A Note on Practical Deployment Issues for Network Coding in the IEEE 802.16 MeSH Mode

Parag S. Mogre, Matthias Hollick, Matthias Kropff, Ralf Steinmetz
Multimedia Communications Lab (KOM)
Technische Universitaet Darmstadt, 64283 Darmstadt, Germany
Email: {pmogre|mhollick|rst}@kom.tu-darmstadt.de

Christian Schwingenschloegl
Corporate Technology (CT IC 2),
Siemens AG, 81739 Munich, Germany
Email: chris.schwingenschloegl@siemens.com

Abstract—**Wireless network coding has the potential to enhance the capacity of Wireless Mesh Networks (WMNs). However, most of the work considering the practical deployment of network coding in WMNs considers only IEEE 802.11 based Medium Access Control (MAC) layers. The recent emergence of sophisticated MAC standards supporting WMNs (e.g. IEEE 802.16) make it necessary to view the deployment issues for network coding from a new perspective. This paper outlines the challenges for deploying network coding in sophisticated, reservation based MAC layers such as the IEEE 802.16 MeSH[1] mode. We present simple yet efficient metrics to quantify and measure the gain which can be obtained via deployment of network coding in the MeSH mode. We also present extensions to the standard's reservation mechanisms to support network coding. Additionally, initial simulation results are provided demonstrating the proof-of-concept for the presented solutions thereby providing a framework for further investigation and deployment of wireless network coding in sophisticated MAC layers.**

I. INTRODUCTION

Wireless network coding (WNC) has been demonstrated to be practically applicable and beneficial using standard off-the-shelf protocol stacks. The work [1] is a landmark in this direction. However, a majority of the practical work involving WNC applications assumes the use of the generic IEEE 802.11 or similar MAC layers. The recent developments in the standardization process show a trend towards more sophisticated mechanisms at the MAC layer to support stringent QoS requirements of multimedia and real time traffic expected in future wireless mesh networks (WMN). The IEEE 802.16 [2] standard and the upcoming IEEE 802.11s standard are examples for the latter.

For our study we select the IEEE 802.16 standard as a prototype for MAC layers having radically different medium access mechanisms. Considering the radical difference in access to the medium as controlled by the IEEE 802.16 specifications in comparison to the IEEE 802.11 MAC, network coding solutions originally designed and deployed using the IEEE 802.11 MAC need to be considered from a new perspective. This paper looks at the issues involved in deploying COPE-like [1] basic network coding solutions in WMNs using the IEEE 802.16 MeSH mode. We first analytically model the bandwidth reservation mechanism in the IEEE 802.16 MeSH mode, thereby motivating the need for looking at the deployment issues for network coding from a newer perspective, breaking away from the myopic IEEE 802.11 only view of WMNs. We next present extensions to the current IEEE 802.16 MeSH mode specifications to enable efficient support for practically deploying network coding in 802.16 WMNs. We also present simplified yet meaningful metrics quantifying the gain obtained by deploying network coding in 802.16 WMNs. Finally, via an initial simulation study, we demonstrate the proof-of-concept for the designed solutions thereby paving the path for further research.

The rest of the paper is structured as follows. Sec. II presents background information about the IEEE 802.16 MeSH mode. In Sec. III we analytically model the MeSH mode's bandwidth reservation scheme and derive design principles for WNC deployment. Sec. IV presents our solutions to efficiently deploy WNC in the MeSH mode. Finally, in Sec. V, via a simulation study we demonstrate the proof-of-concept for the presented solutions. Sec. VI discusses relevant related work. Sec. VII draws conclusions for the work presented in this paper and also give pointers for further research in this context.

II. BACKGROUND ON THE IEEE 802.16 MESH MODE

Using IEEE 802.16 MeSH mode, nodes in the WMN can schedule their transmissions to neighbouring nodes in a contention-free manner. The transmission schedule for individual nodes (SSs) can be centrally computed by a base station (BS), which is termed centralized scheduling, or determined by the individual SSs (distributed scheduling) using a three-way handshake between the transmitting node and the neighbouring node which is to receive the transmission (see Fig. 1). Centralized scheduling is limited to scheduling transmissions only on the links in a BS rooted scheduling tree specified by the BS. In this paper, without loss of generality, we restrict the discussion to distributed scheduling only as it is more flexible than centralized scheduling and can be used to schedule transmissions on all the links in the WMN.

