Cross-Layer and Cooperative Opportunistic Network Coding in Wireless Ad Hoc Networks

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***Abstract*—In this paper, we present a cross-layer framework for optimizing the performance of opportunistic network coding in wireless multihop networks. The target scenario considers a wireless ad hoc network (WANET) with backlogged nodes and with multiple unicast packet flows. Initially, we focus on modeling the expected network-coded throughput individually for each wireless station as a function of parameters at the lower layers, like the maximum number of link-layer retransmissions and the transmission mode at the physical layer (PHY). Based on this analysis, we develop a network-coding algorithm that opportunistically and locally optimizes the expected information content of individual packet transmissions. To address the problem in a multihop setting, we focus on controlling the air time that is consumed by the resulting transmissions of coded packets. More specifically, we devise a distributed-cooperation algorithm that allows nodes to select the optimal PHY transmission mode by also considering the PHY selection of their neighbors. Nodes use only a partial view of the link contention relationships up to their interference range. Compared with existing works on opportunistic network coding and scheduling in ad hoc networks, our approach can yield significant throughput gains without employing complex link-scheduling algorithms.**

***Index Terms*—Cross-layer design, IEEE 802.11, medium access control (MAC) protocol, network coding, packet scheduling, physical layer (PHY) rate adaptation, wireless ad hoc networks (WANETs).**

I. Introduction

RECENTLY, wireless local area networks (LANs) have become the dominant technology for short-range wireless connectivity. Decreasing hardware costs have lead to a continuous increase in the number of wireless autonomous devices. While the goal is to provide wireless connectivity for an increased number of devices, in reality, several fundamental problems may limit the performance of the complete wireless network. One important problem for distributed wireless ad hoc networks (WANETs) is the lowering performance when the number of nodes that compete for the channel is increased [1].

A potential way to improve performance in this case is with the use of network coding [2], [3]. With network coding, routers can algebraically mix packets besides simply forwarding them. The main benefits of network coding are higher throughput, reduced latency, and improved reliability. In the case of wireless networks, network coding leverages the broadcast nature of the channel to increase the information content per packet transmission [4]. For example, in Fig. 1, node B codes the received packets a and b and broadcasts a single packet. This packet can be decoded by both nodes A and C if they have stored packets a and b, respectively. Throughput benefits in the order of three to four times over the baseline IEEE 802.11 have been demonstrated [3]–[5]. Energy reduction has also been demonstrated in [6]–[8]. Of particular interest are works that study the more realistic scenario according to which network coding is executed across random flows in WANETs [9]–[11].

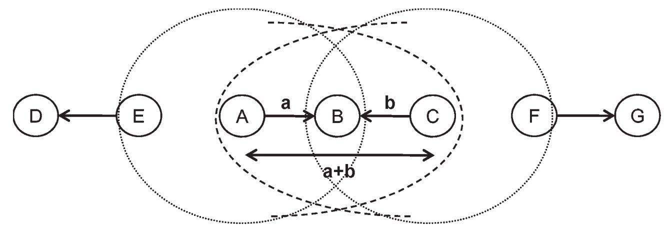

Fig. 1. Selection of a particular PHY transmission mode by nodes A and B may determine whether they can reach each other directly or they need node B as a router. Solid lines in the topology graph indicate packet transmissions, while dashed lines indicate the transmission range of nodes A and C.

However, the performance of random network coding will be influenced by existing algorithms that are typically used in the lower layers of the protocol stack. For example wireless stations make use of the *autorate* mechanism that is responsible for selecting a physical layer (PHY) transmission mode that is optimal for the current channel conditions [12]. However, when network coding is employed a single packet is broadcasted to more than one node, which makes the selection of the optimal PHY mode more challenging (see Fig. 1). This problem is identified but not addressed in related works primarily because there is a lack of practical rate adaptation schemes that are suitable for broadcasting [7], [13], [14]. A potential mechanism for rate adaptation is with the use of power control [13]. Even in this case, the selection of a particular PHY mode has direct impact on the air time consumed by packet transmissions. Therefore, there is a need to allocate the channel air time with criteria that take into account network coding. Furthermore, if link-layer retransmissions are considered, network coding decisions may be invalid at a later point in time since the channel conditions might change [12]. Existing schemes for opportunistic network coding do not also take this issue into account [3], [15]–[17].

The second problem that is particularly important in multihop wireless networks is the existence of hidden nodes. If we refer to the topology in Fig. 1, node B suffers from the hidden node problem, which means that it will back off more frequently because of transmissions from nodes E and F.

Manuscript received April 6, 2009; revised June 25, 2009 and August 27, 2009. First published November 10, 2009; current version published February 19, 2010. The review of this paper was coordinated by Dr. C. Yuen.

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Digital Object Identifier 10.1109/TVT.2009.2035811

Furthermore, the transmission of coded packets from node B reduces spatial reuse since both nodes A and C must receive the packet with a single broadcast transmission. It has been shown that for this scenario, depending on the traffic requirement at nodes E and F, coding packets at every opportunity is suboptimal [18]. Therefore, aggressively coding and exploiting all the possible opportunities should be avoided.

To tackle these issues, we develop a cross-layer and cooperative scheme for nodes that employ opportunistic network coding. We use a simple link-layer network coding protocol, and from that point, we focus entirely on optimizing the performance of network coding jointly with the medium access control (MAC) and PHY layers. We assume that nodes are backlogged and have always packets to transmit, with the purpose of obtaining closed-form expressions for the MAC layer throughput that can be used for real-time optimizations. The analytical model estimates the expected throughput by considering the available packets in the MAC queue, the level of link-layer automatic repeat request (ARQ), and the selected transmission mode at the PHY. Based on the cross-layer performance analysis, we develop an adaptive linear network coding algorithm that opportunistically optimizes the scheduling of broadcast transmissions only within a single hop. The estimated average information rate is used to select the packets that should be coded from the ones that are available in the MAC queue. This means that the optimization is greedy and local in its nature and not end-to-end, thus allowing for fast real-time adaptation of the cross-layer protocol parameters. The final contribution of this paper is a cooperative optimization algorithm that is motivated by the effect of coding and broadcasting decisions on the received air time in the neighborhood of a node.

