

connections, which are created when a SS joins the network, should not be mapped to SAs.

Cryptographic Methods The cryptographic methods include the supported cryptographic algorithms and the key sizes that are used by the PKM protocol. The standard defines two data encryption schemes: one employs the DES in cipher bloc chaining (CBC) mode and the second uses AES in CCM mode. When the encryption algorithm identifier associated with an SA equals 0×01 , data flow that will be transmitted on that connection can be encrypted using the CBC mode of the DES algorithm. When the length of the final block to encrypt is less than 64 bits, a residual termination block processing is used for encryption. When the encryption algorithm identifier related to an SA equals 0×02 , data flows that will be transmitted on that connection will be encrypted using the CCM mode of the AES algorithm. The receiver of an encrypted PDU should decrypt and authenticate it according to the CCM specifications, then discard it if it is invalid.

Keys and Certificates

Key Usage Key information needs be synchronized so that the BS to maintain it for all SAs and client SSs. When a new AK is assigned to an SS, it will remain active until the specified Lifetime value set by the issuing BS expires. The Authorization Reply generated as a response to the Authorization Request should specify the remaining lifetimes of the AK. However, when a SS has not been able to reauthorize before the expiration of its AK, the BS should judge it as unauthorized and remove all the TEKs associated with that SS's primary SA. Finally, the BS needs to support two different and simultaneously active AKs for each SS; that is the reason why both keys present overlapping lifetimes.

Certification Management The IEEE 802.16d uses the X.509 Version 3 certificate format along with other certificate extensions. This format defines the `tbsCertificate.version` and the `tbsCertificate.serialNumber` field that together identify the certificate. These are assigned from the certification authority. We may also distinguish the `tbsCertificate.signature` field, which defines the algorithm processed to sign the certificate, along with the `tbsCertificate.validity` information, which determines when the certificate becomes active and when it expires. Finally, the X.509 format identifies the signature Value field, which contains the computed digital signature of the certificate, the `tbsCertificate.subjectPublicKeyInfo` field, which contains the public key, and the parameters along with the identifier of the algorithm with which the key may be used.

5.5 Enhancing Efficiency and Effectiveness of 802.11 MAC in Wireless Mesh Networks⁸

5.5.1 Increasing Parallelism by Power Control and Enhanced Carrier Sensing

The IEEE 802.11 MAC provides two CA mechanisms, the mandatory basic CSMA/CA and the optional virtual carrier-sensing scheme with RTS/CTS (IEEE 802 LAN/MAN

⁸ Excerpt from the invited article "Enhancing efficiency and effectiveness of 802.11 MAC in wireless mesh networks," *Yuanzhu Peter Chen; †Jian Zhang and †Ivan Marsic (*Memorial University of Newfoundland; †Rutgers University).

Standards Committee, 1999). Under the basic scheme, a station refrains from medium access if it senses ongoing transmission(s) on the wireless channel. The mechanism to determine whether or not the channel is busy is called CCA. A prevalent CCA mode is known as carrier sense with energy detection. That is, the CCA decision is based on whether the energy of a detectable 802.11 signal exceeds a threshold, called *carrier sense threshold*. Given a carrier sense threshold, the corresponding *carrier sense range* is defined as the minimum distance allowed between two concurrent transmitters (Yang and Vaidya, 2005a). On the one hand, it may be true that the smaller the carrier sense range (or the higher the carrier sense threshold), the better the spatial reuse and the higher the efficiency. On the other hand, the interference level at a receiver can also increase as the carrier sense range decreases, that is, concurrent transmitters get closer; effectively this impairs the effectiveness of the CA mechanism. An interference model has been developed to describe the relationship between the transmission power, the carrier sense threshold, and the aggregate throughput. Using such a model, the optimal carrier sense threshold is specified to maximize the aggregate throughput for a regular topology, as described next.

5.5.2 Static Basic Carrier Sensing Based on Interference Model

Yang and Vaidya (2005a) and Kim et al. (2006) derived the worse case interference and signal-interference-noise ratio (SINR) at a receiver station as follows. The thermal noise is ignored for simplicity.

We denote the carrier sense threshold by T_{cs} , the corresponding carrier sense range by D , the transmission power by P_{tx} , and the transmission range by R . When a sender S_0 is transmitting, a concurrent transmitter must be at least a distance D away from S_0 . Therefore, in the worst case there can be a total of 6 interferers distributed on the circle centered at the sender with radius D . This can be approximated using the Honey-grid model (Hekmat and Van Mieghem, 2002) as in Fig. 5.15.

