Network Coding Aware Rate Selection in Multi-Rate IEEE 802.11

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***Abstract*—Network coding has been proposed as an alternative to the conventional store-and-forward routing paradigm for data delivery in networks. When deployed in a multi-rate wireless network, network coding has to interact with rate adaptation. When multicasting packets (a requirement of network coding) in a multi-rate IEEE 802.11 wireless network, one must use care when selecting the transmission rate to use. We refer to this problem as *rate selection*. We analyze the performance of network coding for a small set of scenarios representative of common topologies in a network that lead to coding opportunities. Based on this analysis, we present our Network Coding aware Rate Selection (NCRS) algorithm which takes into account transmission rates used for unicast links to all multicast targets. Simulation results show that in a multi-hop wireless network, network coding with NCRS achieves up to 24% more gain over routing than network coding with other rate selection algorithms.**

I. Introduction

Network coding [4] has been proposed as a method to increase the multicast capacity of wireless networks. In contrast to the store-and-forward paradigm of routing, network coding allows nodes to combine packets before forwarding them. In essence, network coding enables the delivery of different packets to distinct neighbors with a single transmission. Coded packets *must* be multicast for network coding to gain efficiency. Moreover, it is essential that uncoded packets be overheard by neighbors to enable inter-flow coding *i.e.*, uncoded packets *may* need to be multicast.

Unfortunately, in practical wireless networks, channel conditions on and among links often vary widely. IEEE 802.11, a widely prevalent PHY and MAC protocol for wireless networks, attempts to improve the performance of a link under any given condition by transmitting at appropriate transmission rates and modulation schemes. Selecting a transmission rate incurs an inherent tradeoff wherein increasing rate results in decreasing packet delivery probability. These factors can be combined into throughput, frequently the metric for network performance. As link characteristics vary, a different transmission rate may increase throughput. This problem of adapting transmission rate to varying link characteristics has been referred to as *rate adaptation* [6], [9], [17], [18], [24], [28], [31].

A rate adaptation algorithm may determine different transmission rates from a node to its different neighbors. In a network using network coding, we refer to the problem of selecting a transmission rate for all multicast recipients, or any neighbors which may benefit from overhearing, as the *rate selection* problem. If rate selection for uncoded packets precludes overhearing in a neighborhood, few inter-flow coding opportunities will arise. Rate selection for coded packets has to address the following tradeoff - if a low transmission rate is chosen, all destinations may receive a transmission successfully but the transmission time will be longer; if a higher rate is chosen, the transmission time will decrease but destinations with poor link quality may not receive the transmission.

In this paper we propose a rate selection algorithm to maximize throughput in a multi-hop multi-rate wireless network in which network coding is used. Virtually all prior work focuses on maximizing coding gain *i.e.*, maximize the reduction in network traffic due to network coding. Often these methods use the lowest transmission rate available to enable network coding to the largest extent possible. Our solution selects transmission rates to maximize throughput while taking network coding into account. In some cases this entails setting rates that fully leverage network coding, and in others coding is largely precluded and yet, throughput is maximized. The contributions of this work are -

- We first identify the prevalent fundamental building blocks in a network that enable network coding. We analyze the performance of network coding and routing over these building blocks in terms of throughput in a multi-rate environment.
- Based on this analysis, we propose Network Coding aware Rate Selection (NCRS) as a linear programming problem to maximize total throughput on a multicast link.

We present simulation results to compare NCRS with other rate selection schemes that try to either maximize network coding gain or use the highest rates supported by the component links of a multicast link to minimize link occupancy time. We illustrate the wide applicability of NCRS by examining several

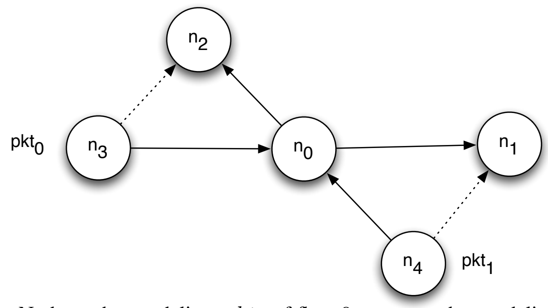


Fig. 1. Node n_3 has to deliver pkt_0 of flow 0 to n_1, n_4 has to deliver pkt_1 of flow 1 to n_2

scenarios that contain multicast links which support different transmission rates on component unicast links. In addition, for a large network, we show that NCRS outperforms the alternative rate selection schemes by up to 24% on average in terms of gain over routing. NCRS is also more robust than these alternatives in that it works for a wide range of channel characteristics.

Note that while the NCRS problem formulation is based on the analysis of building blocks that yield coding opportunities, results for large networks show that NCRS indeed improves the data delivery characteristics of such a network.

The rest of this work is organized as follows: §II discusses network coding and rate adaptation; §III presents the motivation and design details of our rate selection protocol. We analyze a small scenario for throughput with routing and network coding in §IV. Based on this analysis we present our rate selection algorithm NCRS in §V. Results are presented in §VI. Related work for network coding in multi-rate MAC environments is discussed in §VII and §VIII concludes the paper.

II. Background

We now present related work on network coding and introduce the network coding algorithm used in §II-A. §II-B presents related work on rate adaptation and details of multi-rate IEEE 802.11g and rate adaptation scheme used.

A. Network Coding

Several papers have been recently published to propose and fundamentally advance the area of network coding [4], [11], [13], [16], [23], [26]. We use a slightly modified version of COPE [19], a previously proposed network coding protocol for wireless networks. COPE requires nodes to overhear transmissions in their neighborhood. In addition, nodes in COPE need to know which packets have been received by their neighbors. This information is collected in one of the following ways - asynchronous ACKs, packet reception reports, or probabilistic packet delivery information based on Expected Transmission Count (ETX) [14]. Once a node is made aware of the packets available at its neighbors, it codes packets that can be decoded by all neighbors. Note that COPE scans only the 1-hop neighborhood of the transmitting node for opportunity to send coded packets. In addition, encoding and decoding is performed on a per-hop basis.

To illustrate the basic operation of per-hop encoding and decoding refer to Fig. 1. Native packets may need to be overheard at the neighbors of a transmitting node to create inter-flow coding opportunity. On the other hand, a coded packet is useful to multiple neighbors, and hence it must be multicast. For example, nodes n_3 and n_4 have to deliver packets pkt_0 (of flow 0) and pkt_1 (of flow 1) to nodes n_1 and n_2, respectively. Say, node n_3 transmits pkt_0 which is received by n_0. Similarly, n_4 transmits pkt_1 which is received by n_0. Now, assume that the intersection node, *i.e.* n_0, combines these packets together into - pkt_0 XOR pkt_1. Node n_1 can extract pkt_0 from this coded packet only if it has pkt_1. This packet can only be received by overhearing n_4's transmission of pkt_1. Hence native packet transmissions for flow 1 from n_4 must have n_0 as a direct target and n_1 as an overhearing target.

We use COPE's underlying philosophy of keeping track of packets at next hop nodes and transmitting coded packets to efficiently address gaps in delivered packet sequences. We assume the presence of a perfect feedback system that enables nodes to keep track of packets delivered to next hop nodes. While this is a simplified model, it allows us to concentrate on the performance of network coding. We combine packets using XOR (like COPE) and ensure that a coded transmission can be decoded at its target nodes. Note that NCRS is not COPE-specific. Instead, it only uses components of COPE that are common with other network coding schemes.