The rest of this paper is organized as follows. The system model that is used in this paper is presented in Section II, while the link-layer network coding protocol is also described in the same section. One of the most important aspects of this paper is the combined network coding, ARQ, and PHY rate throughput model that is thoroughly described in Section III. In Section IV, we formalize the problem of network coding and cross-layer adaptation, while we also develop the distributed cooperative-optimization algorithms. In Section V, we present comprehensive simulation results for different network topologies. Finally, Section VI presents our conclusions and provides possible directions for future work.

II. Preliminaries

In this paper, we assume the use of the baseline IEEE 802.11 MAC protocol that operates under the distributed coordination function (DCF) [19]. This selection first ensures a fair allocation of the channel among the competing nodes and, second, the compatibility of our algorithms with the popular WLAN standard.

A. Network and Interference Model

The network is modeled with a directed graph $F(\mathcal{N},\mathcal{V})$, where $\mathcal{N}$ and $\mathcal{V}$ are the set of directional links and the set of nodes, respectively. We assume that for any link between two nodes, there is a counterpart in the opposite direction. Let the number of links in the graph be N. For modeling broadcast transmissions, we adopt the concept of hyperarcs for referring to the links that are used in single-hop broadcast transmissions similar to [13]. According to this notation, a hyperarc $(s,\mathcal{D})$ denotes a set of broadcast packet transmissions from node s to all the nodes in set $\mathcal{D}$ with $\mathcal{D}\subset\mathcal{V}$. We also denote by $\mathcal{D}_k$ a specific broadcast transmission that is a subset of the hyperarc $\mathcal{D}$ and with $\mathfrak{D}$ all the possible broadcast realizations for a particular node. For example, for node B in Fig. 1, $\mathfrak{D}=\{(A,C),(AC)\}$. This means that one possible broadcast realization is, for example, $\mathcal{D}=(AC)$ (i.e., the transmission of a coded packet both to nodes A and C with a single broadcast transmission). In this case, the specific broadcast transmissions are $\mathcal{D}_1=AC$ and $\mathcal{D}_2=\emptyset$. Note also that the same data packet is not contained in more than one broadcast coded packet. Mathematically, it can be expressed as $\mathcal{D}_k\bigcap\mathcal{D}_{k+1}=\emptyset$ for any two sets $\mathcal{D}_k$ and $\mathcal{D}_{k+1}$. Finally, let x_e be the air time that is consumed when link e is active with $e\in\mathcal{N}$.

The final important aspect of the general model that we have to built is the conflict graph of F that is named $G(F)$ and contains the interfering relationships among the N links in the network.[1] Each vertex in the conflict graph represents a wireless link in the multihop network, and there is an edge between two vertices if and only if the links represented by the vertices conflict (i.e., they interfere with each other and simultaneous transmission is impossible). On the other hand, a clique in the conflict graph represents a group of links that cannot transmit concurrently, and hence, they must access the channel exclusively. The conflict graph can be partially constructed by each node as follows. The IEEE 802.11 MAC is using carrier sensing multiple access with collision avoidance, which means that each node has a sensing range in which a signal can be detected. The sensing range of a node is determined by the clear channel assessment (CCA) sensitivity, which is the minimal detectable signal strength [19]. We assume that the CCA sensitivity is also the minimal interfering signal strength that can corrupt an intended transmission. Then, the interference range $R_I(s)$ of node s with transmission power P_{tx} can be obtained by

$$R_I(s)=\sqrt[k]{c\frac{P_{\mathrm{tx}}}{CCA}} \tag{1}$$

where k and c are environmental constants [20]. In this paper, we assume that the PHY transmission mode r can change, which means that in this case, P_{tx} will also change. If the distance between two nodes, e.g., A and B, is $dist(A,B)$, the transmission power can be expressed as follows:

$$P_{\mathrm{tx}}(r)=\frac{P_{\mathrm{rx}}(r)\times dist(A,B)^k}{c}. \tag{2}$$

In general, two nodes, e.g., A and B, interfere with each other when the following condition is true:

$$dist(A,B)\le\max\left(R_I(A),R_I(B)\right). \tag{3}$$

[1] Nodes that are within the carrier-sensing range of a given node.

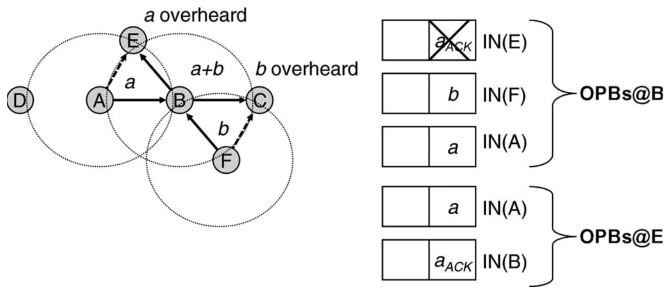


Fig. 2. Operation of single-hop network coding with opportunistic listening enabled. Wireless nodes use the last successfully received packet as an indication of the buffer contents of their neighbors.

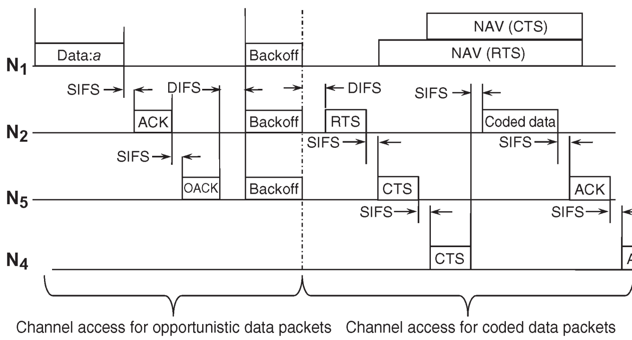


Fig. 3. Channel access with the link-layer network coding protocol.

This condition is calculated online to derive a partial/local view of the conflicting relationships between neighboring nodes.

B. Link-Layer Network Coding

In this section, we specify the protocol that facilitates the transmission of network-coded packets. This protocol is implemented at the link layer of IEEE 802.11 [5]. Its main feature is that it distinguishes the type of MAC service data units (MSDUs) that are transmitted in the network. Three types are defined as follows: *type 1*) unicast uncoded data packets; *type 2*) unicast uncoded data packets targeted to multiple opportunistic receivers; and *type 3*) multicast coded packets targeted to multiple receivers that can decode innovative packets from them. While the transmission of *type 1* and *3* packets is easy to understand, this is not the case for *type 2* packets. This type of packet is acknowledged through a form of opportunistic acknowledgments (OACKs) to indicate that these are not regular data packets that need reliable transmission. Data packets are tagged as *type 2* when there is the possibility that the packet will be used for network coding by the target node. Potential coding opportunities can be identified when the traffic pattern in the neighborhood is being overheard [5]. For example, in Fig. 2, node A indicates that packet a targeted to node B is a *type 2* packet for node E. Node A does so because it has overheard the transmission of coded packets from node B to E. Furthermore, node E can opportunistically acknowledge the transmission of packet a. This allows nodes A and B to know that this packet is available at node E and that it can be used for coding. Fig. 3 graphically summarizes our previous discussion, while more details for this specific protocol can be found in [5].