The MeSH mode supports Time Division Multiple Access (TDMA) with the time axis divided into frames. Each frame is composed of a control-subframe and a data-subframe. The control-subframe is used to broadcast control messages for reserving bandwidth and for maintenance of the WMN. Medium access in the control subframe is controlled by a distributed mesh election algorithm [2], [3] specified in the standard which ensures contention free transmissions. The data subframe is divided into a number of minislots (here also referred to as slot). A slot is addressed by a slot number within

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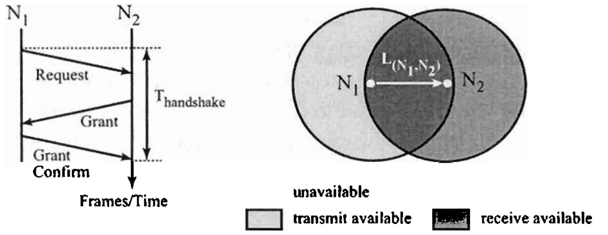
[1] Throughout this document we use the notation MeSH to refer to the mesh mode of the IEEE 802.16 standard.

the data subframe and the frame number for the data subframe. To enable individual nodes to schedule transmissions in a contention-free manner, for each slot (per individual frame) a status is maintained by all the nodes. The slot status reflects the type of actions (reception, transmission or both) which can be scheduled by the node in the given slot. The standard specifies four different slot states: *Available* (*av*), *Transmit Available* (*tav*), *Receive Available* (*rav*), *Unavailable* (*uav*). Nodes can negotiate (schedule) future transmissions in slots with status *av* or *tav*. Nodes are able to receive and hence grant future transmissions from neighbours to themselves in slots with status *av* or *rav*. Slots with status *uav* may not be used for scheduling future transmissions or receptions. Nodes update their local slot states by keeping track of their own reservations, and by overhearing the three-way handshake control messages sent by their neighbouring nodes. Assuming that all the nodes initially had all slots with status *av*, Fig. 1 (b) shows the status of the reserved slots at the neighbouring nodes of the sender and the receiver after a transmission has been scheduled between them using the three way handshake shown in Fig. 1 (a).



(a) Three-way handshake (b) Minislot state during transmission on link $L_{(N_1,N_2)}$

Fig. 1. Distributed scheduling overview

Using the three-way handshake slots are reserved for the transmission, here from node N_1 to N_2 for a certain number of frames. A reservation is given a set of (frame-range, minislot-range) tuples. Where the frame-range and minislot-range identify a contiguous range of frames and minislots, respectively. The standard permits the frame-range to be selected not arbitrarily but from a set of permitted values (e.g. 1 frame, 2 contiguous frames etc.). It is also possible to reserve the set of minislots for an infinite number of frames from a given frame number onwards, where the reservation must then be explicitly cancelled to free the reservation. This latter special case of reservation is denoted by us as a persistent reservation. Additional details about the MeSH mode and the data structures and control messages used can be found in the standard [2]. To make the material more accessible to readers unfamiliar with the MeSH mode, we provide a detailed overview of the MeSH mode specification in [4].

III. IMPLICATIONS OF THE IEEE 802.16 RESERVATION MECHANISM FOR NETWORK CODING

In the previous section we briefly outlined the functioning of the MeSH mode's distributed scheduling. We now look at the pitfalls in implementing COPE-like [1] practical network coding solutions in the WMN using the MeSH mode. A core principle of COPE's packet coding algorithm is to not delay the transmission of packets just for the sake of enabling coding of packets. This is most important especially for the case of delay sensitive applications and multimedia traffic which is expected to be the core beneficiary of the sophisticated QoS features offered by the MeSH mode. COPE can code and transmit packets as soon as a set of matching codable packets are available at the transmitting node. This is not the case for the MeSH mode due to its reservation based nature. To understand the former issue we next look at the reservation of slots in the MeSH mode using distributed scheduling in detail. Transmissions in the MeSH mode are scheduled in a contention-free manner using explicit reservation of slots for individual links before transmission of data on those links.

