Enhancing Efficiency and Effectiveness of 802.11 MAC in Wireless Mesh Networks

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Abstract - *The 802.11 MAC protocol is widely used in wireless mesh networks. However, with multi-hop transmissions prevalent in such networks, neither the current 802.11 DCF basic scheme nor the RTS/CTS scheme can achieve full utilization of network capacity for various reasons. First, the 802.11 MAC provides low spatial reuse (low parallelism of transmissions). Second, the collision avoidance mechanism in 802.11 becomes less effective for multi-hop scenarios. In this article, we review two types of 802.11-based MAC enhancements to improve the efficiency and effectiveness in wireless mesh networks. One class of schemes focus on tuning transmission power and carrier sense threshold. In static strategies, the interference model is introduced and a static optimal strategy is derived for the worst case scenarios. In dynamic strategies, transmission power and carrier sensing threshold are tuned adaptively to various network conditions and access patterns. Another class of schemes exploit the channel-state diversity among the receivers of a specific sender by scheduling the frames based on the receivers' conditions.*

I. Introduction

Compared to single-hop access-point (AP)-based wireless LANs (WLANs), multi-hop mesh networks provide extended coverage and greater flexibility in applications. However, due to their decentralized self-organizing architecture, they present greater complexity in channel access and interference patterns, requiring more sophisticated medium access control than the plain 802.11 MAC protocol. For a conventional WLAN, all mobile stations within an infrastructure basic service set (BSS) directly communicate with the AP and only one transmission at a time is allowed. In contrast, in a mesh network multiple simultaneous transmissions are supported and a well-designed MAC protocol that handles intra-/inter-flow interferences is critical for the network performance. Such a protocol should be able to accommodate a maximum possible number of concurrent transmissions, subject to maintaining the required channel quality for each transmission by mitigating their interferences. However, when deployed in mutltihop mesh networks, the regular IEEE 802.11 MAC is limited in its ability to provide high spatial reuse/parallelism and in handling interference scenarios compounded by multi-hop traffic, leading to poor network performance.

How should we increase parallelism in multi-hop mesh networks, based on the 802.11 MAC paradigm? Several complementary approaches have been proposed recently. In this article, we survey and divide them into two categories, based on what problems of the current 802.11 MAC they address in order to increase parallelism. The approaches in the first category focus on adjusting the transmission power or carrier sensing method in order to improve the spatial reuse without impairing the effectiveness of the collision avoidance mechanism in 802.11 MAC. The second category focuses on solving the head-of-line blocking problem by exploiting channel diversity among receivers through smart scheduling.

II. Increasing parallelism by power control and enhanced carrier sensing

The IEEE 802.11 MAC provides two collision avoidance (CA) mechanisms, the mandatory basic CSMA/CA and the optional virtual carrier sensing scheme with RTS/CTS [10]. Under the basic scheme, a station refrains from medium access if it senses any ongoing transmission on the wireless channel. The mechanism to determine whether or not the channel is busy is called clear channel assessment (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 [19]. 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 at a receiver can also increase as the carrier sense range becomes smaller, i.e., as concurrent transmitters get closer, which may impair the effectiveness of the collision avoidance mechanism. An interference model has been developed to describe the relationship among the transmission power, the carrier sense threshold and the aggregate throughput. By such a model the optimal carrier sense threshold is specified to maximize the aggregate throughput for a regular topology, as described next.

A. Static basic carrier sensing based on interference model

In [19][13], the worse case interference and signal-interference-noise ratio (SINR) at a receiver station is derived 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 by the Honey-grid model [8] as in Figure 1. As illustrated in the figure, the worst case interference occurs when the distances between the receiver R_0 and the six interferers approximately equal $D–R$, $D–R$, $D–R/2$, $D+R/2$, $D+R$, and D, respectively. It can be shown that the interference contributed by other potential interferers in the network can be neglected [7]. Thus, the interference from these six interferers dominates the total interference at R_0. It can be expressed then as