III. Throughput Analysis for a Single Wireless Node

The main idea of this paper is to model analytically the impact of coding decisions on the system throughput and then use this model for the design of the coding and scheduling algorithms. Therefore, the goal of the analysis that we present in this section is to derive a closed-form expression for the expected information rate as a function of the group of packets that are XOR-coded together for a single broadcast transmission, the selected common PHY transmission mode, and the maximum number of link-layer retransmissions. To make our analysis more tractable, we assume that nodes generate data packets of a constant size, while the transmission queues are always backlogged. Furthermore, the acknowledgment (ACK)/OACK frames are transmitted at the lowest and more robust PHY mode, as defined by the IEEE 802.11 standard, while we also assume the use of the IEEE 802.11a PHY specification [21].

A. Packet Success Probability for a Single Coded Packet

Recall that the symbol $\mathcal{D}$ denotes the group of nodes that are the destinations for packet l. If l is a coded packet, then $\mathcal{D}$ contains all the nodes that must receive l since it contains innovative information for each of them. The main problem is that the fate of this transmission is independent for each of the targeted receivers. By considering this important detail, we can calculate the probability of a successful PHY frame transmission for the dth receiver. If we assume that the tagged transmitting node is named s and the common PHY transmission mode that is selected for the broadcast transmission is r, this probability can be calculated by

$$P_{\mathrm{tx}}^{(s,d)}(l,r)=\left[1-P_{e,\mathrm{data}}^{(s,d)}(r)\right]\left[1-P_{e,\mathrm{ack}}^{(d,s)}(r_2)\right], \qquad d\in\mathcal{D} \quad (4)$$

where $P_{e,\mathrm{data}}$ and $P_{e,\mathrm{ack}}$ are the packet-erasure probabilities for data packets and acknowledgments, respectively, while r_2 is the most robust PHY mode in 802.11a. Now, the packet error probabilities can be calculated as

$$P_e = 1-(1-\mathrm{BER}(\gamma,r))^{S_l} \quad (5)$$

where S_l is the size of the packet in bits, and γ is the instantaneous channel signal-to-noise ratio. The BER can be calculated depending on the adopted channel model [22]. Now, for the broadcast transmission defined by hyperarc $\mathcal{D}_k$, the probability of successful delivery by all the intended receivers is given by[2]

$$P_{\mathrm{succ}}^{(s,\mathcal{D}_k)}(l,r)=\prod_{d\in\mathcal{D}_k} P_{\mathrm{tx}}^{(s,d)}(l,r). \quad (6)$$

Equation (6) corresponds to one broadcast transmission $\mathcal{D}_k$ from schedule $\mathcal{D}$, which is one of the possible schedules that belong in $\mathfrak{D}$. The analysis becomes considerably more complex as we consider other parameters of the MAC layer. For example, for our cross-layer analysis, we have to consider a

[2]Note that the fact that opportunistic receivers are also possibly receiving a packet l is not included in the information rate/throughput calculation since these packets do not contain innovative information.

different maximum number of link-layer retransmissions for each packet. Usually, this number is constant and equal to 7 in IEEE 802.11 [19]. However, our objective is to allow the network coding algorithm to be able to select the packets that will be coded in subsequent transmission opportunities, i.e., modify the schedule $\mathcal{D}$. Therefore, we have to consider the impact of retransmissions at each receiver separately. This can be done by following up on our analysis until this point. The probability of successful delivery with n_mth truncated ARQ can be calculated by extending (6) as follows:

$$P_{\text{succ}}^{(s,d)}(l,r,n_m) = 1 - \prod_{i=1}^{n_m}\left[1 - P_{\text{tx}}^{(s,d)}\left(l, r(i)\right)\right], \qquad d \in \mathcal{D}. \tag{7}$$

An important observation with respect to (7) is that the PHY transmission mode r of the possible retransmissions can also change since the packet may have been successfully received by a subset of the receivers. Therefore, we use the notation $r(i)$ to indicate the PHY mode of the ith transmission attempt. From the previous calculations, we can move to the next step and derive the conditional probability that the PHY frame is actually received with the nth attempt out of the maximum n_m. By combining (4) and (7) we have, only for the dth receiver, the following equation:

$$P^{(s,d)}[n|\text{succ}] = \frac{P_{s,tx}^{(s,d)}\left(l, r(n)\right)}{P_{\text{succ}}^{(s,d)}\left(l, r(n), n_m\right)} \cdot \left[1 - P_{\text{succ}}^{(s,d)}(l,r,n)\right]. \tag{8}$$

We can also calculate the probability that with the nth transmission, the packet is received by *all* the intended receivers of the broadcast transmission $\mathcal{D}_k$, i.e.,

$$P^{(s,\mathcal{D}_k)}[n|\text{succ}](l,r,n_m) = \prod_{d\in\mathcal{D}_k} P^{(s,d)}[n|\text{succ}]. \tag{9}$$

B. Impact of Packet Loss on the Transmission Delay

Packet losses and the subsequent retransmissions affect both the transmission time of each individual packet as well as the waiting time for each individual packet in the outgoing MAC queue. For calculating the overall delay, we proceed as follows. First, we consider the backoff procedure that is essentially captured by the contention window (CW) parameter. CW is an integer that is drawn from a uniform distribution over the interval $[0, CW_{\max}]$. When the channel is idle, a station keeps reducing the CW while it attempts to transmit after CW becomes zero. In the case of an unsuccessful transmission, the backoff algorithm doubles the $CW_{\max}$ and reselects a new value for CW, but in the case of a successful transmission, it is reset to $CW_{\min}$ [19]. In the 802.11 MAC, the backoff interval is measured in slot units with duration t_s. In our case, we want to calculate $\overline{T}_{\text{bkf}}(n)$, which is the average duration of the backoff before the nth transmission attempt or, equivalently, the $(i-1)$th retransmission attempt. This is basically directly related to the average value of CW as follows:

$$\overline{T}_{\text{bkf}}(n) = \overline{W} \times t_s. \tag{10}$$

Now, the average value of CW will depend on the average packet loss probability P_{tx} as follows [23]:

$$\overline{W} = \frac{1 - P_{\text{tx}} - P_{\text{tx}}(2P_{\text{tx}})^{n_m}}{1 - 2P_{\text{tx}}} \frac{CW_{\min}}{2} \tag{11}$$

where P_{tx} was calculated in (4). Note that the above equation can lead to minor underestimation of CW since it does not consider the impact of hidden nodes, which is the case in multihop WANETs. However, recall that we can afford a minor overestimation of the throughput since our goal is not to estimate it precisely but instead use the throughput estimation formula by an optimization algorithm.