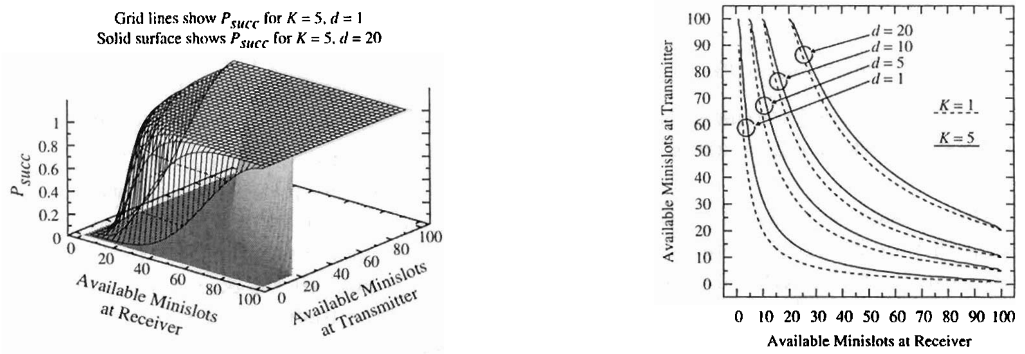
TABLE I
MODEL PARAMETERS FOR DISTRIBUTED SCHEDULING

Parameter	Interpretation of parameter
N	Num. of slots for distributed scheduling in a frame
d	Num. of slots to be reserved (demand)
T	Num. of slots suitable for scheduling transmission at the sender (status *av* or *tav*)
K	Num. of receivers to which the transmission is to be scheduled
k	$1 \cdots$ K, index for intended receivers respectively
R_k	Num. of slots suitable for reception at receiver k (status *av* or *rav*)
C_T, C_{R_k}	$\binom{N}{T}, \binom{N}{R_k}$ respectively

Let us consider the parameters outlined in Tab. I for our analysis. Consider that the parameters hold for a given frame. Let K be the number of neighbours (identified individually by their index k) which should receive the coded packet. This subset of neighbours is selected by looking at the next-hops of the packets available for coding similar to COPE. As we cannot transmit data to neighbours without reserving bandwidth for the transmission, we first need to reserve sufficient bandwidth for the multicast transmission. Here, we face the first pitfall, the MeSH mode does not support mechanisms to reserve multicast bandwidth, and this is so not without reason. Assume that we use enhanced handshake procedures to allow us to reserve multicast bandwidth. Consider that we need to reserve d slots for the transmission, in say a given frame having the parameters as shown in Tab. I. Let S_T and S_k denote the set slots suitable for scheduling at the transmitter and at receiver k, respectively. For the transmitter to be able to successfully negotiate and reserve the same d slots for the multicast transmission to the K receivers we require that, $|(S_T \cap S_k)| \geq d$, for all k. For the given model parameters, using counting theory we derive the probability that a common set of d slots for the transmission is available as given by Eq. (1).

$$P^K_{succ} = \frac{C_T \prod\limits_k \sum\limits_{j=d}^{\min(T,R_k)} \binom{T}{j} \binom{N-T}{R_k-j}}{C_T \left(\prod\limits_k C_{R_k}\right)} \tag{1}$$

Fig. 2(a) shows the success probability (P^K_{succ}) given by



(a) Effect of d on P^{K}_{succ}

(b) Contour plots for P^{K}_{succ} ≥0.9

Fig. 2. Plots showing the probability of successfully reserving d slots in a given frame for simultaneous reception at K neighbouring nodes

