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Performance of Network-Coding in Multi-Rate Wireless Environments for Multicast Applications

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***Abstract*— This paper investigates the interaction between network coding and link-layer transmission rate diversity in multi-hop wireless networks. By appropriately mixing data packets at intermediate nodes, network coding allows a single multicast flow to achieve higher throughput to a set of receivers. Broadcast applications can also exploit link-layer rate diversity, whereby individual nodes can transmit at faster rates at the expense of corresponding smaller coverage area. We first demonstrate how combining rate-diversity with network coding can provide a larger capacity again for data dissemination of a single multicast flow. We present a linear programming model to compute the maximal throughput that a multicast application can achieve with network coding in a rate-diverse wireless network. We then present simulation results comparing the performance of network coding in combination with transmission rate diveristy, for a realistic stream-oriented application. Our results provide preliminary evidence that wireless network coding may lead to a latency-vs-throughput tradeoff.**

I. Introduction

There is an increasing interest in understanding the potential performance gains accruing from the use of network coding in multi-hop wireless environments. In particular, many military battlefield scenarios exhibit two characteristics that appear to motivate the use of network coding: a) the reliance on bandwidth-constrained, ad-hoc wireless links (e.g. using MANETs formed by vehicle-mounted radios in urban insurgencies) and b) the need to disseminate information (e.g., maps, mission commands) to multiple recipients. The initial results on the power of network coding **NC**, such as the original demonstration in [1] of how in-network mixing of packets by intermediate nodes helps to achive a communication capacity that is not achievable solely through routing, were obtained for the case of a lossless, wireline network. More recently, several groups have investigated the potential performance gains realized by network coding for both unicast (e.g., [2]) and multicast (e.g., [3]) traffic in wireless environments, for a variety of application scenarios. All of these approaches fundamentally aim to exploit the wireless broadcast advantage (**WBA**) by using, whenever possible, a single link-layer broadcast transmission (of a packet formed by a linear combination of individual packets) to reach multiple neighboring nodes. By saving on the number of independent transmissions needed, network-coding approaches effectively reduce the fraction of time the wireless channel is held by a single transmitting node and thereby help to increase the overall network throughput.

We believe that there is another degree of freedom in wireless environments, namely *link-layer rate diversity*, that network coding approaches have so far failed to exploit. Most commodity wireless cards are now capable of performing adaptive modulation to vary the link rate in response to the signal-to-interference levels at the receiver. Link rate diversity typically exhibits a *rate-range tradeoff*: if the same transmission power is used for all link transmission rates, then, in general, the faster the transmission rate, the smaller is the transmission range (although, the rate-distance variation in real life is somewhat irregular (e.g., see [4])). While this rate diveristy has been extensively exploited for unicast traffic and is often standardized, its use in link-layer broadcasting is relatively limited. For example, while the current IEEE 802.11a/b/g standards mandate the transmission of the control frames (e.g. RTS/CTS/ACK) at the lowest rate (e.g., 6 Mbps for IEEE 802.11a), transmission rates for broadcast data are typically implementation-specific. Recently, however, there has been some work (e.g., [5]) that demonstrates that effective exploitation of such rate diversity by *routing* algorithms for link-layer broadcasts can result in significant (often 6-fold) reduction in the broadcast latency and increase in the achievable throughput.

In this paper, we investigate the impact that the use of such rate-diversity for link layer broadcasts may have on the performance of network coding. It is easy to conceptualize how the rate-range tradeoff inherent to all link-layer broadcasts might impact the performance of various network coding strategies. Without consideration of rate diversity, network coding algorithms operate on an implicit "more-is-better" assumption: since each broadcast transmission takes the same time, encoding a larger number of packets (for a correspondingly larger set of neighbors) into a single packet *always* results in a more efficient use of the wireless channel. In reality, the existence of the rate-range tradeoff often invalidates this assumption. For example, assume that a node n has a set of packets $\{P_1, P_2, \ldots, P_N\}$ targeted for its neighors $\{n_1, n_2, \ldots, n_N\}$, where the neighbor indices are arranged in non-increasing order of the link transmission rates. Moreover, let R_i be the link rate between the node-pair (n, n_i). In this case, it is possible that combining the first i packets (transmitted at the rate R_i) proves to be more effective than combining the first $i+1$ packets, because the additional multiplexing gain achieved is negated by the need to use a disportionately smaller rate R_{i+1} for the packet broadcast. Our goals in this paper are thus to answer the following questions:

1) Is there a way to compute the throughput that is achievable by any network coding strategy in a network with rate-diverse and unreliable links?
2) How does the consideration of transmission-rate diversity affect the maximum throughput that may be achieved by linear network coding in wireless environments, i.e., how sensitive are the achievable throughput curves to the impact of link-rate heterogeneity?
3) How does the capacity achieved by rate-diversity aware network coding differ in practice from the throughput achieved by rate-diversity aware *routing* algorithms?

Given the closely-coupled interactions between the degree of encoding, the resultant transmission rate and the contentions on the wireless channel, we focus in this paper on the case of single-source multicast[1] problem. Note that the current paper is not *constructive*, i.e., it does not address the design of specific network-coding algorithms that are better at taking advantage of the rate diversity available in a specific network. Instead, our goal is to understand the fundamental interactions between transmission rate diversity and network coding.

A. Contributions of This Paper

This paper makes the following contributions towards understanding the basic performance of network-coding for broadcast/multicast applications in wireless environments:

- It extends the Linear Programming (LP) formulation, originally developed in [6] to ascertain the maximum achievable single-source throughput without rate diversity, to incorporate the rate-range variation on individual links, and thus compute the maximum achievable throughput, without and without NC, in rate-diverse wireless environments.
- It uses both the analytical LP-based formulation, as well as extensive simulation-based studies, to evaluation the relative performance of network coding algorithms vs. pure routing-based broadcasting strategies in rate-diverse wireless networks.
- It studies the impact of NC on not just the network throughput, but also the *dissemination latency*. Such a study suggests the possible existence of a throughput-vs-latency tradeoff that depends on the ‘degree of network coding employed; we believe that such a tradeoff will have important implications in the design of suitable network coding strategies for latency-sensitive information dissemination, such as the timely broadcast of sensor values.

The rest of the paper is organized as follows. Section 2 describes a motivation example. Section 3 describes related work. Section 4 the Linear Programming Model. Section 5 and 6 the results.

II. Motivation

We first use the class ‘butterfly’ network example to understand the relative merits of rate diversity and network coding, and the potential gains that may accrue from a judicious combination of both. Consider the 5-node topology in Figure 1. The links between the nodes are all 11Mbps, except for the link between node 1 and 2 which is 1 Mbps. Node 1 wants to broadcast packet A and node 2 wants to broadcast packet B. Note that, in a wireless environment, the links are not independent; for example, node 1 uses the same interface to simultaneously reach both neighbors 3 and 4. For simplicity, let us assume that each packet is of size 11Mbits.

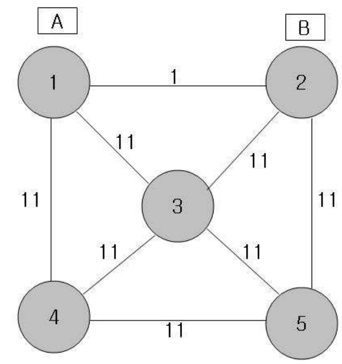

Fig. 1. Network Example

A pure routing-based and rate diversity-*unaware* strategy tries to schedule the dissemination of the broadcast packets so as to avoid collisions among contending links. It is easy to verify that an optimal transmission schedule consists of first having node 1 broadcast packet A to nodes 2, 3 and 4. To ensure that all these neighboring nodes are able to receive this packet, node 1 has to transmit with the lowest rate among the links (1-2,1-3 and 1-4); in this case, 1 Mbps (link 1-2). Therefore, it spends 11 time units. Following that, node 2 transmits B to 1, 3 and 5. Node 3 subsequently transmits B to 4, following this with a transmission of packet A to 5. The scheduling solution is shown below. The total time unit is 24.