In the general case, a packet will be considered lost if the transmission itself fails or the acknowledgment fails. In (4), this distinction was included, but now, we have to properly evaluate what this means for the delay. In the case of a failed acknowledgment for nth data packet transmission, the node waits for an extended interframe space (EIFS) with probability given by

$$P_1(n) = \frac{\left[1 - P_{e,\text{data}}^{(s,d)}\left(l, r(n)\right)\right] P_{e,\text{ack}}^{(s,d)}\left(r(n)\right)}{1 - P_{s,tx}^{(s,d)}\left(l, r(n)\right)}. \tag{12}$$

When the data frame transmission fails, the sender experiences an ACK timeout [19] with probability given by

$$P_2(n) = \frac{P_{e,\text{data}}^{(s,d)}\left(l, r(n)\right)}{1 - P_{s,tx}^{(s,d)}\left(l, r(n)\right)}. \tag{13}$$

In the 802.11 standard, the sender waits for a short interframe space (SIFS) for the arrival of the acknowledgment to allow for the hardware to switch into receiving mode [19]. Therefore, the average waiting time, excluding backoff, before the nth retransmission can be calculated for each of these two cases and for each receiver d by [12]

$$\begin{aligned}\bar{L}_w^{(s,d)}(n) = {} & P_2(n-1) \cdot \left[T_{\text{SIFS}} + T_{\text{ack}}\left(r(n-1)\right) + t_s\right] \\ & + P_1(n-1) \cdot \left[T_{\text{SIFS}} + T_{\text{ack}}\left(r(n-1)\right) + T_{\text{EIFS}}\right].\end{aligned} \tag{14}$$

Now, we have to account for the fact that a (re)transmission might be unsuccessful for certain receivers. Therefore, the overall $\bar{L}_w$, i.e., the worst-case delay is defined by the "slowest" receiver. We can calculate this value as follows:

$$\bar{L}_w^{(s,\mathcal{D}_k)}(i) = \max_{d\in\mathcal{D}} \bar{L}_w^{(s,d)}(i). \tag{15}$$

The value of this formula is that it allows us to correlate the slowest receiver with its impact on the selected broadcast transmission $\mathcal{D}_k$ and, therefore, on the expected information rate of that particular broadcast.

C. Total Delay of Broadcast Transmissions

With our previous analysis, we calculated the average waiting time and the backoff duration when transmissions fail, as well as the impact of heterogeneous receivers. However, the transmission delay should also be calculated in the case of a successful transmission. In 802.11, the duration of a successful frame transmission will consist of the following parameters: the necessary backoff delay; the time required for the data transmission; an SIFS time; the ACK transmission from each receiver; and another DCF interframe space (DIFS) [19]. However, in our calculations, we have to consider the additional delay, given that $n-1$ failed transmissions occurred plus the time for the successful one. By using (9), (10), (14), and (15), we are now ready to derive the average duration for the transmission of a single broadcast transmission $\mathcal{D}_k$, if it is delivered successfully, with the PHY transmission mode r, as follows:

$$\begin{aligned}\bar{L}_{\mathrm{succ}}^{(s,\mathcal{D}_k)}&(l,r)\\ =&\sum_{n=1}^{n_m} P^{(s,\mathcal{D}_k)}[n|\mathrm{succ}](l,r,n_m)\\ &\cdot\Bigg\{\sum_{i=2}^{n}\left[\bar{L}_w^{(s,\mathcal{D}_k)}(i)+\overline{T}_{\mathrm{bkff}}(i)+T_{\mathrm{data}}(l,r_c)\right]+\overline{T}_{\mathrm{bkff}}(1)\\ &\quad+T_{\mathrm{data}}(l,r_1)+T_{\mathrm{SIFS}}+T_{\mathrm{ack}}+T_{\mathrm{DIFS}}\Bigg\}. \end{aligned} \tag{16}$$

Note that the summation term in the second line of (16) represents the total time spent because of failed transmissions (that we derived in Section III-B), while the third and fourth lines correspond to the delay of the final nth successful transmission. The final parameter that has to be calculated is the average transmission time that is consumed when the retransmission limit n_m is reached and the transmission for at least one receiver fails. We can easily rewrite (16) as follows:

$$\bar{L}_f^{(s,\mathcal{D}_k)}(i)=\sum_{i=1}^{n_m}\left[\overline{T}_{\mathrm{bkff}}(i)+T_{\mathrm{data}}(l,r_c)+\bar{L}_w^{(s,\mathcal{D}_k)}(i+1)\right]. \tag{17}$$

Again, this formula serves the purpose of identifying receiving stations that are expected to reduce the information rate since they would require excessive number of retransmissions or a very robust PHY transmission mode.

D. Throughput

From the above analytical expressions, we can now calculate the expected MAC layer information rate at a single backlogged node given a specific broadcast transmission $\mathcal{D}_k$. The expected information rate is equal to the ratio of the expected delivered data payload (or innovative packets decoded) to the expected transmission time that also includes the failed transmissions. Therefore, if the packet size in bits is S_l, the expected information rate can be calculated as

$$I^{(s,\mathcal{D}_k)}=\frac{S_l\cdot\sum_{j\in\mathcal{D}_k}P_{\mathrm{succ}}^{(s,j)}(l_k,r,n_m)}{\sum_{j\in\mathcal{D}_k}\left(1-P_{\mathrm{succ}}^{(s,j)}\right)\bar{L}_f^{(s,j)}+P_{\mathrm{succ}}^{(s,\mathcal{D}_k)}\bar{L}_{\mathrm{succ}}^{(s,\mathcal{D}_k)}}. \tag{18}$$

Furthermore, the total expected information rate for a particular coding schedule that is defined with hyperarc $\mathcal{D}$ is given by

$$I^{(s,D)}=\sum_{\mathcal{D}_k\in\mathcal{D}}I^{(s,\mathcal{D}_k)}. \tag{19}$$

From our experiments, we observed that this formula offers a very good approximation of the average information rate and allows the algorithms we develop next to make fast online decisions.