Eq. (1) for a handshake with K=5 neighbours for a demand (slots to be reserved) of 1 slot and 20 slots, respectively. The total number of slots per frame is 100. The x-axis shows the number of slots suitable for transmission at the transmitter. The y-axis shows the number of slots suitable for reception at the receiver(s). For enabling plotting, all the receiving neighbours are assumed to have the same number of slots suitable for reception. Fig. 2(b) shows the contour plots for P^{K}_{succ} showing the lower bounds beyond which $P^{K}_{succ} \geq 0.9$. Fig. 2(b) shows the contours for different demand levels (d), and different number of intended receivers (K). After analyzing the figures and Eq. (1), we see that P^{K}_{succ} decreases drastically as soon as one of the transmitter or receivers has a low number of slots suitable for the intended communication in the given frame. Further, with increasing d, a large number of slots need to be free for the intended communication to be able to successfully negotiate and reserve slots with a high probability. For the same demand d, and for the given number of free slots at both the transmitter and receivers, P^{K}_{succ} decreases with an increase in the number of intended receivers K. In practice not all receivers share the same number of available slots, and even if a single receiver has a low number of slots suitable for reception P^{K}_{succ} will be very low. We can conclude that on-demand reservation of slots for network coding transmissions cannot be achieved with high success, which means that unlike COPE we need to set up the reservation for the multicast network coding transmission before we know that we have a set of packets which can be coded.

Another important aspect of the IEEE 802.16 MeSH mode is the way the reservations are carried out. Nodes use the three-way handshake shown in Fig. 1 (a) to reserve bandwidth for links to individual neighbours. Nodes use MSH-DSCH messages containing requests, grants, and grant-confirmations to reserve a set of slots for the required transmission. In the above analysis we have computed the value for P^{K}_{succ} considering the entire range of available slots at the transmitter and all the receivers. However, due to message size restrictions, with the bandwidth request in a MSH-DSCH message, the transmitter can only advertise a subset of the slots suitable for transmission to the receivers. This effectively reduces the value of P^{K}_{succ} by reducing the number of slots available at the transmitter for negotiating the reservation. However, a more important problem with multicast reservation is that each node maintains its own independent state for all the minislots, and the individual receivers for the multicast transmission do not have any idea about what slots are suitable at the other receivers and, hence, may issue grants for different slot ranges. Such disjoint grants mean that multiple transmissions are needed (one to each neighbouring node in the worst case), thereby defeating the very goal that the coded transmissions should be simultaneously received by multiple neighbours.

A further aspect to be considered by network coding solutions designed for the MeSH mode is the three-way handshake overhead. Each node may transmit the control messages (MSH-DSCH) for the three-way handshake only in slots in the control-subframe, which have been won by the node using the mesh election algorithm specified by the standard. Ref. [3] provides an analytical model for mesh election and analyzes the three-way handshake delay. Let the mean three-way handshake duration between transmitter t and receiver k be H^{t}_{k}. The standard's scheduling constraints require that slots granted by the receiver may be used for transmission only after the three-way handshake is complete. Which means that is is only meaningful to grant slots in frames occurring after the completion of the three-way handshake. For a multicast handshake as required for network coding it implies that the nodes should start searching for the required d slots in frames after a duration $T^{K}_{H} = \max_{k}(H^{t}_{k})$. Let P_i be the probability of successfully being able to reserve the required slots in frame i for the intended communication (i.e. given set of transmitter, receivers, and d required slots and N total slots in the frame). The mean number of frames that need to be considered starting from a given start frame to reach the first frame in which the demand can be satisfied is given by Eq. (2).

$$F_{mean} = \sum_{n=1}^{\infty} n\, P_{(sf+n)} \prod_{j=1}^{n-1} \left(1 - P_{(sf+j)}\right) \qquad (2)$$

Where, sf is the number of the frame after completion of the multicast handshake. Hence, if the duration of a frame is F_D, the mean waiting time before the reserved frame for the multicast transmission starting from the start of the multicast bandwidth reservation handshake is given by Eq. (3).

$$T_{mean} = T_H^K + F_{mean}\, F_D \tag{3}$$

From the above analytical model we can obtain the following design criteria for network coding solutions for the IEEE MeSH mode:

- *Principle 1*: On demand reservation of multicast slots, i.e. reserving slots after we have a set of packets for coding, is not feasible without high overhead, hence reservation of multicast slots should ideally be done a priori.
- *Principle 2*: The higher the number of neighbours in the multicast reception set, the more difficult it is to get an agreement on a common set of slots for reception, especially in presence of background traffic and different number of available slots at the involved parties. The success probability of getting such a reservation in a given frame further diminishes with an increase in the demanded slots. Hence, the size of the receiver set should be kept as small as possible.
- *Principle 3*: The three-way handshake delay combined with the overhead of reserving the required multicast slots mean that the number of such three-way handshakes required should be kept to a minimum. If possible, the handshake should optimize the probability of getting a successful multicast reservation.

