Evaluating Forwarding Schemes Exploiting Path Diversity and Degrees of Redundancy in a Realistic Wireless Environment

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Abstract—In this paper we validate and extend through simulations the trends revealed by the analytical results of our prior work concerning the throughput-delay trade-off that can be achieved by forwarding schemes exploiting path diversity and different degrees of redundancy focusing on the case of hop-by-hop retransmissions at the link-layer. The simulation environment is based on 802.11 Physical and Mac layer. It employs single source unicast traffic and consists of two scenarios with high and low interference respectively. A key contribution of this study is the demonstration of the throughput-delay trade-off for various forwarding schemes, including network-coding based ones, under a more realistic wireless model where link loss rates are determined dynamically by the SINR criterion.

I. INTRODUCTION

The core notion of network coding introduced in [1] is to allow and encourage mixing of data at intermediate network nodes. Network coding is a generalization of the traditional store and forward technique. Most of the theoretical results in network coding consider multicast traffic but the vast majority of Internet traffic is unicast. Applying network coding in wireless environments has to address multiple unicast flows, if it has any chance of being used. Especially for the case of multicast traffic where all receivers are interested for all packets, intermediate nodes can encode any packets together, without worrying about decoding which will be performed eventually at the destinations.

This study extends our prior work [2], [3] which presented an analytical framework for investigating the performance that can be achieved by exploiting path diversity and different degrees of redundancy for unicast traffic in multi-hop wireless networks. It should be noted that it mostly focuses on [2] which considers hop-by-hop instead of end-to-end retransmissions. More precisely, the aforementioned framework explored the throughput-delay tradeoff for network coding based forwarding schemes and compared it with other schemes, such as, single-path, multi-path, and multi-copy.

The idea of using redundancy is central in channel coding theory. In this work we also use redundant paths to send coded packets in order to recover the loss of information using packets from another path, thus decreasing the delay. The work in [4] uses path diversity for fast recovery from link outages. The work in [5] introduces error correcting network coding as a generalization of classical error correcting codes. The work in [6] studies the coding delay in packet networks that support network coding. The authors in [7] propose efficient algorithms for the construction of robust network codes for multicast connections. The work in [8] presents an approach for designing network codes by considering path failures in the network instead of edge failures. There is a lot of work concerning opportunistic routing in wireless mesh networks, with or without network coding. COPE [9], MORE [10] and MC² [11] investigate network coding with opportunistic routing in wireless networks with broadcast transmissions, focusing exclusively on the throughput improvements. ExOR [12] and ROMER [13] investigate opportunistic routing in broadcast wireless networks without network coding. Moreover, these works also focus on the throughput improvements, except [13] which also considers the packet delivery ratio. The work of [14] considers diversity coding, and investigates the allocation of data to multiple paths that maximizes the probability of successful reception. The work of [15] extends the previous work, in the case where the failure probabilities are different for different paths, and when the paths are not necessarily independent.

The main contribution of this study is the validation and extension through simulations of the trends revealed in our prior work [2] concerning the throughput-delay tradeoff for forwarding schemes exploiting multi-path diversity and different degrees of redundancy under a more realistic wireless model where loss rates are determined dynamically by the SINR criterion for each link. This is the first step of a process that involves an iterative relaxation of all assumptions introduced in [2] in order to stress test model validity and extend the discussion concerning the throughput-delay trade-off under a broader range of wireless models. More precisely, all aforementioned schemes are evaluated on a topology consisting
of wireless lossy links that may interfere with each other with no co-ordination among the transmitters for accessing the shared medium. The type of traffic considered is single-source unicast traffic. Our preliminary results suggest that under the presence of high interference, employing multiple paths to the destination, even with moderate or high redundancy does not guarantee the best throughput-delay balance. In fact, the scheme that achieves both the best delay and throughput in the presence of high interference is single-path forwarding. Moreover, the delay experienced by network-coding based schemes is highly affected by the inter-arrival times of packets belonging to the same packet generation, especially in the presence of high interference. Another interesting observation concerning network coding is that deferring the emission of a packet generation until the previous one is successfully decoded results in a dramatic decrease in the delay at the penalty of a tolerable, in most cases, decrease in throughput when compared to network coding that continually injects packet generations into the network.

The paper is organized as follows: Section II briefly overviews the forwarding schemes and the analytical framework discussed in our prior work. Section III describes the simulation setup along with the wireless scenarios simulated. Section IV presents some preliminary results and remarks concerning the throughput-delay trade-off.

II. NETWORK MODEL

Before describing the simulation setup, we give a brief overview of the analytical framework and the forwarding schemes discussed in [2], in order to introduce the notation and ease the comparison with the simulation results.