As illustrated, the worst-case interference occurs when the distances between the receiver R_0 and the six interferers approximately equal $D - R$, $D - R$, $D - R/2$, $D + R/2$,

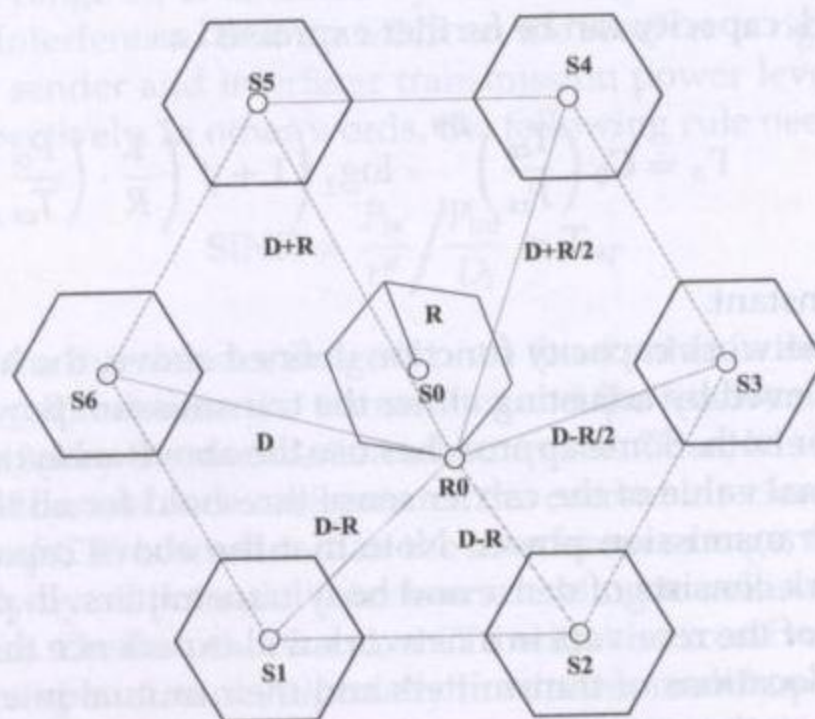


FIGURE 5.15 Worst case interference scenario.

$D + R$, and D , respectively. It can be shown that the interference contributed by other potential interferers in the network can be neglected (Hajek et al., 1997). Thus, the interference from these six interferers dominates the total interference at R_0 . It can be expressed then as

$$I = \frac{2P_{tx}}{(D - R)^\theta} + \frac{P_{tx}}{\left(D - \frac{R}{2}\right)^\theta} + \frac{P_{tx}}{D^\theta} + \frac{P_{tx}}{\left(D + \frac{R}{2}\right)^\theta} + \frac{P_{tx}}{(D + R)^\theta} \quad (5.1)$$

where a path-loss radio propagation model with the path loss exponent θ is assumed. The corresponding SINR at R_0 can be expressed as an increasing function of D/R :

$$\begin{aligned} \text{SINR} = f\left(\frac{D}{R}\right) &= \frac{\frac{P_{tx}}{D^\theta}}{\frac{2P_{tx}}{(D - R)^\theta} + \frac{P_{tx}}{\left(D - \frac{R}{2}\right)^\theta} + \frac{P_{tx}}{D^\theta} + \frac{P_{tx}}{\left(D + \frac{R}{2}\right)^\theta} + \frac{P_{tx}}{(D + R)^\theta}} \\ &= \frac{1}{\frac{2}{\left(\frac{D}{R} - 1\right)^\theta} + \frac{1}{\left(\frac{D}{R} - \frac{1}{2}\right)^\theta} + \frac{1}{\left(\frac{D}{R}\right)^\theta} + \frac{1}{\left(\frac{D}{R} + \frac{1}{2}\right)^\theta} + \frac{1}{\left(\frac{D}{R} + 1\right)^\theta}} \end{aligned} \quad (5.2)$$

Using the Shannon capacity theorem, for a certain channel bandwidth W , the achievable channel rate is at most $\Gamma_c = W \cdot \log_2(1 + \text{SINR})$. The total network capacity can be expressed then as $\Gamma_n = \Gamma_c \frac{U}{U_A}$, where U is the area of the network and U_A is the area "consumed" by each transmitter, that is, $\sqrt{3} \cdot D^2/2$. Thus, U/U_A is the total number of concurrent transmissions in the network. The carrier sense range D is simply $\left(\frac{P_{tx}}{T_{cs}}\right)^{1/\theta}$. So, the network capacity can be further expressed as

$$\Gamma_n = C_0 \left(\frac{T_{cs}}{P_{tx}}\right)^{2/\theta} \cdot \log_2 \left(1 + f\left(\frac{1}{R} \cdot \left(\frac{P_{tx}}{T_{cs}}\right)^{1/\theta}\right)\right) \quad (5.3)$$

where C_0 is constant.

Using the network capacity function defined above, the highest aggregate throughput can be achieved by adjusting either the transmission power P_{tx} or the carrier sense threshold T_{cs} , or both. Some approaches use the above analytical model to determine an invariant optimal value of the carrier sense threshold for all the stations in the network given a fixed transmission power. Note that the above capacity is derived assuming that the network consists of dense and busy transmitters. In practice, however, it is not typical that all of the receivers in a network will experience the worse-case interference. Moreover, the locations of transmitters and their mutual interference in a network are not necessarily stationary or on a regular pattern. Therefore, instead of holding the carrier sense threshold or transmission power of all nodes constant all the time, a class of methods is proposed to adjust these parameters dynamically. These dynamic control

methods are usually combined with the virtual carrier-sensing scheme as described in the following section.

