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WiMAX Mesh Architectures and Network Coding

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8.1 Introduction

The seminal work of Ahlswede *et al.* (2000) introduced the notion of Network Coding (NC) as a means to achieve bandwidth savings for multicast data transmissions. The authors demonstrated that suboptimal results in terms of required bandwidth are achieved in general, if the information to be multicast is considered as a fluid which is to be routed or replicated on a set of outgoing links at each node relaying the information in the network, that is, the transportation network capacity is not equal to the information network capacity. The concept of network coding was later also extended to unicast information transmission. Recently, the application of network coding in wireless networks (Wireless Network Coding (WNC)) is being investigated intensively. In particular, the deployment of WNC in Wireless Mesh Networks (WMNs) to achieve bandwidth savings and throughput gain is very promising. We demonstrate this functionality with the help of Figure 8.1. In a WMN, nodes typically send data to destinations via multi-hop routes. Here, a number of nodes relay the data packets between the source and destination. Readers can find more background information about WMNs and a survey of respective research challenges in Akyildiz *et al.* (2005).

Consider a simple linear WMN topology as shown in Figure 8.1. Assume that nodes N_1 and node N_2 transmit data to each other, which is relayed by the node R_1. Figure 8.1(a) shows the behavior in WMNs without application of WNC. Here, N_1 transmits data to the next hop R_1 in slot (or transmission number) 1. The data received is relayed by R_1 in slot 2 to node N_2. Similarly, data transmitted by N_2 addressed to node N_1 is transmitted and relayed in slots 3 and 4, respectively. Figure 8.1(b) shows how the same data can be transferred to the

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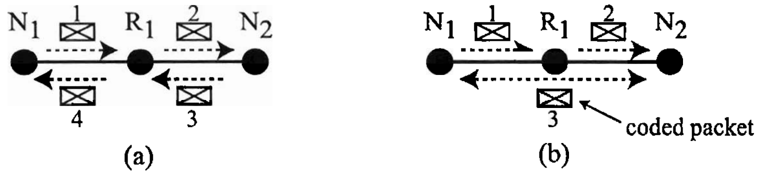

Figure 8.1 Sample topology showing a simple WNC constellation: (a) transmission schedule using traditional packet forwarding; (b) transmission schedule using network coding.

destinations using a simple form of network coding. The node R_1 receives the packets to be relayed in slots 1 and 2. The node R_1 can then code the received packets together using the XOR function and transmit this XOR-coded packet in slot number 3. If the nodes N_1 and N_2 preserve local copies of the packets they transmitted, they can XOR the received coded packet with the packet they transmitted before to recover the data addressed to them. Comparing Figures 8.1(a) and (b) we see that in this simple setup one transmission opportunity or slot for data transmissions can be saved using network coding. This illustrating example clearly shows that WNC is a promising way to improve the throughput of wireless networks.

The work of Katti *et al.* (2006) was one of the first to depart from mainly theoretical investigations and to deploy WNC in real networks using standard off-the-shelf protocol stacks. This has been followed by other work also looking at practical deployments of WNC. However, the majority of research investigating WNC (both practical deployments as well as theoretical investigations) assumes the use of generic IEEE 802.11 or similar Medium Access Control (MAC) layers. Recent standardization developments show a trend towards highly sophisticated mechanisms at the MAC layer for supporting stringent Quality of Service (QoS) requirements of multimedia and real-time traffic expected in future WMNs; the IEEE 802.16 standard (see IEEE (2004)) and the upcoming IEEE 802.11s standard being examples.

In this chapter we choose to study the IEEE 802.16 standard as a prototype for MAC layers providing radically different medium access mechanisms when compared with the generic IEEE 802.11 MAC. The fundamental difference between the contemporary IEEE 802.11 and the IEEE 802.16 standard arises due to the reservation-based medium access supported by the latter. In this work we investigate network coding within the context of WMNs built using the IEEE 802.16 MeSH mode (also referred to as MeSH throughout this document). We analyze the issues involved in deploying COPE-like (see Katti *et al.* (2006)) basic network coding solutions in WMNs using the IEEE 802.16 MeSH mode. The fundamentally different medium access mechanisms of the IEEE 802.16 and 802.11 standards make the direct adoption of network coding solutions designed and developed within the scope of 802.11 inefficient, if not impossible. In this work, we first analytically model the bandwidth reservation mechanism in the IEEE 802.16 MeSH mode, thus motivating the need for investigating deployment issues for network coding from a novel perspective. We break away from the myopic IEEE 802.11-only view of many WMNs. We instead present extensions to the current IEEE 802.16 MeSH mode specifications to enable efficient support for practically deploying network coding in IEEE 802.16-based WMNs. Finally, we present simple yet meaningful metrics for quantifying the gain obtained by deploying network coding in the latter WMNs.

This book chapter is structured as follows. In Section 8.2 we introduce the reservation schemes supported by the IEEE 802.16 MeSH mode and provide some background information on the MeSH mode. In Section 8.3 we present an analytical model for the MeSH mode's bandwidth reservation scheme and derive design principles for WNC deployment. In Section 8.4 we present extensions to the MeSH mode specifications which enable efficient deployment of WNC. Section 8.5 discusses relevant related work, and Section 8.6 draws conclusions for the work presented in this chapter and also gives pointers for further research in this context.

8.2 Background on the IEEE 802.16 MeSH Mode

The IEEE 802.16 MeSH mode (see IEEE (2004)) specifies the MAC and the Physical (PHY) layers to enable the deployment of WMNs. In particular, it specifies the framework for medium access and bandwidth reservation. The algorithms for bandwidth reservation are, however, not defined and left open for optimization by individual vendors. The MeSH mode uses Time Division Multiple Access/Time Division Duplex (TDMA/TDD) to arbitrate access to the wireless medium, where the time axis is divided into frames. Each frame is composed of both a control subframe and a data subframe. The data subframe is further divided into minislots (or slots) carrying a data payload, while MAC layer messages meant for network setup and bandwidth reservation are transmitted in the control subframe. Contention-free access to the wireless medium in the control subframe can be both centrally regulated by a Mesh Base Station (MBS), which may also provide access to external networks such as the Internet or provider networks, or managed by the individual Subscriber Stations (SSs) in a distributed fashion. In the latter case, the SSs manage the access to the medium directly among each other using the distributed mesh election algorithm specified by the standard (see IEEE (2004), Mogre *et al.* (2006) and Cao *et al.* (2005)).