A. Single Path

In single path forwarding only one path is employed in order to route traffic to the destination. Average per packet delay is denoted by \( D_{sp} = \frac{1}{1-\min_i e_i} \) while throughput by \( Thr_{sp} = \frac{1}{D_{sp}} \). For all the equations listed in this section, \( e_i \) denotes the transmission error probability of link ‘i’.

B. Multi-copy

The multi-copy forwarding scheme uses all the available paths to the destination. More precisely it replicates every packet of a single flow on all available paths achieving the maximum possible redundancy. Average per packet delay is denoted by \( D_{mc} = \frac{1}{1 - \prod_{i=1}^{3} e_i} \) while throughput by \( Thr_{mc} = \frac{1}{D_{mc}} \).

C. Multi-path

A source node employing a multi-path forwarding scheme, uses all available paths to the destination in parallel without using any redundancy. It can either distribute packets of the same flow to be routed to the destination through all available paths or route different flows over different paths. Average per packet delay is denoted by \( D_{mp} = \frac{1}{3} \sum_{i=1}^{3} \frac{1}{1-e_i} \) while throughput by \( Thr_{mp} = \frac{3}{D_{mp}} \).

D. Network-coding

As far as network-coding based forwarding schemes are concerned there are some important parameters related to them that need to be discussed first, before describing the variants explored. First of all, a packet generation denotes a set of data packets that are coded together and characterized by a common unique generation id. Assuming a packet generation of \( N \) packets, there are practically \( 2^N - 1 \) linearly independent combinations of those packets that can be generated (coded packets). In order to decode the original data, the decoder (receiver) needs to receive at least \( N \) out of these \( 2^N - 1 \) coded packets. As far as redundancy is concerned, assuming a packet generation of \( N \) packets, a network coding based scheme may choose to inject \( N+k \) packets into the network, with the extra ‘k’ coded packets carrying redundant information. Apart from that, transmitters may choose to defer injection of more packet generations in the network until the previous ‘n’ generations are successfully decoded. As also discussed in section IV, such an approach proves beneficial in cases of heterogenous paths where decoding of a packet generation is delayed by waiting slower paths to accomplish end-to-end packet delivery. Finally, if there are nodes in common in a topology, intermediate nodes may decode information and re-encode it (hop-by-hop coding). Otherwise, end-to-end coding is considered.

Although the analytical framework of [2] discusses several variants of network-coding based on the aforementioned parameters, in the present study we focus on a network coding scheme that: a) uses a packet generation of size two (packets encoded in pairs) b) performs end-to-end coding c) employs a single redundant path. Additionally, it injects a packet generation into the network only upon notification of successful decoding of the previous one by the destination. Taking also into account that a link’s packet error rate is determined dynamically and in accordance with [2], [3], the average delay of this scheme for single hop paths is denoted by:

\[
D_{nc} = \frac{1}{1 - \prod_{i=1}^{3} e_i} \left[ \sum_{i=1}^{3} (1 - e_i) + \sum_{i=1}^{3} \prod_{j=1,j\neq i}^{3} (1 - e_j) + \sum_{i=1}^{3} (1 - e_i)(1 + D_1) \prod_{j=1,j\neq i}^{3} e_j + \sum_{i=1}^{3} 3 e_i \right]
\]

where \( D_1 = \frac{1}{1 - \prod_{i=1}^{3} e_i} \).

Throughput is approximated by: \( Thr_{nc} = \frac{2}{D_{nc}} \). For comparison reasons in the present study we also explore experimentally the throughput-delay trade-off of a network coding scheme that does not wait for a packet generation to be decoded in order to inject the next one. As a result, multiple packet generations can be running on the network at any time.

III. NETWORK SIMULATION

A. Simulation Setup and Scenarios

The aforementioned schemes are evaluated using the Ns2 network simulation (version 2.34) [16]. The wireless setting used is based on the 802.11b/g implementation by dei80211mr
library [17]. Among other features, this implementation supports multiple transmission rates and modulation schemes, and also an SINR-based packet level error model. A custom source routing protocol based on the olsr implementation in [18] is employed to ensure that packets of the same flow will be routed to the destination through the same path. Adding support for simulating network coding requires two main modifications. Firstly, data packets that are coded together and thus belong to the same generation are marked with a common generation id. In this way, receivers are able to distinguish among packets from different generations and decode them. The second modification concerns the assumption introduced in our prior work [2] according to which relaying nodes in the topology remove from their queues a multi-copied packet that is successfully delivered to the destination or any packets that belong to a generation that is successfully decoded by the destination. To support this functionality, a global ack mechanism is simulated which consists of a custom acknowledgment broadcasted throughout the whole network by the destination node upon reception of a packet or successful decoding of a packet generation. This acknowledgment carries the sequence number of the packet received for the case of multi-copy and the generation id of the generation decoded for the case of network coding-based forwarding. Finally, Table I lists the configuration of the most significant parameters of 802.11 MAC and Physical layer. As far as those parameters are concerned, having disabled the Maximum Retransmit Threshold means that a frame which is discarded at the receiver due to low SINR for example, will not be dropped after a certain number of retransmissions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTS/CTS</td>
<td>Off</td>
</tr>
<tr>
<td>Max Retransmit Threshold</td>
<td>Off</td>
</tr>
<tr>
<td>Link Rate</td>
<td>24Mbps</td>
</tr>
<tr>
<td>Transmit Power (EIRP)</td>
<td>20 dBm</td>
</tr>
<tr>
<td>Propagation Model</td>
<td>Freespace</td>
</tr>
<tr>
<td>System Loss</td>
<td>0 dBm</td>
</tr>
</tbody>
</table>