IV. ENABLING WNC FOR THE IEEE 802.16 MESH

This section presents our solution to enable practical deployment of network coding in the IEEE 802.16 MeSH protocol stack. The presented solution is based on the design principles derived in Sec. III. For the purpose of the current discussion we restrict the size of the set of receivers for each multicast transmission to two (*Principle* 2). I.e. a node reserves bandwidth for simultaneous transmission of coded packets to at most two of its neighbours. Further, as seen in Sec. II, our solution only uses persistent reservations for the multicast network coding transmissions. This means that a node reserves a common set of slots for an infinite number of frames for transmission to two neighbours who are to receive the coded packets. The reservation remains valid till the reserving node explicitly cancels the reservation. This design choice of using only persistent reservations has as a background *Principle 3* and reduces the number of three-way handshakes for multicast bandwidth reservation. Next our design needs to address *Principle 1.* To enable a priori reservation of bandwidth for network coding we need to be able to associate a figure of merit with the use of network coding at a given node. We next present an analytical model, which enables the quantification of the bandwidth savings obtained in WMNs as those using the MeSH mode with TDMA used for scheduling transmissions.

Definition 1: *Degree of freedom of a slot*: We define the degree of freedom or scheduling freedom of a slot as the number of types of activities which may be scheduled in a particular slot given its current status. The degree of freedom of a slot is given by the function $\lambda(s)$ where s is the slot status. We define $\lambda(s)$ as follows:

$$\lambda(s) = \begin{cases} 2 & \text{iff s} \in \{av\} \\ 1 & \text{iff s} \in \{tav,\ rav\} \\ 0 & \text{iff s} \in \{uav\} \end{cases} \tag{4}$$

The values for $\lambda(s)$ reflect the scheduling possibilities a node has in a given slot. E.g. in slots with status *av* the node can either schedule a transmission or reception of data, i.e. it has two possibilities, hence, $\lambda(av)$=2. From the above we can define similarly the degree of freedom of the WMN for a given range of frames as the summation of $\lambda(s)$ for all *s* at all the nodes in the network. The total degree of freedom reflects the capability to set up additional transmissions in the WMN.

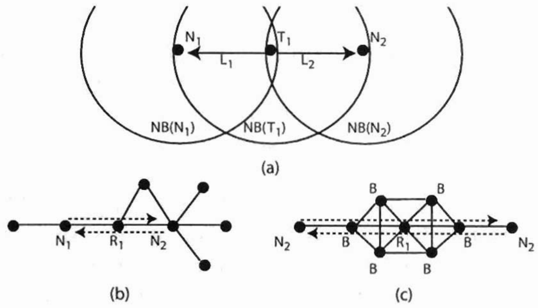


Fig. 3. Distributed scheduling concept and network topologies used for the simulation study

