A Simplified Queueing Model to Analyze Cooperative Communication with Network Coding

José Marcos C. Brito
National Institute of Telecommunication - Inatel
Santa Rita do Sapucaí, Brazil
brito@inatel.br

***Abstract*—Cooperative communication and network coding are two important techniques to improve the performance of telecommunications networks. Chieochan and Hossain proposed an interesting algorithm using these techniques, called BE-ONC (Buffer Equalized Opportunistic Network Coding), and analyzed its performance via simulation. In this paper, we proposed a simplified analytical queuing model to investigate the performance of wireless networks with cooperative communication and network coding. The proposed model was implemented and used to evaluate the performance of the BE-ONC algorithm. We also compared the performance of a system with cooperative communication and network coding to the performance of a system without cooperation.**

Keywords- cooperative communication; network coding; queueing mode; performance

I. INTRODUCTION

The traffic in telecommunications networks has grown exponentially. This is a consequence of the growth of the Internet, the development of new multimedia applications, and the huge proliferation of mobile terminals. To transmit this enormous traffic with QoS (Quality of Service), it is necessary to improve the performance of current telecommunications networks. One approach that has been widely studied as a solution to improve the performance of telecommunications networks is to use cooperative networks or cooperative communication [1-6].

Cooperation can be defined as the process of working together, as opposed to working separately (in competition) [1]. The basic idea of cooperative communication is to establish an additional path, via a relay node, connecting the source node to the destination node [1, 5]. Some cooperation techniques proposed in the literature are disclosed in [2,5,7], and those methods are classified as follows:

- Amplify-and-Forward (AF) - in this case, the relay amplifies the signal received from the source node and transmits this signal to the destination node.
- Decode-and-Forward (DF) - in this technique, the relay decodes the packet and re-encodes it prior to forwarding the packet to the destination node.
- Coded Cooperation - this is a technique that integrates cooperation into channel coding. The basic idea is that each user attempts to transmit incremental redundancy to its partner [5].
- Cooperative ARQ (Automatic Repeat reQuest) Protocols [7] – in this technique, the source node broadcasts its packets to the destination and relay nodes. If the destination node correctly receives the packet, the transmission is complete. However, if the packet is received incorrectly in the destination node but is correctly received in the relay node, re-transmission of the packet is performed by the relay. Finally, if packet errors are detected by the destination and relay nodes, the source node re-transmits the packet.

Another way to establish a cooperative communication is to use the technique called network coding. The theory of network coding was introduced by Ahlswede et al. [8]. In this paper, we are interested in a cooperative communication technique using network coding called BE-ONC (buffer equalized opportunistic network coding), which was proposed by Chieochan and Hossain [9] for Wi-Fi networks. In that work, the performance of their algorithm has been analyzed using simulations only.

The first goal of this paper is to propose a simplified queuing model to analyze the performance of the BE-ONC algorithm and subsequently compare the performance of a system with cooperation and network coding to that of a system without cooperation. The delay required for the successful transmission of a packet in the network is used as the parameter to assess system performance.

The remainder of this paper is organized as follows: in Section II, we summarize the BE-ONC algorithm and present the queuing model used in [9] to simulate the performance of this algorithm. In Section III, we present a simplified analytical model to evaluate the performance of the BE-ONC algorithm and reveal some of the numerical results. The conclusions and a preview of future initiatives are presented in Section IV.

II. THE BE-ONC ALGORITHM [9]

This section summarizes the BE-ONC algorithm proposed in [9] as a cooperative communication algorithm based on network coding for Wi-Fi networks.

The network analyzed in [9] is composed of two wireless users, one relay node, and one access point (AP) as illustrated in Figure 1. The wireless users broadcast packets to the relay and to the AP. After transmitting a packet, a wireless user waits for a positive acknowledgment (ACK) from the relay or the AP. If an ACK is received, the packet is deemed to have been successfully transmitted and is removed from the user's queue. If an ACK is not received, the wireless user re-transmits the packet.