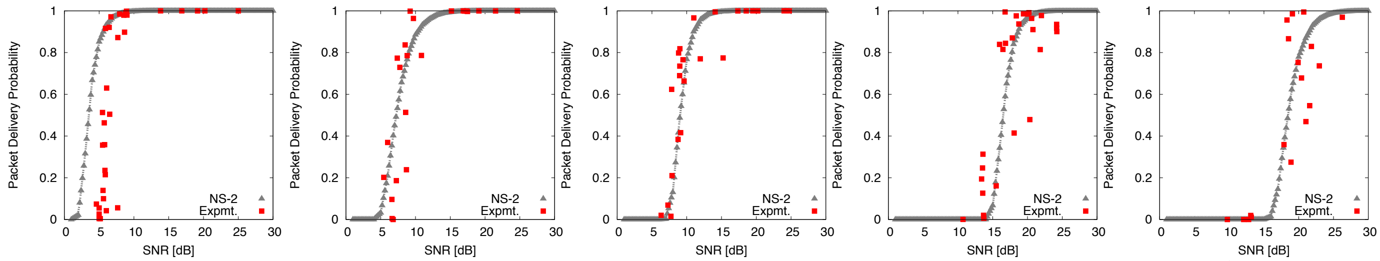
In this paper, we consider only unicast flows. As a result, there is little opportunity for intra-flow coding and so virtually all coding that occurs is inter-flow coding.

B. Multi-Rate IEEE 802.11g and Rate Adaptation

In this section we provide background on rate adaptation and IEEE 802.11g [1] and discuss details of the rate adaptation algorithm used. When selecting the transmission rate for a multicast link, referred to as a *hyperarc* with "direct" and "overhearing" targets, it is possible that rate adaptation will select different rates to different targets of the hyperarc. The problem of determining a single transmission rate for all hyperarc targets is referred to as *rate selection*.

Since IEEE 802.11 does not specify a rate adaptation algorithm, various algorithms have been proposed to address this void. These schemes differ in their approach to channel quality measurement and criteria for switching to a different rate. But at the core, *most* rate adaptation schemes aim to maximize throughput given a channel condition. AARF [24] employs a threshold on consecutive successful transmissions to probe the higher rate. A binary exponential backoff mechanism is used to determine this threshold. If the probe fails, the threshold is doubled, and so on (up to a maximum of 50). Rate adaptation has been an active field of research lately and several schemes [6], [9], [17], [18], [28], [31] have been proposed.

IEEE 802.11g, the multi-rate wireless protocol used in this work, allows transmissions at 6, 9, 12, 18, 24, 36, 48, and



(a) 12Mbps (b) 18Mbps (c) 24Mbps (d) 48Mbps (e) 54Mbps

Fig. 2. Experiment vs. simulation results for 1500Byte packets

54Mbps. Since we deal with static networks in this paper, stable Signal-to-Noise Ratios (SNRs) are observed at nodes. Hence, like [12] and [17], we measure channel conditions at the receiver by measuring SNR of data packets. For the same SNR, transmitting at a lower rate will tend to result in a lower error rate. To verify this, we first plot packet delivery probability vs. SNR in Fig. 2 for a unicast link with different transmission rates from an experiment. Note that plots for some of the transmission rates are not shown due to lack of space. The experimental setup used a Linksys WRT54G with DD-WRT access point as a sender and a Netgear WG111v2 wireless card as receiver. For each result 10000 packets of 1500Bytes were sent from the access point. We then present corresponding results from a NS-2 simulation for comparison in Fig. 2. Since the simulation characteristics closely mirror those exhibited by the experiments and that presented in prior work [6], [15], we generate further results for rate selection using NS-2.

Though IEEE 802.11g allows transmission rates from 6Mbps to 54Mbps, the maximum achieved throughput does not increase linearly due to protocol overhead. For a given packet size, we can translate these transmission rates into maximum throughput in terms of packets-per-second (pps). We simulate a unicast link with a packet size of 1500Bytes in NS-2 (simulation details presented later in §VI) with the results shown in Table I.

We now have the packet delivery probability for any given SNR (cf. Fig. 2) and the maximum throughputs achieved with all rates (cf. Table I). Therefore it is straightforward to determine the SNR range for which each rate maximizes throughput. This is shown in Table I. Note that 9Mbps is never selected as a transmission rate (similar to an observation made in [24]). We use this generic rate adaptation scheme to determine transmission rates on unicast links. Since we concentrate on static networks in this work, any rate adaptation scheme that maximizes throughput will only do as well as our rate adaptation scheme. In addition, our approach to rate selection is orthogonal to the rate adaptation solution by design.

III. Network Coding and Rate Selection

In this section we present the basic motivation and design of our rate selection protocol. The purpose of this protocol is to adequately deliver packets and to gather SNR information which is then used in the rate selection algorithm (cf. §V).

TABLE I
Transmission Rates and Rate Adaptation for 1500Byte packets

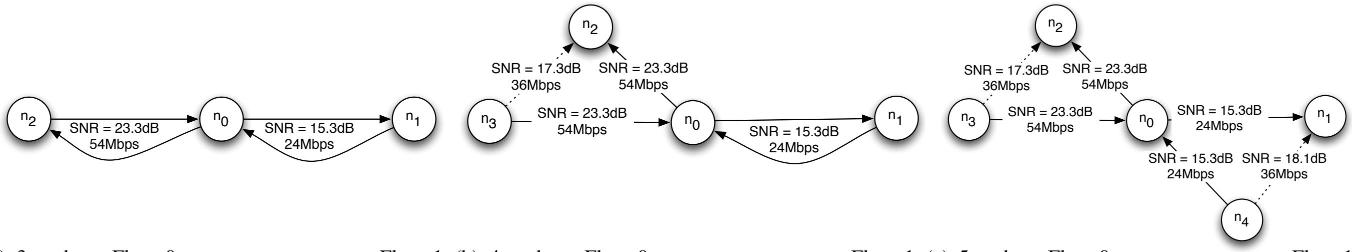
Mbps	pps	SNR Range	Mbps	pps	SNR Range
6	376	≤ 3.77	24	905	9.99-15.61
9	508	NA	36	1071	15.61-18.40
12	616	3.77-8.90	48	1182	18.4-23.10
18	783	8.9-9.99	54	1222	> 23.10

To enable inter-flow coding 2 or more flows need to *intersect appropriately i.e.*, with requisite overhearing requirements as demonstrated with an example (cf. Fig. 1) in §II-A. The large majority of coding opportunities in practical networks will code only a few packets. We posit that in many cases coding is limited to two packets. While scenarios may occur that result in more packets being coded, since the likely cases will involve just two packets, we use this as the basis for our analysis.

For the frequently occurring instance of coding only two packets, the three simple scenarios shown in Fig. 3 (disregard SNR and rate annotations in the figures for now) exhaustively represent all possible inter-flow coding patterns that may occur in a large network with our per-hop encoding and decoding approach. Solid arrows represent actual next-hop relationships. Dotted arrows denote overhearing required to make network coding at the intersection node n_0 feasible. Note that to enable network coding in a large network these patterns will need to be detected in a distributed manner.