5.5.3 Dynamic Schemes with Virtual Carrier Sensing

5.5.3.1 Virtual Carrier Sensing and Its Inefficiency and Ineffectiveness

As a complement to the basic CA scheme, virtual carrier sensing (Bharghavan et al., 1994) is dedicated to solving the collision problem due to hidden stations (Tobagi and Kleinrock, 1975a). The idea is to reserve the wireless channel by preceding the data frame transmission with an RTS/CTS handshake. The neighboring stations that receive the RTS/CTS frames are blocked from transmitting for a period of time specified in the frames. This is achieved by setting the NAV of an overhearing node's MAC agent; this counts down as the transmission progresses. Therefore, the transmission range of the RTS/CTS effectively determines the blocking area. The original design (Bharghavan et al., 1994) assumes that the stations are able to interfere with the upcoming DATA/ACK frames only if they can receive RTS/CTS, that is, that the transmission range of control frames equals the interference range. However, there commonly exists a disparity between the RTS/CTS transmission range and the interference range. Instead, it may result in one of the two opposite situations, that is, either the failure of CA or unnecessary false blocking, depending on which range is larger.

In our discussion, we define the *interference range* of a receiver R as the distance from R within which another transmitter may interfere with the current frame reception. Recall the two conditions needed for a receiver to receive a frame with an acceptable error rate: (1) the power of the received signal exceeds a threshold, called *receiver sensitivity*, denoted by P_{rth} , and (2) the SINR exceeds another threshold, called *capture threshold*, denoted by T_{cap} . The distance that a signal propagates before its power drops below P_{rth} , that is, the transmission range R , can be derived by solving

$$\frac{P_{\text{tx}}}{R^\theta} = P_{\text{rth}} \quad (5.4)$$

The interference range D_1 is obtained by calculating the shortest distance between the receiver and an interferer so that the SINR on the receiver is right above the capture threshold when the sender and interferer transmission power levels for DATA frames are P_{tx} and P_{inf} , respectively. In other words, the following rule needs be satisfied:

$$\text{SINR} = \frac{P_{\text{tx}}}{r^\theta} \bigg/ \frac{P_{\text{inf}}}{D_1} \geq T_{\text{cap}} \quad (5.5)$$

This shows that the interference range is not a fixed value in that it changes with the actual distance r ($r \leq R$) between the transmitter and the receiver, and with the capture threshold T_{cap} that is set by the modulation scheme used. Thus, it is common that the CTS transmission range does not necessarily match the current interference range. When the transmission range of CTS is smaller than the interference range, the CTS frame cannot be decoded correctly by all potential interferers, leading to collisions, referred to as the ineffectiveness of CA. On the other hand, a CTS with an excessively large transmission range may cause low spatial reuse, especially in wireless multihop networks, referred to as its inefficiency.

An example shown in Fig. 5.16a assumes that all nodes transmit RTS/CTS/DATA/ACK frames with the same power and modulation scheme. Although node X

As a consequence to the fact that the receiver (R) is located at a distance R from the sender (S), the receiver will receive the data frame with a delay of $2R$ (the propagation delay). This delay is not taken into account in the CSMA/CD protocol. The receiver will receive the data frame with a delay of $2R$ and will start the timer for the CSMA/CD protocol. This delay is not taken into account in the CSMA/CD protocol. The receiver will receive the data frame with a delay of $2R$ and will start the timer for the CSMA/CD protocol. This delay is not taken into account in the CSMA/CD protocol.

