I^2MIX: Integration of Intra-flow and Inter-flow Wireless Network Coding

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***Abstract*—Wireless network coding has been shown to reduce the number of transmissions by exploiting the broadcast nature of the wireless medium. Multiple packets may be encoded into a single packet when their respective next hops have enough information to decode them. Previous research has shown that packets belonging to different flows may be encoded (inter-flow coding) when they are passing through a common router. Similarly, it has also been shown that coding packets of the same flow (intra-flow coding) may provide better reliability by not relying on the reception of any single packet. In this work, we first present IMIX, an intra-flow wireless network coding scheme which has the potential to save transmissions and therefore improve network throughput. We then propose I^2MIX, the first design to the best of our knowledge, that can benefit from integrating inter and intra flow wireless network coding. Finally, we show through trace based evaluations that I^2MIX can reduce the total number of transmissions by 21-30%.**

I. INTRODUCTION

In wireless networks, transmissions are broadcast, and all neighbors of a transmitting node will receive the packet. This fundamental difference between wired and wireless networks has spawned many schemes unique to wireless communication. At the network layer, opportunistic routing schemes such as ExOR [1] enable all potential next-hops to aid in forwarding. However, there may be significant overhead due to duplicated packets and the negotiation between forwarding nodes. Wireless network coding is another method of exploiting broadcast transmissions. In contrast, [2] uses the broadcast nature at MAC layer, by including packet id in a special RTS and next-hops can tell the sender whether they already heard the packets through CTS.

In wireless network coding, routers encode (mix) the content of multiple packets and broadcast the resulting coded packets on the wireless medium. One specific coding scheme, termed COPE [3], encodes multiple packets destined to different next hops and broadcasts them together. This is possible as long as the sender knows all of the participating next hops have enough knowledge to decode their packet(s). This can occur when a sender has multiple flows intersecting at it, thus it is termed inter-flow coding [4]. To find coding opportunities, every node in COPE needs to timely inform its neighbors of which packets it has overheard. This control information required in COPE introduces additional overhead that reduces the maximum gain achievable. Conversely, it is also possible to perform intra-flow coding [4]. One such intra-flow scheme, termed MORE [5], uses random linear combinations while transmitting to give each transmitted packet unique information. By doing this, they remove the possibility of useless duplicated transmissions and remove the need for inter-candidate coordination.

However, it seems difficult to deploy COPE and MORE simultaneously because COPE assumes a network using best-path routing and MORE uses opportunistic routing. In this paper, we address the integration of inter-flow and intra-flow coding in order to benefit from both of them.

The main contributions of this paper are as follows:

- We describe IMIX, an intra-flow coding scheme that uses linear coding with best path forwarding. In 802.11 a down stream node may overhear packets meant for upstream nodes (we use the term ”long jumps” for this). IMIX makes use of this overhearing to reduce number of transmissions. Since IMIX uses linear coding, packets obtained by overhearing will not be duplicated by actual transmissions. By using linear coding, IMIX can achieve the same performance as a perfect acknowledgment scheme [4], with much lower complexity.
- We introduce OSPR (*Opportunistic Single-Path Routing*), which selects routes with least ETX value, taking overhearing opportunities into consideration. OSPR aids in improving the performance of IMIX. OSPR is light weight and can be easily embedded into both proactive and reactive routing protocols.
- We propose I^2MIX, which is the first scheme, to the best of our knowledge, that can benefit from both inter-flow and intra-flow coding. I^2MIX is an extended version of IMIX that also includes inter-flow coding. I^2MIX has additional improvements resulting from moving the decoding process from endpoints in IMIX to each hop. By doing this we trade additional computing resources for more network performance improvement, which is considered more valuable.
- We show by trace based evaluation the performance improvements that can be obtained by IMIX and I^2MIX.

The rest of this paper is organized as follows, Section II presents and discusses the design of IMIX. In section III, an IMIX aware routing scheme is introduced. Section IV presents the design of I^2MIX. In section V, we evaluate the performance of IMIX and I^2MIX. Section VI discusses related work, and section VII concludes and discusses future work.