A rate selection algorithm has to address an overhearing tradeoff and a multicast tradeoff. Consider the 5 node scenario in Fig 3(c). Nodes n_3 and n_4 have to transmit at a rate such that overhearing is successful at n_2 and n_1, respectively. If these nodes do not enable successful overhearing, coding will not occur at n_0. For example, let SNR at n_0 and n_2 from n_3 be 23.3dB and 17.3dB, respectively. If n_3 transmits at 54Mbps (corresponding to 23.3dB, cf. Table I), packets will be overheard at n_2 with probability 0.22 - (cf. Fig. 2). Hence promoting overhearing at n_2 may require reducing the transmission rate at node n_3. But this may reduce throughput at direct target n_0. This is the *overhearing tradeoff*. To address this tradeoff we maximize total throughput at hyperarc targets - direct and overhearing, as presented in detail in §V.

Now consider node n_0 in Fig. 3(c) which is connected to n_1 and n_2 with links supporting 15.3dB and 23.3dB



(a) 3 nodes : Flow 0 : $n_2 \rightarrow n_0 \rightarrow n_1$, Flow 1 : $n_1 \rightarrow n_0 \rightarrow n_2$

(b) 4 nodes : Flow 0 : $n_3 \rightarrow n_0 \rightarrow n_1$, Flow 1 : $n_1 \rightarrow n_0 \rightarrow n_2$

(c) 5 nodes : Flow 0 : $n_3 \rightarrow n_0 \rightarrow n_1$, Flow 1 : $n_4 \rightarrow n_0 \rightarrow n_2$

Fig. 3. Small scenarios for inter-flow network coding of 2 flows (not to scale)

SNR, respectively. Coded packets need to be transmitted at a rate such that n_1 can receive them. If 54Mbps is used (corresponding to 23.3dB), these packets are not received at n_1 and hence the transmission rate needs to be reduced. But if uncoded packets are transmitted instead of coded packets, those destined for n_2 can be transmitted at 54Mbps, while those destined for n_1 can be transmitted at 24Mbps. Hence n_0 can possibly transmit uncoded packets at a higher rate to a single destination or it can transmit coded packets at a lower rate. We refer to this as the *multicast tradeoff*. Since we code only 2 packets, we adopt the simple policy of coding whenever possible. On a related note, Vieira et al. [30] and Yomo et al. [32] consider the interaction of network coding and multi-rate MAC and recognize that coding more packets may require reducing transmission rate - similar to the multicast tradeoff.

Next, we present details of adapting RTS/CTS exchange for multicast packets in §III-A. We then explain how SNR of data packets from neighbors is collected in §III-B.

A. Multicast and RTS/CTS Exchange

As shown earlier, network coding requires multicast of all coded and some native packets. These multicast transmissions are prone to loss due to hidden terminal problems. Hence, in spite of its overhead, the RTS/CTS mechanism is employed to prevent excessive loss of multicast transmissions crucial to network coding. But requiring every destination - direct or overhearing - to reply with a CTS to the RTS is infeasible with respect to the overhead imposed. Hence we employ the common method [19] of selecting one of the destinations as the target for a RTS. Only this node replies with the CTS and sends the ACK after successful reception of the data packet. We refer to this node as *cts-node* for the transmission. Note that packet reception at non-cts-nodes is still prone to losses due to hidden terminal collisions.

The selection of the cts-node is critical. Assume that the 3-node scenario (cf. Fig. 3(a)) occurs in a large congested network and nodes n_1 and n_2 are connected to n_0 by links with SNRs of 15.3dB and 23.3dB, respectively. Let rate selection algorithm in node n_0 decide to transmit coded packets at 36Mbps. At this rate, packet delivery probability is 0.81 for n_1 and close to 1 for n_2 (cf. Fig. 2). Hence, if n_1 is the cts-node for coded packets of node n_0, there will be more retransmissions per packet but each packet will be delivered to both destinations with a high probability. If n_2 is the cts-node, few, if any, retransmissions will be required, but n_1 may not receive some of the packets.

We select the direct target with most packet collisions as the cts-node to minimize losses due to hidden terminal collisions. If all direct targets have similar degrees of loss due to collisions, the direct target with best link conditions (measured by SNR) is selected as the cts-node to minimize the number of retransmissions per packet. If multiple direct targets have the same SNR, one of these is picked randomly as the cts-node. An overhearing destination is not selected as the cts-node to avoid the flow from being penalized to promote overhearing.

B. Receiver Based SNR Measurement

While we do not modify the RTS and CTS packets, some information is piggybacked on to data and ACK packets to enable network coding and rate selection. For rate selection, we must collect the SNR of data packet transmissions at neighbors. Though all neighbors may not be overhearing targets, neighboring nodes overhear all packets. Nodes maintain a per-neighbor exponential weighted average of SNRs of data packets received. This information is collected in one of the following ways -

- Data packets contain exponentially averaged SNR for the directed link from cts-node to the current node.
- ACKs from the cts-node contain exponentially averaged SNR of packets received from source node.
- Overhearing targets and some direct targets may not be selected as the cts-node. Hence exponentially averaged SNRs of transmissions from each neighbor can be piggybacked on to data packets or sent in periodic control packets (similar to packet reception reports in COPE [19]).

IV. Throughput Analysis

To explore the impact of multi-rate IEEE 802.11g on the gain over store-and-forward routing for network coding, we analyze throughput for routing and network coding for the 5-node scenario (cf. Fig. 3(c)). We use this analysis as the basis of our rate selection algorithm presented in §V. *The analysis for 3 and 4-node scenarios are similar and are not presented* *due to lack of space.* We verify the analysis presented here in §VI to see the impact of our assumptions stated below.

We first analyze components required to evaluate throughput over a hyperarc in §IV-A. The throughput of routing and network coding on the 5-node scenario is then analyzed in §IV-B.

Note that the packets-per-second (pps) version of rates is used in the analysis below and the network is assumed to be in steady state. Also, collision loss is not accounted for in this analysis as the interference range is $2\times$ the receiving range and this results in RTS/CTS eliminating hidden terminal problems in all three scenarios in Fig. 3. Hence all packet losses in the analysis below are due to low SNR. Though this assumption breaks down in a large network, it provides us with a stepping stone to the rate selection algorithm proposed in §V. Larger simulation scenarios presented in §VI indeed incur packet loss due to collisions arising from hidden terminal problems.

A. Hyperarc Throughput

To estimate throughput over a hyperarc, we need to find the total number of transmissions and account for retransmissions. We first look at retransmissions and subsequently analyze the total number of transmissions.

1) Number of Retransmissions per Packet: For this analysis we assume that the network is loaded with Continuous Bit Rate (CBR) unicast flows. These flows impose traffic at constant rate and employ hop-by-hop retransmissions to ensure data delivery. When an intermediate node receives a packet, it does not immediately forward it. Instead, it is stored in an internal network coding buffer at the routing layer which is separate from the transmission buffer in the link layer. At the load rate determined by rate of the CBR flow, a packet for this flow, referred to as primary-native packet, is extracted from the network coding buffer (possibly coded with packets from other flows) and enqueued into the transmission buffer.