As a result, flows on different paths experience both inter- and intra-path interference. The horizontal distance $d_h$ (link length) is the same for every pair of nodes and chosen so that each node to interfere only with its one-hop neighbor. By fixing the vertical distance $d_v$ (link separation) between pair of nodes that belong to different paths, the amount of inter-path interference is controlled. Distance $d_v$ is fixed in such a way that nodes that are k hops away from the source and belong to a different path each, interfere with each other. In the second scenario (orthogonal channels scenario), transmitters of the same path share the same channel while transmitters on different paths use orthogonal channels. Consequently a flow forwarded along a path experiences only intra-path interference. In both scenarios all nodes use a fixed transmission rate of 24Mbps, packet size is fixed to 1500 bytes, and source node S generates UDP constant bit rate traffic. Additionally, all nodes are static. Each scenario is replayed with source node S using one of the aforementioned transmission schemes each time in order to distribute traffic to the three available paths. For reasons of fair performance comparison, for all schemes employing multiple-paths, the flows forwarded through different paths are all assigned equal sending rates which are fixed to 9Mbps. It should also be noted that simulation time is 60 seconds.

### B. Throughput and delay measurements

As already stated this study aims at evaluating various forwarding schemes in terms of their throughput-delay tradeoff. Before presenting simulation results a brief discussion about how delay and throughput are measured for each scheme is needed. For the case of single- and multi-path, delay is estimated as the average per-packet delay with per-packet delay denoting the time interval between dequeuing a packet for transmission at source node S and successful reception of that packet at destination D. As far as multi-copy is concerned, delay is also estimated as average per-packet delay. However, in this case, per-packet delay denotes the interval between dequeuing a packet with sequence number ‘k’ at S and the time when the first packet with sequence number ‘k’ is received at D. In case of network coding based schemes, delay is estimated as average per-generation delay where per-generation delay is the interval between dequeuing the first coded packet of a specific packet generation ‘i’ at source node S and the time when destination D receives a second coded packet for that generation. Recall that destination D is able to decode a generation when it receives at least two coded packets of that generation. For all transmission schemes delay averaging stops when 10,000 packets are successfully received or decoded (for network coding). It should also be noted that both per-packet and per-generation delay estimations, disregard queuing delay at the source node and the time needed for the destination to send back the acknowledgment of a packet reception or generation decoding (global ack mechanism) throughout the network. Additionally, encoding and decoding delays are disregarded for network coding. Throughput on the other hand is estimated as the rate at
which the application layer at the destination receives data. In case of a multi-copy scheme, although the destination node may receive more than one packets with the same sequence number only the first of them is taken into account for throughput estimation. As far as network-coding based schemes are concerned, only packet generations that are successfully decoded contribute to throughput which consists of two decoded packets.

**IV. Simulation Results**

The aforementioned forwarding schemes are evaluated under two scenarios a) single channel scenario where flows experience both intra- and inter-path interference and b) orthogonal channel scenario where flows experience only intra-flow interference. Table II lists throughput and delay achieved in the single channel scenario by the following forwarding schemes: single-path (SP), multi-path (MP), and multi-copy (MC). For the case of network coding-based forwarding schemes, NC(1,1) denotes a forwarding scheme that employs one path for redundant information using a packet generation of size two. Moreover, it defers injection of the next packet generation into the network until it receives an acknowledgment indicating that the previous packet generation was successfully decoded at the destination. NC(1,n) on the other hand, denotes a network coding based forwarding scheme using one path for redundant information, a packet generation of size two, injecting packet generations into the network without waiting for the previous ones to be acknowledged.