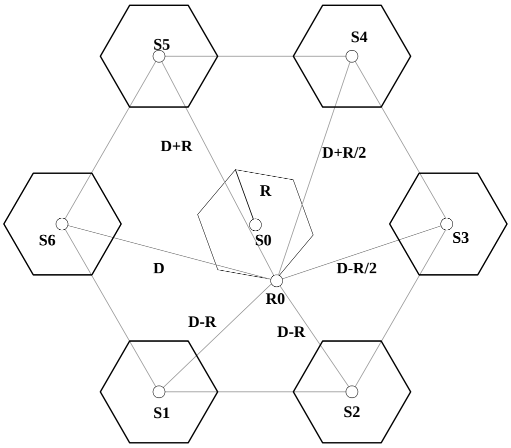

Figure 1 Worst case interference scenario

$$I = \frac{2P_{tx}}{(D-R)^{\theta}} + \frac{P_{tx}}{\left(D-\frac{R}{2}\right)^{\theta}} + \frac{P_{tx}}{D^{\theta}} + \frac{P_{tx}}{\left(D+\frac{R}{2}\right)^{\theta}} + \frac{P_{tx}}{(D+R)^{\theta}} \qquad \textbf{(1)}$$

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

$$SINR = f\left(\frac{D}{R}\right) = \frac{\frac{P_{tx}}{D^{\theta}}}{\frac{2P_{tx}}{(D-R)^{\theta}} + \frac{P_{tx}}{\left(D-\frac{R}{2}\right)^{\theta}} + \frac{P_{tx}}{D^{\theta}} + \frac{P_{tx}}{\left(D+\frac{R}{2}\right)^{\theta}} + \frac{P_{tx}}{(D+R)^{\theta}}} = \frac{1}{\frac{2}{\left(\frac{D}{R}-1\right)^{\theta}} + \frac{1}{\left(\frac{D}{R}-\frac{1}{2}\right)^{\theta}} + \frac{1}{\left(\frac{D}{R}\right)^{\theta}} + \frac{1}{\left(\frac{D}{R}+\frac{1}{2}\right)^{\theta}} + \frac{1}{\left(\frac{D}{R}+1\right)^{\theta}}} \qquad \textbf{(2)}$$

By the Shannon Capacity Theorem, given a certain channel bandwidth *W*, the achievable channel rate is at most $\Gamma_c = W \cdot \log_2(1+SINR)$. Then, the total network capacity can be expressed 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, i.e., $\sqrt{3} \cdot D^2 / 2$. 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

$$\Gamma_n = C_0 \left(\frac{T_{cs}}{P_{tx}}\right)^{2/\theta} \cdot \log_2\left(1 + f\left(\frac{1}{R} \cdot \left(\frac{P_{tx}}{T_{cs}}\right)^{1/\theta}\right)\right) \quad \textbf{(3)}$$

where C_0 is constant.

By 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 are 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.

B. Dynamic schemes with virtual carrier sensing

II.B.1 Virtual carrier sensing and its inefficiency and ineffectiveness

As a complement of the basic collision avoidance scheme, virtual carrier sensing [3] is dedicated to solving the collision problem due to hidden stations [17]. 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 done by setting the *network allocation vector* (NAV) of an overhearing node's MAC agent, which counts down as the transmission progresses. Therefore, the blocking area is decided by the transmission range of the RTS/CTS. The original design [3] assumes that the stations are able to interfere with the upcoming DATA/ACK frames only if they can receive RTS/CTS, i.e., 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, i.e., either the failure of collision avoidance 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: (*i*) the power of the received signal exceeds a threshold, called *receiver sensitivity*, denoted by P_{rth}, and (*ii*) 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}, i.e., the transmission range R, can be derived by solving

$$\frac{P_{tx}}{R^{\theta}} = P_{rth} \qquad \textbf{(4)}$$

The interference range, D_I is obtained by calculating the shortest distance between the receiver and a 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, i.e., satisfying

$$SINR = \frac{P_{tx}}{r^{\theta}} \bigg/ \frac{P_{\inf}}{D_I} \geq T_{cap} \qquad \textbf{(5)}$$

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} which is decided by the modulation scheme (and thus data rate) 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 collision avoidance. On the other hand, a CTS with an excessively large transmission range may cause low spatial reuse, especially in wireless multi-hop networks, referred to as its inefficiency.

