

Network Coding Aware Queue Management in Multi-Rate Wireless Networks

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Abstract—While network coding can potentially provide significant throughput benefits by combining packets prior to forwarding them, the achievable gains are directly related to the coding opportunities at a relay that performs encoding. If the relay does not have packets destined for distinct destinations, that can be encoded together, the network coding gains could be marginal. Towards increasing the opportunities for network coding, in this paper we propose a queue management scheme, that arbitrates the rate at which distinct transmitters send packets to a common relay which applies network coding. Our queue management approach prioritizes the channel access of nodes that do not have enough enqueued packets at the common relay, thereby essentially attempting to balance the number of packets from the distinct senders at the relay. We perform extensive simulations of our approach (built as a wrapper on top of the popular network coding approach COPE) in multi-rate scenarios. We find that our approach yields throughput gains of up to 57% compared to COPE due to enhanced opportunities towards encoding packets.

I. INTRODUCTION

Network coding has been proposed to increase the capacity of wireless networks towards the ever increasing demand for wireless capacity due to the emergence of high bandwidth applications. The fundamental idea in network coding is to reduce the number of wireless transmissions by encoding together different packets. In contrast with the traditional *store* and *forward* paradigm, network coding uses a *store*, *code* and *forward* approach. Network coding has been applied in both multicast and unicast contexts. In particular, the COPE architecture [1] for network coding in wireless mesh networks has received a lot of attention; COPE has shown that it can improve the throughput of unicast traffic in dense networks with bursty flows. In addition, network coding aware rate adaptation algorithms [2] [3] have recently been proposed; these are built on top of the COPE architecture to further increase throughput.

Scenario of Interest: First, let us revisit network coding in brief. Let us consider the five node topology as in Fig. 1. The five nodes typically occur in larger networks and thus, this topology is often analyzed for its simplicity. In this topology there are two flows, from *Alice* to *Dave* and from *Bob* to *Chloe*. *Jack* is the relay node and is responsible for forwarding packets. When COPE is used, *Jack* transmits an XOR of the packets ($\mathbf{a} \oplus \mathbf{b}$) received from *Alice* (\mathbf{a}) and *Bob* (\mathbf{b}). Using network coding the number of transmissions is reduced from four to three. However, in this example, to decode the coded packet successfully, *Chloe* and *Dave* have to correctly overhear packets \mathbf{a} and \mathbf{b} , respectively. The radio channel

conditions between the sender and the overhearing node, and the transmission rates of *Alice* and *Bob*, affect the overhearing at *Chloe* and *Dave*. If *Chloe* cannot overhear the packet from *Alice*, it will not be able to decode the XORed packet from *Jack* and the native packet will have to be retransmitted.

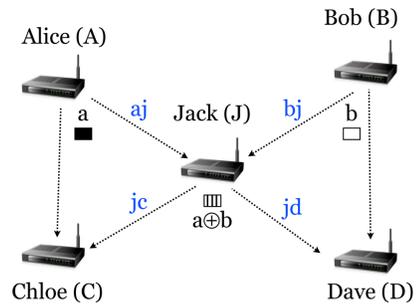


Fig. 1. A topology of five nodes with network coding. Two flows *Alice* → *Dave* and *Bob* → *Chloe* go via *Jack* who performs network coding.

Loss in Coding Opportunities: When a relay node that performs network coding (*Jack*) has packets for different next hops (*Chloe* and *Dave*), it computes the probability that the receiver nodes can decode the coded packet. If the probability is greater than a certain threshold, it XORs native packets destined for these next hops and sends the coded packet on the wireless channel. However, if the relay does not have packets for the different next hop nodes (*Chloe* and *Dave*), it has to send each native packet as they are and thus, the coding opportunity is lost. To visualize the problem, assume that *Jack* maintains virtual queues for *Chloe* and *Dave*. If there is *imbalance* between these virtual queues, the likelihood that one of these queues becomes empty increases and consequently *Jack* loses coding opportunities.

Losing coding opportunities can be detrimental to throughput gains possible with network coding and should be avoided, especially in the presence of heavy traffic. Let us again consider our example with *Alice*, *Bob* and *Jack*. If CSMA/CA is the MAC protocol in use, each node in the same *Carrier Sense* range has the same probability of accessing the channel in the long term. Since the input traffic for *Jack* is twice its output rate, it starts accumulating packets in the queue. If *Jack* uses network coding, it drains the queue faster. However, at each instance that *Jack* loses a coding opportunity, it reduces the rate at which its queue is drained and this contributes to an accumulation of packets in its queue.