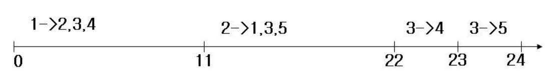

Fig. 2. Broadcast Scheduling

We can improve it by using Network Coding. In the usual Network Coding solution, Node 3 sends A XOR B to node 4 and 5, in a single transmission. Node 4 has A and can recover B from A XOR B. Node 5 has B and can recover A from A XOR B. The scheduling solution is shown below.The total time unit is 23 instead of 24.

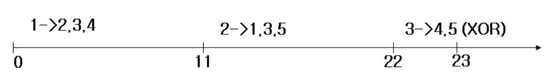

Fig. 3. Broadcast Scheduling

Let us now consider the rate diversity aware case, where different nodes may employ different rates for their broadcast transmissions. First, consider a *pure routing* based approach, where, as before, the network must schedule the transmissions to avoid contentions among interfering links. It is then easy to

[1]The multi-source, network coding problem is part of our future work.

verify that the entire broadcast dissemination can be completed in 4 time units. Namely, 1 first transmits A to 3 and 4 (taking a total of 1 time unit). Node 2 then similarly transmits B to 3, 5 (taking an additional 1 time unit). Following this, node 3 broadcasts A to 2 and 5 at 11 Mbps, and follows up with a broadcast of packet B to 1 and 4, again at 11 Mbps.

Interesting enough, combining network coding with rate diversity can reduce the overall transmission latency even further. To illustrate this, consider the following network coding-based transmission strategy. Node 1 first sends the packet A to 3 and 4 using the 11 Mbps transmission rate (node 2 cannot receive at this high rate..). Next, Node 2 sends packet B to 3 and 5 using the faster rate (11Mbps). Then node 3 sends (at 11 Mbps) the XOR message to 4 and 5, and also to nodes 1 and 2. Node 1 will retrieve B by applying XOR(A, A XOR B), as it is already aware of its own packet A. An identical reasoning applies for node 2. Figure 4 illustrates the transmission schedule in this case. Note that the total time consumed by this combination is 3 time units.

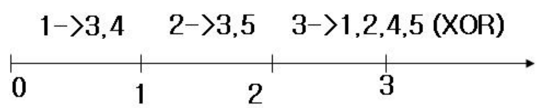

Fig. 4. Broadcast Scheduling

This canonical example serves to illustrate two important points. First, we have established that a combination of network coding and transmission rate diversity may prove to be mutually beneficial, resulting in an overall network throughput that is higher than that achievable by either strategy alone. Second, the example suggests that the gains from exploiting rate diversity (a reduction from 24 time units to 4) *may* be more spectacular than the gains accruing purely from network coding (a reduction from 24 time units to 23). Of course, we need to obtain the quantitative nature of the improvements in more practical, generalized topologies.

III. Related Work

Recently [1] it was demonstrated that, in general, it is suboptimal to restrict the interior routing network nodes to perform only routing. Multicast capacity is defined as the maximum rate that a sender can communicate common information to a set of receivers. It is given by the minimum of maximum flow(s,t) between sender s and each receiver t. It was shown that network coding can achieve multicast capacity. Li, Yeung, and Cai [7] showed that it is sufficient for the encoding function to be linear. In addition to throughput, network coding offers additional benefits as robustness and fewer network resources consumed. For wireless networks, network coding can also potentially improve in terms of energy efficiency and congestion control. We explore network coding but implement random linear coding into ODMRP [8].

In ad hoc networks, the maximum throughput of a multicast application of network coding was establish using a Liner Programming model [6] assuming a common link capacity. We extend this model to consider multi-rate.

Multi-rate multicast can reduce broadcast latency [5] by 3-5 times. In [5], an heuristic, WCDS, is presented that allows to find the optimal network layer broadcast that results in minimum broadcast latency. We explore those ideas by considering network coding.

IV. The LP Formulation for Obtaining Capacity of Network Coding under Transmission Rate Diversity

In this section we describe our Linear Programming formulation for studying the bounds achievable with/without NC.

We represent the network with a directed hypergraph $H = (N, A)$, where N is the set of nodes and A is the set of hyperarcs. hyperarc(i, J) represents that a packet transmitted by node i can be received by all nodes in J. We assume the network is time-slotted, transmissions are limited to start at slot boundaries.

Let L_m be the set of possible rates.