If a packet is lost, hop-by-hop link layer retransmissions are used to deliver the packet. The number of link layer retransmissions per packet is limited to a maximum of 5 in 802.11g. If these link layer retransmissions are unsuccessful, the network coding layer retransmits the primary-native packet possibly coded with another packet. These retransmissions are hop-by-hop as well and are referred to as routing layer retransmissions.

Now, let iJ denote a hyperarc where node n_i is the source of the hyperarc and J is the set of next hop destinations (direct and overhearing) n_j. Let transmission rate on hyperarc iJ be R_{iJ} and packet delivery probability to node n_j be q^j_{iJ}. q^j_{iJ} depends on R_{iJ} and the SNR SNR_{ij} at node j *i.e.*,

$$q^j_{iJ} = q(R_{iJ}, SNR_{ij}) \tag{1}$$

where $q()$ is a function that translates a rate and SNR tuple to the corresponding packet delivery probability (derived from Fig. 2). We assume that the underlying rate adaptation mechanism does not change transmission rate R_{iJ} during link and routing layer retransmissions.

Note that regardless of the transmission rate of data packets, ACKs are transmitted at 6Mbps. Now, the packet delivery probability for ACK packets at 6Mbps is close to 1 for SNR greater than 4dB. Hence the probability of receiving the ACK packet from the cts-node with the assumption of no collision-related loss is very close to 1 and we assume that ACKs are not lost due to low SNR at the source node. Hence, the expected number of link layer transmissions per packet on hyperarc iJ with n_j being the cts-node is

$$L^j_{iJ} = \sum_{m=1}^{5} m(1 - q^j_{iJ})^{m-1} q^j_{iJ} \tag{2}$$

where the limit 5 is due to link layer retransmissions per packet being limited to a maximum of 5 in 802.11.

The probability of link layer retransmissions delivering the packet to the cts-node n_j is

$$q'^j_{iJ} = \sum_{m=1}^{5} (1 - q^j_{iJ})^{m-1} q^j_{iJ} \tag{3}$$

The probability of these link layer retransmissions delivering the packet to a non-cts-node n_k is

$$q'^k_{iJ} = \sum_{m=1}^{5} \left((1 - q^j_{iJ})^{m-1} q^j_{iJ} (\sum_{l=1}^{m} (1 - q^k_{iJ})^{l-1} q^k_{iJ})\right) \tag{4}$$

where $\sum_{l=1}^{m} (1 - q^k_{iJ})^{l-1} q^k_{iJ}$ is the probability of n_k receiving a packet when exactly m link layer transmissions are used.

When link layer retransmissions fail to deliver a packet to the cts-node n_j, routing layer retransmissions are required. The expected number of such routing layer retransmissions is

$$T^j_{iJ} = \sum_{m=1}^{\infty} m(1 - q'^j_{iJ})^{(m-1)} q'^j_{iJ} = 1/q'^j_{iJ} \tag{5}$$

Since retransmissions are designed to guarantee packet delivery to the cts-node, the probability of these routing layer transmissions delivering a packet to the cts-node n_j is assumed to be 1. These retransmissions may not deliver the packet to a non-cts-node. The probability of packet delivery to a non-cts-node n_k after routing layer retransmissions is

$$q"^k_{iJ} = \sum_{m=1}^{\infty} \left((1 - q'^j_{iJ})^{m-1} q'^j_{iJ} (\sum_{l=1}^{m} (1 - q'^k_{iJ})^{l-1} q'^k_{iJ})\right) \tag{6}$$

where $\sum_{l=1}^{m} (1 - q'^k_{iJ})^{l-1} q'^k_{iJ}$ is the probability of n_k receiving a packet when exactly m routing layer transmissions are used.

Now, the expected total number of retransmissions per packet Z_{iJ} on a hyperarc iJ with cts-node being n_j is

$$Z^j_{iJ} = L^j_{iJ} T^j_{iJ} \tag{7}$$

Hence, if the total number of transmissions on a hyperarc is N, the expected number of unique packets received at the cts-node n_j will be N/Z^j_{iJ}, while that at a non-cts-node n_k will be $Nq"^k_{iJ}/Z^j_{iJ}$. Note that all further analysis using L, T, or Z is for expected values.

2) Number of Transmissions on a Hyperarc: The number of transmissions on a hyperarc in a node n_i depends on the node's transmission probability p_i and medium sharing among flows within the node. Bianchi [5] analyzes transmission probability of nodes in a fully connected network without hidden terminals. But our small scenarios for network coding are not fully connected. Analyzing a node's transmission probability in a multi-hop multi-rate wireless network which uses IEEE

802.11 (CSMA/CA with RTS/CTS) is difficult. In fact, it is a function of the offered load and congestion in the network.

A node contends for the medium as one on behalf of all flows traversing it. The assigned medium is shared among the flows using a transmission buffer (FIFO buffer with tail-drop). We estimate the number of packets that a node transmits on behalf of a hyperarc using $NumTx()$ in Algorithm 1.

Algorithm 1 $\{N^j, ...\}$ $\textsc{NumTx}(\{(B^j, A^j, R^j, L^j, T^j), ...\}, p)$

for $j \in [1, n]$ **do**
  $d^j = min(T^j B^j, A^j)$
  $r^j = L^j d^j / R^j$
end for
if $\sum_{j=1}^{n} r^j \leq p$ **then**
  for $j \in [1, n]$ **do**
    $N^j = L^j d^j$
  end for
else
  for $j \in [1, n]$ **do**
    $f^j = L^j d^j / \sum_{m=1}^{n} L^m d^m$
  end for
  $D = \sum_{j=1}^{n} f^j / R^j$
  $U = 1/D$
  for $j \in [1, n]$ **do**
    $N^j = f^j U p$
  end for
end if
return $\{N^j, ...\}$

$NumTx()$ takes a set of n tuples - one for each hyperarc emanating from the node, and the transmission probability p for the node as arguments. A tuple for a hyperarc consists of - incoming load ($\equiv B$, in pps), application level constant bit-rate ($\equiv A$, in pps), transmission rate ($\equiv R$, in pps), number of link layer transmissions per packet ($\equiv L$), and number of routing layer transmissions per packet ($\equiv T$). $NumTx()$ returns the set of number of transmissions $\{N^j, ...\}$ for each outgoing hyperarc j.

In $NumTx()$, first, for each hyperarc j, the load imposed on the link layer is determined as d^j. The number of packets entering the routing layer for hyperarc j is B^j. Due to routing layer retransmissions these packets impose a maximum load of $T^j B^j$ packets on the link layer. The link layer drains packets from the network coding buffer at rate A^j. Hence the rate of packets being enqueued for flow i in the transmission buffer is $d^j = min(T^j B^j, A^j)$. The fraction of time that the node requires to transmit all of the load d^j when link layer retransmissions are taken into account is $r^j = L^j d^j / R^j$. But the fraction of time that the node is allotted is p. Hence if $\sum_{j=1}^{n} r^j \leq p$, all imposed load can be transmitted and the number of total transmissions for hyperarc j is $N^j = L^j d^j$.