Reservation of bandwidth for transmission of data messages in the data subframe can be both centrally managed by the MBS, that is, centralized scheduling, or a contention-free transmission schedule can be negotiated by the nodes individually without involving the MBS, that is, distributed scheduling. Centralized scheduling is limited to scheduling transmissions on a scheduling tree specified and rooted at the MBS. Distributed scheduling is more flexible and can be used to schedule transmissions on all of the links, including those in the scheduling tree in the WMN. Using distributed scheduling, a SS negotiates its transmission schedule via a three-way handshake with the neighboring node to receive the transmission (see Figure 8.2(a)). Given the limitations of centralized scheduling, without loss of generality, we assume that only distributed scheduling is used for the rest of this chapter.

Nodes in the mesh network use a three-way handshake to request and reserve a range of minislots for a contiguous range of frames (e.g. reservation *Resv*(*e*, 2–3,102–105) is used to denote that minislots numbered 2 to 3 are reserved for transmission on link with identifier *e* for the frames numbered 102 and 105). The number of minislots reserved is termed the demand level, denoted as $\Delta(MS)$, and the number of frames for which the reservation is valid as demand persistence, denoted as $Per_{\Delta F}$, where ΔF is the number of frames for which the reservation is valid. Where as per the standard's specification $\Delta F \in \{1, 2, 4, 8, 32, 128, \infty\}$. We may thus have reservations with demand levels 1 ... maximum number of minislots; and with demand $Per_1, Per_2, Per_4, \ldots, Per_\infty$. Only slots reserved with persistence Per_∞

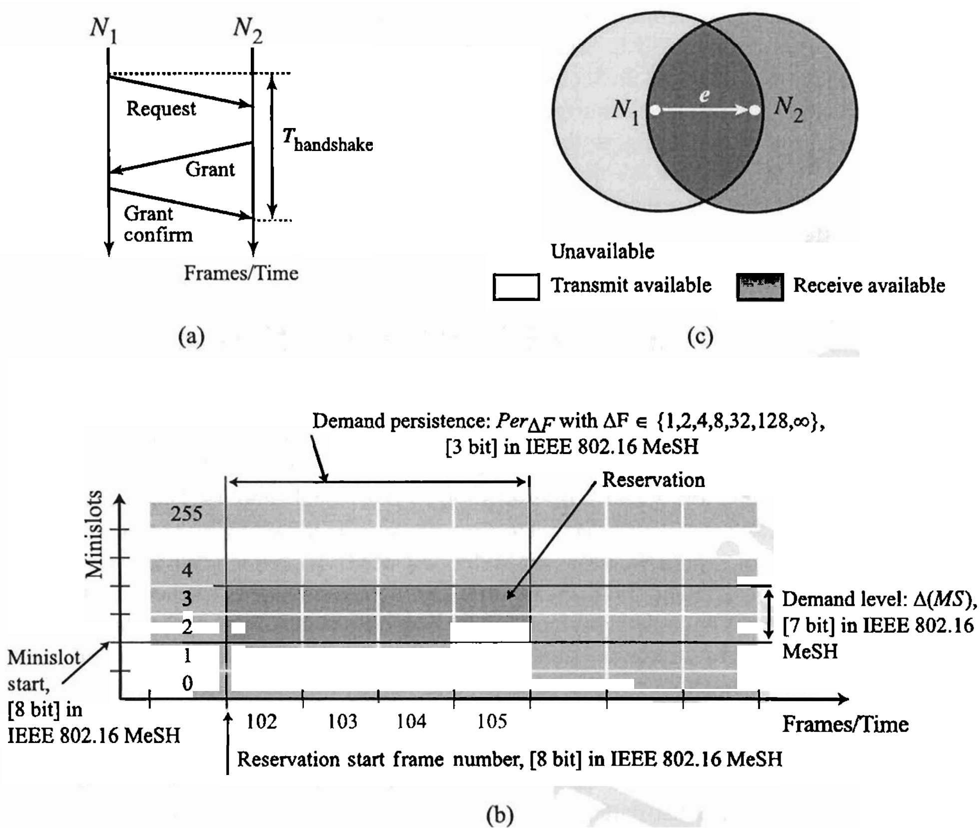

Figure 8.2 Basic elements of distributed scheduling: (a) three-way protocol handshake; (b) scope of validity of a minislot reservation using distributed scheduling; (c) minislot status for a transmission from N_1 to N_2.

can be freed when no longer required via a cancel three-way handshake. The latter special case of reservation of slots with persistence Per_{∞} is what we call a persistent reservation. Figure 8.2(b) illustrates minislots reserved using distributed scheduling. To compute conflict-free schedules, each node needs to maintain the states of all minislots in each frame.

Depending on the activities which may additionally be scheduled in a slot, the slot has one of the following states: *available* (*av*: transmission or reception of data may be scheduled), *transmit available* (*tav*: only transmission of data may be scheduled), *receive available* (*rav*: only reception of data may be scheduled), *unavailable* (*uav*: neither transmission or reception of data may be scheduled). Consider edge $e = (N_1, N_2) \in E$ in Figure 8.2(c), with E representing the set of edges in the WMN. Figure 8.2(c) shows how nodes in the network will update their slot states when a transmission is scheduled on edge e, provided that all of the nodes were in state *av* at the beginning of the handshake. Neighbors of the receiver (N_2) overhear the grant and update the state for the granted slots to reflect that they may not transmit in the granted slots. Neighbors of the transmitter (N_1) overhear the grant confirm message and update their local slot states to reflect that they cannot receive any other transmission without interference in the confirmed slots. This handshake process is similar to the Request to Send (RTS)/Clear to Send (CTS) mechanism used by 802.11-based nodes. A transmission may be scheduled on an edge $e = (N_1, N_2)$ in a given slot m and frame f if and only if $s_m^f(N_1) \in \{av, tav\}$ and $s_m^f(N_2) \in \{av, rav\}$, where $s_m^f(N)$ denotes the state of slot m in frame f at node N. Additional details about the MeSH mode and the data structures and control messages used can be found in IEEE (2004). To make the material more accessible to readers unfamiliar with the MeSH mode, we provide a detailed overview of the MeSH mode specification in Mogre *et al.* (2006).