Let z_{iJ} ($< L_{max}$, the maximum link capacity) be the average at which packets are inject into hyperarc (i, J).

The wireless medium contention is modeled as in [5], and incorporate L_m .

$$\sum_k \lambda_k c_{km}(i, J) - z_{iJ} \geq 0, \forall (i, J)\epsilon A, \quad (1)$$

$$\sum_k \lambda_k \leq 1 \quad (2)$$

where

$$c_{km}(i, J) = \begin{cases} L_m & \text{if } (i, J)\epsilon A_k \\ 0 & \text{otherwise} \end{cases}$$

$\lambda_k \epsilon [0, 1]$ means the fraction of time allocated to A_k.

The maximum throughput multicast, from source s to non-empty set of terminal nodes T, is formulate as follows:

Maximize f:

subject to

$$\sum_k \lambda_k c_{km}(i, J) - z_{iJ} \geq 0, \forall (i, J)\epsilon A, \sum_k \lambda_k \leq 1 \quad (3)$$

$$(4)$$

where

$$c_{km}(i, J) = \begin{cases} L_m & \text{if } (i, J)\epsilon A_k \\ 0 & \text{otherwise} \end{cases}$$

Time-share constraint:

$$\Sigma_{P \subset J | P \cap K \neq} z_{iJP} - \Sigma_{j \epsilon K} x^t_{iJj} \geq 0, \quad (5)$$

$$\forall (i, J)\epsilon A, K \subset J, t\epsilon T \quad (6)$$

Data-flow constraint:

$$\Sigma_{J|(i,J)\epsilon A} \Sigma x^t_{iJj} - \Sigma_{J|(i,I)\epsilon A, i\epsilon I} x^t_{jIi} = \begin{cases} f & \text{if i=s,} \\ -f & \text{if i=t, } \forall i\epsilon N, t\epsilon T \\ 0 & \text{otherwise} \end{cases}$$

Domain constraints:
$x^t_{iJj} \geq 0 \forall (i,J) \epsilon A, j \epsilon J, t \epsilon T$
$z_{iJ} \geq 0 \forall (i,J) \epsilon A$
$\lambda_k \geq 0, \forall k$

V. Interaction of Network Coding and Rate Diversity and Impact on Throughput

In this section we show how the combination of network coding and rate diversity affects the performance of practical, distributed broadcasting protocols. Our simulations are performed using the Qualnet simulator. At the MAC layer, we used 802.11b. The rates ranged from 1Mbps (nodes at most 483.741m apart) to 11Mbps (283.554m). The network terrain had size 1000m x 1000m. The nodes were static.

In the experiments illustrated here, we have one source sending multicast packets for 120secs at a fixed rate. The network size was 50 nodes. (We also performed the simulations with a network of 20 nodes and observed qualitatively similar results–accordingly, we only present the results for the larger-sized 50 node wireless network.)

To vary the "degree of network coding" used, we vary the number of consecutive packets that a node attempts to linearly combine before a single transmission. We refer to this "level of coding" with the symbol NC. Thus, the case $NC = 0$, corresponds to the case of pure-routing, where each received packet is forwarded immediately by an intermediate forwarding node. As the value of NC increases, the degree of network coding is higher, as the network nodes implicitly try to achieve greater bandwidth savings by encoding a proportionately higher number of packets. A large value of NC could, however, result in significantly high forwarding delay (as a node could wait indefinitely until it received an appropriate number of consecutive packets). To keep this delay bounded, a practical implementation uses a transmission timer, which is reset at every encoded transmission: in case of timer expiry, a node will immediately transmit by combining the number of packets currently available, even if this is smaller than NC. (To avoid complicating our studies unnecessarily, we do not vary the value of the transmission timer.)