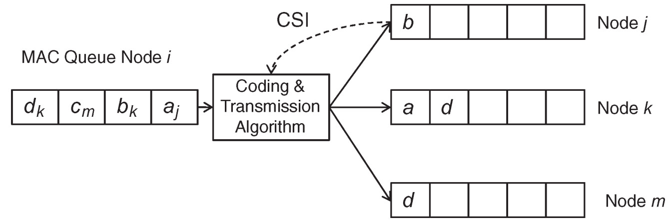


Fig. 4. Packet coding and transmission to multiple receivers. The introduction of a lightweight ACK mechanism of the link layer allows the optimization algorithm to evaluate faster the optimality of coding and scheduling decisions.

IV. Problem Formulation and Optimization Algorithms

A. Network Information Rate Problem

With our previous analysis, we calculated the expected average information that can be transmitted with the broadcast transmission $\mathcal{D}_k$ of a single coded packet as a function of the PHY transmission mode r and the maximum number of allowed retransmissions n_m. Now, the goal of opportunistic network coding is to maximize the information contained in each broadcast packet by selecting an optimal group of packets that should be coded together from all the available in the outgoing MAC queue [3], [5]. This aspect of our system can be seen in Fig. 4. Since nodes forward packets, a particular scheduling/coding decision will affect the queue utilization and eventually the rate of incoming packets in the tagged node [24]. Although this is the case in a real ad hoc network, in this paper, we assume for our analysis endogenous traffic arrivals, which means that the queue is stable and the station always generates packets for transmission. Our analysis does not intend to model and optimize the performance of network coding in the complete WANET but instead to be used to drive the decisions of an opportunistic network coding algorithm at a single station. This way, we are able to use the developed model and the associated algorithm for experiments where also naturally exogenous traffic arrivals exist. Another aspect is that a coding decision for a certain group of packets impacts heavily the air time share that the node obtains and eventually the performance of network coding.

To proceed with the formal definition of the problem, let us denote the group of packets that exist in the MAC queue and can be used for coding as $\mathcal{L}$. We overload the hyperarc notation $\mathcal{D}$ with the term $\mathcal{L}$ so that $\mathcal{D}(\mathcal{L})$ expresses the set of possible broadcast schedules that can be used for the given group of packets. Assume also that l_k is the coded packet that results from the kth broadcast transmission, where $\mathcal{D}_k\in\mathcal{D}(\mathcal{L})$. Therefore, the cross-layer opportunistic network coding problem can be written as follows:

$$\begin{aligned}&\max_{\mathcal{L}\in\mathrm{Queue}}\sum_{\mathcal{D}_k\in\mathcal{D}(\mathcal{L})}I^{(s,\mathcal{D}_k)}\\ &\text{subject to}\\ &\quad\sum_{\mathcal{D}_k\in\mathcal{D}}x_k\le\mu_{\mathcal{D}}(e),\qquad\sum_{e\in S(j)}\mu_{\mathcal{D}}(e)\le 1,\qquad x_k\ge 0\\ &\quad r\in\mathcal{R},\quad n_m\in\{0,\dots,n_m^{\max}\}.\end{aligned} \tag{20}$$

```
opportunistic_clc_coding()
Calculate I from (18) ∀r ∈ R
Calculate optimal r* from (21)
if r* ≠ r^curr then
    INIT_PHY_CHANGE(neighbors)
    Broadcast our PHY rates r for each link in clique j
    RATE_INFO(neighbors,I(R))
end if
if RATE_INFO received from all neighbors then
    Calculate optimal r*_coop, ∀ r ∈ R
    PROPOSE_PHY(neighbors,r*_coop), ∀i ∈ S(j)
end if
if ACCEPT_PHY received from all neighbors then
    Select the optimal PHY r*_coop
    Use the new constraint to re-solve (20)
else
    goto 2:
end if
Update clique capacities and fanout degrees
```

Fig. 5. Cooperative PHY rate selection algorithm. Capitalized words indicate the type of the message used by the cooperative algorithm.

Several constraints are analyzed next. The first important parameter in the above expressions is x_k and denotes the proportion of time that a broadcast transmission $\mathcal{D}_k$ from hyperarc/schedule $\mathcal{D}$ is activated. Therefore, essentially, the first constraint expresses the fact that the total air time x_k that node s obtains for broadcast transmission k should be less than or equal to what it deserves. Subsequently, in the second constraint, $S(j)$ is the set of links that form clique j, for all the links e that are within the interference range of the tagged node s. This constraint expresses the total air time that the links of all the nodes in the neighborhood are active which cannot be more than one. In other words, each clique's capacity is shared among the links that are part of that clique. More importantly, however, this constraint helps determine the validity of a particular schedule D.

B. Cooperative Air-Time Allocation Algorithm

The selection of a particular PHY transmission mode affects both the air time that is consumed by each transmission and the performance of network coding [18]. The reason for this strong dependency is that local decisions on the PHY mode will affect the air time that is received by nodes in the immediate neighborhood. To this aim, in this section, we focus on calculating the air time share that a node must obtain when it exercises network coding, and it can also adapt the cross-layer parameters as we explained in Section IV-A. Fig. 5 presents the pseudoalgorithm, while in Section IV-C, we describe its operation.