On the other hand, if $\sum_{j=1}^{n} r^j > p$, load imposed on the node is more than it can transmit. The fraction of packets f^j of a hyperarc in the transmission buffer is proportional to the load imposed. Hence $f^j = L^j d^j / (\sum_{m=1}^{n} L^m d^m)$. The average inter-transmission delay is $D = \sum_{j=1}^{n} f^j / R^j$ and hence the number of packets transmitted per unit time on average is $U = 1/D$. Now, for each flow, the number of packets transmitted is proportional to the fraction of packets in the buffer and since the node transmits for only p fraction of the time, the number of transmissions for hyperarc j is $N^j = f^j U p$.

B. Throughput for 5-Node Scenario

Now that we have estimated the number of retransmissions per packet and total transmissions on a hyperarc, we analyze throughput for routing and network coding for the 5-node scenario (cf. Fig. 3(c)). We include the number of packets delivered on each hop of the unicast routes in the evaluation metric in this section. We present results for packets delivered to only final destinations in §VI.

Two unicast flows are deployed in the 5-node scenario (cf. Fig. 3(c)) - flow $0 : n_3 \rightarrow n_0 \rightarrow n_1$ and flow $1 : n_4 \rightarrow n_0 \rightarrow n_2$. We analyze the number of packets of flow 0 received by n_0 and n_1 and the number of packets of flow 1 received by n_0 and n_2 for routing and network coding per unit time.

1) Routing: The total number of unique packets received with routing is

$$X = X_0^0 + X_0^1 + X_1^0 + X_2^1 \tag{8}$$

where X_i^j is the number of unique packets of flow j received by node n_i in unit time when routing is used.

Let N_{iJ} denote the number of transmissions (including retransmissions) on hyperarc iJ by node n_i. Hence number of transmissions by node n_3 is

$$\{N_{3\{0\}}\} = NumTx(\{(B^0, A^0, R_{3\{0\}}, L^0_{3\{0\}}, T^0_{3\{0\}})\}, p_3) \tag{9}$$

where A^l is the CBR flow rate of flow l. Since the incoming load for the routing layer at the source of a flow is the same as its application level load rate, $B^0 = A^0$.

Similarly, number of transmissions by node n_4 is

$$\{N_{4\{0\}}\} = NumTx(\{(A^1, A^1, R_{4\{0\}}, L^0_{4\{0\}}, T^0_{4\{0\}})\}, p_4) \tag{10}$$

The number of unique packets of flow 0 received by node n_0 is :

$$X_0^0 = N_{3\{0\}} / Z^0_{3\{0\}} \tag{11}$$

Similarly,

$$X_0^1 = N_{4\{0\}} / Z^0_{4\{0\}} \tag{12}$$

We now compute the number of transmissions for flows 0 and 1 by node n_0 as the following where M_{iJ} is the tuple for hyperarc iJ,

$$\{N_{0\{1\}}, N_{0\{2\}}\} = NumTx(\{M_{0\{1\}}, M_{0\{2\}}, p_0) \tag{13}$$

where tuple for flow 0 is

$$M_{0\{1\}} = (X_0^0, A^0, R_{0\{1\}}, L^1_{0\{1\}}, T^1_{0\{1\}}) \tag{14}$$

and tuple for flow 1 is

$$M_{0\{2\}} = (X_0^1, A^1, R_{0\{2\}}, L^2_{0\{2\}}, T^2_{0\{2\}}) \tag{15}$$

Hence the number of unique packets of flow 0 received by node n_1 is

$$X_1^0 = N_{0\{1\}} / Z^1_{0\{1\}} \tag{16}$$

Similarly, the number of unique packets of flow 1 received by node n_2 is

$$X_2^1 = N_{0\{2\}} / Z^2_{0\{2\}} \tag{17}$$

Hence X in Eqn. 8 can be computed to evaluate throughput for routing.

2) Network Coding: Like the previous subsection, the total number of unique packets received with network coding is

$$Y = Y_0^0 + Y_0^1 + Y_1^0 + Y_2^1 \quad (18)$$

where Y_i^j is the number of unique packets of flow j received by node n_i in unit time when network coding is used. Again, let N_{iJ} be the number of transmissions on hyperarc iJ.

Now, node n_3 has to multicast at rate $R_{3\{0,2\}}$ to allow node n_2 to overhear its transmissions. Since n_2 is an overhearing target, n_0 is selected as the cts-node. Hence number of transmissions by node n_3 is

$$\{N_{3\{0,2\}}\} = NumTx(\{(A^0, A^0, R_{3\{0,2\}}, L^0_{3\{0,2\}}, T^0_{3\{0,2\}})\}, p_3) \quad (19)$$

Similarly number of transmissions by node n_4 is,

$$\{N_{4\{0,1\}}\} = NumTx(\{(A^1, A^1, R_{4\{0,1\}}, L^0_{4\{0,1\}}, T^0_{4\{0,1\}})\}, p_4) \quad (20)$$

The number of unique packets of flow 0 received by node n_0 is

$$Y_0^0 = N_{3\{0,2\}}/Z^0_{3\{0,2\}} \quad (21)$$

Note that we do not select overhearing targets as cts-node. As a result we do not need to include $Z^2_{3\{0,2\}}$ in Eqn. 21.

Similarly,

$$Y_0^1 = N_{4\{0,1\}}/Z^0_{4\{0,1\}} \quad (22)$$

Node n_0 may be able to code some packets and will have to transmit remaining packets in native form. Let α be the fraction of CBR rate of flow 0 that is transmitted as coded packets. A packet of flow 0 is coded with a packet of flow 1. Remaining packets of both flows have to be transmitted in native form. Also, without loss of generality, assume that node n_2 has a higher SNR than n_1 of data packets received from n_0. Hence n_2 is the cts-node for all coded transmissions of n_0.

The number of coded transmissions N_c and native transmissions for flows 0 and 1 - N_u^0 and N_u^1, respectively - by node n_0 are computed as the following where, again, M_{iJ} is the tuple for hyperarc iJ:

$$\{N_c, N_u^0, N_u^1\} = NumTx(\{M_{0\{1,2\}}, M_{0\{1\}}, M_{0\{2\}}\}, p_0) \quad (23)$$

where tuple for multicast hyperarc $0\{1,2\}$ is

$$M_{0\{1,2\}} = (Y_0^0\alpha, A^0\alpha, R_{0\{1,2\}}, L^2_{0\{1,2\}}, T^2_{0\{1,2\}}) \quad (24)$$

and tuple for unicast hyperarc for flow 0 is

$$M_{0\{1\}} = (Y_0^0 - Y_0^0\alpha, A^0 - A^0\alpha, R_{0\{1\}}, L^1_{0\{1\}}, T^1_{0\{1\}}) \quad (25)$$

and tuple for unicast hyperarc for flow 1 is

$$M_{0\{2\}} = (Y_0^1 - Y_0^0\alpha, A^1 - A^0\alpha, R_{0\{2\}}, L^2_{0\{2\}}, T^2_{0\{2\}}) \quad (26)$$

Now, our network coding approach transmits coded packets packets only if they can be decoded at the hyperarc targets. Hence the number of unique packets of flow 0 received by n_1 is :

$$Y_1^0 = N_c q"^1_{0\{1,2\}}/Z^2_{0\{1,2\}} + N_u^0/Z^1_{0\{1\}} \quad (27)$$

Similarly, the number of unique packets of flow 1 received by n_2 is :

$$Y_2^1 = N_c/Z^2_{0\{1,2\}} + N_u^1/Z^2_{0\{2\}} \quad (28)$$

Hence N^{nc} in Eqn. 18 can be computed to evaluate throughput for network coding.