8.3 Design Principles for Network Coding in the IEEE 802.16 MeSH Mode

Having outlined the function of the MeSH mode's distributed scheduling in the previous section, we now discuss the pitfalls in implementing COPE-like (see Katti *et al.* (2006)) practical network coding solutions in 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 especially important 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 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.

We next formulate our model. Consider the parameters outlined in Table 8.1. Assume that the parameters hold for a given frame. Let K be the number of neighbors (identified individually by their index k) which should receive the coded packet. This subset of neighbors is selected by looking at the next hops of the packets available for coding similar to COPE. As we cannot transmit data to neighbors without reserving bandwidth for the transmission, we first need to reserve sufficient bandwidth for the multicast transmission[1]. Let us assume that we use enhanced handshake procedures to allow us to reserve multicast bandwidth, and let us consider that we need to reserve d slots for the transmission in a given frame having the parameters as shown in Table 8.1. Now let S_T and S_k denote the set of 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

$$P_{\text{succ}}^K = \frac{C_T \prod_k \sum_{j=d}^{\min(T,R_k)} \binom{T}{j}\binom{N-T}{R_k-j}}{C_T(\prod_k C_{R_k})} \tag{8.1}$$

[1]Here, we face a severe pitfall: the IEEE 802.16 MeSH mode does not natively support mechanisms to reserve multicast bandwidth. See Section 8.4 for our solution to introduce multicast reservations in the MeSH mode of IEEE 802.16.

Table 8.1 Parameters for modeling the bandwidth reservation mechanism of the IEEE 802.16 MeSH mode.

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

Figure 8.3 shows plots of the success probability (P^K_{succ}) given by Equation (8.1) for a handshake with $K = 1$ neighbors for a demand (slots to be reserved) of 1, 5, 10 and 20 slots, respectively. The total number of slots per frame is 100. The x-axis shows the number of slots suitable for transmission on the transmitter side. The y-axis shows the number of slots suitable for reception at the receiver(s). The plot shows the case where all of the receiving neighbors are assumed to have the same number of slots available for reception. Comparing Figures 8.3(a) and (b), (c) and (d), we note that a higher number of slots need to be available for transmission at the sender, and a higher number of slots need to be available at the receiver(s) with an increase in the number of slots to be reserved, to successfully reserve the required slots in a given frame with a high probability. In short, the probability of successfully reserving d common slots for transmission to a fixed number of receivers in a given frame decreases with increasing d, given that the number of receivers, the number of available slots at the transmitter and the receiver(s) remain unchanged.

Figure 8.4 shows contour plots for P^K_{succ} showing the minimum number of slots suitable at the transmitter and the receivers beyond which P^K_{succ} exceeds the values shown in the graph for reserving d minislots in a given frame. Comparing Figures 8.4(a) and (b) or Figures 8.4(c) and (d) we see that for the same demand d, the number of suitable slots needed at the transmitter and receiver(s) for successfully reserving (with a certain probability of success) the required number of slots increases with the number of receivers (K) involved in the handshake. Analysis of the figures and Equation (8.1) reveals that P^K_{succ} decreases drastically as soon as the transmitter or one of the 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 needs 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 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; a single receiver having a low number of slots suitable for reception results in P^K_{succ} to 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 prior to the arrival of a set of packets which can be coded.

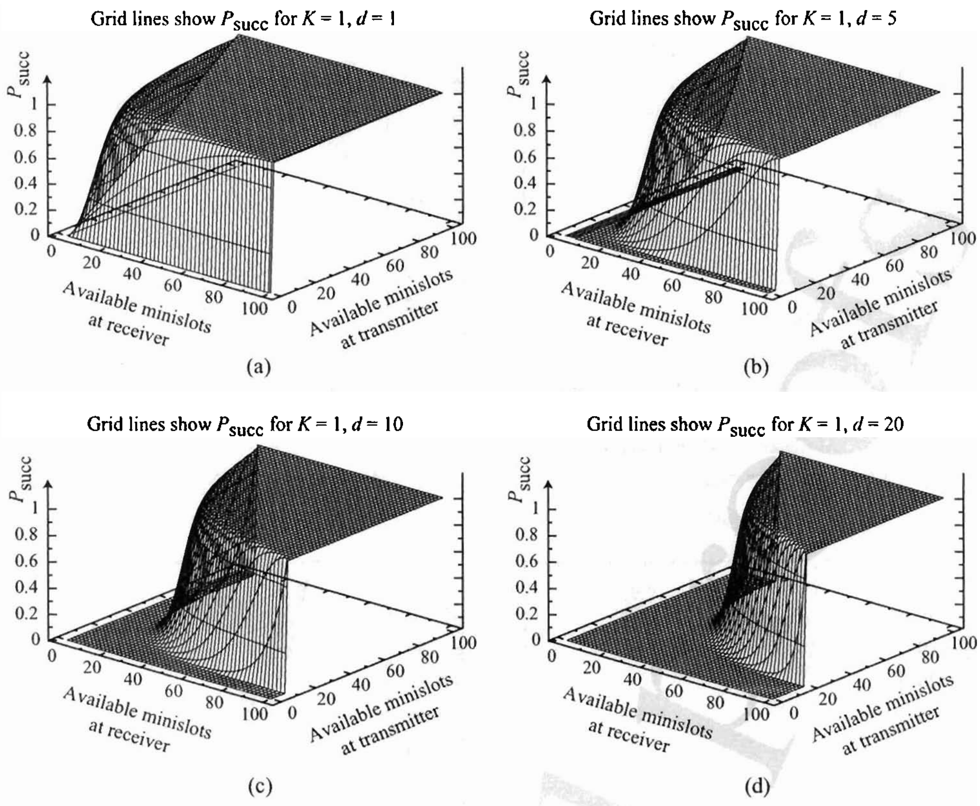

Figure 8.3 Plots showing the probability P^K_{succ} of successfully reserving d slots in a given frame for simultaneous reception at K neighboring nodes: (a) $K = 1, d = 1$; (b) $K = 1, d = 5$; (c) $K = 1, d = 10$; (d) $K = 1, d = 20$.