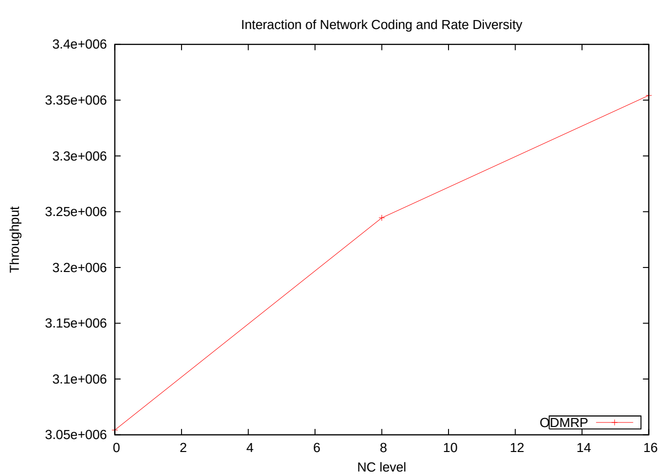

Fig. 5. Throughput vs. level of network coding.

Figure 5 shows the variation in throughput vs. level of network coding for ODMRP, without any transmission-rate diversity (the link-layer broadcasts all occur at a fixed rate of 11 Mbps). The throughput is plotted for $NC = \{0, 8, 16\}$. We can observe, as expected, that, the level of network coding increases, the throughput increases. The greater gain is observed when we move from a non-network coding situation (NC=0) to the NC level equals 8. Further increases in the 'degree of NC' do not provide as spectacular improvements in capacity, indicating that the benefits of network coding saturates at some modest value of NC.

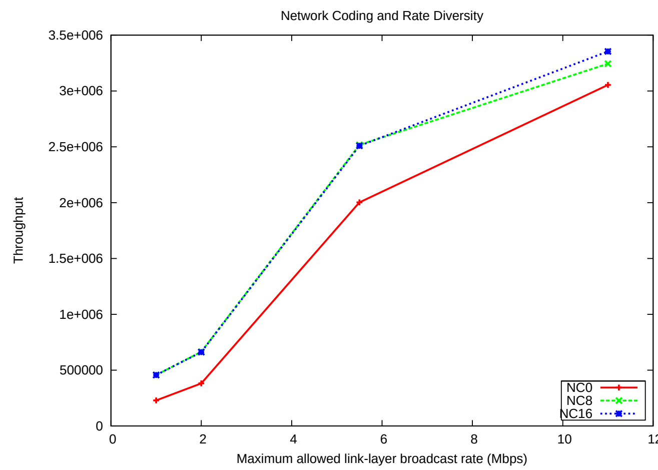

Fig. 6. Throughput vs. rate diversity

Figure 6 shows the throughput vs. rate diversity (maximum transmission rate allowed in Mbps) for different levels of NC. A rate value of 5.5 Mbps on the x axis implies that the nodes were allowed to transmit at all link rates, up to a *maximum* of 5.5 Mbps. The figure leads to several important observations:

- In all cases, as expected, the use of network coding (a higher value of NC) results in an increase in the achieved throughput.
- It appears to be clear that *incorporation of link-layer rate diversity* has a far greater impact than the use of network coding. For example, for ODMRP, increasing the transmission rate from 1 to 11 Mbps results in 10-fold increase in throughput (for $NC = 0$); however, increase NC to 16 only results in a two-fold increase in the throughput (at 1 Mbps).

Taken together, the observations suggest that the design of network coding strategies and link diversity-aware routing strategies *must be done jointly*. In particular, it appears that the gains from network coding can be somewhat modest for wireless multicast flows, unless the power of link layer rate diversity is adequately harnessed.

VI. Throughput Study in Practical Routing Protocols

While Section IV provides a centralized solution to the maximum throughput possible, it is perhaps of greater interest to ascertain how the combination of network coding and rate diversity affects the performance of practical, distributed broadcasting protocols.

Figure 7 show the variation in throughput vs. link-layer broadcast rate for a 7X7 grid network, with 49 nodes. In this particular figure, all nodes are constrained to use a common transmission rate (and thus range) for all their broadcast transmissions. Accordingly, a value of $x = 6Mbps$ indicates that all broadcast transmissions occur at 6 Mbps. The transmission rate is varied over the 802.11b-specific values of $\{1,\ 2\ ,5.5,\ 11\}$ Mbps. We can see that changing the link transmission rate has a significant impact on the throughput achieved with the use of network coding. In contrast, the throughput is less sensitive to the link transmission rate, when network coding is not employed.