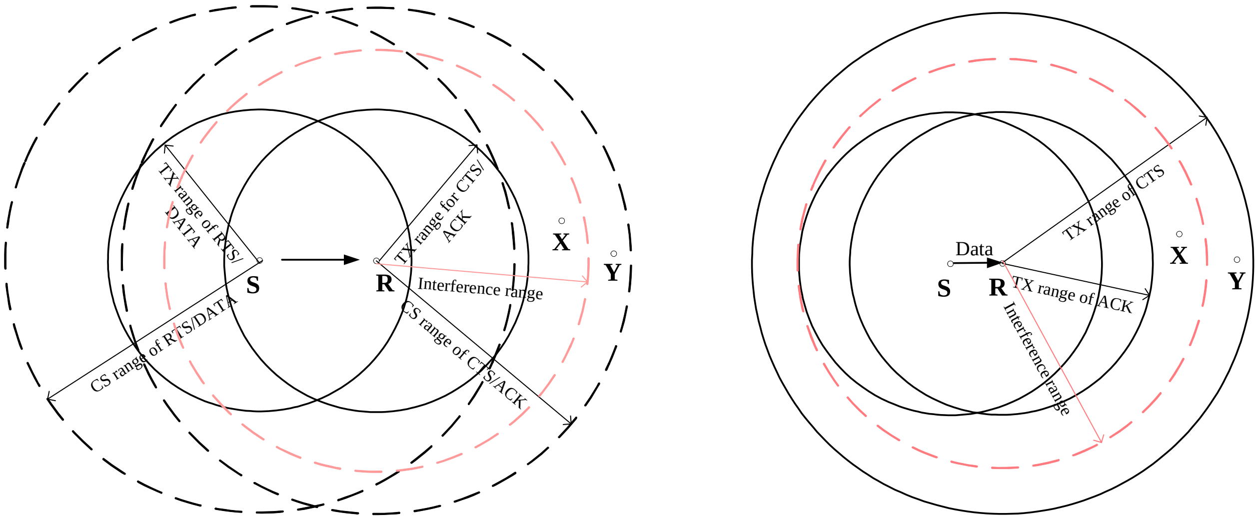

Figure 2 (a) Ineffectiveness of collision avoidance and (b) inefficiency of spatial reuse

An example shown in Figure 2(a) assumes that all nodes transmit RTS/CTS/DATA/ACK frames with the same power and modulation scheme. Although node X 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.

In order to avoid such collisions, some researchers have proposed to extend the transmission range of RTS/CTS by increasing the RTS/CTS transmission power. For example in [6], 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, i.e., the interference range of receiver *R* is also increased due to a larger P_{inf} in Eqn (5). This paradox can be mitigated by multi-channel schemes, e.g., PCMA in [15], by transmitting RTS/CTS frames on a different channel than the DATA/ACK frames.

For the networks with only one channel, a way to enlarge the RTS/CTS range without increasing the transmission power is to use a lower-rate modulation scheme which requires lower receiver sensitivity P_{rth}. In Eqn (4), using the same P_{tx} but a smaller P_{rth}, the corresponding transmission range increases. Thus, as shown in Figure 2(b), the CTS frame of receiver *R* can reach some potential interferers, such as node *X*, that it could not before. On the other hand, an excessively large transmission range of CTS may lead to the other extreme situation, i.e., inefficiency. As shown in Figure 2 (b), 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, the problem becomes: how to improve the spatial reuse/efficiency without impairing the effectiveness of collision avoidance, as discussed next.