With our algorithm, a node calculates the cross-layer parameters that maximize the expected information rate I for a given group of packets that are contained in its transmission buffer according to (18). The node also calculates the optimal parameters that maximize I when the PHY transmission mode is used as a constraint. This way, the node can derive for this locally optimal PHY r^* and schedule $\mathcal{D}$, which maximize the information rate I. When the optimal PHY r^* is identified and is different from the current PHY mode r^{curr}, a PHY mode change should be initiated. This is accomplished by notifying all the nodes within its interference range with a message named INIT_PHY_CHANGE. After that, the node sends a message named RATE_INFO that contains the information for the calculated tuples *information rate/PHY mode*. For example, in Fig. 1, if we denote with the subscript the node that sent a particular message, the following message will be transmitted by node $A : m_A = \{I_A(r_1), I_A(r_2), I_A(r_3), \ldots\}$. This step ensures that all the nodes for which a PHY mode change will have an impact are notified. After the initial notification is sent, the node also receives similar information from the nodes with whom they share a specific clique in the form of $RATE\_INFO$ messages. By collecting this information, the node identifies the PHY rate that maximizes the information rate for all its broadcast transmissions. We can easily formalize this for a node s, since the information rate I includes the impact of PHY mode on all the outgoing links of a node. Therefore, if the subset $X \subset G$ denotes the nodes that are located within the maximum interference range of node s, we can write

$$r^*_{\mathrm{coop}} = \arg\max_{r \in \mathcal{R}} \sum_{x \in X} I_x(r) \tag{21}$$

subject to

$$\sum_{e \in S(j)} \mu_{\mathcal{D}}(e) \leq 1. \tag{22}$$

Equation (21) considers the total information rate that is achieved by the nodes that are sharing a specific clique j. Note that it is possible that $r^*_{\mathrm{coop}} \neq r^*$ since this algorithm derives the PHY mode that is optimal for the neighborhood. It also considers all the cliques/links in which node s participates. These nodes are the ones that must share the same clique, and therefore, constraint (22) has to be in place. The advantage of this *cooperative PHY rate selection* algorithm is that it requires participation only from the neighbors of each node within its maximum interference range. Note also that when a node identifies the optimal PHY transmission mode, it sends a request for approval for the new PHY with the message PROPOSE_PHY, and it applies the selected rate when all the nodes approve it [25], [26]. The important condition is that a node approves a PHY rate change from one of its neighbors if this change does not reduce its own expected information rate. This way, it is ensured that successive requests from nodes that independently execute this local optimization do not degrade the performance and the optimality of the selected PHY mode. As a consequence of the previous condition, convergence is established since every node that participates in a clique will have the same information, and based upon all the information, it will identify a unique optimal PHY for the node that initiated the request for a PHY change. Therefore, distributed consensus is ensured by disseminating all the information to the nodes that require it. Note that this cooperative approach has been used in the past but with different optimization objectives that include minimizing power consumption [26] or achieving fairness [25] but not in the context of network coding.

TABLE I
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value	Parameter	Value
Transmission range R_{tx}	250m	PHY header	24 bytes	Slot time	20 μs
Carrier-Sensing range R_{cx}	350m	ACK frame	38 bytes	Rtx limit	7
Routing protocol	Shortest path	Transport protocol	UDP	CWmax	1023
Propagation model	TwoRayGround	PHY header bit rate	1 Mbps	CWmin	31
Packet payload	1000 bytes	PHY rates	6/9/12/18/24/36/48/54 Mbps	DIFS	50 μs
UDP header	20 bytes	MAC header	28 bytes	SIFS	10 μs

C. Network Coding Algorithm

A greedy heuristic algorithm is adopted to solve the linear program in (20) and identify the optimal group of packets that should be coded. The algorithm operates naturally on MSDUs that are passed from the upper layers and are encoded by starting from the head-of-line (HOL) packet in the outgoing MAC queue. An important issue that needs to be mentioned is that since network coding is exercised through XORing packets within a single hop, there is no need to transmit any coding coefficients that will be used for decoding [27]. This is true because the HOL packet is allowed to be coded only if it has been overheard or transmitted by a neighboring node. This is precisely what the link-layer protocol that we described in Section II allows the coding algorithm to do.

The algorithm that we develop in this section greedily codes the maximum number of packets possible. For each candidate combination $\mathcal{L}$, it calculates the expected $I(l, r, n_m)$ from (18). Each node also measures the packet erasure rate based on the transmission history for each receiver so that they can be used by the analytical model. Therefore, (18) offers a very good estimate of the information rate for a particular group of receivers. Subsequently, the algorithm calculates $I'(l, r', n'_m)$ for broadcast schedule $\mathcal{D}'$ by removing from $\mathcal{D}$ the slowest receiver in terms of its PHY rate and PER, i.e., $\{\mathcal{D}'\} \leftarrow \{\mathcal{D}\} - 1$. If I' is higher than I, the algorithm continues this procedure to prune from the schedule not only slow receivers but also receivers for which coding is suboptimal. Note that when a receiver is pruned from the broadcast group of coded packets, this is accounted as separate regular unicast transmission. If the pruning cannot increase the estimated information rate, a previous valid schedule defined by $\mathcal{D}$ is used to code the selected group of packets.

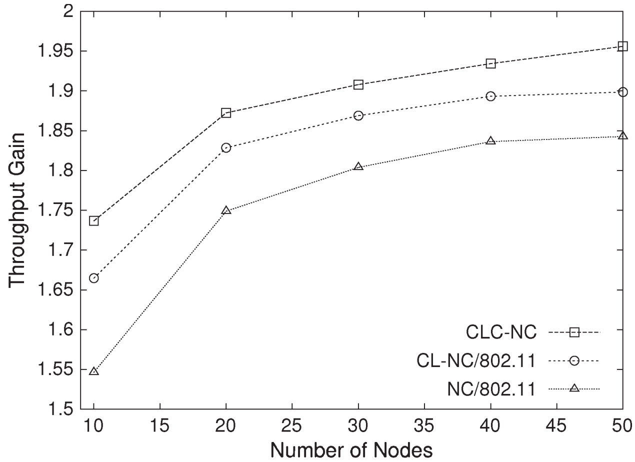
To quantitatively see the impact of this algorithm, consider again the example in Fig. 1. Here, if the traffic load from E$\rightarrow$D increases, hidden node related collisions at A also increase [28]. As the traffic load from E$\rightarrow$D is increased, there is a certain threshold at which when network coding is applied from node B, the throughput is decreased. This is precisely what our analytical model indirectly quantifies. In this sense, the increased collisions at node A also affect the number of retransmissions that node B has to use to maximize the network-coded throughput, and this is accounted for in the developed model. Therefore, since the average performance of each receiver is captured in terms of the packet loss rate and the achieved information rate, not only can we select the PHY rate of the transmission and the level of ARQ, but we can also decide whether coding is effective for that particular node or not.