Balancing the aforementioned virtual queues can avoid such losses of coding opportunities. One solution could be to use a perfect schedule wherein *Alice* and *Bob* send packets to *Jack*'s queue at equal rates. *Jack* can explicitly tell *Alice* and *Bob* when to transmit. However, *Jack* may be unaware of whether or not *Alice* and *Bob* have packets to transmit; thus a perfect schedule is difficult to implement. Moreover, today most systems use the popular IEEE 802.11 MAC standard. A second simple approach could be for *Jack* to delay the transmission of a packet until a coding opportunity is created (e.g., *Alice*'s packet is not forwarded unless there is also a packet from *Bob*). However, this can result in the filling up of *Jack*'s queue and can also cause unnecessary delays; in fact, COPE is built on the underlying principle of never delaying packets.

Our contributions: Based on these considerations, in this paper we propose a queue management approach to increase the probability of coding packets (coding opportunities) in a multi-rate wireless network. Our proposed approach adaptively prioritizes channel access of the transmitters to a relay, based on the states of the virtual queues at the relay. Specifically, the probability of these nodes accessing the channel is adaptively varied by tuning the *Contention Window (CW)* size at the MAC layer. Adjusting the *CW* size can be implemented via minor modifications to the IEEE 802.11 standard and has also been used in other contexts (e.g., in [4] and [5]). Based on how many packets are in the virtual queues and the quality of the links, the relay node (*Jack*) provides the sender nodes (*Alice* and *Bob*) with suggested values of CW_{min} , towards balancing its virtual queues. The value of CW_{min} is inserted in the header of a COPE packet when such a packet is transmitted by *Jack*.

The paper is organized as follows. In Section II we present previous studies on network coding and queue management. In Section III we propose our queue management approach. In Section IV we evaluate the performance of our approach via extensive simulations. Section V concludes our work.

II. RELATED WORK

In this section, we describe relevant related work. We first discuss related work on network coding and later that on queue management.

A. Related work on network coding

Most of the work on network coding in the literature is related to multicast traffic. Network Coding was introduced for the first time by Ahlswede *et al.* [6], who showed that routers can achieve multicast capacity by mixing information in different messages. This work was followed by that of Li *et al.* who showed that linear codes achieve the maximum capacity bound [7]. They proposed *linear network coding* where the output at a relay is obtained as a linear combination of its input flows. However, this approach needs centralized knowledge about the network topology. Koetter and Medard proposed *random network coding* where the linear codes are substituted with codes generated by a polynomial algorithm

[8]. Chou *et al.* proposed a distributed scheme for practical network coding which does not need centralized knowledge of the network topology [9].

Katti *et al.* applied network coding to unicast traffic and integrate network coding into the current network stack [1]. They proposed COPE, a distributed scheme for network coding. With COPE each station is in promiscuous mode to overhear packets which are then stored for a short time T and used for decoding. A relay needs to know which packets its neighbors have in order to be able to code. This information can be sent in periodic reception reports or can be estimated using a routing protocol based on the ETX/ETT metric. COPE by default uses the lowest rate available (*i.e.*, 6 Mbps in IEEE 802.11g). It has been shown in [2] and [3] that network coding aware rate adaptation algorithms can further increase the capacity of wireless networks. None of these efforts however, examine the loss of coding opportunities due to a mismatch in the transmission rates of senders to a common relay. Note that in our work we consider this problem in a multi-rate setting.

B. Related work on queue management

Most of the queue management algorithms in the literature are proposed to improve congestion control with TCP (e.g., [10], [11]). In the context of network coding, queue models for both unicast [12] and multicast flows have been studied in [13], [14]. Seferoglu *et al.* propose a queue management algorithm for TCP flows with COPE in [15]. They observe that a mismatch between flow rates can reduce coding opportunities. This mismatch is due to the fluctuation of wireless channel quality. They propose a change to the congestion control mechanisms of TCP to deal with this issue. In particular, when a node is congested, it chooses which packets to drop and the source reduces its packet generation rate. However, their solution does not consider that different flows may have different data rates. In contrast, our approach considers the use of multiple bit-rates in wireless networks; it is also independent of the transport protocol, and thus can be used with both UDP and TCP.