An important aspect of the IEEE 802.16 MeSH mode is the way the reservations are carried out. Nodes perform the three-way handshake shown in Figure 8.2(a) to reserve bandwidth for links to individual neighbors; distributed scheduling messages (`MSH-DSCH`) containing `Request`, `Grant` and `Grant-confirmation` are exchanged 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 of 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 of the minislots. Thus, the individual receivers for the multicast transmission do not possess a common view about which slots are suitable at the other receiver(s) and may, hence, issue grants for different slot ranges. Such disjoint grants require multiple transmissions

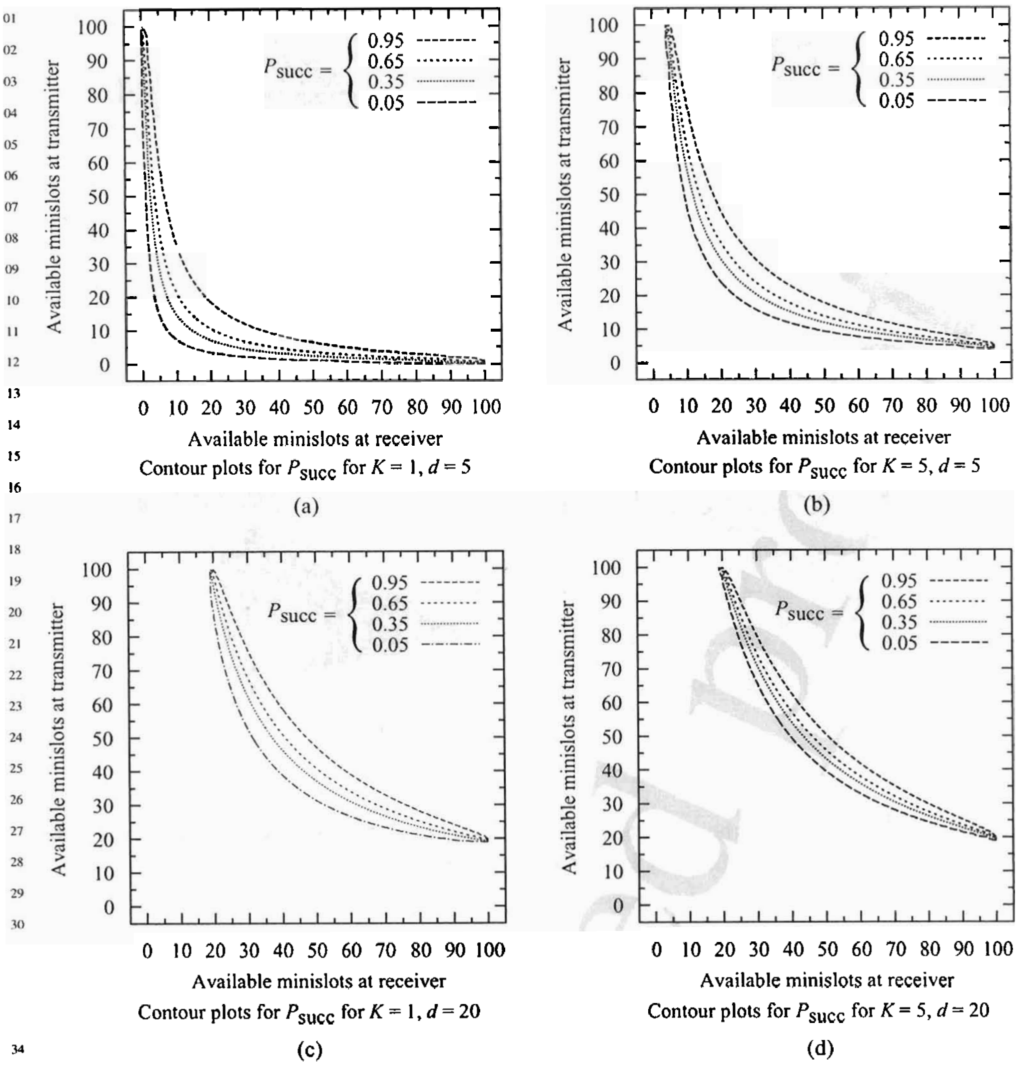

Figure 8.4 Contour plots showing the probability of successfully reserving d slots in a given frame for simultaneous reception at K neighboring nodes: (a) $K = 1, d = 5$; (b) $K = 5, d = 5$; (c) $K = 1, d = 20$; (d) $K = 5, d = 20$.

(one to each neighboring node in the worst case), thereby defeating the goal that coded transmissions should be simultaneously received by multiple neighbors.

Another critical aspect that needs to be considered by network coding solutions designed for 802.16's MeSH mode is the three-way handshake overhead. Each node may transmit the control messages (MSH-DSCH) for the three-way handshake only in transmission opportunities belonging to the control subframe, which have been won by the node using the mesh election algorithm specified by the standard. Cao *et al.* (2005) provide an analytical model for mesh election and analyze the three-way handshake delay. Let the mean three-way handshake duration between transmitter t and receiver k be H_k^t. 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. Hence, it 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 $T_H^K = \max_k (H_k^t)$. 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 a 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

$$F_{\text{mean}} = \sum n = 1^{\infty} n \, P_{(sf+n)} \prod_{j=1}^{n-1} (1 - P_{(sf+j)}). \tag{8.2}$$

Here, 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

$$T_{\text{mean}} = T_H^K + F_{\text{mean}} F_D. \tag{8.3}$$

From the above analytical model we can obtain the following design criteria for network coding solutions for the MeSH mode of IEEE 802.16.

- *Principle 1.* On-demand reservation of multicast slots for WNC, that is, reserving slots after a set of packets for coding is present, is not feasible without prohibitive overhead; hence, reservation of multicast slots should ideally be performed *a priori*.

- *Principle 2.* The higher the number of neighbors in the multicast reception set, the more difficult it is to obtain 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 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 obtaining a successful multicast reservation.