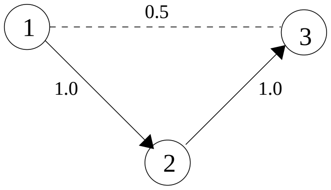


Fig. 1. An example for single hop IMIX

II. IMIX:Intra-flow MIXing

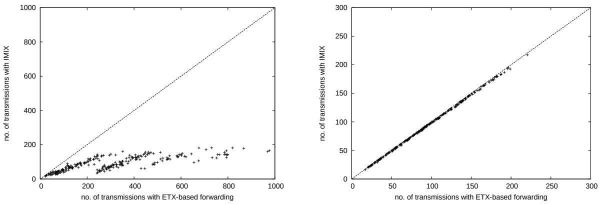
In [5], the authors proposed that intra-flow coding can be used to dramatically improve the performance of opportunistic routing. Later, [4] extended the usage of intra-flow coding to best-path routing. However, their primary goal was to increase reliability for single hop transmissions, while we attempt to use coding for any packets heard on the medium. In previous research, the potential of intra-flow coding to exploit overheard transmissions in best-path routing has never been explored. Consider the simple scenario showed in Fig. 1, suppose there is a path from node 1 to node 3 via node 2 with 100% delivery ratio. Node 1 can also reach node 3 with a 50% delivery ratio. Assuming links are symmetric, the ETX value of path 1→2→3 will be 2, and of path 1→3 will be 4. The former one will be chosen by current routing algorithms. Using this path, the lower bound of the total transmissions for n packets is $2n+2$ (2n packets and 2 acknowledgments). By using wireless network coding, this number can be decreased further. Suppose that node 1 sends the random linear combinations of n packets. Node 2, after receiving n coded packets, should be able to decode them (since the coefficients are randomly generated, we can suppose these combinations are linearly independent). At node 3, approximately $n/2$ coded packets should have been received simultaneously from node 1. Thus, only $n/2$ more packets are needed for node 3 to decode the original n packets. Node 2 will send new random linear combinations of all the packets it received, and node 3 will send an acknowledgment to node 2 after receiving $n/2$ packets. The total number of transmissions can thus be reduced to $1.5n + 2$.

We describe this network coding scheme, called IMIX (*Intra-flow MIXing*), as follows:

Definition *(IMIX)* At each hop within a single flow,

1) The sender codes n packets with random linear coding, and keeps sending randomly coded packets until it receives an acknowledgment from the next hop.
2) The next hop sends an acknowledgment immediately after receiving n linearly independent coded packets. If the next hop is the destination, it will recover the original data using the coded packets and the coefficients in the header, otherwise it will forward the packets by following rule 1.

IMIX is not dependent on the routing protocol. It can operate below any single path routing protocol. The coding gain of IMIX is the result of possible overheard transmissions from all previous hops in the path. If there are no overhearing opportunities, the necessary transmissions will be the same as that with linear coding mentioned in [4]. This property guarantees that this scheme will not increase the number of transmissions, even in the worst case.



(a) IMIX vs. Normal forwarding (b) IMIX vs. Normal forwarding with perfect acknowledgments

Fig. 2. Due to intra-flow wireless coding, IMIX has much better performance than normal forwarding. Though, if we assume perfect acknowledgments, IMIX does not significantly outperform normal forwarding.

Notice that more overhearing opportunities doesn't always imply more coding benefits. The reason is, with high packet overhearing from up stream nodes, a node needs fewer packets from its previous hop to decode the packets, which will decrease the opportunities for subsequent hops to overhear transmissions. Now the question is, how many overhearing opportunities can we take advantage of in a wireless network?

In Fig. 2(a) we compare IMIX with normal ETX based best-path forwarding. We use the trace data from Roofnet [6], and the settings of the evaluation are introduced in section V. Fig. 2(a) shows that IMIX can reduce the transmissions by half or more. Unfortunately, most of the gains in Fig. 2(a) are not from overhearing, but from the poor performance of the acknowledgment scheme used by normal forwarding. Traditionally, acknowledgments will be sent for every single data packet, but with intra-flow coding, only one acknowledgment is needed for every n packets [4]. We achieve the same performance as an optimal acknowledgment scheme, without the cost of increased protocol complexity and larger sized ACKs from the receiver.