III. OUR PROPOSED QUEUE MANAGEMENT APPROACH

As discussed, ensuring balanced throughput from *Alice* and *Bob* can increase *Jack*'s coding opportunities (Fig. 1). We propose to tune the CWs at the senders towards achieving this. We propose a queue management algorithm initiated by *Jack* towards estimating the proper CW sizes for *Alice* and *Bob*. *Jack* then feeds back this information to *Alice* and *Bob*.

First, let us look at how the queue is managed at the relay node *Jack* in the COPE architecture. With COPE, each packet enqueued in the *output queue* at *Jack* is also enqueued in a *virtual queue* to the packet's next hop (*Chloe* or *Dave*). When *Jack* senses the channel to be idle, it dequeues the first packet in the output queue and searches the virtual queues to check whether there is a packet with a different next hop, that can be encoded with the dequeued packet (see Fig. 2). The use of virtual queues speeds up the search.

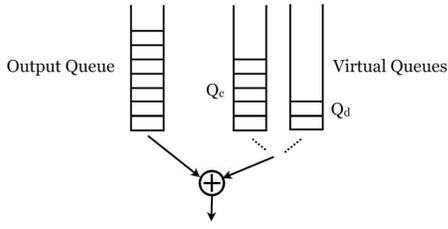


Fig. 2. Output queue and Virtual queues at the relay node for different next hop recipients. Q_c and Q_d are the sizes of the Virtual queues headed to *Chloe* and to *Dave* respectively.

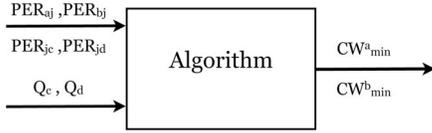


Fig. 3. Block representation of our queue management algorithm.

Having unbalanced virtual queues increases the probability that some of these become empty and thus, cause *Jack* to miss out on coding opportunities. With our queue management algorithm we want to *reduce* the probability that a virtual queue becomes empty. We achieve this by appropriately prioritizing the channel access of either *Alice* or *Bob*. Based on (i) information on the size of the virtual queues destined to *Chloe* and *Dave* (Q_c, Q_d in Fig. 2), and (ii) the packet error rates (PERs) on the four links aj, bj, jc, jd , (see Fig. 1), our algorithm computes the appropriate CW sizes for *Alice* and *Bob*, towards balancing their virtual queues at *Jack*. In other words, our algorithm takes $Q_c, Q_d, PER_{aj}, PER_{bj}, PER_{jc}$ and PER_{jd} as input and outputs the values of CW_{min}^a and CW_{min}^b , the contention window sizes for *Alice* and *Bob* (see Fig. 3).¹ Next, we describe the key design elements of our algorithm, and then present the algorithmic details.

The effect of PER on the sizes of the virtual queues: The imbalance in the virtual queues maintained at *Jack* is primarily because of mismatches in the packet error rates (PER) on the various links in the considered network. Specifically, we make the following observations:

- For the links *Alice* \rightarrow *Jack* and *Bob* \rightarrow *Jack*, when the medium access is fair as in CSMA/CA and $PER_{aj} > PER_{bj}$, *Alice* has to transmit a packet more times than *Bob*. Thus, at *Jack* the virtual queue that enqueues packets from *Alice* will have fewer packets than that from *Bob*.
- For the receiver links *Jack* \rightarrow *Chloe* and *Jack* \rightarrow *Dave*, when $PER_{jc} > PER_{jd}$, *Jack* accumulates more packets headed to *Chloe* (due to a requirement for a higher number of retransmissions).

Tuning CW_{min}^a and CW_{min}^b for balancing queues: By considering the entire path along which packets are delivered (*Alice* \rightarrow *Dave* and *Bob* \rightarrow *Chloe*), one can estimate which virtual queue will tend to have fewer packets (at *Jack*). Based on this, we propose to tune the congestion windows used for

¹The algorithm does not use explicitly any information about the quality of the overhearing links, but we simply assume that this quality is sufficient not to make network coding infeasible.

MAC access by *Alice* and *Bob*, towards balancing the virtual queues.

