Control Frame Shaping in Power Controlled and Directional MAC Protocols [*]

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Abstract

This paper discusses the ideal shapes of control frames (i.e., RTS/CTS frames) in the IEEE 802.11 MAC layer for efficient power control and directional beam forming in mobile ad hoc networks (MANETs). Control frames are used to coordinate concurrent transmissions for collision avoidance. Most existing schemes are either overly conservative (i.e., using omnidirectional control frames without power control) or overly aggressive (i.e., using directional control frames with the minimal power). The former has low spatial reuse and the latter increases collisions. We propose two control frame shaping *schemes that encourage spatial reuse while avoiding the collisions. The first scheme, called* adaptive power control, *uses a single RTS/CTS exchange to solve the hidden terminal problem caused by heterogeneous transmission powers. The second scheme, called* control frame relay*, uses multiple RTS/CTS frames to avoid both the hidden terminal and deafness problems. In designing these schemes, we assume an existing topology control protocol. By exploiting the benefits of regulated traffic and neighbor awareness that accompany a topology control process, the shapes of control frames can be reduced significantly. Extensive simulations were conducted and simulation results show that the proposed scheme outperforms several existing protocols in terms of spatial reuse and collision avoidance.*

Keywords*: Directional antenna, media access control (MAC), mobile ad hoc network (MANET), power control, simulation, topology control.*

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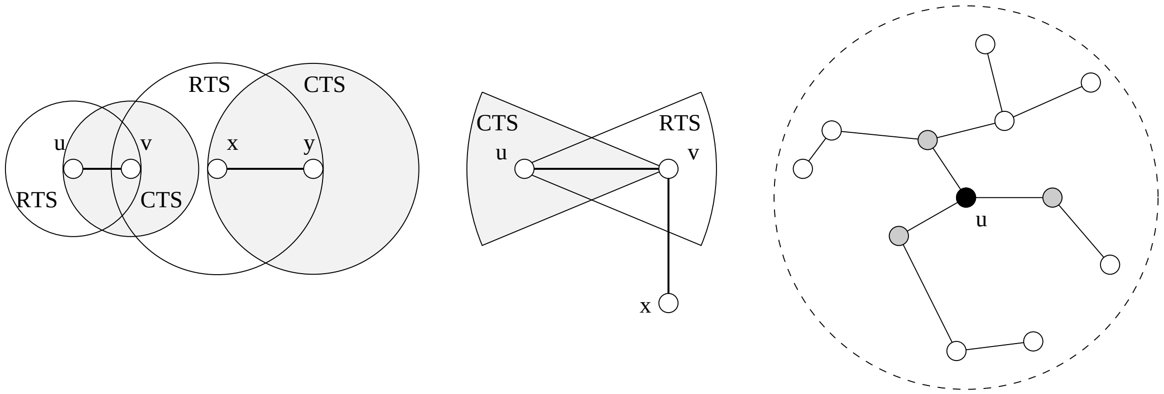
1 Introduction

The capacity of a mobile ad hoc network (MANET) is constrained by its spatial reuse ratio, i.e., the ability to pack as many simultaneous transmissions as possible into a single network without causing a collision. Two physical layer techniques have been proposed to improve spatial reuse. By applying power control [23], a sender can reduce its transmission power to reach the receiver only (as shown in Figure 1 (a)). Using a directional antenna [28], a sender can focus its transmission power to a narrow beam pointing to the receiver (as shown in Figure 1 (a)). Both techniques have the potential of increasing the network capacity significantly [29]. The challenge is how to realize this potential.

In MANETs, a media access control (MAC) layer coordinates transmissions of different nodes to maximize spatial reuse and avoid collision. The de facto standard in the MAC layer of MANETs is the IEEE 802.11 DCF [1], which uses an RTS/CTS mechanism to avoid collisions among neighbors. Specifically, before transmitting a data frame, two control frames, called request-to-send (RTS) and clear-to-send (CTS), are transmitted from the sender and receiver, respectively, to block transmissions from their neighbors. When this scheme is extended to support power control and directional antennas, the problem of *control frame shaping* arise: to which direction(s) should RTS/CTS be transmitted and, for each of these directions, which transmission power should be used.