In order to correctly obtain the gain by overhearing, we must assume perfect acknowledgments so that our results are not skewed towards IMIX due to its robust acknowledgment scheme. We use this assumption for normal forwarding in the remainder of this paper. With this assumption, retransmissions will occur only when data packets are lost, but not acknowledgments. Fig. 2(b) shows the gain achieved by IMIX over normal routing under this assumption. We can see that the gain from overheard transmissions is not significant. This can be best explained as a side effect of the ETX based route decision process. During the ETX route selection process between a node pair, an intermediate node which is physically closer to the destination is more likely to be selected as the next hop. This will result in longer links and less total hops. Both of which will decrease the probability of overhearing transmissions from previous hops. In fact, during our evaluation we found that even though there are overhearing opportunities on certain links, the transmission quality of most of these links are poor and would not contribute significantly to coding gain.

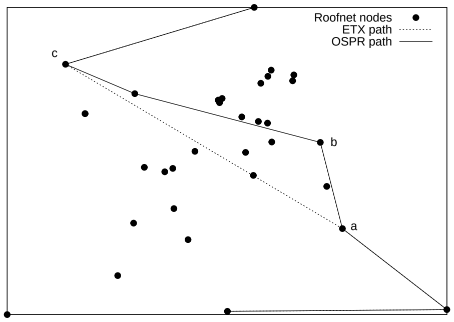


Fig. 3. A Roofnet scenario

Since ETX-based routing does not work well with IMIX, in order to find out how many overhearing opportunities exist in wireless networks, an overhearing aware routing algorithm is needed to maximize the coding gains of IMIX. We will discuss this algorithm in the next section.

III. OSPR:OPPORTUNISTIC SINGLE-PATH ROUTING

An overhearing aware routing algorithm must take into account the overhearing probabilities from each of the upstream nodes at a given node. We first describe the metric for calculating the number of necessary transmissions with overhearing and then give the algorithm for finding the routes with the metric. If we define $\mathcal{S}_i$ as the number of necessary transmissions for each packet from the ith hop of a path (0 for the source) to the its next hop, we can capture the possibility of a transmission being overhearing by another node in this path with

$$\mathcal{S}_i \times r_{i,j}$$

Here $r_{i,j}$ is the delivery ratio on the link between the ith and jth node on a path. Using IMIX, a node uses the overheard packets from all hops preceding it. Because there is no duplication in information due to the use of linear coding, the possibility of one packet being overheard by the $i+1$ node in a path can be expressed as:

$$\sum_{j=0}^{i-1} (\mathcal{S}_j \times r_{j,i+1})$$

Note that the maximum probability of overhearing a transmission is one, therfore any value greater than one should be treated at one. The resulting equation for the number of necessary transmissions for each packet from the ith node to its next hop in a path is:

$$\mathcal{S}_i = \frac{1 - \min(1, \sum_{j=0}^{i-1} (\mathcal{S}_j \times r_{j,i+1}))}{r_{i,i+1}}$$

By using the value $\mathcal{S}_i$, it is possible to select routes that maximize intra-flow coding gain. Our routing algorithm that uses this coding opportunity metric is called OSPR (*Opportunistic Single-Path Routing*). Compared with normal best path routing, OSPR routes have a higher probability of including more hops, and therefore can provide more overhearing opportunities. Fig. 3 shows the difference between the OSPR path and the ETX based best-path, which are calculated for the same node pair in the Roofnet [6] topology. Although the OSPR path has two more hops, it can actually achieve better throughput under IMIX by providing more overhearing opportunities.

TABLE I
NOTATION

$\mathcal{S}_i$	no. of necessary transmissions for each packet by the ith hop
$r_{m,v}$	delivery ratio on link $m \rightarrow v$
spt	the SPT tree being built
u	the last joined node
v	a neighbor of the last joined node
$O(v)$	the probability of each packet overheard by v
$\mathcal{P}^u_{spt}$	set of nodes along the shortest path from the root of spt to u
rest(m)	the probability that node m still need to transmit a packet
dis^v_u	the minimal distance from root to v through u
$\mathcal{D}^v$	the minimal distance from root to v
$parent(v)$	the parent node of v in spt

Alg 1 : SPT Updating procedure for OSPR: Update(v, spt, u)