8.4 Enabling WNC for the IEEE 802.16 MeSH Mode

In this section we present our solution to enable practical deployment of network coding in the IEEE 802.16's MeSH protocol stack. The presented solution is based on the design principles derived in Section 8.3. For the purpose of the current discussion, without loss of generality, we restrict the size of the set of receivers for each multicast transmission to two

(*Principle* 2), that is, a node reserves bandwidth for simultaneous transmission of coded packets to at most two of its neighbors. Further, our solution only uses persistent (Per_∞) reservations, that is, the reservation remains valid till the reserving node explicitly cancels the reservation (see Section 8.2), 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 neighbors which shall receive the coded packets. This design choice of using only persistent reservations has *Principle 3* as a background and reduces the number of three-way handshakes for multicast bandwidth reservation. Still a valid design needs to address *Principle 1*. However, to enable *a priori* reservation of bandwidth for network coding, one needs to be able to associate a figure of merit with the use of network coding at a given node. Towards this end, we next present an analytical model, which enables the quantification of the bandwidth savings obtained in TDMA-based WMNs such as IEEE 802.16's MeSH mode.

8.4.1 Modeling the Coding Gain

Definition 8.1 (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:

$$\lambda(s) = \begin{cases} 0 & \text{for } s \in \{uav\}, \\ 1 & \text{for } s \in \{tav, rav\}, \\ 2 & \text{for } s \in \{av\}. \end{cases} \tag{8.4}$$

The values for $\lambda(s)$ reflect the scheduling possibilities a node has in a given slot. In slots with status *av* the node can either schedule a transmission or reception of data, that is, it has two possibilities, hence $\lambda(av) = 2$. It follows that $\lambda(rav) = \lambda(tav) = 1$ (only one degree of freedom left at the node) and $\lambda(uav) = 0$ (node possesses no degree of freedom). From the above we can define the degree of freedom of the entire WMN for a given range of frames as the summation of $\lambda(s)$ for all s at all the nodes in the network. This total degree of freedom reflects the capability to set up additional transmissions in the WMN.

We use the above measure as an aid to decide when to deploy network coding in the network. Consider Figure 8.5; three nodes (N_1, N_2, R_1) and two links (e_1, e_2) form the network to be analyzed. The circles depict the reception ranges for transmissions by nodes at the center of the circle. Here $NB(X)$ represents the set of neighboring 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. For example, assume that n slots are reserved for transmission on link e_1 in Figure 8.5, and also assume that all of the nodes have the slots with status *av* before the transmission is scheduled. Then the cost of the transmission: $\mu(e_1, n) = n(|NB(N_1)| + |NB(R_1)|)$ (as a change to status *rav* or *tav* from *av* corresponds to a cost of one degree of freedom per slot per node, and a change to status *uav* corresponds to a cost of two degrees of freedom per slot per node). Similarly $\mu(e_2, n) = n(|NB(N_2)| + |NB(R_1)|)$. Thus, the total costs for the two transmissions gives $C_{\text{forwarding}} = \mu(e_1, n) + \mu(e_2, n)$, where, to simplify 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

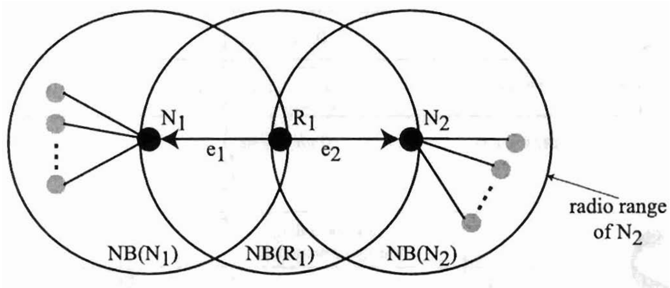

Figure 8.5 Relay constellation for analyzing the network coding gain using the IEEE 802.16 MeSH mode's distributed scheduling.

a multicast transmission on links e_1 and e_2 simultaneously using network coding. Assume that we intend 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. Thus, the cost for the multicast coded transmission is

$$\begin{aligned} C_{\text{coding}} &= \mu(e_1, e_2, n + \epsilon) \\ &= (n + \epsilon)(|NB(N_1)| + |NB(N_2)| + |NB(R_1)| - |NB(N_1) \cap NB(N_2)|). \end{aligned}$$

Now, the gain in the scheduling degrees of freedom in the WMN equals $C_{\text{forwarding}} - C_{\text{coding}}$.

The nodes in the IEEE 802.16 WMN should choose to deploy network coding and persistently reserve multicast bandwidth only if the gain obtained is positive. The appropriate choice of n, that is, how many slots need to be reserved, remains. For this purpose we use the running average of the required bandwidth (in slots per frame) for the data cross flows (e.g. in Figure 8.5 the cross flows at node R_1 are the packets from N_1 to be forwarded to N_2 and vice versa).

8.4.2 Network Coding Framework

Figure 8.6 shows the logical building blocks of the MAC Common Part Sublayer (CPS) we propose for supporting WNC in IEEE 802.16's MeSH mode. The MAC CPS contains the core functionality for MAC within the IEEE 802.16 MeSH mode specifications. Packets arriving at the MAC layer from the network or higher layers are classified by a service-specific packet classifier which is located in the Convergence Sublayer (CS) of the MAC layer. The packet classifier enables classification of packets according to different scheduling services applicable to the packets. Transmissions/receptions at the PHY layer occur either in the control subframes or in the data subframes, as shown in Figure 8.6. The MAC management module is responsible for handling/processing the default protocol management messages of IEEE 802.16's MeSH mode at the MAC layer. Management messages defined for the purpose of supporting WNC in the MeSH mode are processed by the network coding management Module. Regular unicast data transmissions are regulated by the unicast data management module, which transmits queued data for each outgoing link in slots reserved for transmission on the respective links. The network coding data management module is responsible for the multicast transmission of coded data packets using packets from the fragment pool. In addition, the