V. Network Coding aware Rate Selection (NCRS)

In this section we present Network Coding aware Rate Selection (NCRS) - based on the analysis in the previous section. We then present two baseline schemes for comparison.

A. NCRS

The goal of our rate selection algorithm is to maximize total throughput on the targets of a hyperarc. Consider the hyperarc $0\{1,2\}$ (*i.e.*, multicast link from n_0 to n_1 and n_2). Based on Eqns. 27 and 28, the total throughput at targets of hyperarc $0\{1,2\}$ is -

$$\frac{N_c q"^1_{0\{1,2\}}}{Z^2_{0\{1,2\}}} + \frac{N_c}{Z^2_{0\{1,2\}}} = \frac{N_c(1 + q"^1_{0\{1,2\}})}{Z^2_{0\{1,2\}}} \quad (29)$$

Based on Eqn. 29, NCRS is defined as the following for multicast on hyperarc iJ in node n_i

$$NCRS(\{(R_{i\{j\}}, SNR_{ij})\}) = \{(\gamma_i^l, R^l)\} \text{ where} \quad (30)$$

$$\{R^l\} \text{ is the set of transmission rates available,} \quad (31)$$

$$n_j \in J, \text{ and } \gamma_i^l \text{ is solution of} \quad (32)$$

$$\text{Maximize} \sum_l \gamma_i^l \delta_i^l \text{ where } \sum_l \gamma_i^l = 1, \quad (33)$$

$$\delta_i^l = R^l(1 + \sum_{k \neq m, n_k \in J} q"^k_{iJ})/Z^m_{iJ}, \quad (34)$$

$$n_m \text{ is a direct target and is cts-node,} \quad (35)$$

$$min_j(R_{i\{j\}}) \leq R^l \leq max_s(R_{i\{s\}}), \quad (36)$$

$$n_s \in J \text{ and } n_s \text{ is a direct target} \quad (37)$$

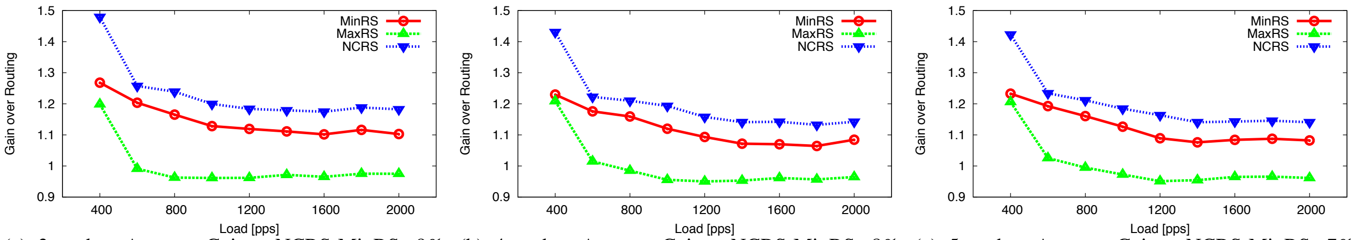
The formulation of NCRS is a linear programming problem to maximize throughput on hyperarc iJ. It proposes to use each possible rate R^l for γ_i^l fraction of time in node n_i (cf. Eqns. 30-33). δ^l (cf. Eqn. 34) corresponds to expected throughput on the hyperarc when R^l is selected as the transmission rate. We maximize total throughput at direct targets as well as overhearing targets to address the issue of overhearing tradeoff (cf. Eqn. 34). Note that NCRS is not restricted to coding of only two packets and allows for hyperarcs with several targets. Finally, the cts-node is selected from among direct target nodes (cf. Eqn. 35).

We limit the maximum rate that can be selected to be from among those to direct targets only and not overhearing targets (cf. Eqns. 36-37). This is because using a high rate to increase overhearing may be detrimental to the performance of direct targets. A lower rate can be selected to enable better overhearing.

While we use long term estimates of the channel quality, to address rate fluctuations due to variations in link conditions on smaller time-scales, we limit the possible rates to be selected to range from the minimum rate adaptation rate over all targets to the maximum rate adaptation rate among direct targets (cf. Eqns. 36-37).

Solving the NCRS formulation corresponds to picking $\gamma_i^l = 1$ for which δ_i^l is maximum. Though the problem of rate selection is based on multicast, our explicit recognition and treatment of the overhearing targets as compared to direct targets makes NCRS specific to network coding.

Note that NCRS does not account for all flows traversing through a node *i.e.*, it does not use $NumTx()$. This simplification is needed to keep the problem tractable and means



(a) 3 nodes, Average Gain - NCRS-MinRS: 9%, NCRS-MaxRS: 24%

(b) 4 nodes, Average Gain - NCRS-MinRS: 8%, NCRS-MaxRS: 20%

(c) 5 nodes, Average Gain - NCRS-MinRS: 7%, NCRS-MaxRS: 20%

Fig. 4. Gain over routing for packets delivered to all hops for small scenarios

that NCRS does not need a node's transmission probability p_i. Additionally, NCRS is scalable as it requires only two-hop information for a hypearc.

For comparison, we consider the baseline schemes as explained below.

B. MinRS and MaxRS

We define Minimum Rate Selection (MinRS) as

$$MinRS(\{(R_{i\{j\}}, SNR_{ij})\}) = min_j(R_{i\{j\}}) \ , n_j \in J \quad (38)$$

MinRS selects the minimum transmission rate over the component unicast links of the hyperarc. This approach to rate selection is used in Tan et al. [29], Chou et al. [12], and Yomo et al. [32]. MinRS maximizes combined packet delivery probability on all targets - direct or overhearing. Since packet delivery probability is only a component of throughput, MinRS falls short of NCRS which maximizes throughput. MinRS results in a more balanced distribution of number of packets delivered to the targets of a hyperarc though.

MinRS permits maximum overhearing and as a consequence enables maximum coding opportunity. Still, it allows the links to operate at the highest rate which meets this condition. In COPE [19], the transmission rate was set to the minimum supported by the air interface (*i.e.*, 6Mbps for IEEE 802.11g) in an attempt to maximize the coding gain. Since we compare network coding with rate selection schemes against routing with rate adaptation, comparing with COPE with a constant 6Mbps transmission rate is unfair. MinRS allows the use of higher transmission rates while still preserving overhearing. Hence, comparison with MinRS is fair.

For another baseline for comparison, we define Maximum Rate Selection (MaxRS) as

$$MaxRS(\{(R_{i\{j\}}, SNR_{ij})\}) = max_j(R_{i\{j\}}) \text{ where } n_j \in J \text{ and is a direct target} \quad (39)$$

MaxRS selects the maximum transmission rate over the component unicast links to direct targets of the hyperarc. Note that for MaxRS, like NCRS, the maximum rate among only direct targets is selected.