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$O(v) \Leftarrow 0$
for all $p \in \mathcal{P}^u_{spt}$ do
  if $r_{m,v} > 0$ then
    $O(v)$ += $r_{m,v} * \text{rest}(m)$
rest$(m) \Leftarrow (1 - min(1, O(v)))/r_{m,v}$
$dis^v_u \Leftarrow \text{rest}(u) + \mathcal{D}^u$
if $dis^v_u < \mathcal{D}^v$ then
  $\mathcal{D}^v \Leftarrow dis^v_u$
  $parent(v) \Leftarrow u$
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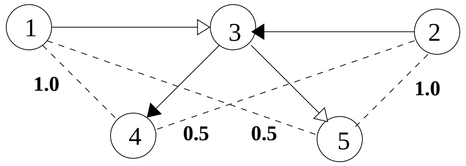
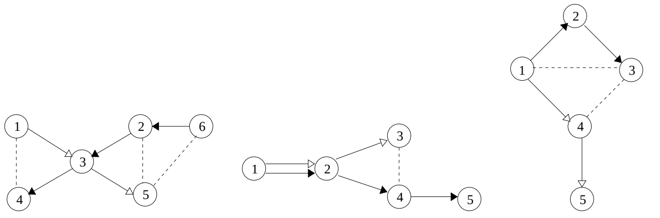
OSPR can be implemented by simply replacing the distance updating procedure in Dijkstra algorithm by Alg 1. The notation used here is listed in Table I. The time complexity of the modified Dijkstra algorithm is $O(n^3)$, larger than the $O(n^2)$ complexity of original Dijkstra but still acceptable. OSPR can be applied not only in proactive routing protocols, but also in most reactive protocols. For example, in DSR, $\mathcal{S}_i$ can be calculated and carried in route requests at each hop, so the destination can find the best route by comparing the route requests from different neighbors.

Now we can answer the question proposed in last section, how many overhearing opportunities can we take advantage of in a wireless network? Evaluation results in section V shows that the performance of IMIX is affected by the routing algorithm. With IMIX using ETX based best paths, IMIX can save no more than 2% of transmissions in comparison with normal best-path forwarding. In contrast, with OSPR the overhearing savings increase but are partially offset by the longer hops taken by OSPR. We further analyze and show more evaluation results about running IMIX with OSPR In section V.

It is interesting to compare OSPR with opportunistic routing. Their gains are both based on the broadcasting nature of wireless transmissions. Both take advantage of possible long jumps towards the destination which are not reliable enough for traditional best-path routing. But opportunistic routing can



(a) A typical scenario in which I^{2}MIX can benefit from both intra-flow and inter-flow coding



(b) Linear coding gain (c) "Early-Forwarder" gain (d) "Gossip" gain

Fig. 4. Scenarios in which I^{2}MIX can have gain. Dashed lines represent overheard transmissions, with the delivery ratio noted beside the line. Solid lines show links actually used for transmissions, which we assume has a delivery ratio of one.

also use multiple forwarding candidates which may exist in some scenarios to reduce transmissions, while IMIX can only benefit from just a portion of them. However, according to [7], The majority of the the node pairs in Roofnet have only one good candidate, and about 90% have no more than two. Since, this work is on coding we intend to explore this in future work.

IV. I^{2}MIX:INTRA-FLOW&INTER-FLOW MIXING

The major distinctions between IMIX and MORE are: First, IMIX uses an acknowledgment at each hop, but MORE uses it from end-to-end; Second, and most importantly, IMIX relies on best-path routing instead of opportunistic routing, which is used in MORE. The latter one can not work well with inter-flow coding (because inter-flow coding - like COPE - needs the information of the next hops, which is unknown in opportunistic routing). Conversely, IMIX still has a chance to benefit from inter-flow coding. In this section we present an improved version of IMIX - I^{2}MIX (*Intra-flow&Inter-flow MIXing*). To the best of our knowledge, I^{2}MIX is the first scheme that can combines both intra-flow and inter-flow coding. The description is as follows:

Definition *(I^{2}MIX)* At each node with packets in its sending queue:

1) The sender codes a set of packets in its queue using random linear coding, and continues sending randomly coded packets until receiving an acknowledgment from all the respective next hops of each coded packet
2) If a receiver is the next hop of the coded packets, it sends an acknowledgment as soon as it is able to recover the original data from the coded packets. It then examines those packets sent to it, and puts them in its sending queue unless the node is the destination.