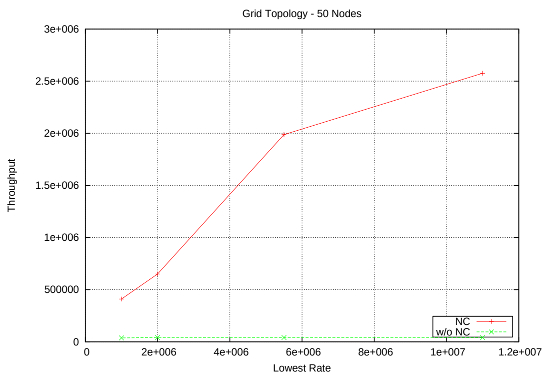

Fig. 7. Throughput vs. link-layer in grid topology.

Figure 8 show the variation in throughput vs. link-layer broadcast rate for a network with 50 nodes and random topology. The nodes were randomly displaced in a 1000x1000 terrain. In this case, a point on the x-axis implies that the network can use *all broadcast rate* below the corresponding value. As expected, permitting a larger set of transmission rates always improves the throughput achieved in the presence of network coding. However, the gain is maximum (the slope of the curve is the highest) when the rate increases from 2 to 5.5 Mbps;a subsequent increase in the maximum permitted broadcast rate to 11 Mbps results in a smaller increase in the throughput, as the higher rate has a lower 'Rate Area Product' (RAP), a metric for the broadcast effectiveness of a link layer rate introduced in [5]. Intuitively, the larger transmission rate is not as advantageous as the increase in the transmission rate is accompanied by a sharp falloff in the transmission range, which lowers the number of nodes that can be 'covered' by a single transmissionl

Figure 9 illustrates the corresponding throughput of a network of 50 nodes, with random topology, with the key difference that a point on the x-axis implies the use of the corresponding rate in *all* broadcast transmissions. (In other words, this is the analogue of Figure 7 for the case of a randomly generated topology.) While network coding is again shown to improve throughput, we observe an additional phenomenon: increasing the data rate associated with broadcast transmissions may not always increase throughput (due to the associated decrease in communication range.)

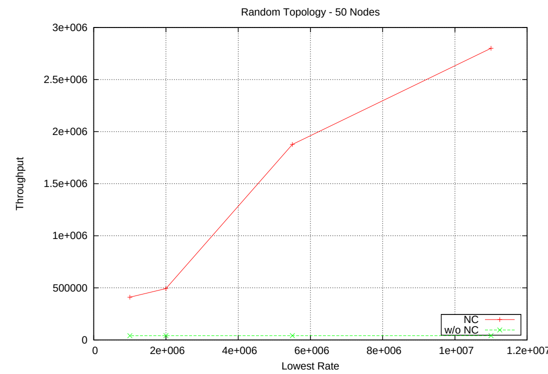

Fig. 8. Throughput vs. link-layer in random topology.

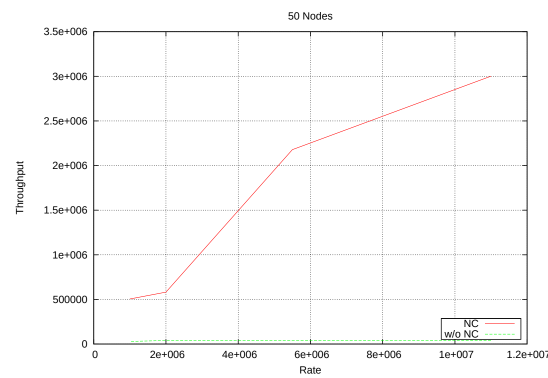

Fig. 9. Throughput vs. link-layer in random topology.

VII. Latency Study

In this section we show the latency cost associated with the use of network coding, and the impact on this cost of variations in the link layer transmission rate. As background, it is well known that network coding can result in higher *per-packet* delay, as the essence of the algorithm is to delay the transmission of certain packets until additional packets have been collected and can be combined into a single broadcast transmission. However, it has also been shown that relatively file-insensitive applications, such as file transfer, can benefit signficantly from network coding: the overall transfer latency of files (the time till the reception of the last packet) can be significantly reduced.