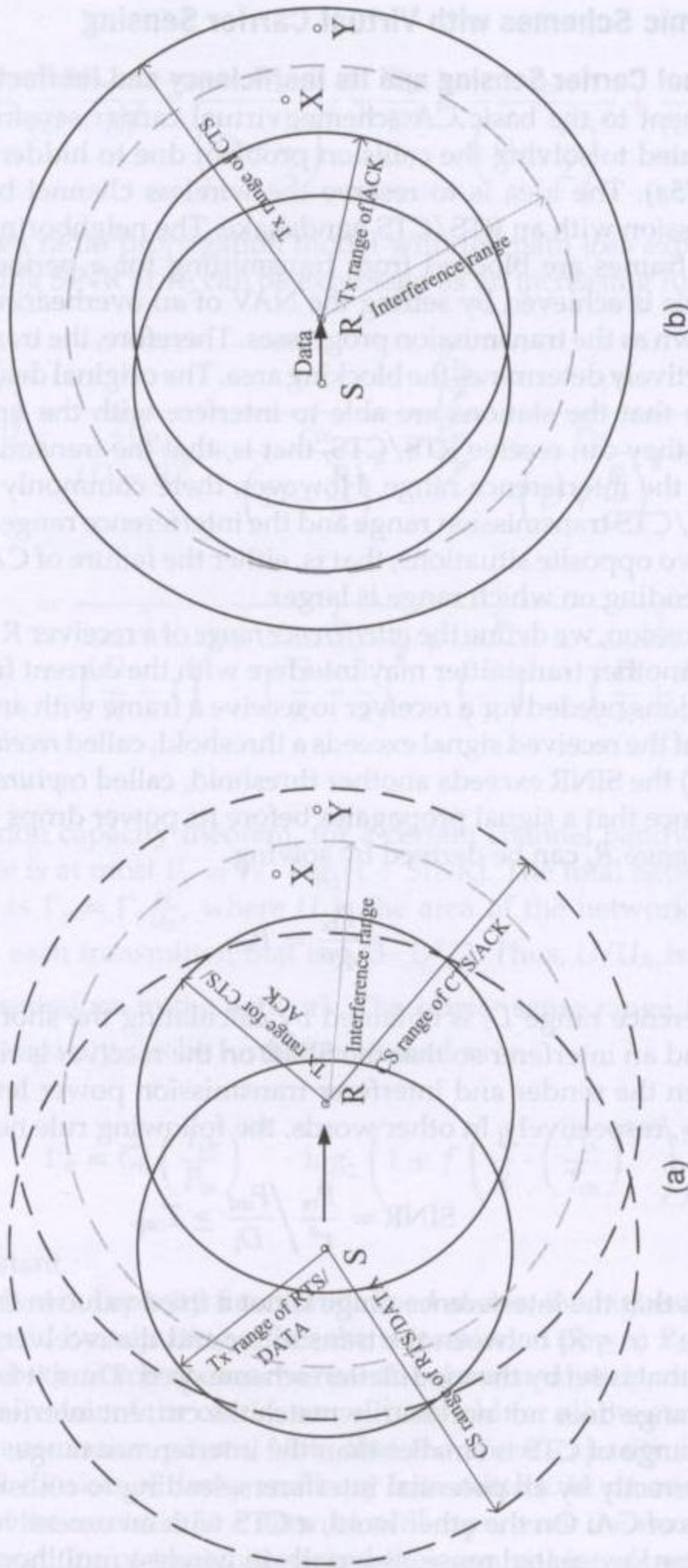


FIGURE 5.16 (a) Ineffectiveness of CA and (b) inefficiency of spatial reuse.

may sense node R's transmission since it is within R's carrier sense range, it cannot decode the CTS frame since it is outside of the transmission range of CTS of node R. Therefore, although node X will stay silent for the period of this CTS transmission, it may still transmit during the DATA frame from S to R since it failed to set its NAV based on the CTS frame. This may result in a DATA frame collision since node X is within the interference range of receiver R. This is the so-called hidden station problem, which still cannot be avoided by the original RTS/CTS scheme.

A solution for avoiding such collisions could be the increase of the RTS/CTS transmission range (i.e., increasing the RTS/CTS transmission power). For example, see the work by Gomez et al. (2001): the RTS and CTS are sent at the highest power level, and the data and ACK at a lower power level. However, it turns out that the above collision problem cannot be well solved by such a strategy. The reason is that by enlarging the CTS transmission range of receiver R to defer more potential interferers, at the same time we also increase the interference of RTS/CTS frames at the neighboring nodes due to the higher transmission power, that is, the interference range of receiver R is also increased due to a larger P_{inf} in Eq. (5.2). This paradox can be mitigated by multichannel schemes, for example, PCMA provided in the study of Monks et al. (2001), by transmitting RTS/CTS frames on a different channel than the DATA/ACK frames.

For single-channel networks, a way to enlarge the RTS/CTS range without increasing the transmission power is to use a lower-rate modulation scheme that requires lower receiver sensitivity P_{rth} . In Eq. (5.1), using the same P_{tx} but a smaller P_{rth} , the corresponding transmission range increases. Thus, as shown in Fig. 5.16b, the CTS frame of receiver R can now reach some potential interferers, such as node X. On the other hand, an excessively large transmission range of CTS may lead to inefficiency. As shown in Fig. 5.16b, node Y is unnecessarily blocked although its transmission would not interfere with the data reception of R (because it is beyond its interference range). Thus, as discussed next, the problem becomes: *how to improve the spatial reuse/efficiency without impairing the effectiveness of CA.*

5.5.3.2 Soft Blocking Schemes

The IA-MAC (Cesana et al., 2003) provides a single-channel solution. Its idea is similar to (Monks et al., 2001), but operating in single-channel networks. The idea, here referred to as "soft blocking," is to conditionally set the NAV of every node that overhears a CTS frame. Assume that a low-rate modulation scheme is selected for RTS/CTS frames and their transmission range is sufficiently large, as in Fig. 5.16b. To improve efficiency, if a node, say node Y, can tell that its transmission will not interfere with the reception at receiver, say R, Y may choose then not to set its NAV when overhearing a CTS. Node Y decides this by using the transmission power information carried explicitly and/or implicitly by RTS/CTS frames. The process is described below. Before and upon receiving an RTS from the sender, the receiver can measure the interference $P_{\text{I-current}}$ and the power of the received RTS as $P_{\text{rcv-RTS}}$, respectively. The minimum SINR should not drop below the capture threshold, which is

$$\text{SINR} = \frac{P_{\text{rcv-RTS}}}{P_{\text{I-current}} + P_{\text{I-add}}} \geq T_{\text{cap}} \quad (5.6)$$