Fig 4(a) shows how I^{2}MIX can benefit from both intra-flow and inter-flow coding. Assume node 1 is sending n packets to node 5 via node 3, and node 2 is sending n packets to node 4 via 3. With normal forwarding, node 3 needs to send at least $2 * n$ packets. Using IMIX or COPE, the number of packets will be decreased to n. By using I^{2}MIX, the number of transmissions at node 3 can be further decreased. Since both node 4 and 5 have heard $1.5*n$ packets coded from the original $2*n$ packets, when node 3 broadcasts the coded combinations of the packets to 4 and 5, only $0.5*n$ more coded packets are needed for both of them to be able to decode. In other word, the number of transmissions at node 3 is reduced to $0.5*n$.

The key differences between I^{2}MIX and IMIX are: First, in I^{2}MIX, packets from all flows are coded together at a node, while in IMIX, packets are only coded with other packets from the same flow. Second, in I^{2}MIX, before the sender stops transmitting the current combination and move to the next one, it needs an acknowledgment from the next hop of each flow. Third, the packets need to be decoded at each hop in I^{2}MIX. This means there is a trade off between reducing transmissions and increasing computing complexity. Since communication resources are considered more valuable and increase at a slower rate than computing resources, it seems to be an obvious choice to prefer more computing usage to save communication resources.

The distinctions between I^{2}MIX's and COPE's inter-flow coding methods are: First, I^{2}MIX performs linear coding for packets from different flows, instead of a simple XOR as COPE does. Second, unlike COPE, I^{2}MIX needs no reception reports, which will cause constant overhead even when there are few coding opportunities. By using linear coding, I^{2}MIX will catch every existing coding opportunity, and no extra transmissions will be introduced.

Besides gains already seen in IMIX and COPE, I^{2}MIX also has other benefits:

Linear coding gain: Inter-flow coding gain in I^{2}MIX is similar to COPE, but can be improved upon. The reason is because we use linear coding, thus overheard packets will not be duplicates. As we show in Fig. 4(b), When node 5 is able to hear from more than one previous hop in another flow, the packets it hears from different senders will each contain new information, which will provide more inter-flow coding opportunities for node 3.

"Early-Forwarder" gain: As Fig. 4(c) shows, when link 2→4 has better delivery ratio than link 2→3, node 4 may recover the original packets earlier than node 3 and start to forward the received packets immediately. If node 3 is close to node 4, the packets it heard from 4 will help it to decode the coded packets it received from node 2.

"Gossip" gain: There are a number of other scenarios in which one node can overhear useful packets. We term all these additional scenarios "Gossip" gain. Fig. 4(d) shows one of these scenarios. The packets node 3 overhears through link 4→3 while node 4 transmits to node 5 can help it decode the packets it has overheard through link 1→3 while node 1 was transmitting to nodes 2 and 4.

In I^{2}MIX, packets from all flows will be coded together at each node. Although it provides us the integration of inter-flow and intra-flow coding, this blindness in coding may cause a problem which has already been shown in Fig. 4(d). In this scenario, when node 1 is sending, it will code packets from flow 1→2→3 and flow 1→4→5 together, which may increase the difficulty for node 3 to decode its overheard packets through link 1→3 since the coded packets now contain the packets from flow 1→4→5, which are currently useless to it. In fact, this problem exists in all inter-flow coding schemes. In COPE, overheard packets may be coded packets, for which a node can do nothing but drop. To the best of our knowledge, this problem has not been solved yet.

The coding gain from both intra-flow and inter-flow coding in I^{2}MIX will be reduced by the problem mentioned above. Fortunately, this reduction is not very significant for the following reasons: First, it only affects overheard packets, because the transmission to the specified next hop will be guaranteed by the receipt of an acknowledgment. Second, each node that overhears transmission will be able to successfully decode their packet as long as at least one of the actual next hops from the sender has a delivery ratio less than the delivery ratio from the sender to the overhearing node. Third, even if the overheard packets can not be decoded directly, they may be able to be decoded together with some cached packets or future packets.