MaxRS maximizes throughput at the direct target with best SNR. This may decrease throughput at other targets of the hyperarc. The combined throughput of MaxRS over all targets of the hyperarc will be less than or equal to that for NCRS. Additionally, MaxRS may lead to a more skewed distribution of the number of packets delivered to hyperarc targets.

Note that for any hyperarc iJ, the same cts-node is selected for MinRS, MaxRS and NCRS to ensure a fair comparison.

VI. Results

Simulation results in this work are generated using NS-2.34. We use the IEEE 802.11g MAC scheme provided by [2]. Network coding was implemented at the routing layer. The packet size is set to 1500Bytes. The receiving range is set to 85m and interference range is twice the receiving range. All simulation scenarios presented in this section are for static nodes. As a result, signal quality is stable in our simulations. Note that for all results presented in this work, the rate selection schemes use network coding. We compare these rate selection schemes to "routing" with rate adaptation.

First, results for the three representative small scenarios (cf. Fig. 3) are presented in §VI-A. We then present results for the 3-node scenario with varying SNR combinations on the multicast hyperarc $0\{1, 2\}$ in §VI-B. Finally, we present results for varying number of flows deployed in a 50 node network in §VI-C.

A. 3, 4, 5-node Scenarios

The SNR and rates selected by rate adaptation on all unicast links are annotated in Fig. 3. To compare the rate selection schemes, we use the metric "gain over routing", defined as the ratio of number of packets delivered to nodes in the network by the relevant rate selection scheme to that for routing, for the same duration. To demonstrate the gain of the rate selection schemes under different network loads, we vary the CBR load rate of the flows in Fig. 4. All flows in a simulation are assigned the same CBR load rate.

Simulation results for the 3, 4 and 5-node scenarios are shown in Fig. 4. NCRS outperforms MinRS by an average of 9%, 8%, and 7% and MaxRS by an average of 24%, 20%, and 20% for the three scenarios (in order). Note that these simple scenarios serve only as examples to illustrate differences among the rate selection schemes. Larger networks presented in §VI-C yield significant gain improvements. On a side note, for the 3-node scenario MinRS outperforms routing by only 12% on average. This low gain of network coding with MinRS is due to asymmetry in link qualities connecting nodes n_1 and n_2 to n_0 leading to fewer coding opportunities.

For clarity, we do not plot gain over routing from the analysis in §IV for MinRS, MaxRS and NCRS in Fig. 4. Note

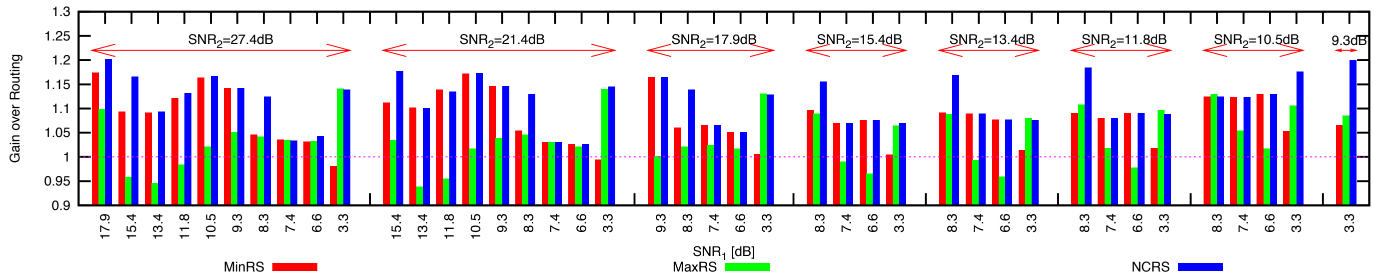
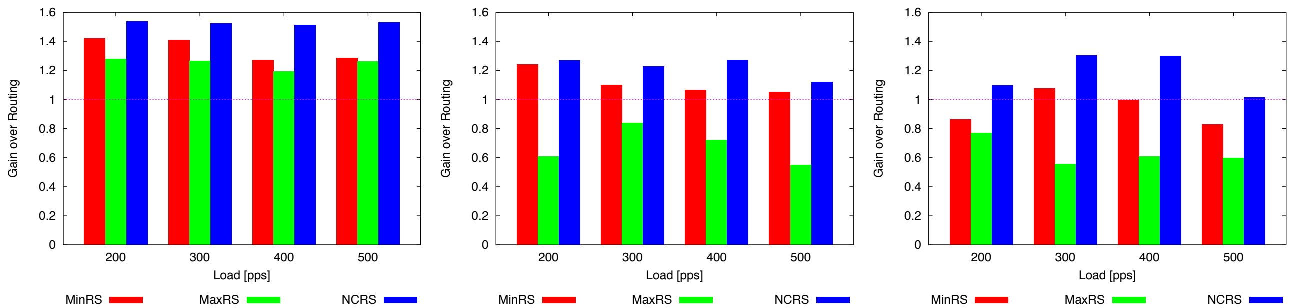


Fig. 5. Gain over routing for packets delivered to all hops for 3-node scenarios with varying SNR combinations - SNR_1 = SNR on $n_0 \rightarrow n_1$, and SNR_2 = SNR on $n_0 \rightarrow n_2$, Load = 1500pps, Maximum Gain - NCRS-MinRS: 16%, NCRS-MaxRS: 21%



(a) 4 flows, Average Gain - NCRS-MinRS: 18%, NCRS-MaxRS: 28%

(b) 8 flows, Average Gain - NCRS-MinRS: 11%, NCRS-MaxRS: 54%

(c) 12 flows, Average Gain - NCRS-MinRS: 24%, NCRS-MaxRS: 55%

Fig. 6. Gain over routing for packets delivered to destinations for randomized grids and random flows

TABLE II
TRANSMISSION RATES [MBPS] FOR HYPERARCS IN SMALL SCENARIOS

Hyperarc	MinRS	MaxRS	NCRS	cts-node
0{1,2}	24	54	36	2
3{0,2}	36	54	36	0
4{0,1}	24	24	24	0

that transmission probabilities p_i-s are computed from the simulations and passed as parameters to the analysis. The average deviation of the analysis results from simulation results is 4%, 4%, and 3% over all the rate selection schemes for 3, 4, and 5-node scenarios, respectively. This small disparity between simulations and analysis validates the formulation of NCRS (cf. Eqns. 30-37) which is based on this analysis.

Table II shows the transmission rates selected by the rate selection schemes for all hyperarcs. Hyperarc $3\{0,2\}$ is an example of NCRS decreasing transmission rate to promote overhearing while hyperarc $4\{0,1\}$ demonstrates that NCRS does not increase transmission rate to promote overhearing.

B. Varying SNR Combinations for 3-Node Scenario

Previous results for the three small scenarios were for the same SNR combination of 15.3dB and 23.3dB for hyperarc $0\{1,2\}$. We now explore gain over routing for the 3-node scenario (cf. Fig. 5) for different SNR combinations on hyperarc $0\{1,2\}$ such that the rates selected by rate adaptation on the links are different. While there are infinite such combinations possible, we show only some of them here.