We consider the fraction of $\frac{PER_{receiver}}{PER_{sender}}$. Based on this fraction, we define $sender_{min}$ and $sender_{max}$ to be the following:

$$sender_{min} | \min \left\{ \frac{PER_{jd}}{PER_{aj}}, \frac{PER_{jc}}{PER_{bj}} \right\} \quad (1)$$

$$sender_{max} | \max \left\{ \frac{PER_{jd}}{PER_{aj}}, \frac{PER_{jc}}{PER_{bj}} \right\}, \quad (2)$$

where, the notation $|$ refers to the sender (*Alice* or *Bob*) with the minimum (or maximum) value of the aforementioned fraction. If the virtual queue gets drained faster than the rate at which the packets come into the queue, the queue tends to empty faster. In contrast, if packets arrive to the queue faster than they are drained, the queue tends to fill up. $sender_{min}$ is the sender (between *Alice* and *Bob*) whose queue tends to fill up (the fraction is typically < 1); $sender_{max}$ refers to the sender whose virtual queue tends to empty out (the fraction is typically > 1). Thus, our goal is to appropriately increase the probability of packet transmission of $sender_{min}$ or decrease that of $sender_{max}$ so as to balance the virtual queues at *Jack*.

Consider a link with a packet error rate PER_{link} . Then, the average number of successful packet transmissions on this link is:

$$\frac{1}{(1 - PER_{link})}. \quad (3)$$

The transmission probability (assuming a fixed contention window W) is:

$$p = \frac{2}{(W + 1)}. \quad (4)$$

To increase the rate at which the sender with the higher queue imbalance $sender_{min}$ sends packets to *Jack*, we decrease its Contention Window to:

$$CW_{min}^i = K * (CW_{min}^j + 1) - 1 \quad (5)$$

where i is the $sender_{min}$ node and j is the other node. K is a coefficient that depends on the PERs of the links on the two paths (defined below). Suppose that *Alice* is $sender_{min}$ and we want to increase her transmission probability while keeping the contention window of *Bob* (viz. CW_{min}^b) fixed at 31 (unchanged from default settings). We compute the contention window of *Alice* to be:

$$CW_{min}^a = K(CW_{min}^b + 1) - 1 \quad (6)$$

where $K = \frac{(1 - PER_{aj})(1 - PER_{jc})}{(1 - PER_{bj})(1 - PER_{jd})}$. Note here that $K \leq 1$ since A is $sender_{min}$, i.e., the contention window size is decreased. This decrease balances the delivery probability of the packets on the two paths *Alice* \rightarrow *Dave* and *Bob* \rightarrow *Chloe* and, in turn, balances the virtual queues at *Jack*.

Alternatively, one can decrease the probability of transmission of *Bob* by increasing his contention window. We fix the window of *Alice* to be $CW_{min}^a = 31$; we compute CW_{min}^b using (6) except that in lieu of K we use a new coefficient $K' = K^{-1} \geq 1$.

The above solution is used in our queue management algorithm. In particular, when the virtual queues become highly unbalanced, we reduce or increase the contention window. The details of the algorithm are presented later.

Communicating to the sender nodes the value of the congestion window to use : We insert the value of CW_{\min} in the COPE header by adding a new field. Thus, whenever *Jack* sends a packet to *Chloe* or *Dave*, nodes *Alice* and *Bob* can overhear the packet by operating in promiscuous mode and extract the suggested minimum CW values from the header. The overhead for adding the field is negligible; only a few bits per node are needed.

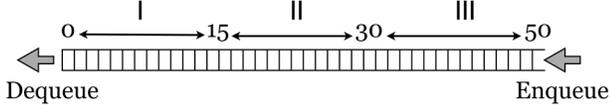


Fig. 4. FIFO output queue divided in three segments.

Details of the algorithm: Recall that our core objective is to ensure that the output queues at the relay node (*Jack*) have enough packets from both paths to prevent the loss of coding opportunities. Furthermore, the relay node should not have too many enqueued packets; if it does, packets may be dropped resulting in a degradation of the end-to-end throughput. Depending on the queue (buffer) capacity, we propose to divide the output queue into three segments as shown in Fig. 4. The example values (15 and 30) are for a queue capacity of 50 packets.