V. EVALUATION

In this section we evaluate the performance of our proposed schemes using the link-level measurement trace of MIT Roofnet [6], a 38-node multi-hop wireless network. The measurement trace recorded packet delivery over each link of the network for a total of 90 seconds with transmission rates: 1, 2, 5.5 and 11 Mbps. We compute the average delivery ratio over 90 seconds for each link, and use this average value as its link-level delivery probability. We assume that perfect acknowledgments are used throughout the evaluation as explained in Section II.

To minimize the randomness in traffic generation, we generate a one-packet flow between every node pair. The number of transmissions with ETX based best-paths is defined by the sum of the ETX cost on the paths between all of these node pairs. Similarly, the number of transmissions with IMIX can be defined by the sum of $\mathcal{S}_i$ (defined in section III) on all paths. For inter-flow coding, we calculate the gain differently. We capture the gain from inter-flow coding by rules similar to that of COPE. If a node is at the intersection of two flows, and its next hop on each flow (suppose they are node a and b) can overhear from some previous hops on the other flow, we assume there is a coding opportunity, and the gain can be found by the overhearing possibility on either a or b - depending on whose value is less. Also, since finding an optimal mixing algorithm is NP-hard [8], for simplicity we only XOR code two packets together.

A. IMIX

We discussed in Section II that, with the assumption of perfect acknowledgement, linear coding has no gain when comparing with a regular ETX based scheme. Fig. 5(a) shows the gain with IMIX over a regular ETX based scheme with and without OSPR. It can be seen that the gain is negligible whelm IMIX is deployed on an ETX based path. Even with OSPR, the gains are not much (about 2-5%) and this can be explained with the results in Fig. 5(b). The longer hops chosen by IMIX increase the base ETX value and thus offset some of the gains. This is the penalty for preferring short hops with more overhearing opportunities for long hops. OSPR based paths show gains inspite of this additional overhead. Fig. 5(b) shows the cumulative distribution of fraction of flows vs. transmission savings for 2Mbps data rate. It can be seen that only about 20% of the nodes have any gain at all for an ETX based path. For OSPR based path, this increases to 65% (indicating the overhearing opportunities created by OSPR) but only about 30% of the nodes have a gain above 5% and the low average gain reflects this. These results are consistent with those reported in [2]. With the perfect acknowledgment assumption relaxed, the gains will be much higher with IMIX as shown before. We feel that the Roofnet topology is also a significant factor affecting the gain. A denser topology might yield better gains due to the increase in overhearing opportunities along the OSPR path.