To calculate the maximum additional interference $P_{\text{I-add}}$ that the system can tolerate, the receiver calculates Eq. (5.3). The receiver then inserts the result ($P_{\text{I-add}}$) in the CTS

frame to advertise it to its neighbors. When a neighbor overhears this CTS frame, it first measures its power. Given the assumption of symmetry of the channel and equal transmission power for all nodes, the interference of a neighboring node at the receiver is about the same as the power that the neighboring node perceives from the receiver (via the CTS frame). If the perceived power of the CTS is higher than $P_{I\text{-add}}$, this neighbor sets its NAV according to the CTS and stays silent. Otherwise, it ignores the CTS frame presuming that its transmission will not disturb the current reception. Therefore, the parallelism/efficiency is improved by such a "soft blocking" scheme with virtual carrier sensing. Yet, the CA is still effective. The method is simple with no need for power control, its overhead on CTS is negligible, and the symmetry assumption is reasonable. Note that the collision may still occur if *aggregate interference* is considered. For example, in the worst interference case in Fig. 5.15, assume that the transmission will not be disturbed by single transmission from any of the six interferers. But the cumulative interference from the concurrent transmissions may be higher than the maximum additional interference. Since these interferers are out of the sensing range of each other, they may start their transmissions simultaneously, which leads to reception failures at receiver R_0 in Fig. 5.15.

5.5.3.3 Power Control Schemes

Power control in 802.11 MAC was originally proposed for the purpose of power saving (Gomez et al., 2001; Jung and Vaidya, 2002). It was first designed by Jung and Vaidya (2002), using a power control scheme, called POWMAC, to enhance spatial reuse and to manage interference in wireless multihop networks, aiming at improving the network throughput. The basic idea can be illustrated as follows. In Fig. 5.16b, node X is blocked since its transmission with regular power level disturbs the reception at R. However, if node X has a packet for a receiver nearby, say node Y, X may lower its "voice" (power) so that its interference is below the additional tolerable value for reception at R and yet its power is strong enough for reception on Y.

POWMAC considers the additional tolerable interference as a resource, which is shared with other concurrent transmissions. Like IA-MAC, power and interference information is exchanged via RTS/CTS handshakes. The process is as follows. When a sender i has a frame for a receiver j , it first calculates the maximum allowable transmission power (P_{MAP}) it can use without disturbing its neighbors:

$$P_{\text{MAP}}(i) = \min_u \{P_{\text{MTI}}(u)/G_{iu}, P_{\text{MAX}}\} \quad (5.7)$$

Here, P_{MTI} is the maximum tolerable interference (described below) of i 's neighbor u and G_{iu} is the channel gain between nodes i and u that can be estimated if both the transmission power and received signal strength are known. Sender i then places P_{MAP} into its RTS frame and transmits it with the maximal power P_{MAX} . In addition, the sender also includes the estimated number N of future unintended transmitters that could interfere with the receiver, based on the current network load (Muqattash and Krunz, 2004). Upon receiving this RTS, the receiver j determines whether the regular transmission power P_{load}^{ij} of DATA frame is within the range $P_{\text{min}}^{ij} \leq P_{\text{load}}^{ij} \leq P_{\text{MAP}}$, where P_{min}^{ij} is the minimum power required for DATA frame so that it can be decoded given the current interferences from existing transmissions. If P_{load}^{ij} does not fall within this range, the receiver sends a negative CTS back to sender i to reject the request. Otherwise, it

calculates the maximum additional interference power $P_{I\text{-add}}$ that it can tolerate from N future unintended transmitters, in addition to the existing ones. The calculation of $P_{I\text{-add}}$ is similar to the related process described in IA-MAC. Unlike IA-MAC, a POWMAC receiver further splits the total tolerable $P_{I\text{-add}}$ across N potential interferers:

$$P_{\text{MTI}} = \frac{P_{I\text{-add}}}{N} \quad (5.8)$$

As Eq. (5.5) shows, the maximum tolerable interference for any single sender P_{MTI} is a fraction of the aggregate interference $P_{I\text{-add}}$. The calculated P_{MTI} is then broadcast with the CTS frame to neighboring potential transmitters so they can use it to properly set their maximum allowable transmission power P_{MAP} , Eq. (5.4).