We use the above measure as an aid to decide when to deploy network coding in the network. Consider Fig. 3 (a). We have three nodes (N_1, N_2, T_1) and two links (L_1, L_2) on which we focus in the network. The circles depict the reception ranges for transmissions by nodes at the centre of the circle. $NB(X)$ represents the set of neighbouring nodes of node X. We can now define the cost of a transmission on a link L by $\mu(L, n)$ as the loss in degree of freedom of the network for the range of frames for which the *n* slots are reserved for transmissions on link *L*. E.g. assume that *n* slots are reserved for transmission on link L_1 in Fig. 3 (a), and also assume that all the nodes have the slots with status *av* before the transmission is scheduled. Then the cost of the transmission: $\mu(L_1,n)$= n ($|NB(N_1)|$+ $|NB(T_1)|$) (as a change to status *rav*, or *tav* from *av* corresponds to a cost of 1 degree of freedom per slot per node, and a change to status *uav* corresponds to a cost of 2 degrees of freedom per slot per node). Similarly $\mu(L_2,n)$= n ($|NB(N_2)|$+ $|NB(T_1)|$). Thus the total costs for the two transmissions gives $C_{forwarding}$ = $\mu(L_1, n)$ + $\mu(L_2, n)$ (where, for simplifying the computations, the cost of a set of transmissions is defined as the sum of the cost of the individual transmissions). Let us now look at replacing the above two transmissions via a multicast transmission on links L_1 and L_2 simultaneously using network coding. Assume that to code data in both directions transmitted within *n* slots; due to the additional coding overhead $n + \epsilon$ slots are needed to be reserved for the multicast transmission. This the cost for the multicast coded transmission: C_{coding}= $\mu(L_1, L_2, n+\epsilon)$= $(n+\epsilon)$ ($|NB(N_1)|$+$|NB(N_2)|$+ $|NB(T_1)|$-$|NB(N_1) \cap NB(N_2)|$). Now, the gain in the scheduling degrees of freedom in the WMN = $C_{forwarding}$-C_{coding}.

The nodes in the 802.16 WMN can choose to deploy network coding and persistently reserve multicast bandwidth only if the gain obtained is positive. What now remains is the choice for *n*, i.e. how many slots should be reserved. For this purpose we use the running average of the required bandwidth (in slots per frame) for the data cross flows (e.g. in Fig. 3 (a) the cross flows at node T_1 are the packets from N_1 to be forwarded to N_2 and vice versa).

We now consider the policies for reserving slots for network coding with the help of the above example. We again refer to Fig. 3 for our example. Once the cross-flows N_1 to be forwarded to N_2 and vice versa are detected and are stable at node T_1, the node can compute the gain obtained for deploying network coding for the flows in question and replacing the two transmissions on links L_1 and L_2 with a single multicast transmission. Here, let $s(L_1)$ and $s(L_2)$ denote the sets of *n* slots reserved for the unicast transmissions on links L_1 and L_2 respectively. Node T_1 may now, as usual select a set of suitable slots still free and use these to reserve $n + \epsilon$ slots for the multicast coded transmission to nodes N_1 and N_2. However, with increasing traffic (either the cross flows, or other unrelated background traffic) the number of slots additionally available reduces and this implies that the probability of successfully reserving multicast bandwidth decreases as shown in Sec. III. To avoid this we introduce the novel slot allocation strategy termed as *replacement strategy* here. The core idea is to consider the reuse of the slots already reserved for transmission to the nodes N_1 and N_2 in addition to the additionally available slots at the transmitter to negotiate and reserve a common set of slots for transmission to neighbours N_1 and N_2. To enable this in addition to the available slots at the transmitter, the sets $s(L_1)$ and $s(L_2)$ are also sent with the request for multicast bandwidth by node T_1. Nodes N_1 and N_2 may then use these slot ranges for the grant if reception is allowed by the current network schedule in these slots. The additional range of slots available for the grants increases the probability of successful reservation of the multicast bandwidth. Here, we see that N_1 is guaranteed to be able to receive in slots $s(L_1)$ and N_2 is guaranteed to be able to receive in slots $s(L_2)$. Thus, in the best case the multicast handshake is now reduced to the case of a unicast handshake thereby further increasing the probability of successful reservation (***Principles** 2,3*). Readers interested in the exact implementation details and extensions to the MeSH mode (the control messages and extensions to the three-way handshake) can find them in [5].

