in the air: practical wireless network coding," in *Proceedings of ACM SIGCOMM*, 2006.

[4] S. Chachulski, M. Jennings, S. Katti, and D. Katabi, "Trading structure for randomness in wireless opportunistic routing," in *Proceedings of ACM SIGCOMM*, August 2007.

[5] J. Le, J.-S. Lui, and D. M. Chiu, "Dcar: Distributed coding-aware routing in wireless networks," in *Proceedings of the 28th IEEE International Conference on Distributed Computing Systems (ICDCS)*, pp. 462–469, June 2008.

[6] H. Seferoglu, A. Markopoulou, and K. Ramakrishnan, "I2nc: Intra- and inter-session network coding for unicast flows in wireless networks," in *Proceedings of IEEE International Conference on Computer Communications (INFOCOM)*, pp. 1035–1043, April 2011.

[7] D. Koutsonikolas, Y. C. Hu, and C.-C. Wang, "Xcor: Synergistic interflow network coding and opportunistic routing," *MobiCom SRC*, 2008.

[8] K. Chung, Y.-C. Chou, and W. Liao, "Caor: Coding-aware opportunistic routing in wireless ad hoc networks," in *Proceedings of 2012 IEEE International Conference on Communications (ICC)*, pp. 136–140, June 2012.

[9] Y. Yan, B. Zhang, J. Zheng, and J. Ma, "Core: a coding-aware opportunistic routing mechanism for wireless mesh networks [accepted from open call]," *IEEE Wireless Communications*, vol. 17, pp. 96–103, June 2010.

[10] T. Mehmood, L. Libman, H. R. Dehkordi, and S. K. Jha, "Optimal opportunistic routing and network coding for bidirectional wireless flows," *Computer Networks*, vol. 57, no. 18, pp. 4030 – 4046, 2013.

[11] A. Darehshoorzadeh, L. Cerd-Alabern, and V. Pla, "Modeling and comparison of candidate selection algorithms in opportunistic routing," *Computer Networks*, vol. 55, no. 13, pp. 2886 – 2898, 2011.

[12] R. Laufer, H. Dubois-Ferriere, and L. Kleinrock, "Multirate anypath routing in wireless mesh networks," in *Proceedings of IEEE International Conference on Computer Communications (INFOCOM)*, pp. 37–45, April 2009.

[13] X. Mao, X.-Y. Li, W.-Z. Song, P. Xu, and K. Moaveni-Nejad, "Energy efficient opportunistic routing in wireless networks," in *Proceedings of the 12th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems*, MSWiM '09, (New York, NY, USA), pp. 253–260, ACM, 2009.

[14] M. Naghshvar and T. Javidi, "Opportunistic routing with congestion diversity in wireless multi-hop networks," in *Proceedings of IEEE International Conference on Computer Communications (INFOCOM)*, pp. 1–5, March 2010.

[15] D. S. J. D. Couto, D. Aguayo, J. Bicket, and R. Morris, "A high-throughput path metric for multi-hop wireless routing," *Wireless Networks*, vol. 11, pp. 419–434.

[16] Z. Zhong and S. Nelakuditi, "On the efficacy of opportunistic routing," in *Proceedings of IEEE International Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, pp. 441–450, June 2007.

[17] *MIT Roofnet.* http://pdos.csail.mit.edu/roofnet/doku.php.