In existing MAC protocols, the control frame shaping mechanism is simplified to two selections: omnidirectional versus directional transmission, and maximal versus minimal power. The most conservative schemes [28, 2, 25] use omnidirectional transmission and maximal power. More aggressive schemes select direction transmission [9, 17], minimal power [12], or both [30]. The conservative schemes cannot significantly increase the network capacity, while the aggressive schemes are vulnerable to transmission failures. We show two transmission failures caused by the aggressive schemes. In Figure 1 (a), control frames are transmitted using the minimal power. As the distance of link (u, v) is less than that of (x, v), a CTS from v does not block a transmission from x. This causes a collision at v and is called the *hidden terminal problem* using heterogeneous transmission powers [23]. The second example uses directional control frames. In Figure 1 (b)), the receiver v transmits the CTS to the sender u only. An uninformed neighbor x then tries to send a packet to v and will not succeed. This is called the *deafness problem* [8], as v is pointing its reception beam towards u and cannot hear from x. The hidden terminal and deafness problems cause retransmissions and link failures, both damaging the network throughput.

We believe mature control frame shaping is critical for balancing spatial reuse and collision avoidance. Unfortunately, without a knowledge of local traffics, even the maximal shape (i.e., omnidirectional transmssion with the maximal power) cannot prevent the hidden terminal problem. We propose control frame shaping based on local information provided by a topology control protocol



(a) Minimal RTS/CTS (b) Directional RTS/CTS (c) Topology control

Figure 1. Control frame shapes and topology control.

[5, 19, 20, 21, 31, 32, 37, 38]. Note that power control and directional antennas are usually applied to dense networks, which also apply topology control to improve energy and channel efficiency. In a typical topology control protocol, each node selects a minimal set of *logical neighbors* to maintain network connectivity. For example, node u in Figure 1 (c) selects only three logical neighbors (gray nodes) from its 1-hop neighbors. In this paper, we identify two benefits of topology control, which can be exploited to improve spatial reuse, but were usually ignored by existing schemes:

- *Regulated traffic*. After topology control, data traffic is confined to *logical links* (i.e., links between logical neighbors). The control frame shaping scheme only needs to consider neighboring logical links, instead of all 1-hop neighbors. For example, if node v in Figure 1 (b) has only two logical neighbors u and x, it only needs to transmit two directional CTS frames, instead of using an omnidirectional one, to block x's transmission.

- *Neighbor awareness*. Most topology control schemes collect *1-hop information* (i.e. locations of 1-hop neighbors) at each node. The direct benefit is that it eliminates the need of a neighbor locating mechanism at MAC layer [28, 27, 18, 36]. More importantly, each node can adjust its control frame shapes based on the 1-hop information without extra cost.

We propose two control frame shaping schemes to support efficient power control and directional beam forming in MANETs. The first scheme, called *adaptive power control*, uses a single RTS/CTS pair to solve the hidden terminal problem caused by heterogeneous transmission powers. The second scheme, called *control frame relay*, uses multiple RTS/CTS frames to avoid both the hidden terminal and deafness problems. In these schemes, the control frame shapes are minimized to prevent only interferences among logical links. The interference of control frames is also considered and blocked. To avoid the deafness problem, control frames are transmitted to logical neighbors of the sender and receiver with the minimal power. Extensive simulations were conducted and simulation results show that the proposed scheme outperforms several existing protocols in terms of spatial reuse and collision avoidance.

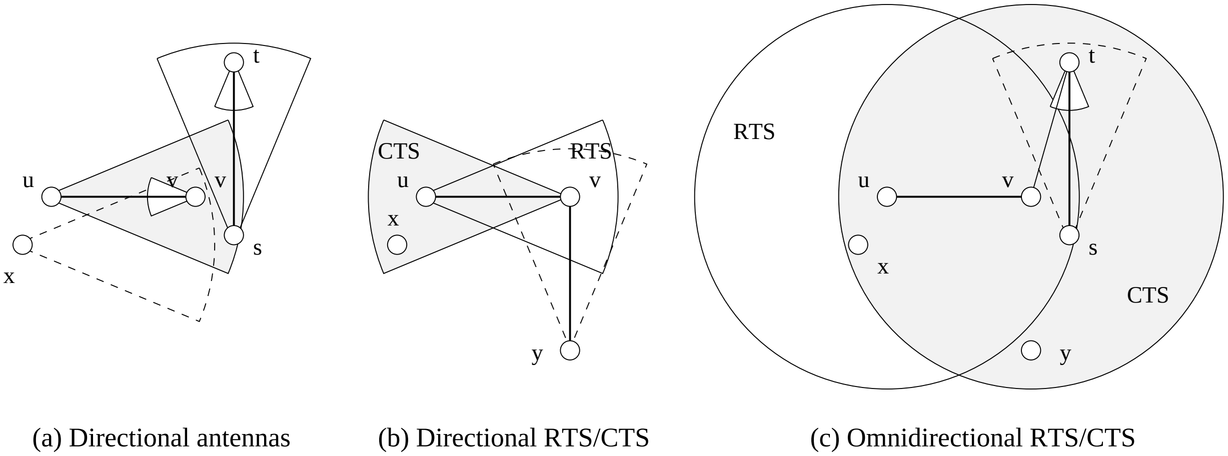
So far, no existing method provides a comprehensive solution for control frame shaping in MANETs using both power control and directional antennas. Both busy tone-based [23, 24, 39] and TDMA [3, 34] protocols exist, which also support power control and directional antennas in the MAC layer. A major drawback of these protocols is the prevalence of interoperability problems with the existing standard and hardware. This paper focuses on single channel CSMA solutions that are compatible with the IEEE 802.11 standard.