Over all these SNR combinations, NCRS improves gain by up to 16% over MinRS and 21% over MaxRS. At best MinRS and MaxRS outperform NCRS by 1% in some cases. This is because NCRS governs performance on only the single multicast hyperarc but not the remaining 4 unicast links in the scenario. Out of the 41 cases considered, NCRS accrues more than 5% gain for 16 of the cases and brings an average improvement of 9% in these cases. This indicates the wide-ranging applicability of rate selection.

Overall, for some combinations MinRS outperforms MaxRS, while for others MaxRS brings more gain over routing than MinRS. Notably, for most of these SNR combinations NCRS does at least as well as the maximum of MinRS and MaxRS. This indicates the flexibility of NCRS in different network conditions.

C. Randomized Grids

We now present results for randomized 5×10 grids of nodes in Fig. 6. Nodes were initially separated from grid neighbors along both axes by 25m. Their location coordinates were then randomized along both axes in both directions. This randomization provides us with links connecting "grid neighbors" with SNRs ranging from 8dB to 27dB *i.e.*, links that support 12Mbps to 54Mbps transmission rates.

Flows in this large network can either be disjoint or have common node(s)/link(s). Flows with multiple common links which are traversed in opposite directions degenerate to a *chain of nodes* with nodes at extremes sending data to each other. Most coding opportunities stem from these chains. A chain is often used as an example for network coding in

COPE [19]. For example, the 3-node scenario in Fig. 3(a) is a chain of 3 nodes.

We deploy 4, 8, and 12 flows randomly in different randomized grids. Each flow spans 3 to 5 nodes and is deployed either along a row or a column. Flows of less than 3 nodes do not provide inter-flow coding opportunities and flows of more than 5 nodes can not fit in a column. To provide sufficient coding opportunities, these flows are deployed in pairs as chains. With respect to Fig. 3, the intersection of flows can lead to 4 node or 5 node scenarios while the overlap of flows may lead to multiple 3 node scenarios.

Gain over routing in terms of number of packets delivered only to destinations for MinRS, MaxRS and NCRS is presented in Fig. 6. As the load or number of flows increase, congestion increases and more multicast packets vital for network coding are lost due to hidden terminal collisions at non-cts-nodes. For the three sets of flows, NCRS brings an average of 18%, 11%, and 24% more gain than MinRS and 28%, 54%, and 55% more gain than MaxRS. Crucially, NCRS outperforms both MinRS and MaxRS over all load levels.

VII. Related Work

Interest in network coding has led to an array of research work [20], [25], [27] to gauge the gains that can be achieved in wireless networks. We now present an overview of research addressing network coding combined with a multi-rate MAC.

The problem of multicast tradeoff was also recognized by Yomo et al. [32]. But it assumes perfect overhearing and only addresses rate selection for the hyperarc rooted at the intersection node. In fact, its solution for rate selection for this hyperarc is the same as MinRS - albeit with a modification. Of the n possible destinations, the transmission rate is selected to correspond to the k-th smallest SNR to the destinations. Only the $n-k+1$ packets destined for the targets with SNR greater than or equal to the threshold SNR are coded. k is dynamically adjusted depending on the conditions on the n links. For coding only 2 packets, as is used in this work, always transmitting a coded packet is shown in [32] to lead to nearly the same average network capacity as dynamically adjusting k. Moreover, Yomo et al. [32] were aware of the overhearing requirement of network coding and left it for future work.

The issue of overhearing for network coding for COPE-like schemes has also been observed in Kim et al. [22]. It addresses the joint problem of rate adaptation and network coding for a star-network that is essentially a generalization of the small scenarios in this paper. Given transmission rates of all sources in such a topology, only certain coding opportunities may arise due to the overhearing requirements that are met. These opportunities are analyzed in terms of clique partitioning of an undirected graph of destination nodes where these nodes are connected if each can overhear the other's source's transmission at the selected transmission rate. When only 2 packets can be coded by an intersection node, as is used in this work, and overhearing requirements are met, [22] adopts the approach used in this paper that coding packets is better than not coding (as indicated by Yomo et al. [32] as well).

For the transmission of coded packets from the intersection node itself, Kim et al. [22] uses MinRS. Though this transmission does not require overhearing, using MinRS is suboptimal compared to NCRS which maximizes the combined throughput on a hyperarc. In addition, for each star topology, Kim et al. [22] solves the problem of rate selection of all n transmitters at the intersection node. This requires the intersection node to be made aware of link qualities between each of the n sources and their $n-1$ overhearing destinations. In contrast, NCRS determines the transmission rates of all hyperarcs independently and requires very little information overhead in addition to that required by the rate adaptation and network coding schemes (cf. §III). Kim et al. [22] also does not show results for an IEEE 802.11 MAC or address the issue of link layer retransmissions in such a network.

While COPE [19] (and hence our network coding scheme) is an inter-session network coding scheme, MORE [10] is an intra-session network coding scheme based on the opportunistic routing and MAC scheme ExOR [8]. Afanasyev et al. [3] propose a rate selection scheme called *Modrate* to optimize overhearing for ExOR. Modrate minimizes the expected transmission time (extended from ETT [7]) while taking into account all possible paths a packet can take as a result of overhearing. But a node in ExOR that overhears a packet may forward it. This is in contrast to our inter-session coding where nodes are required to overhear packets to enable coding at the intersection node and do not themselves transmit these packets in any form - native or coded. As a result, Modrate treats all downstream nodes of a flow equally and is different from our NCRS scheme which treats direct and overhearing targets differently. In fact, Afanasyev et al. [3] leave combining Modrate and COPE's inter-session coding for future work.

Kim et al. [21] also recognize the problem of rate selection and propose different rate selection schemes for different packets - native packets that need to be overheard, native packets that do not need to be overheard, and coded packets. Rate selection for native packets that need to be overheard maximizes throughput at only the direct target while ensuring that the overhearing target receives more than β fraction of the packets. For a 5 node scenario, the suggested mechanism to set β leads to $\beta \approx 0.89$ *i.e.*, the overhearing target should receive at least 89% of the packets. This limits the range of rates that can be selected. In contrast, our approach maximizes cumulative throughput at all targets without such constraints.

Packet loss based rate adaptation algorithms [6], [24] need to differentiate between loss due to collision and poor channel characteristics as collisions can mislead them into decreasing the transmission rate. Wong et al. [31] propose to selectively enable RTS/CTS exchange to prevent collisions. If a packet loss is encountered in spite of RTS/CTS, it is attributed to collision. Since network coding requires multicast of some packets, RTS/CTS is a necessity. Moreover, since the underlying rate adaptation mechanism as well as our rate selection algorithm NCRS use SNR instead of packet loss to characterize link quality, collisions do not impact NCRS.

VIII. Conclusions

We address the problem of rate selection for network coding in multi-hop wireless networks with multi-rate IEEE 802.11g. We analyze the performance of network coding on a representative small scenario and propose a rate selection algorithm NCRS based on this analysis. We show results to illustrate the wide applicability of rate selection for network coding in wireless networks. Additionally, NCRS achieves a gain of up to 24% and 55% on average over MinRS and MaxRS, respectively, for large multi-hop wireless scenarios.

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