V. PERFORMANCE EVALUATION

We implemented the proposed network coding extensions into an extended version of the JiST/SWANS [6] simulator comprising an implementation of the MeSH mode. In this section we present a proof-of-concept for the proposed network coding solutions and evaluate selected aspects of our proposed solutions. Consider the network topology shown in Fig. 3 (b). We set up data cross flows as shown by the arrows in the figure between the nodes N_1 and N_2, with data flows generating 100 packets per second with each packet of size 600 bytes. Network coding is deployed at node R_1. The goal here is to measure the gain which is obtained using network coding. To avoid influence of background traffic in this experiment there is no other data traffic other than the two flows mentioned above. To compare the results with standard forwarding (i.e. no network coding) we repeat the above experiment with network coding disabled. Fig. 4 shows the simulation results obtained for a frame for the system operating in the steady state, i.e. for the case of network coding being enabled, a frame after which the bandwidth for network coding has been reserved. For the selected network parameters the traffic demand was equal to seven slots per flow where the total number of slots in the frame was 98. On the right side we can see the difference in the scheduling degrees of freedom available in the WMN with and without network coding being enabled. This difference is seen as the gain via deployment of network coding in the network. We see that even for a small and not so dense network deploying network coding increases the scheduling degrees of freedom allowing the WMN to schedule additional traffic in the slots freed. We also analyze the distribution of the slot states in the network in operation at the steady state with and without network coding.

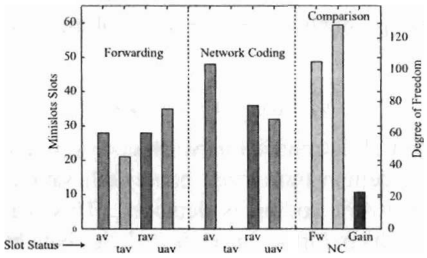


Fig. 4. Comparative analysis of network coding vs. standard forwarding

One can see that using network coding increases significantly the number of slots with status *av* which permits the maximum degree of freedom for a large number of slots, which in turn increases the WMN's possibilities for scheduling additional traffic.

We next evaluate and compare the two bandwidth reservation/allocation schemes outlined by us in Sec. IV for multicast transmissions. For this experiment we use the network topology in Fig. 3 (c). We set up two cross flows as shown by the arrows in the figure each flow generating 100 packets per second with packet size 600 bytes. Between the nodes labelled *B* in Fig. 3 (c) and between node R_1 and nodes *B* we set up random traffic flows. We repeat the experiment for increasing number of background flows and traffic. The goal of the random traffic is to influence the availability of slots in the neighbourhood of node R_1 which has network coding deployed. Fig. 5 shows the variance in the number of slots available for usage by the two schemes, namely the strategy of allocating only additional free slots for scheduling the multicast transmission (new allocation strategy) or the policy of additionally allowing the conversion of unicast reservations into multicast reservations (replacement strategy).

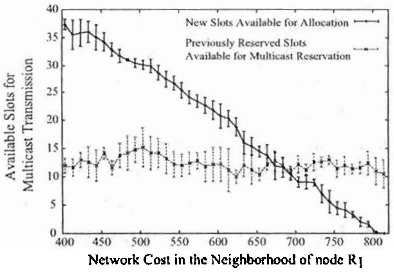


Fig. 5. Comparative analysis of bandwidth reservation/allocation policies

From Fig. 5 we see that the total number of slots additionally available for scheduling the multicast transmissions decreases with an increase in the background traffic. The x-axis represents the magnitude of the background traffic as measured by the sum of the individual background transmissions as discussed in Sec. IV. We see that the slots already reserved by node R_1 for unicast transmission to its neighbours are always available for the replacement strategy and are further guaranteed to be available at at least one of the neighbours to which the slots are reserved. Thus, it is seen that in highly congested WMNs the replacement strategy permits the negotiation and reservation of multicast bandwidth with a higher success probability than the usage of the new-allocation strategy.