- If the output queue size $(Q_c + Q_d) \leq 15$ and the value $|Q_c - Q_d| < 2$, we increase the transmission probability of the $sender_{\min}$ node as per (6). If the virtual queues become highly unbalanced ($|Q_c - Q_d| \geq 2$) we divide by 2 the CW_{\min} of the node with fewer packets.
- If the queue size is such that $15 < (Q_c + Q_d) \leq 30$ and $|Q_c - Q_d| < 4$, we increase the transmission probability of the $sender_{\min}$ node as per (6). Otherwise we decrease the transmission probability of the $sender_{\max}$ node.
- If the queue size is $(Q_c + Q_d) > 30$, there is a risk that the queue becomes full and begins to drop packets. In this case, we reduce the transmission probability of the node with the higher number of packets: the higher the difference $|Q_c - Q_d|$, the higher the CW_{\min} of the node whose queue has more packets. We double the window size until the virtual queue size decreases to below 30.

In the third case, note that when we reduce the transmission probability of the sender node (*Alice* or *Bob*) with the higher number of packets in the queue, *Jack* has higher probability of accessing the channel and is able to drain his queue faster.

The pseudocode of our queue management algorithm, applied at *Jack* which is the relay node, is provided in Algorithm 1. The notation [...] under each “else” in the algorithm defines the same actions taken in the corresponding “if” part, in which the roles of CW_{\min}^a and CW_{\min}^b have been swapped and K is substituted with K^{-1} .

Input : $Q_c, Q_d, PER_{aj}, PER_{bj}, PER_{jc}, PER_{jd}$
Output: CW_{\min}^a, CW_{\min}^b

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 $CW_{\min}^{default} = 31;$ 
find  $sender_{\min}, sender_{\max}$  and  $K;$ 
if  $(Q_c + Q_d) \leq 15$  then
  if  $|Q_c - Q_d| < 2$  then
    if  $A == sender_{\min}$  then
       $CW_{\min}^a = K * (CW_{\min}^{default} + 1) - 1;$ 
       $CW_{\min}^b = CW_{\min}^{default};$ 
    else
      [...]
  else
    if  $Q_d > Q_c$  then
       $CW_{\min}^a = CW_{\min}^{default};$   $CW_{\min}^b = \frac{1}{2} * CW_{\min}^{default};$ 
    else
      [...]
if  $15 < (Q_c + Q_d) \leq 30$  then
  if  $|Q_c - Q_d| < 4$  then
    if  $A == sender_{\min}$  then
       $CW_{\min}^a = K * (CW_{\min}^{default} + 1) - 1;$ 
       $CW_{\min}^b = CW_{\min}^{default};$ 
    else
      [...]
  else
    if  $A == sender_{\max}$  then
       $CW_{\min}^a = K * (CW_{\min}^{default} + 1) - 1;$ 
       $CW_{\min}^b = CW_{\min}^{default};$ 
    else
      [...]
if  $(Q_c + Q_d) > 30$  then
  if  $|Q_c - Q_d| < 2$  then
    if  $A == sender_{\max}$  then
       $CW_{\min}^a = K * (CW_{\min}^{default} + 1) - 1;$ 
       $CW_{\min}^b = CW_{\min}^{default};$ 
    else
      [...]
  if  $2 \leq |Q_c - Q_d| < 10$  then
    if  $Q_d > Q_c$  then
       $CW_{\min}^a = 2 * CW_{\min}^{default};$   $CW_{\min}^b = CW_{\min}^{default};$ 
    else
      [...]
  if  $10 \leq |Q_c - Q_d| < 15$  then
    if  $Q_d > Q_c$  then
       $CW_{\min}^a = 4 * CW_{\min}^{default};$   $CW_{\min}^b = CW_{\min}^{default};$ 
    else
      [...]
  if  $|Q_c - Q_d| \geq 15$  then
    if  $Q_d > Q_c$  then
       $CW_{\min}^a = 8 * CW_{\min}^{default};$   $CW_{\min}^b = CW_{\min}^{default};$ 
    else
      [...]

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Algorithm 1: Pseudo code of our queue management algorithm.