Reducing per-packet latency and jitter is important for many real-time or interactive multimedia applications, such as VoIP or video conferencing. In such cases, it is apparent that network coding may not be a good choice. However, there is an interesting *an emerging class* of *quasi-real time* applications that lies between the extremes of file-sharing and VoIP/video conferencing. Consider, for example, an image of a city street being disseminated by a camera sensor to multiple armored carriers and soldiers in an urban battlefield. Minimizing per-packet latency is not critical, as the sensor's data is useful only when the entire image can be reconstructed. However, there is an intrinsic value associated with the *freshness* of the data: for effective decision making, the sensor data must be disseminated rapidly, within a specific bound.

Figure 10 shows the conventional latency metric of time to

Last Packet Arrival for a multicast stream on the random topology, that involved the transfer of 512 consecutive packets. This time implicitly provides a direct measurement of the average file download latency (FDL), where the average is computed across the 50 receiving nodes. The multicast application sent 512 packets. It is interesting to note that, in some cases, increasing the link-layer transmission rate *did not* reduce the FDL. Moreover, while the download times were essentially identical, the FDL with network coding was slightly higher than the FDL observed in a pure-routing based dissemination approach. The network coding algorithm used for this, and all subsequent figures, used a Galois field size of 8.

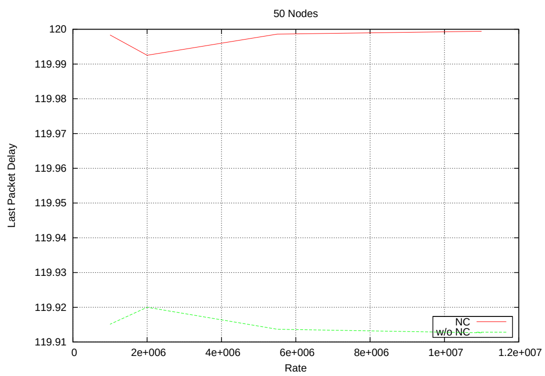

Fig. 10. Average Time till Arrival of Last Packet (File Download Latency).

Figure 11 shows the maximum of FDL, observed across all the 50 receiving nodes. The results indicate that the maximum and average FDL values are essentially identical. This illustrates a central property of network coding strategies: they delay the transmission of packets so as to ensure that all receiving nodes receive their final packet (i.e., receive the entire file) at about the same time, resulting in very low variance in the FDL values across nodes.

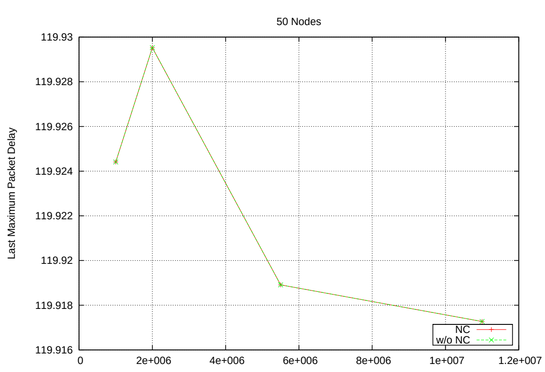

Fig. 11. Maximum FDL value across 50 Nodes.

The relative performance of network coding and pure routing is, however, very different when we consider a slightly different metric. Figure 12 shows the maximum value (across nodes) of the average *per-packet* latency encountered by each node. This metric thus provides a measure of the average per-packet latency incurred by our algorithms, and leads to a couple of interesting observations. First, observe that the average per-packet latency is much lower (only about 20 msecs) compared to the total FDL. Second, we note that this average per-packet latency *actually increases* as the link layer transmission rate is increased from 5.5Mbps to 11 Mbps. *This suggests that the choice of a transmission rate is also closely coupled to the use or absence of network coding.*

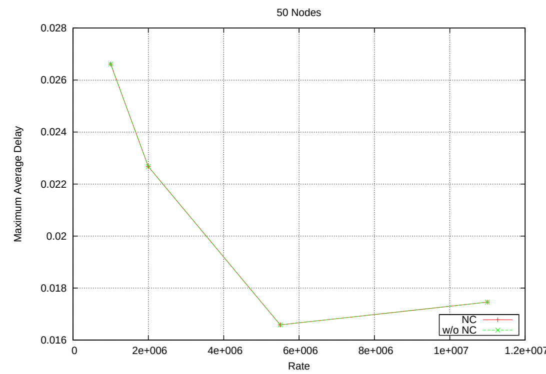

Fig. 12. Maximum of Average Packet Arrived.