VI. RELATED WORK

Ahlswede et al. introduced network coding in their seminal work [7] and demonstrated that bandwidth savings are possible when network coding is deployed. This was followed by literature which further investigated the benefits that can theoretically be obtained via application of network coding (e.g. [8], [9]). The work [1] is one of the first which considers the deployment of network coding in a realistic setting. The authors in [1] present their architecture COPE, which uses opportunistic network coding to code multiple packets from different sources together before forwarding. The authors show that gains obtainable via opportunistic network coding can overhaul the gains in the absence of opportunistic listening. They deployed their architecture in a mesh network which uses the IEEE 802.11a MAC layer. In a MAC based on IEEE 802.11 [10] an RTS (request to send)/CTS (clear to send) scheme is specified to enable access to the medium for unicast data transmissions. The RTS/CTS scheme ensures that when a node transmits unicast data, all nodes in the direct neighbourhood of both the sender as well as receiver do not transmit any data simultaneously. Thus, this means that when a node transmits any data/ack all of its neighbours are silent themselves and will be able to receive the unicast data/ack transmission as long as none of their neighbours transmits simultaneously. This provides a conducive environment for opportunistic listening. However, as shown in Sec. II, (see Fig. 1), the neighbours of the node transmitting data in a slot may schedule simultaneous transmissions making opportunistic listening difficult if not impossible. Further, the 802.16 standard introduces a security and privacy sublayer in the MAC layer which encrypts data on a per link basis before transmission making opportunistic listening impossible. Another key aspect of the 802.16 MAC is the need for a priori reservation of minislots before transmission of data can take place, the implications of which have been presented in Sec. III. The key question which the work in [1] addresses is, which of the pending outgoing packets should be combined together before transmission, using information obtained via opportunistic listening as well as heuristics based on usage and availability of the ETX metric [11]. In contrast, we for our work do not rely on the availability of any particular routing metric or routing algorithm. The key questions which we address in this paper are when does network coding start to help in terms of throughput/bandwidth savings and how to manage dynamically the multicast reservations for network coding without leading to conflict with other existing data transmission schedules. To the best of our knowledge this is the first paper which addresses the issue of network coding in 802.16 based mesh networks.

VII. CONCLUSIONS AND FUTURE WORK

We presented an analytical model for the distributed bandwidth reservation process of the IEEE 802.16 MeSH mode. The analysis was used to derive design principles for implementing and deploying efficient network coding solutions for the MeSH mode. We designed solutions for deploying network coding in the MeSH mode using the derived design principles as a roadmap. Finally, we implemented the proposed solutions and presented the proof-of-concept via a simulation study. Our next steps will involve looking into the performance of the proposed network coding solutions in various operating modes of the MeSH mode. Further research is also needed into other optimizations to efficiently deploy network coding solutions in sophisticated MAC layers such as the MeSH mode.

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REFERENCES

[1] S. Katti et al., "XORs in the Air: Practical Wireless Network Coding," *ACM SIGCOMM CCR*, vol. 36, no. 4, pp. 243–254, October 2006.
[2] IEEE, "IEEE 802.16 Standard," IEEE Std. 802.16-2004, October 2004.
[3] M. Cao et al., "Modelling and performance analysis of the distributed scheduler in IEEE 802.16 mesh mode," in *MobiHoc '05*, 2005, pp. 78–89.
[4] P. S. Mogre et al., "The IEEE 802.16-2004 MeSH Mode Explained, KOM-TR-2006-08," KOM, TU Darmstadt, Germany, ftp.kom.tu-darmstadt.de/pub/TR/KOM-TR-2006-08.pdf, Tech. Rep., 2006.
[5] M. Kropff, "Network Coding for Bandwidth Management in IEEE 802.16 Mesh Networks," Master's thesis, TU Darmstadt.
[6] R. Barr, "JiST/SWANS," http://jist.ece.cornell.edu/docs.html, 2004.
[7] R. Ahlswede et al., "Network Information Flow," *IEEE Transactions on Information Theory*, vol. 46, no. 4, pp. 1204–1216, July 2000.
[8] S. R. Li et al., "Linear Network Coding," *IEEE Transactions on Information Theory*, vol. 49, no. 2, pp. 371–381, February 2003.
[9] Y. E. Sagduyu and A. Ephremides, "Joint Scheduling and Wireless Network Coding," in *NetCod 2005*, 2005.
[10] IEEE, "IEEE 802.11 Standard," IEEE Std. 802.11, January 1999.
[11] D. De Couto et al., "High-Throughput Path Metric for Multi-Hop Wireless Routing," in *MobiCom 2003*, September 2003.