The relay receives packets from wireless user 1 and wireless user 2. If a packet is correctly received by the relay but not by the AP, it is queued in the relay to be re-transmitted to the AP. The relay tries to combine two packets using an XOR (eXclusive OR) operation before transmitting them to the AP. Although the relay is allowed to re-transmit packets, it does not generate traffic [9].

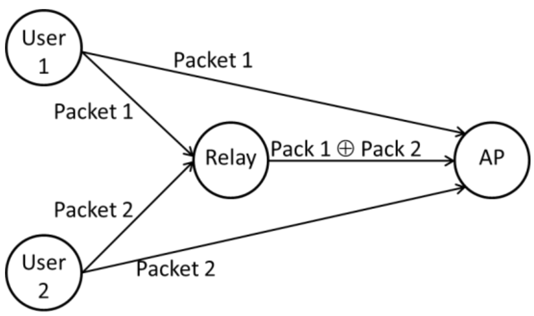

Figure 1. Wireless cooperative relay network with network coding.

Packets transmitted by wireless users are classified as non-urgent and urgent. The relay maintains two buffers, and only packets not received (or received with error) by the AP are queued in the relay node. If both buffers are empty, an incoming packet from user j (j = 1 or 2) is queued on queue j. Non-urgent packets coming from user j (j = 1 or 2) are also queued on queue j. Urgent packets are queued in the less congested buffer.

If the relay has packets in both queues (1 and 2), it combines the head-of-line (HOL) packets (using an XOR operation) and transmits the resulting packet to the AP. If the combined packet is correctly received by the AP, both HOL packets are removed from the relay's queue. If only one queue has a packet, the relay transmits the HOL packet of this queue. Again, if the packet is correctly received by the AP, it is removed from the relay's queue.

Figure 2 illustrates the queuing model presented in [9] that was used to analyze the performance of the algorithm. Again, the analyses performed in [9] are executed via simulations only.

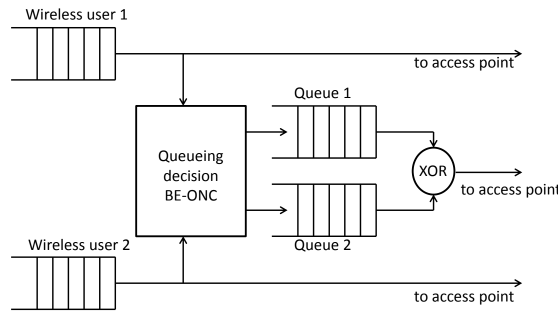

Figure 2. Queueing model presented in [9].

III. The Proposed Simplified Queueing Model

The mathematical analysis of the queuing model used to accomplish the simulations performed in [9] is quite difficult. To overcome this problem, we propose a simplified queuing model of the cooperative network in this paper.

Following [9], we assume that packets arrive randomly at each wireless user's buffer according to a Poisson process.

In addition, to model the relay's queue as a Markovian process, we consider the service time to be exponentially distributed in all queues in the network.

The above assumptions are important to compute the packet delays using the relevant theoretical results pertaining to networks of queues presented in the literature.

Figure 3 illustrates the simplified queuing model proposed in this paper. In that figure, P_1 represents the probability of a packet being queued in the relay and is computed by:

$$P_1 = PER_{uap} \cdot (1 - PER_{ur}) \quad (1)$$

where PER_{uap} is the packet error rate in the wireless link between a wireless user and the AP, and PER_{ur} is the packet error rate in the wireless link connecting a wireless user and the relay.

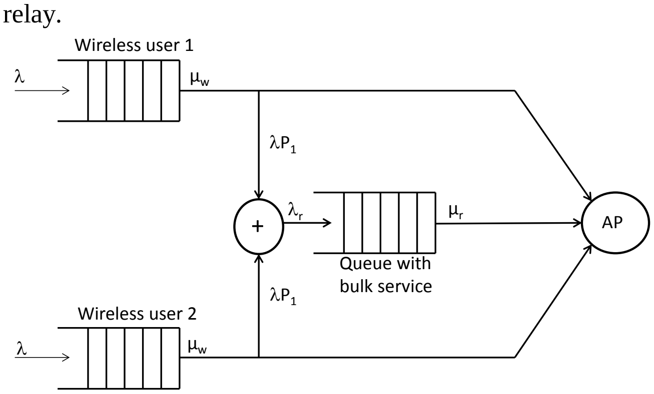

Figure 3. The proposed simplified queueing model.