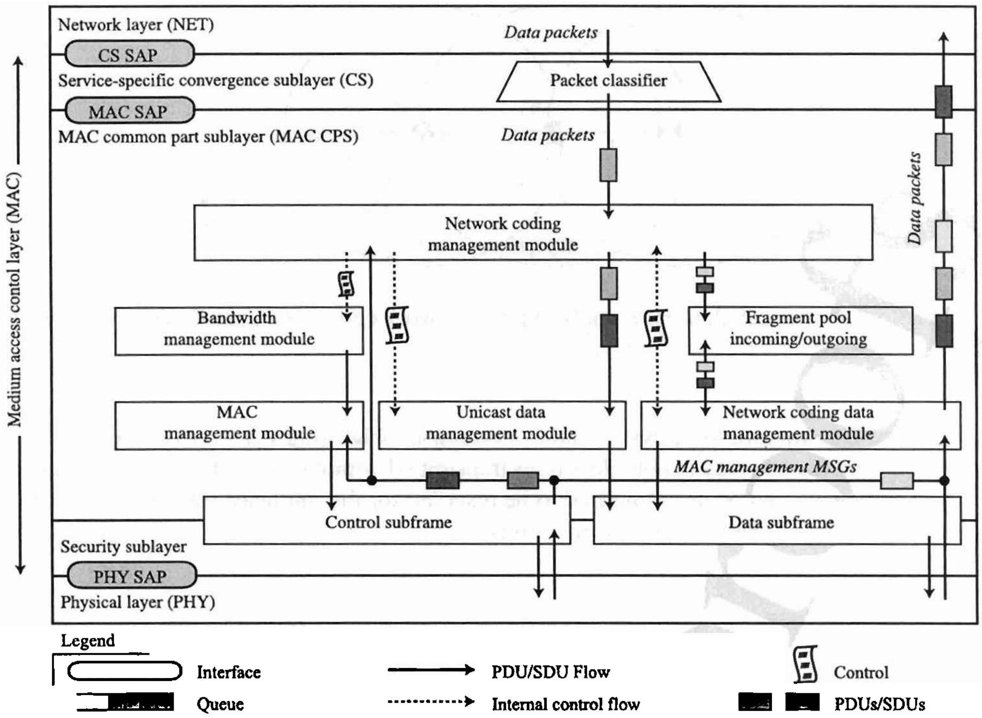

Figure 8.6 Block diagram showing the logical components of our framework extending IEEE 802.16's MeSH mode to support WNC.

network coding data management module is responsible for decoding received coded packets before these can be further processed either at the MAC or higher layers.

8.4.3 Reservation Strategies

The IEEE 802.16 MeSH mode lacks mechanisms to enable reservation of bandwidth for multicast transmissions which is needed for enabling WNC. Hence, we introduce additional management messages for reserving bandwidth for multicast transmissions[2]. Towards this end, we extend the three-way handshake used for reserving bandwidth for a single outgoing link to be able to reserve slots for simultaneous transmission on multiple outgoing links. In particular, we propose two different strategies for reserving slots for the multicast network coding transmissions.

We now consider the policies for reserving slots for network coding, again referring to Figure 8.5 as an example. Once the cross-flows N_1 to be forwarded to N_2 and vice versa are detected and are stable at node R_1, the node can compute the gain obtained for deploying network coding for the flows in question and replace the two transmissions on links e_1

[2]In this context multicast transmission implies packets transmitted by a node on the wireless medium which are intended to be received simultaneously by multiple direct neighbors. This is not to be confused with transmission of multicast data to a set of nodes in the network, where this set may consist of nonneighboring nodes.

and e_2 with a single multicast transmission. Here, let $s(e_1)$ and $s(e_2)$ denote the sets of n slots reserved for the unicast transmissions on links e_1 and e_2, respectively. Node R_1 may now 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 is reduced, implying the decrease of the probability of successfully reserving multicast bandwidth, as shown in Section 8.3. We introduce our novel slot allocation strategy termed the *replacement strategy* to counteract this decrease in slots: 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 neighbors N_1 and N_2. In addition to the available slots at the transmitter, the sets $s(e_1)$ and $s(e_2)$ are therefore also sent with the request for multicast bandwidth by node R_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 $s(e_1)$ and N_2 is guaranteed to be able to receive in slots $s(e_2)$. Thus, in the ideal case, the multicast handshake is now reduced to the case of a unicast handshake, thereby further increasing the probability of successful reservation (*Principles 2 and 3*).

Figure 8.7 illustrates our advanced two-phase handshake mechanism for reserving slots for the network coding transmissions using the same base topology as in Figure 8.5. We refer to Figure 8.7(a), (b), and (c) for the following discussion. Each subfigure shows the network topology augmented by the status of the reservation (illustrated using the particular slot numbers of the reserved slots; one-sided dotted arrows indicate unicast reservations, two-sided dotted arrows indicate multicast reservations). The topology shown in Figure 8.7(a) depicts the reservation state prior to the network coding handshake. Figure 8.7(b) and (c) show the reservation state of the new allocation strategy and the replacement strategy after the handshake, respectively. Unicast slots can correspondingly be freed for the given example after a successful multicast reservation has been established (please note, however, that we do not show the protocol interactions to actually free these slots). The message sequence chart in Figure 8.7(a) shows the initialization of the handshake process, which is common to both handshake variants. Figures 8.7(b) and (c) show the subsequent message sequence of the new allocations strategy and the replacement strategy, respectively.

Let us consider the reservation state as shown by the topology in Figure 8.7(a). Here, node R_1 may deploy network coding for relaying the packets between nodes N_1 and N_2. We employ our two-phase handshake mechanism for reserving slots for coded transmissions: the two phases are the initial handshake shown in Figure 8.7(a) followed by either the handshake to reserve as yet unused slots in Figure 8.7(b) or the handshake to repurpose existing unicast reservations in Figure 8.7(c), depending on our strategy used for reserving slots for network coding. The two-phase network coding handshake should be followed by normal three-way handshakes to free any superfluous slots reserved for unicast transmissions. Here, we should recall that we will only reserve slots for network coding for flows which are stable and, hence, will usually have persistent reservations (Per_∞). Similarly, for the current discussion we assume that slots are reserved for network coding with persistence[3] Per_∞.

[3] It is also possible to reserve slots for NC with persistences less than Per_∞; here the two-phase handshake presented can be optimized and adapted slightly for efficiently reserving non-Per_∞ slots.