II.B.2 Soft blocking schemes

The IA-MAC [4] provides a single-channel solution. Its idea is similar to [15], 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 Figure 2(b). To achieve high efficiency, some node, say node *Y*, may choose not to set its NAV when overhearing a CTS if it can tell its transmission will not interfere with the reception at receiver *R*. 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 $P_{I\text{-}current}$ and the power of the received RTS as $P_{rcv\text{-}RTS}$, respectively. The minimum SINR should not drop below the capture threshold, i.e.,

$$SINR = \frac{P_{rcv-RTS}}{P_{I-current} + P_{I-add}} \geq T_{cap} \qquad \textbf{(6)}$$

To calculate the maximum additional interference $P_{I\text{-}add}$ that it can tolerate from future unintended transmitters, the receiver solves Eqn (6). The receiver puts the calculated $P_{I\text{-}add}$ in 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 at the same time, the collision avoidance 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 Figure 1, 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 Figure 1.

II.B.3 Power control schemes

Power control in 802.11 MAC was originally proposed for the purpose of power saving [6][12]. It was first in [16] that a power control scheme, called POWMAC, was designed to enhance spatial reuse and to manage interference in wireless multi-hop networks, aiming at improving the network throughput. The basic idea can be illustrated as follows. In Figure 2(b), 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 finds the maximum allowable transmission power (P_{MAP}) it can use without disturbing any of its neighbors:

$$P_{MAP}(i) = \min_{u}\{P_{MTI}(u)/G_{iu}, P_{MAX}\} \qquad \textbf{(7)}$$

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 which 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 [16]. Upon receiving this RTS, the receiver j determins if the regular transmission power P^{ij}_{load} of DATA frame is within the range $P^{ij}_{min} \leq P^{ij}_{load} \leq P_{MAP}$, where P^{ij}_{min} is the minimum power required for DATA frame so that it can be decoded given the current interferences from existing transmissions. If P^{ij}_{load} 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:

$$P_{MTI} = \frac{P_{I-add}}{N} \qquad \textbf{(8)}$$

As Eqn (8) 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}, Eqn (7).

As we have seen, with more flexible allocation of transmission power and adaptive blocking area, a power control scheme for 802.11 MAC further improves spatial reuse and thus the network throughput. In the soft-blocking scheme, the state of a neighboring node is either "on", i.e., in the blocking range, or "off", i.e., 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 in Section II.B.1. For implementation, it is imperative for the 802.11 products to measure or control the power with level of accuracy required by POWMAC protocol [1]. Moreover, for multi-rate wireless networks with rate-adaptive MAC [9], the throughput gain through power control may be ambiguous. That is because the resource of additional tolerable interference can be used differently by rate adaptation mechanism to increase the link rate instead of increasing the number of concurrent transmissions, as in POWMAC.

II.B.4 Self-learning carrier sensing

Compared to above schemes, the method of self-learning carrier sensing [5] 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 mapping curve is updated after every access request. Before each access attempt, the sender looks up the mapping curve with the current sensed signal strength to obtain the estimated success ratio. If the obtained success ratio is lower than some threshold, which indicates high likelihood of media access activities from other nodes, the sender will back off and wait until it believes 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.

III. Exploit channel- and/or spatial-diversity with MAC-layer scheduling

A. Head-of-line blocking problem

Another type of methods [18][20][11][14] for increasing concurrent transmissions and improving parallelism in mesh networks is to exploit the channel/spatial-diversity by re-scheduling the frames in the sender's queue. In wireless mesh networks, some stations can be particularly overloaded. For example, a mesh network gateway [2] needs to deliver simultaneously multiple down-stream data flows between the Internet and many wireless stations; a mesh router may have to serve several neighbors by forwarding their packets along multi-hop 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. In 802.11, each time when a DATA or RTS transmission times out, the sender doubles the contention window, so to wait for a longer backoff time before the retransmission, for the purpose of collision avoidance. The frame will not leave the queue until the transmission is acknowledged or until the maximal number of retries is reached. This frame has thus been blocking the subsequent frames from being transmitted although their receivers may be available at this time. Due to the exponentially-growing backoff time overhead, HOL blocking problem can greatly lower channel utilization and network capacity. Simulation indicates that the MAC layer backoff time fraction at the sender may reach up to 70% [20]. 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 wired Internet connection and be blocked in the queue.