As noted above, with more flexible allocation of transmission power and adaptive blocking area, a power control scheme for 802.11 MAC can further improve spatial reuse and the network throughput as such. In the soft-blocking scheme, the state of a neighboring node is either "on," that is, in the blocking range, or "off," that is, out of the range. In contrast to such a simple on-off control, dynamic power control schemes provide more flexible methods for dealing with various interference scenarios in wireless mesh networks. Note that the performance of POWMAC highly depends on the accuracy of the propagation model and the interference-error model described above. For implementation, it is imperative for the 802.11 products to measure and compare the power with the level of accuracy the POWMAC protocol (Abdesslem et al., 2006) requires. Moreover, for multirate wireless networks with rate-adaptive MAC (Holland et al., 2001), the throughput gain through power control may be ambiguous. That is because the rate adaptation mechanism may use the resource dedicated to tolerate additional interference to increase the link rate instead of increasing the number of concurrent transmissions, as in POWMAC.

5.5.3.4 Self-Learning Carrier Sensing

Compared to above schemes, the method of self-learning carrier sensing (Chen et al., 2006a) does not require any propagation modeling or power control. Here, the sender collects the historical RTS/CTS success ratio and the signal strength, and builds a black-box mapping model to describe their relationship. The update of the mapping curve is triggered by an access request event. Prior to an access attempt, the sender looks up the mapping curve indexing the current sensed signal strength and obtains the estimated success ratio. If the success ratio is lower than some threshold, the sender backs off and waits until it reckons the channel is clear. This method, although simple, is adaptive and easy to implement. On the other hand, this 2-D mapping can be flawed and inaccurate in the case when more media access behaviors and patterns are present.

5.5.4 Exploit Channel and/or Spatial Diversity with MAC-Layer Scheduling

5.5.4.1 Head-of-Line Blocking Problem

Another type of method (Jain and Das, 2005; Kim et al., 2006a; Wang et al., 2004; Zhang et al., 2006) for increasing concurrent transmissions and improving parallelism in mesh networks is to exploit the channel/spatial-diversity by rescheduling the frames in the sender's queue. In wireless mesh networks, some stations can be particularly overloaded. For example, a mesh network gateway (Aguayo et al., 2004) needs to deliver

simultaneously multiple down-stream data flows (e.g., between the Internet and the wireless stations). Similarly, a mesh router may have to serve several neighbors by forwarding their packets along multihop paths. The efficiency of such stations is critical to the capacity of a mesh network. However, the performance of the regular 802.11 MAC protocol is susceptible to the head-of-line (HOL) blocking problem.

The HOL blocking problem occurs when the frame currently at the head of the queue in the sender's MAC layer cannot be transmitted successfully due to, say, the temporary unavailability of the receiver. As discussed in Section 5.3, in 802.11, each time a DATA or RTS transmission times out, the contention window is doubled. The frame will not leave the queue until the transmission is acknowledged or until the maximal number of retries is reached. This frame is thus blocking the subsequent frames from being transmitted although their receivers may be available at this time. Due to the exponentially-growing backoff time overhead, the HOL blocking problem can greatly lower channel utilization and network capacity. Simulations (Zhang et al., 2006) indicate that the MAC layer backoff time fraction at the sender may reach up to 70%. For a loaded mesh router or gateway, HOL blocking problem could result in a serious congestion. During the backoff process at a mesh gateway, more and more frames could arrive from wireline Internet connection and be blocked in the queue. For a loaded mesh router, the backoff forces the router to spend more time in receiving than transmitting. With more frames arriving and the head frame blocking the queue, the router's queue eventually overflows and it starts dropping packets. This may further trigger an upper layer (e.g., TCP) backoff, leading to further degradation of throughput performance. Thus, in order to improve the performance of multihop mesh networks, the HOL blocking problem must be addressed.

5.5.4.2 MRTS

A straightforward solution to the HOL problem is to reschedule the frames in the sender's queue based on the status of their next-hop nodes. For example, node B in Fig. 5.17 cannot receive traffic from A as it is blocked from another transmission. Instead of waiting for B, node A may first send its traffic queued to other nodes available, such as E. As a

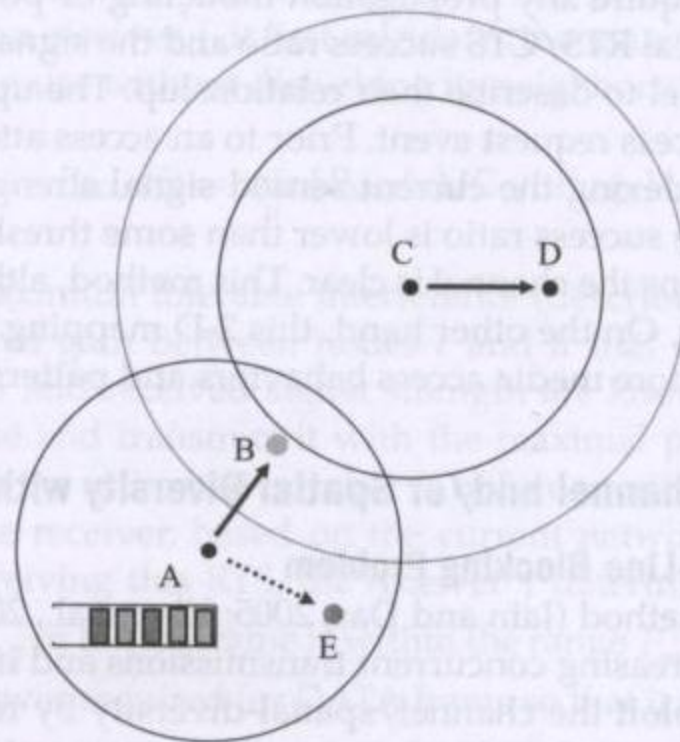


FIGURE 5.17 Rescheduling for HOL blocking problem.