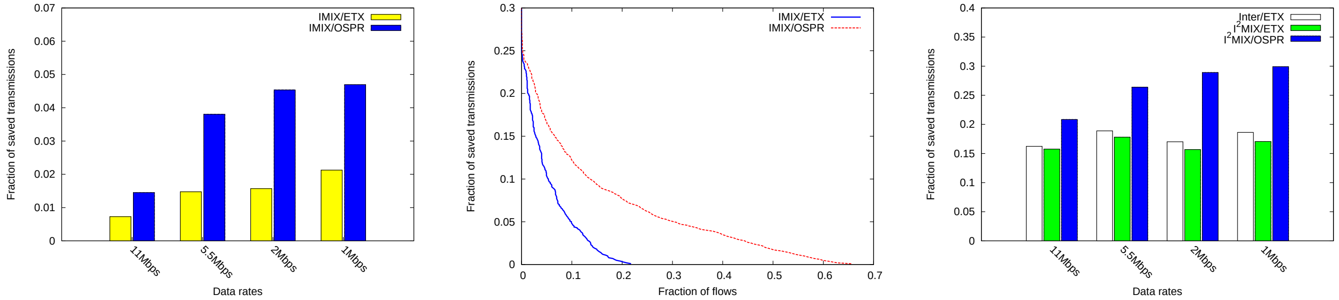
B. I^{2}MIX

The evaluation result of I^{2}MIX is shown in Fig. 5(c). I^{2}MIX performs slightly worse than inter-flow coding on an ETX based path and performs significantly better on an OSPR path. This is because, when using an ETX based path, some coding opportunities are lost due to the useless overheard (coded) packets. This loss can easily be outweighed by choosing an OSPR path which increases overhearing opportunities. Routing on an OSPR path creates more coding opportunities because more nodes overhear packets and will be able decode coded packets. We obtained a gain of 21-30% in our evaluation of I^{2}MIX with OSPR. While these gains are significant, they may not accurately reflect the complete potential for gain because of the evaluation methodology and the topology. As mentioned in [3], the majority of gains in inter-flow coding are obtained by reducing the traffic at intersecting nodes, which are also likely to be congested nodes. This kind of improvement can not be shown in our offline evaluation and can enhance the real world performance of I^{2}MIX. The ”First-help-others” gain and ”Gossip” gain can also be not shown in this offline evaluation. It is reasonable for us to believe that I^{2}MIX can have more gain in our future simulations.

At lower data rates, the transmission range and thus the overhearing probability increases in the network which leads to an increased gain. For both IMIX and I^{2}MIX the gains are higher at lower data rates which can be observed in Fig. 5.

VI. RELATED WORK

Network coding was first proposed for improving multicast capacity in wired networks [9]. There have been several coding schemes proposed for wireless networks, which can be divided into two categories, inter-flow wireless network coding and



(a) Transmissions saved by IMIX (b) Transmissions saved on fraction of flows (c) Transmissions saved by I^{2}MIX

Fig. 5. Evaluation results for IMIX, OSPR and I^{2}MIX, with Roofnet topology

intra-flow wireless network coding [4]. An example of inter-flow coding is COPE [3], in which the intersecting nodes of multiple flows keep track of coding opportunities, and perform XOR coding whenever there is an opportunity found. MORE [5] uses intra-flow coding to improve the performance of ExOR [1], which is an opportunistic routing scheme that can take advantage of the broadcasting nature of wireless. By using linear coding to reduce reliance on the reception of any single packet, MORE can increase the unicast throughput of ExOR by 22-45%. Linear coding has been extensively used for various applications. Specifically, [10] [11] and [12] show that linear coding can achieve the best capacity for multicast traffic, and the required polynomial time complexity is bounded at $O(n^2)$ for encoding algorithms, $O(n^2)$ for testing innovation and $O(n^3)$ for decoding [13]. Our work differs from other inter-flow coding schemes as we propose to use linear coding for inter-flow coding. IMIX differs from other intra-flow coding schemes because it takes advantage of the overhearing opportunities.

Recently, a link layer mechanism RTS-id [2] was proposed, which is similar to IMIX in that it reduces duplicated packets by taking advantage of overheard packets. Though both schemes depend on link layer caching, their strategies are completely different. In RTS-id, a special RTS which contains the ID of the next data packet is used. If the receiver already has this packet in its cache, it will reply with a special CTS to save the duplicated transmission of the data packet. IMIX uses linear coding to take advantage of caching. We believe the savings in RTS-id is a subset of the saving in IMIX. This is because the duplication of packets has already been eliminated in IMIX, and in RTS-id duplication may still occur because overheard packets are not exploited. Also, as we discussed in this paper, without a proper routing strategy, there are not enough benefits from overhearing transmissions. We believe RTS-id can have more gain if it works with the IMIX aware routing algorithm, OSPR, proposed in this paper.

VII. CONCLUSIONS

Previous intra-flow coding schemes such as MORE work only with opportunistic routing, but inter-flow coding requires best-path routing, which means they cannot be applied together. To achieve the goal of integrating intra-flow and inter-flow wireless network coding, we proposed IMIX, an intra-flow wireless network coding scheme based on best-path routing that can benefit from broadcast transmissions. Since IMIX is not able to gain much from traditional ETX-based best-paths, we presented a routing algorithm called OSPR, which can find the paths that expand the coding gain of IMIX. Finally, intra-flow coding and inter-flow coding are integrated within I^{2}MIX, an updated version of IMIX which can save between 21-30% of the transmissions in our evaluations based on the Roofnet topology, with the tradeoff resulting from applying hop-by-hop decoding instead of end-to-end decoding.

Our next step is to investigate the performance of the above schemes with simulations in the QualNet simulator [14]. The results presented in this paper assume a fixed rate for the whole network and we intend to investigate the effects of dynamic rate selection on IMIX and I^{2}MIX.

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