The queue for each wireless user is modeled as an M/M/1 queue. The arrival rate in each user's queue is λ packets/second. Because the packet stays in the HOL of the

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user's queue until it has been correctly received by the relay or the AP, the packet error rate in the wireless links (between a user and relay and between a user and AP) must be considered to calculate the real service time in the user's queue. Defining μ, in packets/second, as the capacity of the output link of a user's queue, the effective mean service time in the user's queue can be computed from:

$$E(t_{sw}) = \frac{1}{\mu_w} = \frac{1}{\mu} \cdot P \cdot \sum_{k=1}^{\infty} k(1-P)^{k-1} = \frac{1}{\mu \cdot P} \qquad (2)$$

where P is the probability of a packet being received without error by the relay or AP. This probability can be written as a function of the packet error rate in the wireless links as:

$$P = 1 - (PER_{ur} \cdot PER_{uap}) \qquad (3)$$

Substituting (3) in (2), we can rewrite the mean service time in the user's queue as:

$$E(t_{sw}) = \frac{1}{\mu_w} = \frac{1}{\mu \cdot [1 - (PER_{ur} \cdot PER_{uap})]} \qquad (4)$$

Considering the M/M/1 model, the total time spent by a packet in a user's queue is determined as:

$$E(T_u) = \frac{1}{\mu_w - \lambda} \qquad (5)$$

To account for the XOR operation on the HOL packets shown in Figure 2, the queue in the relay node is modeled as one with bulk service. The corresponding state transition diagram is illustrated in Figure 4. If only one packet is in the queue, it is immediately transmitted by relay. If two or more packets are in the queue, the relay executes an XOR operation between the two packets in the HOL and transmits the combined packet.

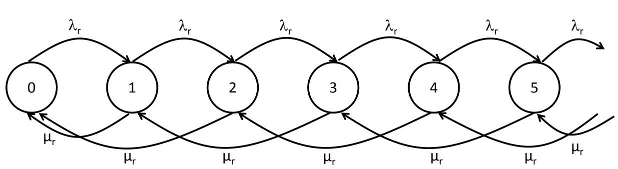

Figure 4. State transition diagram of the relay's queue.

From Figure 3, the arrival rate in the relay's queue is given by:

$$\lambda_r = 2\lambda \cdot P_1 \qquad (6)$$

To compute the effective mean service time in the relay's queue, we need to consider the packet error rate in the link between the relay and the AP. Defining μ as the capacity of the output link in the relay node, the mean service time in the relay's queue can be computed from:

$$E(t_{sr}) = \frac{1}{\mu_r} = \frac{1}{\mu \cdot [1 - PER_{rap}]} \qquad (7)$$

where PER_{rap} is the packet error rate in the wireless link between the relay and the AP.

The total time spent in the queue with bulk service (illustrated in Figure 4) can be computed by [10] [11]:

$$E(T_r) = \frac{r_0}{\lambda_r(1-r_0)} + \frac{1}{\mu_r} \qquad (8)$$

where r_0 is the positive root of the operator equation (9) having a value less than 1 [10]:

$$\mu \cdot r^3 - \mu \cdot r - \lambda_r \cdot r + \lambda_r = 0 \qquad (9)$$

Solving (9), the only positive root with a value less than 1 is given by:

$$r_0 = \frac{-\mu + \sqrt{\mu^2 + 4\mu\lambda}}{2\mu} \qquad (10)$$

Finally, we can compute the mean time required to transmit a packet (without error) from the wireless user to the AP as:

$$E(T_t) = E(T_u) \cdot (1 - P_1) + [E(T_u) + E(T_r)] \cdot P_1 \qquad (11)$$

To compare the performances of systems with different capacities, it is advantageous to normalize equation (11) as a function of a packet's transmission time (1/μ), resulting in the normalized delay:

$$E(T_{tn}) = \{E(T_u) \cdot (1 - P_1) + [E(T_u) + E(T_r)] \cdot P_1\} \cdot \mu \qquad (12)$$

Figure 5 illustrates the behavior of the normalized delay as a function of the utilization factor in the wireless link ρ. The utilization factor is the ratio of the load for each wireless user λ relative to the transmission capacity of its output wireless link μ.