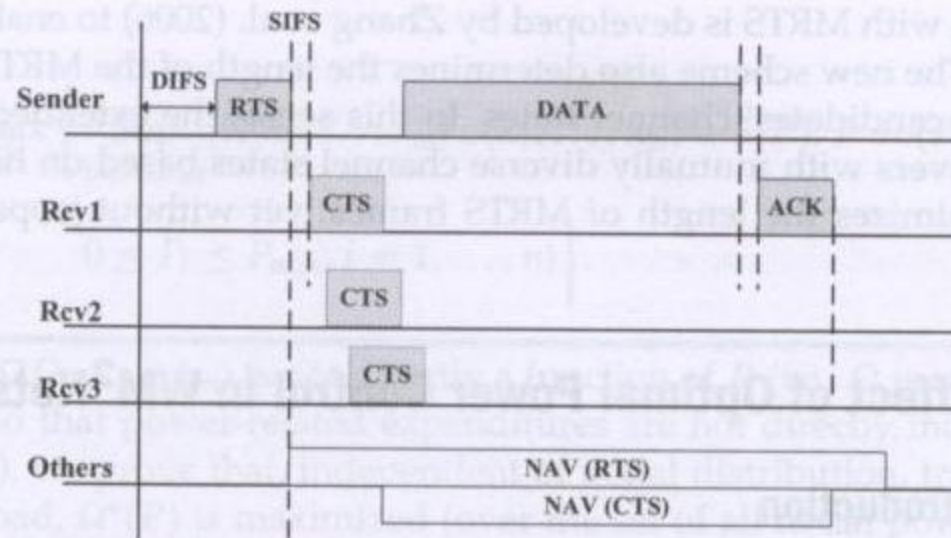


FIGURE 5.18 MRTS protocol timeline.

result, the backoff overhead is avoided whereas the channel utilization is also improved. In addition, the number of concurrent transmissions is increased.

To obtain the state information of the next-hop neighbors, a multicast RTS/CTS (MRTS) handshake is proposed by Jain and Das (2005) and Wang et al. (2004). An MRTS, in contrast to a unicast RTS in conventional RTS/CTS, is directed to a list of receivers. That is, an MRTS frame contains a list of next-hop receivers for which the sender has DATA packets currently queued. Each element of the list contains a receiver's address and the NAV of its corresponding packet. The priority among different receivers is decided by the order in which the receivers are arranged in the MRTS frame. That is, the earlier a receiver's address appears on the MRTS list, the sooner this receiver can return a CTS. This mechanism helps to avoid the collision of CTS frames returned by the receivers. Unless it is blocked by an ongoing transmission in its neighborhood, the first candidate receiver (Rcv1 in Fig. 5.18) that successfully receives the MRTS replies with a CTS. If a lower-priority candidate (Rcv2 or Rcv3) detects that all higher-priority candidates remained silent for certain period of time, it has the right to reply with a CTS. The lower a receiver's priority is, the longer its waiting time is. For example, the n -th receiver has to wait for $SIFS + (n - 1) \times \text{slot_time}$. Such a right-to-reply is implicitly propagated down the chain until a nonblocked receiver sends a CTS or all receivers remain silent and the sender times out. The sender finds the responding receiver's address from the received CTS frame. Then, the sender retrieves the corresponding frame from its queue and transmits it to that receiver. The dialog ends with an ACK from the receiver if the transmission is successful. Since the MRTS probes the availability of multiple receivers almost simultaneously, the likelihood of MRTS failure, that is, no receiver available, is low. Hence, the idle time due to backoff on the loaded stations can be significantly lowered and their utilization is improved.

The multicast characteristic of MRTS provides another appealing feature. That is, it measures the channel conditions of multiple receivers almost simultaneously. Therefore, based on the observed MRTS responses, the sender can estimate the neighbors' channel states and their correlations, that is, how diverse/correlated the states of any two neighbors are. From this, it may also estimate their geographical relations since geographically proximal stations are likely to share similar channel states. The use of such information may enhance the channel-state diversity of the MRTS receiver list, and thus further improve the success ratio of MRTS. An extension of the adaptive channel-state-based

scheduling with MRTS is developed by Zhang et al. (2006) to enable receiver candidate selection. The new scheme also determines the length of the MRTS list, which is adaptable to the candidates' channel states. In this sense, the extended scheme constructs a list of receivers with mutually diverse channel states based on historical observations. It also minimizes the length of MRTS frames, yet without jeopardizing their success ratio.