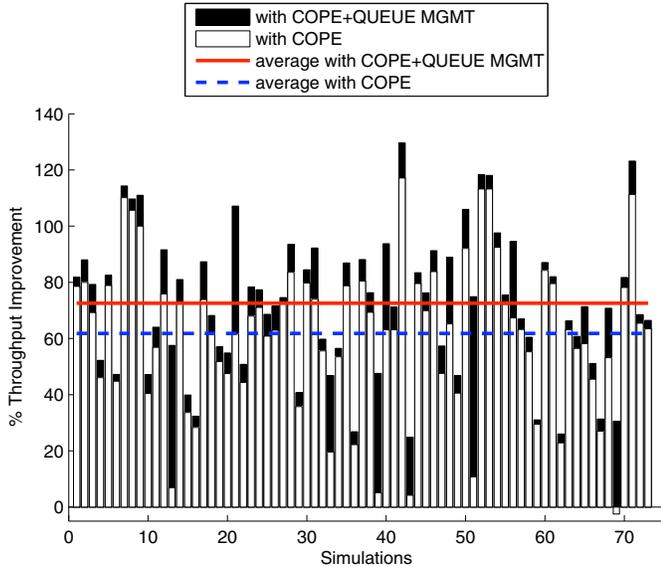


Fig. 5. Throughput gain over a typical IEEE 802.11 system in two cases: with COPE and with COPE + QUEUE MGMT.

IV. SIMULATION RESULTS

In this section, we use NS 2.34 [16] simulations to evaluate the proposed queue management algorithm. Since multi-rate transmissions are not supported by NS 2 by default, we used an external library [17]. For the implementation of COPE we began with the Google project [18] and retained the basic structure implemented in the project. We made some modifications and, in particular, changed the coding and decoding processes to exactly conform to the corresponding operations of COPE.

We use IEEE 802.11g, which allows transmissions at 6, 9, 12, 18, 24, 36, 48 and 54 Mbps. Since we deal with static networks, stable Signal-to-Noise Ratios (SNRs) are observed at nodes. The SNR is measured from packets sent on the wireless link; it depends on the distance between two nodes and on the noise power. For the same SNR, transmitting at a lower rate will result in a lower error rate. We use an SNR-based rate adaptation algorithm where each node chooses the highest rate so as to allow all of its neighbors to overhear packets with $PER \leq 0.2$.

We consider the five node topology in Fig. 1. Two saturated UDP traffic flows are initiated from *Alice* to *Dave* and from *Bob* to *Chloe*. Each node uses a transmission power of 20 dBm. The 2.4 GHz frequency band is used. The free-space path loss channel model is assumed. The packet size is set to 1500 Bytes. The positions of the nodes are generated randomly and the noise power is randomly chosen from the set $N = \{10^{-10}, 2 \times 10^{-10}, 3 \times 10^{-10}, 4 \times 10^{-10}, 5 \times 10^{-10}\}$; these values are chosen to be close to the default settings in NS 2. The combination of node positions and noise powers allows us to vary the PER on each link. We consider 73 different combinations. The simulations last for 100 seconds and the results shown are the average over three simulations;

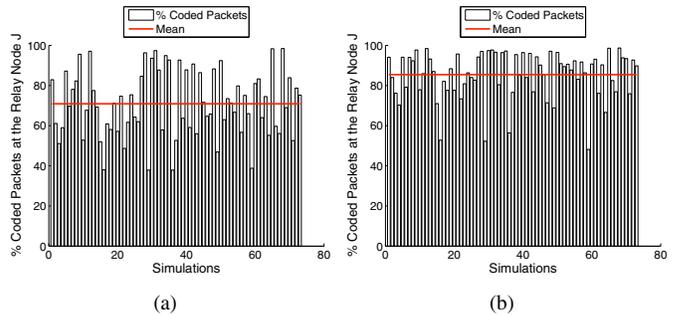


Fig. 6. Fraction of coded packets over total number of sent packets at the relay node with (a) COPE and (b) COPE + QUEUE MGMT. The average increases from 70% to 85%.

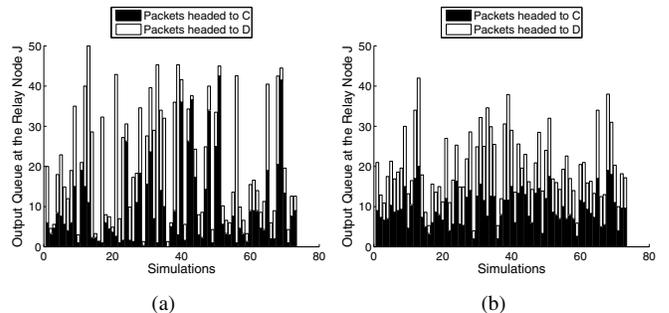


Fig. 7. Size of the output queue with packets headed to *C* and *D* with (a) COPE and (b) COPE + QUEUE MGMT. In the second case the virtual queues are more balanced.

we check the results from the three runs and verify that we have sufficient statistical confidence.