The packet error rate in a wireless link is strongly dependent of the link quality. For example, packet error rates from 0.018 to 0.738 are reported in [12]. The results presented in Figure 5 consider PER_{uap} = 0.3 and PER_{ur} = PER_{rap} = 0.1.

Finally, it is interesting to compare the normalized delay in the cooperative system with network coding to the performance of a system without cooperation (without the relay node). To be fair in this comparison, the transmission capacity of the relay is equally divided between the two wireless users. Thus, the transmission capacity for each wireless user is 1.5μ. In this case, the total packet-transmission delay from a wireless user to the AP is computed from:

$$E(T_{twc}) = \frac{1}{1.5\mu \cdot (1 - PER_{uap}) - \lambda} \quad (13)$$

and the normalized delay without cooperation is given by:

$$E(T_{twcn}) = \frac{\mu}{1.5\mu \cdot (1 - PER_{uap}) - \lambda} \quad (14)$$

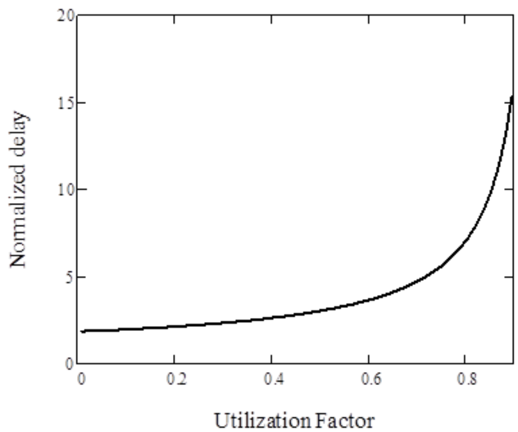

Figure 5. Normalized delay as a function of utilization factor, ρ, considering PER_{uap} = 0.3 and PER_{ur} = PER_{rap} = 0.1.

Figures 6 and 7 compare the performance of the system with cooperation and network coding vis-à-vis the system without cooperation. In Figure 6, we consider PER_{uap} = 0.3 and PER_{ur} = PER_{rap} = 0.1, and in Figure 7, PER_{uap} = 0.4 and PER_{ur} = PER_{rap} = 0.1.

We can observe that the system with cooperation performs better than the system without cooperation once a given packet error rate threshold in the link between the wireless user and the AP has been exceeded. The threshold is a function of the following parameters: PER_{uap}, PER_{ur}, PER_{rap} and ρ. To investigate the value of this threshold, we define a performance factor, Δ, as the ratio between Equation 12 and Equation 14. The behavior of this parameter is illustrated in Figure 8 and Figure 9.

If the performance factor, Δ, is greater than 1, the system without cooperation performs better than the system with cooperation. If Δ < 1, the system with cooperation performs better than the system without cooperation.

Figure 8 shows the influence of the utilization factor, ρ, considering PER_{uap} = 0.4 and PER_{ur} = PER_{rap} = 0.1.

Figure 9 shows the influence of the packet error rate in the link between the wireless user and AP, PER_{uap}, considering ρ = 0.8 and PER_{ur} = PER_{rap} = 0.1.

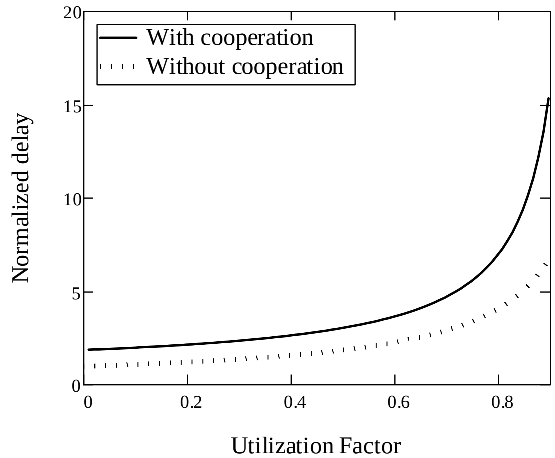

Figure 6. Comparing the normalized delay between systems with and without cooperation, considering PER_{uap} = 0.3 and PER_{ur} = PER_{rap} = 0.1.