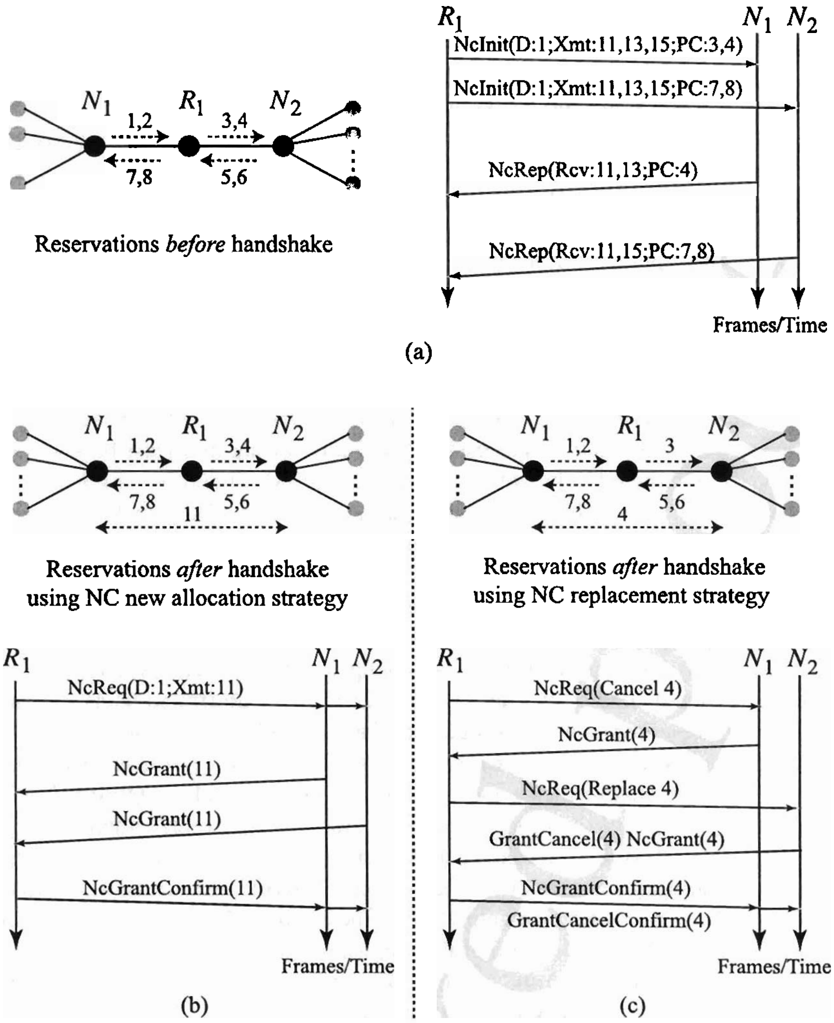

Figure 8.7 Example of our two-phase handshake variants for multicast bandwidth reservations supporting network coding in IEEE 802.16 MeSH mode: (a) NC initialization hand shake; (b) NC new allocation strategy; (c) NC replacement strategy.

8.4.4 Implementation Issues

We define new message types in addition to the existing protocol messages in IEEE 802.16's MeSH mode to carry the information related to network coding multicast reservations. The messages `NcInit` (Network Coding Initialization), `NcRep` (Network Coding Reply), and `NcReq` (Network Coding Request) are preferably transmitted in the data subframe in slots reserved for transmission to the addressed node, thus minimizing the latency of the handshake. The messages `NcGrant` (Network Coding Grant) and `NcGrantConfirm`

(Network Coding Grant Confirmation) are transmitted in the schedule control subframe. The message `NcInit` is used to initiate the process of reservation of slots to multiple neighboring nodes for the transmission of coded data, it contains the following fields.

- `D`: the value for `D` specifies the number of slots to be reserved for the transmission of coded data to multiple neighbors.
- `Xmt`: this field specifies the slots which are suitable and available for transmission of data at the node initiating the network coding handshake.
- `PC`: pseudo cancel, which specifies the set of slots which the addressed node should also check for their suitability for receiving data transmissions considering that the node initiating the handshake will free these slots reserved by it for transmissions to some other node.

The nodes addressed by the `NcInit` message reply using the `NcRep` message. The `NcRep` message has the following fields.

- `Rcv`: this field specifies the set of slots which are suitable at the node for receiving data transmissions.
- `PC`: this field specifies the set of slots which would be suitable for reception at the node if the transmitter of the initiating `NcInit` message would free these currently reserved slots.

After this initial handshake (Figure 8.7(a)), the initiator of the handshake knows which slots are suitable for transmitting the coded packets to the intended receivers. The intended receivers on the other hand know which slots should not be used in the near future for concurrent grants, as the relay would be initiating the next phase of the NC reservation process using these indicated slots. The next phase of the NC reservation may use either the new allocation strategy (Figure 8.7(b)) or the replacement strategy (Figure 8.7(c)). We next discuss the remaining handshake messages followed by a brief outline of both the reservation strategies.

The `NcReq` message is the NC counterpart for the normal request message used in the three-way handshake (Figure 8.2(a)) for distributed scheduling. `NcReq` can specify the number of slots to be reserved with the slots to be used for transmission as shown in the new allocation strategy. `NcReq` has the following fields.

- `D`: the value for `D` specifies the number of slots to be reserved for the transmission of coded data to multiple neighbors (similar to `NcInit`).
- `Xmt`: this field specifies the particular slots selected for the multicast network coding reservation (a subset of the `Xmt`-slots given in `NcInit` and `Rcv`-slots given in `NcRep`).
- `Cancel`: this field indicates that the given slots shall be cancelled and repurposed for a novel multicast reservation.
- `Replace`: this field specifies the slots for which the novel multicast reservation is to be issued.

For the replacement strategy, as discussed previously, the relay reuses some slots already reserved by itself for unicast transmission to one of the intended recipients of the coded data to schedule new coded transmissions to multiple recipients. Hence, when using the replacement strategy, based on which neighboring node is being addressed, the `NcReq` message is used with differing intentions. The relay sends a `NcReq` message with a `Cancel` indication, notifying the neighbor that it is cancelling the slots specified by the `Cancel` field (which had been reserved previously for a unicast transmission to some other neighbor) and that the node being addressed should reserve these slots for the multicast NC transmission. The neighbor then replies using a `NcGrant` message granting the slot for the NC transmission (the semantic of the `NcGrant` message is similar to the `Grant` message in IEEE 802.16). The relay uses the `NcReq` message with a `Replace` indication to address a node to which it has reserved the slots specified in the `Replace` field. This tells the neighbors that these slots which had been reserved previously for the unicast transmission from the relay to itself will be used for the transmission of coded (multicast) data by the relay to itself. The addressed neighbor then responds by simultaneously cancelling the unicast reservation and granting the same slots for the NC transmission. A `NcGrantConfirm` confirms the novel multicast reservation to all neighbors (similar to the `GrantConfirm` in IEEE 802.16). Readers interested in the exact implementation details and extensions to the MeSH mode (the control message formats and extensions to the MeSH mode specifications) can find them in Kropff (2006).