V. PERFORMANCE EVALUATION

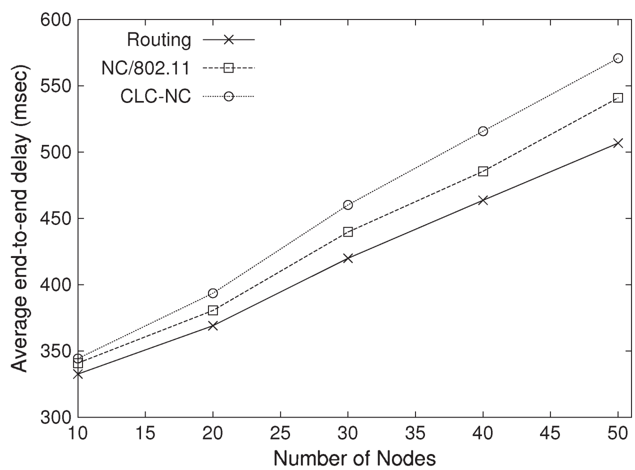
In this section, we evaluate the performance of the proposed cross-layer and cooperative network coding system through a simulation tool built in C. We considered a 1000 m $\times$ 1000 m geographical area for which random network topologies were generated. For each simulation round, the nodes that are used are randomly placed in the square area. Furthermore, we consider CBR packet flows between the nodes in the WANET. All nodes are part of a unicast traffic either as a source or a destination. This means that the number of unicast flows is 50% of the number of nodes that we tested for a particular experiment. We also assume that nodes are backlogged and always have a packet to transmit either for their immediate neighbors or for a node more than one hop away. The remaining parameters are specified in Table I. We implemented and simulated three versions of distributed protocols and coding algorithms. The first one is named NC/802.11 and implements the basic network coding features on top of the MAC that include pseudobroadcast and the transmission of separate receiver reports [3]. The second system named CL-NC considers the cross-layer network coding algorithm without any form of cooperation. The final system we tested is named CLC-NC to indicate that both cross-layer optimization at individual nodes, as well as cooperative PHY rate selection, are employed.

A. Number of Nodes

Fig. 6 demonstrates the impact of assigning a different number of nodes to the overall network while the packet flows traverse only one or two hops. More specifically, the percentage of single-hop flows that we configured for this experiment is 60%. This distinction is important since packets that are destined directly to their neighbors cannot be coded. Fig. 6(a) presents results for the throughput gain for the three systems under test. The first observation that we can definitely make is an increase in the throughput gain as the number of nodes is increased for all the systems that employ network coding. However, with NC/802.11 and CL-NC, the nodes that code gradually obtain a smaller fraction of the available bandwidth as the network density increases. This event hinders their ability to transmit more coded packets, and therefore, the throughput gain is also decreased. In this case, we see that the cooperative algorithm is extremely useful since it allows nodes to make more efficient use of the available bandwidth, despite the additional message passing overhead it introduces. As the number of nodes is increased, the use of the cooperative algorithm is more crucial because with the increased node density, coding decisions for a single broadcast transmission have more important effects on



(a)



(b)

Fig. 6. Simulations results for different number of nodes in the wireless network.

the throughput. Therefore, the global optimality of the PHY transmission mode can only be ensured with the existence of the cooperative algorithm.

Since the results in Fig. 6(a) might be misleading in terms of the performance of the protocols under test, we also present the average end-to-end delay that we measured for the transmitted packets. The results in Fig. 6(b) suggest that more nodes do not necessarily increase the delay for CLC-NC when compared with conventional routing. The first reason is that the analytical estimation of the expected information rate introduces no delay for the execution of the algorithm. Second, the link-layer network coding protocol allows coding only for a single hop. These two aspects allow CLC-NC to have low computational overhead and low latency.

B. Multihop Flows

The performance increase that can be achieved by the proposed algorithms becomes more significant as the number of hops that a flow traverses is increased. For a higher node density and an increasing portion of incoming traffic per node, the significance of our scheme is even more important, as the results in Fig. 7 indicate. This is a result that we expect since the offered load can be distributed to more nodes while the coding gain is also increased. Both the proposed schemes can capitalize even more on the use of denser topologies since the coding opportunities are increased. Another important observation is that the proposed algorithms are less sensitive to the number of nodes that contend for the medium because of the optimized coding decisions when hidden nodes are present. In addition, recall that even with light multihop load and increased node density, neither of the proposed schemes buffers opportunistically overheard packets. The link-layer protocol stores only packets that are actually needed for coding/decoding. At the same time, the NC/802.11 scheme, even for a light load, still suffers from contention related losses since frequent out-of-band acknowledgments are sent for coded packets. A subtle point is that the CLC-NC scheme introduces a message passing step that can increase the contention over the network by injecting nondata traffic like NC/802.11. However, this overhead is only experienced during the initial execution of the algorithm and not continuously for every group of coded packets. Mobility that may require more frequent invocations of the cooperation algorithm is examined next.

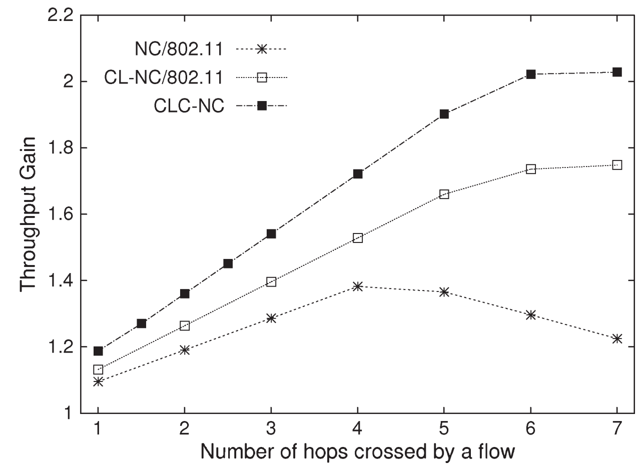


Fig. 7. Throughput gain for a different number of hops crossed by a flow. The percentage of multihop flows is 40%.