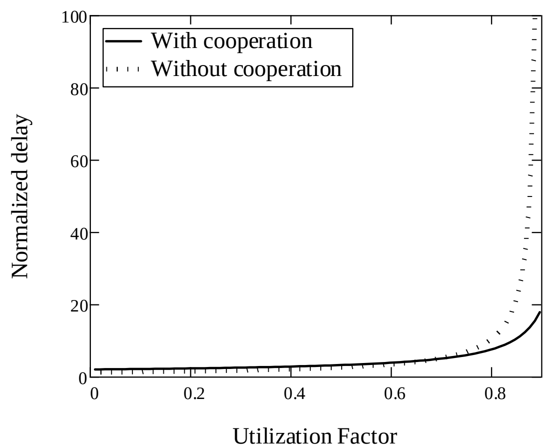

Figure 7. Comparing the normalized delay between systems with and without cooperation, considering PER_{uap} = 0.4 and PER_{ur} = PER_{rap} = 0.1.

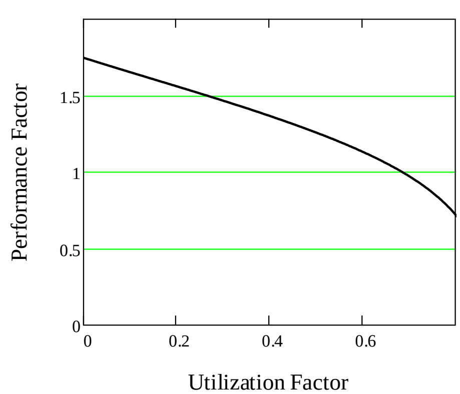

Figure 8. Performance Factor as a function of Utilization Factor, considering PER_{uap} = 0.4 and PER_{ur} = PER_{rap} = 0.1.

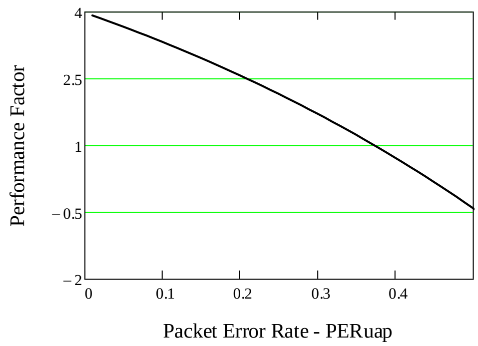

Figure 9. Performance Factor as a function of the Packet Error Rate in the link between the wireless user and AP, PER_{uap}, considering ρ = 0.8 and $PER_{ur} = PER_{rap} = 0.1$.

IV. Conclusions and Future Work

In this paper, we proposed an analytical approach based on a simplified queuing model to analyze the performance of cooperative communication with network coding, and we used this model to evaluate an algorithm previously proposed in the literature. The parameter used to evaluate the performance characteristics is the delay to transmit a correct packet from a wireless user to an AP.

Additionally, we compare the performance of a system with cooperation and network coding to a system without cooperation. We concluded, concurrent with the literature, that cooperation increases the performance if the packet error rate in the direct link between the wireless user and AP is greater than a given threshold.

The main advantage of the proposed queuing model is its simplicity, making it easier to investigate the influence of system parameters on a network's performance. This type of model is very useful in that it provides valuable insight relative to the performance of the network.

The weakness of the proposed model is that the classification of the traffic (i.e., urgent and non-urgent traffic) used in the algorithm proposed in [9] is not considered in our model. In future endeavors, we intend to expand the model by incorporating the traffic classification aspects of the algorithm proposed in [9].

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