For a loaded mesh router, the backoff makes the router 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 multi-hop mesh networks, the HOL blocking problem must be addressed.

B. MRTS

A straightforward solution for HOL problem is to reschedule the frames in sender's queue based on the status of their next-hop stations. For example, in Figure 3, node *B* is unavailable for receiving any frames from *A* since it is blocked by another transmission. Instead of waiting for *B*, node *A* may first send the frames queued for other available receivers, such as *E*. As a result, the backoff overhead is avoided and the channel utilization is improved. In addition, the number of concurrent transmissions is increased.

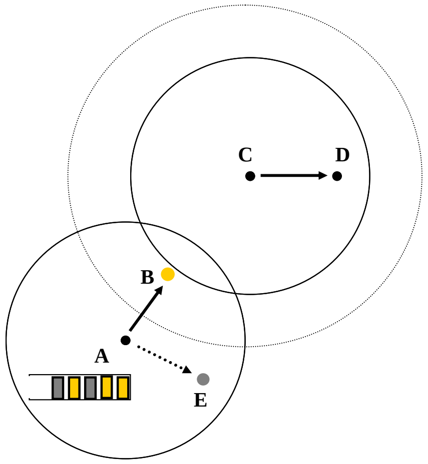

Figure 3 Rescheduling for Head-of-line blocking problem

To obtain the state information of the next-hop neighbors, a multicast RTS/CTS (MRTS) handshake is proposed in [11][18]. 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

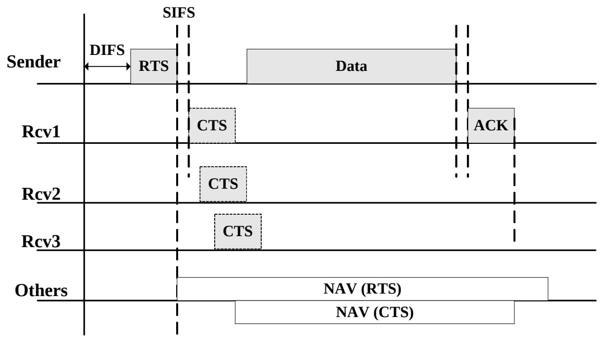

Figure 4 MRTS protocol timeline

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 is to avoid the collision of CTS frames returned by the receivers. The first candidate receiver (Rcv1 in Figure 4) that successfully receives MRTS replies with a CTS, unless it is blocked by an ongoing transmission in its neighborhood. 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 + $(n-1)\times$slot_time. Such a right-to-reply is implicitly propagated down the chain until a non-blocked 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, i.e., 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 good 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, i.e., 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. In [20], an extension, the adaptive channel-state-based scheduling with MRTS is developed to select the receiver candidates and decide the length of the MRTS list adaptively based on the candidates' channel states. The extended scheme constructs a list of receivers with mutually diverse channel states based on historical observations, which minimizes the length of MRTS frames without impairing their success ratio.

IV. Summary

In this article, we discuss the inefficiency (low spatial reuse) and the ineffectiveness of collision avoidance of regular 802.11 MAC in wireless multi-hop mesh networks. Due to these reasons, neither the current 802.11 DCF basic scheme nor the RTS/CTS scheme can achieve full utilization of network capacity. We review two types of 802.11-based MAC enhancements for wireless mesh networks. The first class of schemes focus on transmission power control and novel carrier sensing strategies. A static optimal strategy based on the worst interference model and some dynamic approaches are described. By accurate control and planning based on interference and error models, these approaches seek to increase the number of simultaneous transmissions and, at the same time, to avoid collisions and maintain the quality of each link. Their performance can be highly dependent on the accuracy of modeling and the ability in power measuring and control of wireless devices. The second class of schemes focus on solving head-of-line blocking problem on a specific loaded sender by re-scheduling the frames based on the receivers' conditions. The MRTS scheme probes multiple receivers for their availability. Due to the channel-state diversity among the receivers, the likelihood of MRTS acceptance is increased. Therefore, the spatial reuse and the throughput performance are improved.

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