8.5 Related Work

The seminal work of Ahlswede *et al.* (2000) introduced network coding and demonstrated that bandwidth savings are possible when network coding is deployed. This was followed by literature which further investigated the benefits that can be obtained theoretically by applying network coding (see, e.g., Li *et al.* (2003) and Sagduyu and Ephremides (2005)). The work of Katti *et al.* (2006) is one of the first that considered the deployment of network coding in a realistic setting. Katti *et al.* (2006) present their COPE architecture, which uses opportunistic network coding to combine multiple packets from different sources 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 (see IEEE (1999)) a basic access scheme as well as an RTS/CTS scheme are 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 neighborhood of both the sender as well as the receiver do not transmit any data simultaneously. Thus, when a node transmits any data or acknowledgements following the successful RTS/CTS handshake, all of its neighbors remain silent themselves and will be able to receive the unicast data/acknowledgement transmission as long as none of their neighbors transmits simultaneously. This provides a conducive environment for opportunistic listening. However, as shown in Section 8.2, the neighbors of the node transmitting data in a slot may schedule simultaneous transmissions making opportunistic listening difficult if not impossible. Further, the IEEE 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 IEEE 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 Section 8.3. The key question which the work of Katti *et al.* (2006) addresses is to determine 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 Expected Transmission Count (ETX) routing metric (see De Couto *et al.* (2003)). In contrast, we do not rely on the availability of any particular routing metric or routing algorithm. The key questions which we addressed in this book chapter are as follows. When does network coding help in terms of throughput/bandwidth savings considering advanced MAC layers?

- How can we dynamically manage the multicast reservations for network coding without leading to conflict with other existing data transmission schedules in reservation-based MAC layers?

- How do we design practical solutions to deploy WNC in IEEE 802.16's MeSH mode?

8.6 Conclusions and Outlook

We discussed the applicability of WNC for WMNs based on the IEEE 802.16 MeSH mode with particular emphasis on MAC layer issues. First, 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 next designed solutions for deploying network coding in the MeSH mode using the derived design principles as a roadmap. Furthermore, advanced strategies for reserving slots for transmission of coded data were presented. The presented solutions have been initially discussed and investigated by means of simulations in Mogre *et al.* (2008); the results provide a proof of concept for the presented solutions and give pointers for future investigation.

However, MAC layer mechanisms alone are not sufficient for obtaining the maximum possible gain via deployment of network coding in IEEE 802.16's MeSH mode. Our work presented in Mogre *et al.* (2007) presents a first step towards effectively deploying network coding in IEEE 802.16's MeSH mode, where routing, scheduling and network coding are optimized simultaneously. In the future, we will look for further improvements to the latter work, and perform an evaluation of more advanced multicast bandwidth reservation strategies. Solutions which are suitable for coding real-time data and other delay sensitive data are of special interest, as these form the major class of traffic which benefits from the use of advanced bandwidth reservation mechanisms provided by the MeSH mode.

In summary, any solutions for network coding to be deployed in MAC layers supporting bandwidth reservation need to be able to work seamlessly with the specified reservation schemes. Furthermore, in most cases a one-to-one mapping of network coding solutions designed and developed within the scope of the IEEE 802.11 standard will not work optimally in advanced MAC layers. Owing to this fact, a lot of interesting and challenging aspects persist for further research in deploying network coding efficiently in next-generation WMNs.

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References

Ahlswede, R., Cai, N., Li, S.R. and Yeung, R.W. (2000) Network information flow. *IEEE Transactions on Information Theory,* **46**(4), 1204–1216.

Akyildiz, I.F., Wang, X. and Wang, W. (2005) Wireless mesh networks: a survey. *Computer Networks,* **47**(4), 445–487.

Cao, M., Ma, W., Zhang, Q., Wang, X. and Zhu, W. (2005) Modelling and performance analysis of the distributed scheduler in IEEE 802.16 mesh mode. *Proceedings of the 6th ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc 2005),* pp. 78–89.

De Couto, D., Aguayo, D., Bicket, J. and Morris, R. (2003) High-throughput path metric for multi-hop wireless routing. *Proceedings of the 9th Annual International Conference on Mobile Computing and Networking (MobiCom 2003),* pp. 134–146.

IEEE 1999, IEEE Standard for Information Technology, Telecommunications and Information Exchange between Systems, Local and Metropolitan Area Networks, Specific Requirements, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, *IEEE Standard 802.11-1999.*

IEEE 2004, IEEE Standard for Local and Metropolitan Area Networks, Part 16: Air Interface for Fixed Broadband Wireless Access Systems, *IEEE Standard 802.16-2004.*

Katti, S., Rahul, H., Hu, W., Katabi, D., Medard, M. and Crowcroft, J. (2006) XORs in the air: practical wireless network coding. *ACM SIGCOMM Computer Communication Review,* **36**(4), 243–254.

Kropff, M. (2006) Network coding for bandwidth management in IEEE 802.16 mesh networks. *Master's Thesis* TU Darmstadt.

Li, S.R., Yeung, R.W. and Cai, N. (2003) Linear network coding. *IEEE Transactions on Information Theory,* **49**(2), 371–381.

Mogre, P.S., d'Heureuse, N., Hollick, M. and Steinmetz, R. (2007) A case for joint near-optimal scheduling and routing in TDMA-based wireless mesh networks: a cross-layer approach with network coding support (poster abstract and poster). *Proceedings of the IEEE International Conference on Mobile Adhoc and Sensor Systems (MASS 2007).*

Mogre, P.S., Hollick, M. and Steinmetz, R. (2006) The IEEE 802.16-2004 MeSH mode explained, *Technical Report, KOM-TR-2006-08.* KOM, TU Darmstadt, Germany, ftp://ftp.kom.tu-darmstadt.de/pub/TR/KOM-TR-2006-08.pdf.

Mogre, P.S., Hollick, M., Kropff, M., Steinmetz, R. and Schwingenschloegl, C. (2008) A note on practical deployment issues for network coding in the IEEE MeSH mode. *Proceedings of the IEEE International Workshop on Wireless Network Coding (WiNC 2008).*

Sagduyu, Y.E. and Ephremides, A. (2005) Joint scheduling and wireless network coding. *Proceedings of the First Workshop on Network Coding, Theory, and Applications (NetCod 2005).*