We compare the throughput of the system obtained without COPE, with COPE and with COPE + QUEUE MGMT. Fig. 5 shows the throughput improvements of the system in the 73 different topologies (based on PERs) with COPE and with COPE + QUEUE MGMT with respect to the throughput without COPE. We notice that our algorithm enhances the performance of COPE when COPE's gain is low. On average our algorithm increases COPE's performance by 7.5%, with a maximum improvement of 57%. Furthermore, the fraction of encoded packets at the relay node increases from 70% with COPE to 85% with COPE + QUEUE MGMT (Figs. 6 (a) and (b)). Lastly, the average difference between the virtual queues is 10 packets with COPE and 2.7 packets with COPE + QUEUE MGMT (Figs. 7 (a) and (b)). This shows that our algorithm is able to balance the virtual queues at the relay node and thereby improve coding opportunities.

A. The Best Improvement Case

First we consider the case where our algorithm provides a system gain of 57%. This case is shown in Fig. 8. The noise power is fixed to $N = 4 \times 10^{-10}$. We observe that the receiver links have different values of PER ($PER_{jc} = 0.18$ and $PER_{jd} = 0.009$). Packets headed to *Chloe*, denoted by *C*, will tend to accumulate at the relay node queue (as shown in Fig. 10 (a)).

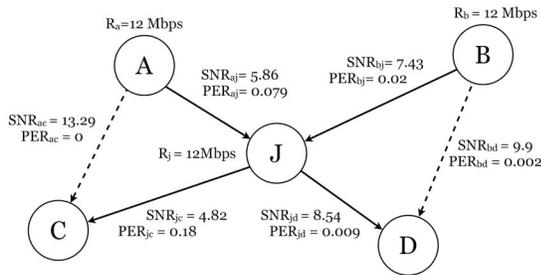


Fig. 8. SNR (in dB), data rate and PER for each link in the case where we obtain the best throughput improvement with COPE + QUEUE MGMT.

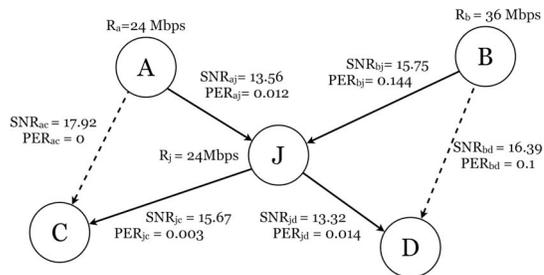


Fig. 11. SNR (in dB), PHY rate and PER for each link in a case where we obtain about a 7% throughput improvement with COPE+QUEUE MGMT.

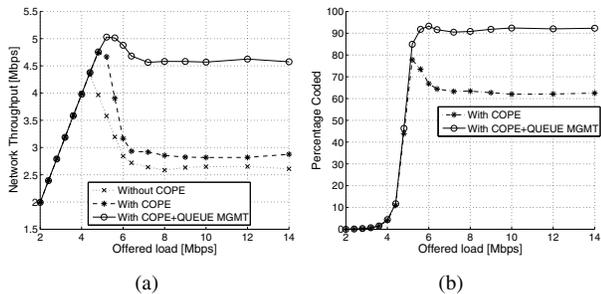


Fig. 9. (a) COPE+QUEUE MGMT provides 57% increase in UDP throughput in the presence of saturated traffic. (b) Percentage of packets encoded at the relay node *Jack*.

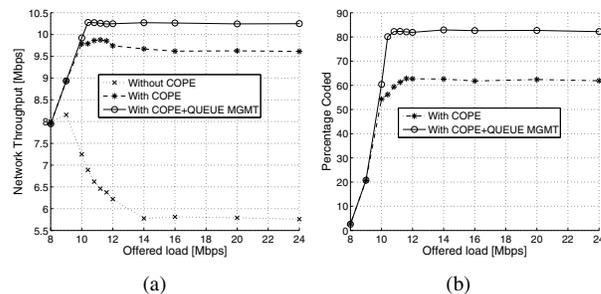


Fig. 12. (a) COPE+QUEUE MGMT provides 7% increase in UDP throughput in the presence of saturated traffic. (b) Percentage of packets encoded at the relay node *Jack*.