5.6 On the Effect of Optimal Power Control in WM²Nets⁹

5.6.1 Introduction

We consider a wireless mesh network with n nodes and m source-destination pairs (and a given offered traffic load for each pair), using a scheduling-based MAC protocol such as time division multiple access (TDMA), and a routing mechanism that may be unicast or multicast based, $m \leq n(n-1)$. Under a given set of nodal transmit power levels $P = (P_1, \dots, P_n)$, $0 \leq P_i \leq P_{\max}$, $i = 1, \dots, n$, we define the source-destination throughput vector $\lambda = (\lambda_1, \dots, \lambda_m)$ to be achievable for the wireless mesh network if there exists an associated *temporal* (based on the channel sharing MAC protocol) and *spatial* (based on the underlying routing mechanism) *joint scheduling-routing scheme* (henceforth referred to as *joint scheduling and routing scheme*) that yields the throughput vector λ . Let $S(P)$ denote the set of all achievable source-destination throughput vectors under the power vector P .

In this study, we analyze the effect of nodal transmit power vector P on the maximum (or supremum) level of a general (real-valued) function of the source-destination throughput levels $\Omega(\lambda_1, \dots, \lambda_m)$ subject to $\lambda \in S(P)$. We refer to the latter supreme level attained under power vector P as the *conditional* (with respect to P) *supreme value of the objective function* and represent this value by $\Omega^*(P)$. That is,

$$\Omega^*(P) = \text{Sup}_{(\lambda_1, \dots, \lambda_m)} \{ \Omega(\lambda_1, \dots, \lambda_m) : (\lambda_1, \dots, \lambda_m) \in S(P) \}. \quad (5.9)$$

Given a selected power vector P , the conditional supreme value of the objective function $\Omega^*(P)$ is achieved (in finite time or asymptotically in time) as the system designer selects an *optimal joint scheduling and routing scheme* over the underlying (finite or infinite) operational time period T . The objective is to characterize the key features of a power vector solution that maximizes the conditional supreme value of the objective function $\Omega^*(P)$ over the set of power vectors $P = (P_1, \dots, P_n)$, $0 \leq P_i \leq P_{\max}$, $i = 1, \dots, n$. We call such a power vector an *optimum power vector*, identify an associated optimal joint scheduling and routing scheme as an *optimum joint scheduling and routing scheme*, and denote the resulting value of the objective function as the *optimum objective function value*. Let Ω^* denote the optimum objective function value. Then, we have

$$\Omega^* = \text{Max}_P \{ \Omega^*(P) : P = (P_1, \dots, P_n), 0 \leq P_i \leq P_{\max}, i = 1, \dots, n \}, \quad (5.10)$$

⁹ Excerpt from the invited article "On the effect of optimal power control in wireless mesh networks," Arash Behzad and Izhak Rubin, Electrical Engineering Department, University of California (UCLA), Los Angeles, CA 90095-1594, E-mail: {abehzad, rubin}@ee.ucla.edu

Library of Congress Cataloging-in-Publication Data

Aggélou, George.

Wireless mesh networking / George Aggélou.

p. cm.

ISBN 978-0-07-148256-1 (alk. paper)

1. Wireless communication systems. I. Title.

TK5103.2.A415 2008

621.384—dc22

2008023925

Copyright © 2009 by The McGraw-Hill Companies, Inc. All rights reserved. Printed in the United States of America. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a data base or retrieval system, without the prior written permission of the publisher.

1 2 3 4 5 6 7 8 9 0 DOC/DOC 0 1 4 3 2 1 0 9 8

ISBN 978-0-07-148256-1

MHID 0-07-148256-3

Sponsoring Editor

Stephen S. Chapman

Proofreader

Lee A. Young

Production Supervisor

Pamela A. Pelton

Indexer

Slavka Zlatkova

Editing Supervisor

Stephen M. Smith

Art Director, Cover

Jeff Weeks

Project Manager

Sandhya Joshi, Aptara[®], Inc.

Composition

Aptara[®], Inc.

Copy Editor

Subathra Natarajan, Aptara[®], Inc.

Printed and bound by RR Donnelley.

McGraw-Hill books are available at special quantity discounts to use as premiums and sales promotions, or for use in corporate training programs. To contact a special sales representative, please visit the Contact Us page at www.mhprofessional.com.

This book is printed on acid-free paper.

Information contained in this work has been obtained by The McGraw-Hill Companies, Inc. ("McGraw-Hill") from sources believed to be reliable. However, neither McGraw-Hill nor its authors guarantee the accuracy or completeness of any information published herein, and neither McGraw-Hill nor its authors shall be responsible for any errors, omissions, or damages arising out of use of this information. This work is published with the understanding that McGraw-Hill and its authors are supplying information but are not attempting to render engineering or other professional services. If such services are required, the assistance of an appropriate professional should be sought.