As table II shows lowest delay is achieved by multi-copy (apart from single-path) which is expected since every packet is also transmitted through the "fastest" path each time. Complementary to [2], for scenarios with high interference which varies dynamically based on the set of transmitting nodes each time, single-path forwarding achieves equally low delay with multi-copy. It is also interesting to note that network-coding utilizing one redundant path and allowing multiple packet generations to be running on the network at any time (NC(1,n)) exhibits significantly higher delay from both multi-copy and multi-path. The main reason for such a bad performance is the high interference present in the single channel scenario both in the form of intra-path and inter-path interference. As a result, a significant number of frames will need to be retransmitted several times in order to accomplish end-to-end delivery. Successive frame retransmissions not only increase delay but also increase the amount of interference imposed on the other links. In the case of network coding-based forwarding schemes, packets delivered to the destination having experienced few retransmissions will have to wait for packets being retransmitted multiple times in order for data to be decoded at the destination. On the other hand, network coding (NC(1,1)) where the source of traffic defers injecting packets of the next generation until the previous one gets acknowledged by the destination, achieves a dramatic improvement in terms of delay when compared to NC(1,n). Confirming the trend observed in [2] this delay is higher than multi-copy but lower than multi-path.

As far as throughput is concerned, among all schemes utilizing multiple paths in parallel to the destination, multi-path achieves the highest throughput. However, although it employs zero redundancy, its throughput is only 6.8% higher than multi-copy which employs the highest redundancy. This is due to the high interference among active links which results in significant channel time wasted retransmitting frames over lossy links. This is also the main reason for which single-path achieves higher throughput than multi-path. As our results show, in a rather lossy environment, such as, the one described in the single channel scenario, where there is no co-ordination among transmitters, utilizing more than one paths to the destination may not prove the optimal approach. It should also be noted that, complementary to the trends observed in [2] concerning the throughput-delay trade-off, the NC(1,1) scheme achieves significantly lower throughput than multi-copy which is somehow expected since the source node does not inject continually packets into the network due to idle times introduced between successive packet generations.

Focusing on the throughput-delay tradeoff for the two network coding-based forwarding schemes, it is interesting to note that the variant that allows only one packet generation to be running on the network at any time (NC(1,1)) achieves by far lower delay at the expense of a 20.5% decrease in throughput. Overall, in the single channel scenario where high interference is experienced by nodes, single-path forwarding achieves the best performance both in terms of delay and throughput.

In order to evaluate the effect of interference in the throughput-delay tradeoff of schemes employing multiple paths, throughput and delay measurements for the orthogonal channels scenario are presented in table III. Recall that in this scenario, different paths use orthogonal channels and thus nodes exhibit only intra-path interference.

As this table shows, multi-copy still achieves by far the lowest delay. As far as network coding-based forwarding
schemes are concerned, it is interesting to note that in the absence of interference among different paths (inter-path interference), there is a dramatic decrease in the delay of the scheme that employs one redundant path and allows multiple packet generations to be running on the network at any time (NC(1,n)). The effect of inter-path interference on throughput becomes more obvious by observing the high throughput achieved by multi-path and network coding-based forwarding schemes. Finally, the results presented in that table reveal that in a topology where only intra-path interference is present, the best throughput-delay balance is achieved by multi-path forwarding.

V. Future Work

The long term goal of this study is to develop an adaptive forwarding scheme that will switch among the different schemes discussed in the present study in order to meet specific application requirements, such as, low delay, high throughput or a good balance of both. Part of our future work is to identify under which wireless settings it is advantageous to exploit the underlying path diversity by introducing redundant information into the network and also identify the amount of redundancy required. The analytical framework introduced in [2] expresses the throughput-delay tradeoff for various schemes employing multiple paths and is restricted by several assumptions. Part of our future work is to gradually relax these assumptions and explore the validity of the models proposed. The present study removed the assumption of constant packet error rate for all links of a specific path by allowing dynamic packet error rates determined by the SINR criterion for all links. Further steps include allowing co-ordination among nodes based on 802.11 MAC layer, traffic of varying rates and paths of varying length and channel conditions and also multi-cast traffic apart from unicast.

Focusing on network coding-based schemes, we plan to further explore their throughput-delay tradeoff under more complex topologies and also how it is affected by the underlying path diversity and packet generation size.

VI. Conclusions

As our results suggest, in the presence of high interference, the best throughput delay balance is achieved by single path forwarding. Compared to the trends revealed by the numerical results of our prior work [2], the shortfall in network-coding based schemes’ performance is due to the large number of frame retransmissions caused by interference. Successive frame retransmissions cause large inter-arrival times between coded packets of the same packet generation.

On the other hand, when the amount of interference is significantly reduced, the best throughput-delay balance is achieved by multi-path with second best the network coding scheme employing one redundant path and allowing only one generation to be running on the network each time. Still however, the inter-arrival time between two coded packets that the destination must wait, in order to decode a specific packet generation, causes network-coding schemes to exhibit higher delay than multi-path in the low interference scenario.

Concerning the two variants of network coding discussed, we observe that waiting at the source node for a packet generation to be decoded before injecting the next one into the network results in a dramatic decrease of delay at the penalty of an affordable, at most cases, decrease in throughput.

REFERENCES