C. Mobility

Although the proposed protocol and the associated algorithms were not engineered with mobility as a concern, a real-life system must still be evaluated for these conditions. We considered a single mobile node for this experiment and the exact mobility pattern is shown in Fig. 8. The proposed algorithms exhibit considerably better performance as can be seen in Fig. 9 and for different mobile speeds. A detailed look at the simulation traces indicates that when out-of-band acknowledgment reports are lost they severely affect performance since they correspond to groups of packets. This means that stale coded packets remain in the buffers without being acknowledged, something that prevents them of being used any further. With the analytically driven algorithms, faster and more accurate feedback is provided to the network coding algorithm regarding the expected information rate before each broadcast transmission. This is because with CLC-NC, the loss of a packet or even an OACK simply removes that particular coding

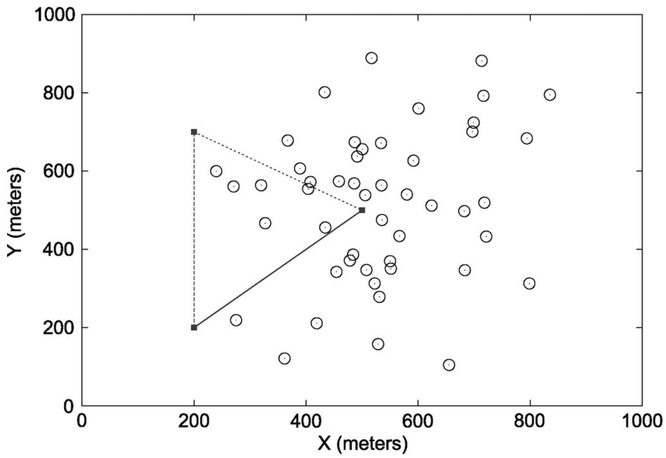


Fig. 8. Mobility pattern for a single node.

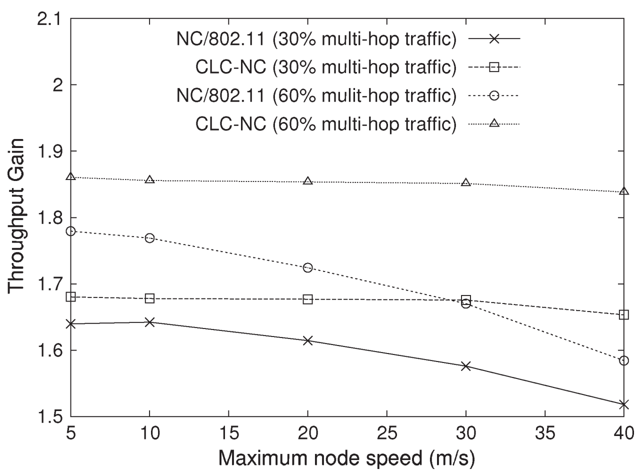


Fig. 9. Throughput gain with mobility.

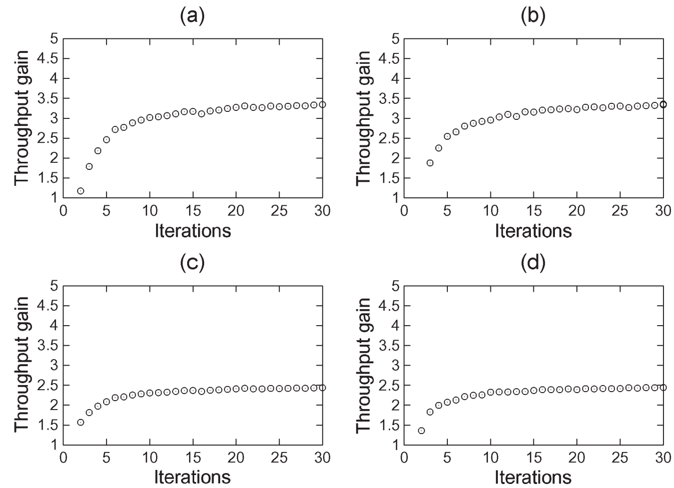


Fig. 10. Total throughput gain in the complete network versus the number of iterations of the cooperative algorithm. The term iterations refers to the number of invocations of the cooperative PHY rate-adaptation algorithm that are executed by a single node. Simulations are presented for different number/density of wireless nodes. (a) Nodes $= 25$, degree $= 5$. (b) Nodes $= 50$, degree $= 5$. (c) Nodes $= 25$, degree $= 3$. (d) Nodes $= 50$, degree $= 3$.

opportunity, but it does not impact the effectiveness of subsequent coding decisions. Another reason for this result with 802.11/NC is that when a decision for joint coding and PHY rate adaptation is made, this node does not know the fate of the previous transmissions at all the intended receivers. Therefore, it is likely that its current joint coding/PHY rate adaptation decision will be suboptimal for the current network conditions. However, CLC-NC can do better than that since the PHY rate is selected for each coded packet individually, and the feedback that is received through the ACK ensures that the next joint coding/PHY rate selection decision will be correct, even with high mobility.

D. Algorithm Convergence

The convergence of the cooperative PHY rate adaptation algorithm is one aspect that we briefly analyzed in the previous sections, while we showed it that can be ensured by a specific design choice in the proposed protocol. The throughput gain that is achieved in the complete network versus the number of iterations of the distributed algorithm is presented in Fig. 10. The reason why the total throughput gain in the complete network is presented is because the throughput gain per node fluctuates, depending on its actual location. The important message that we desire to convey with this figure is that with successive iterations, we obtain a throughput gain that is increased monotonically. Furthermore, what we can observe in all the results is that the number of iterations needed for this set of experiments is independent from the network size. This is a direct consequence of the fully distributed air-time allocation algorithm that requires information only from single-hop neighbors. The dominant factor that determines the convergence speed is the node degree that expresses the number of neighbors of each node. This is something that is expected since the nodes have to wait for a longer period before they make a decision about the optimal PHY transmission mode. Another important conclusion from these results is that optimal performance can be achieved with a fairly low number of messages, which means that the consumed bandwidth for message passing is negligible is static networks.

VI. CONCLUSION

In WANETs, combining network coding with cross-layer adaptation is a necessity due to the exploitation of the broadcast nature of the channel. However, the optimal configuration for the MAC protocol parameters is not easy in this scenario. To attack this problem, we initially considered the above aspects in a joint analytical throughput model that quantifies the relative tradeoffs only for a single node. We also explored cooperation as a next step, and we developed a distributed algorithm for calculating the optimal and information-fair PHY rates of each wireless link. The developed model is used by an opportunistic network-coding algorithm and not for modeling arbitrary WANET topologies. Our algorithm improved throughput performance not only by selecting optimally transmission parameters but also by indirectly addressing another basic problem, which is the decision whether coding is effective or not in the presence of hidden nodes. Further performance improvement was observed even for scenarios with a mobile node. In the future, we plan to investigate the potential of energy reduction in scenarios that include nodes that have power budget constraints.

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