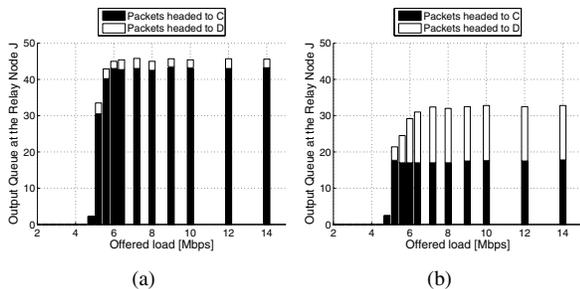


Fig. 10. Size of the output queue with packets headed to *Chloe* and *Dave* (a) with COPE and (b) COPE + QUEUE MGMT. In case (b) the output queue size is reduced and the virtual queues are more balanced.

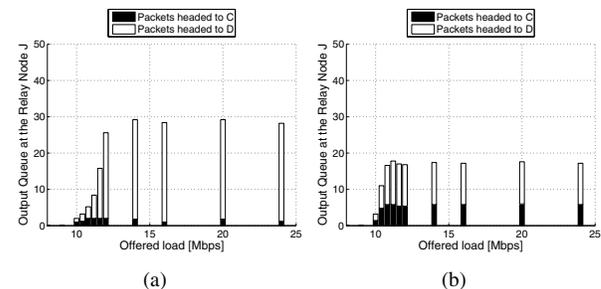


Fig. 13. Size of the output queue with packets headed to *Chloe* and *Dave* with COPE (a) and COPE+QUEUE MGMT (b). In the second case the output queue is reduced and the virtual queues are more balanced.

We gradually increase the offered load in the considered scenario. We see in Fig. 9(a) that the systems have the same throughput as long as the offered traffic is low. At high traffic loads, the performance degrades. However, COPE with our algorithm is able to better cope with the performance degradation by adaptively tuning the transmission probabilities via contention window adjustments. We point out that the fraction of encoded packets is higher with our algorithm (see Fig. 9 (b)). If we look at the output queue at the relay node with only COPE (Fig. 10(a)), we see that the relay node does not accumulate packets in its output queue if the offered load is less than 5 Mbps. After that, the average queue size quickly becomes 45 packets. This means that packets have a high probability of being dropped because the output queue often reaches the maximum size of 50 packets. Moreover, the virtual queues are highly unbalanced. Our algorithm (Fig. 10(b)) reduces the size of the output queue to 30 packets and balances the number of packets headed to different next hop nodes,

thereby increasing coding opportunities at the relay.

B. The Average Improvement Case

In this case, COPE + QUEUE MGMT provides throughput gains of about 7% over COPE as seen in Fig. 12(a). Here, we see that there is a difference in the PERs on sender links ($PER_{bj} = 0.144$ and $PER_{aj} = 0.012$ as in Fig. 11). In addition, the receiver links have low values of PERs. As seen from Fig. 13(a), without the queue management scheme the relay node accumulates packets headed to *Dave*, denoted by *D*. This is because of the fact that the relay node receives more packets from *Alice* (denoted by *A*), since $PER_{aj} < PER_{bj}$, and thus is able to encode only 60% of the packets, losing coding opportunities. Again, our algorithm reduces the size of the output queue while making the virtual queues more balanced (Fig. 13(b)).

V. CONCLUSIONS

In this paper we proposed a queue management algorithm on top of the COPE architecture to increase the coding opportunities and network throughput. Our algorithm balances the virtual queues headed to different next hop recipients at a relay node, by adaptively tuning the contention windows of the sender nodes. We simulated our scheme considering a five node topology and the IEEE 802.11g standard. We compared the system without COPE, with COPE and with COPE + QUEUE MGMT. Our algorithm achieves a best case throughput gain of 57% over COPE, with an average gain of 7.5%. As a future work we plan to investigate the scalability of our approach by implementing it and studying the behavior of the relay nodes in a larger network.

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