To further understand the statistics associated with per-packet latency both with and without network coding, we have also computed the histogram of the per-packet delays experienced by all packets at each of the receiver nodes. Figures 13 and reffig:DelayNO2000000 plot the histogram of the delays encountered by the packets at each node (the histogram thus consists of $512 * 50 \sim 25,000$ sample values). We can clearly see that the latency values experienced in the presence of network coding are much higher. We can also observe that the distribution of the delays are more uniform than without NC. As explained earlier, network coding algorithms essentially hold some packet back till other packets are available for mixing, resulting in a more uniform delay distribution between nodes. We can thus conclude that network coding introduces a 'throughput-latency' tradeoff that may impact the applicability of coding strategies to several information dissemination-centric applications of interest.

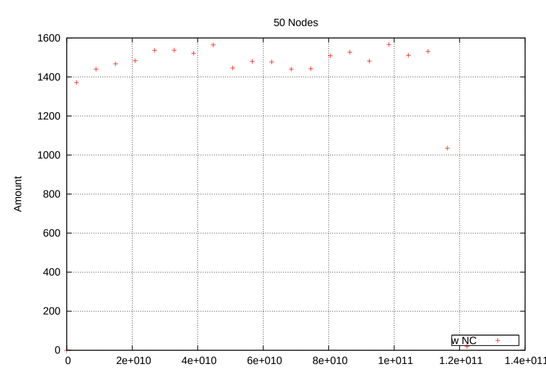

Fig. 13. Histogram Delay w/NC.

Figure 14 shows the histogram of all the average packet arrived for each rate.

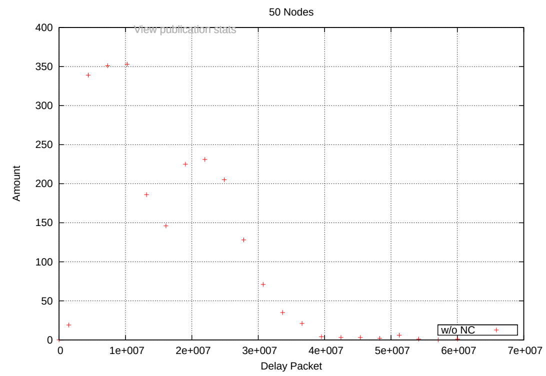

Fig. 14. Histogram Delay without NC.

VIII. Conclusion

We have demonstrated in this paper that multi-rate link layer broadcasts and network coding can be mutually combined to increase network throughput in multicast applications. We have also developed and solved a modified linear programm that enables us to calculate the throughput achievable in any given wireless network with transmission rate diversity, with or without the corresponding use of network coding. Simulation studies conducted using a practical routing protocol, ODMRP, suggest that the impact of rate diversity on the overall achievable throughput is larger in the presence of network coding, than when a pure routing solution is employed. As part of our ongoing work, we are completing simulation studies employing network coding when the underlying broadcast forwarding tree is computed using a rate-diversity aware algorithm, such as WCDS.

We have also observed through simulations that NC introduces a 'throughput-latency' tradeoff, not just for worst case latency but even in terms of the average delay experienced by packets. We believe that this observation has important implications for the use of network coding in many latency-sensitive broadcast applications, such as the dissemination of sensor data to mission commanders for situational awareness in a battlefield network. Our studies show that the gains achieved by network coding in throughput (the savings in the number of distinct transmissions) do not always result in corresponding savings in the latency–especially as many packets suffer extremely large latency while waiting to be combined with other packets.

For future work, we plan to further investigate this 'throughput-latency' trade-off. In particular, our studies suggest that there might be an optimal level of coding that trades off appropriately between throughput and delay with potential applications. One idea might be to explore the use of growth codes in such environments. Alternately, we may make the level of coding an adaptive function of the network utilization/congestion, with the amount of network coding being applied increasing with an increase in the congestion levels of the network.

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