The proposed schemes take a cross-layer approach [16] that allows information sharing between the MAC and topology control protocols. Fast convergence can be achieved using complete 1-hop information. However, such a tight coupling is not a requirement. In the cases of looose coupling, where partial or no neighborhood information is available, a neighbor discovery mechanism [28, 36] can be used to identify active links, and the frame shapes can be adjusted in an incremental learning process.

The major contributions of this paper are as follows:

1. We have developed a single channel mechanism to detect and avoid the hidden terminal problem caused by the heterogeneous transmission powers in a power control scheme.
2. We have proposed to tailor the shape of control frames based on logical neighbor information, so as to alleviate the deafness problem and minimize the interference caused by control frames.
3. We have presented optimization techniques that speed up the control frame shaping process by sharing the 1-hop information with a topology control component.
4. We have evaluated the performance of the proposed mechanisms via both analytical and simulation studies.

The remainder of this paper is organized as follows: Section 2 introduces MAC schemes that support power control and directional antennas. It also briefly introduces localized topology control in MANETs. The proposed control frame shaping schemes are discussed in Section 3. Section 4 presents simulation results. Then we compare the proposed schemes with related work in Section 5. Section 6 concludes this paper.



(a) Directional antennas (b) Directional RTS/CTS (c) Omnidirectional RTS/CTS

Figure 2. Directional MAC protocols.

2 Preliminaries

This section introduces several existing solutions to extend the IEEE 802.11 MAC protocol to support power control and directional antennas. We show that each of these solutions has its limitations. These limitations will be addressed later in the proposed control frame shaping schemes. Some properties of localized topology control that can be exploited in a control frame shaping process are also discussed.

2.1 MAC layer support of directional antennas

Directional antennas have been employed to improve spatial channel reuse in MANETs. Using the directional beam forming technology, a sender can focus its transmission power to the preferred receiver. Similarly, a receiver can enhance the received signal from a certain direction and reduces interferences from other directions. As shown in Figure 2 (a), when all nodes use directional transmission and reception modes, communication in one direction ($u \rightarrow v$) will not interfere with another direction ($s \rightarrow t$).

On the other hand, directional antennas incur new challenges to the MAC layer. The first one, called the *directional hidden terminal problem*, is illustrated in Figure 2 (a). After the sender u forms its transmission beam towards the receiver v, another node x in the opposite direction cannot sense this transmission. Node x may transmit in the same direction, which causes a collision at v.

Various extensions of the IEEE 802.11 MAC protocol have been proposed to solve the above problem. The original IEEE 802.11 protocol was designed for omnidirectional antennas. It uses a sequence of ready-to-send (RTS), clear-to-send (CTS), DATA, and acknowledge (ACK) frames for virtual channel sensing and collision detection: The sender first sends an RTS, and the receiver replies with a CTS. The RTS and CTS frames reserve the channel for the following DATA and ACK frames, such that neighbors of the sender and receiver will "sense" a busy channel for a period of time as indicated in the CTS and RTS frames. In addition, a missing CTS or ACK is viewed as a collision, upon which the sender uses a doubled backoff delay before its next attempt to transmit to avoid congestion.

We consider two directional variants of the above handshake sequence. In both schemes, DATA and ACK are transmitted directionally. The difference lies in the shapes of CTS and RTS frames.

Directional RTS/CTS [9, 17]: In this approach, the RTS is transmitted to the receiver's direction only, and the CTS is transmitted to the sender's direction. Since the sender and receiver have formed their reception beams towards each other, only nodes in these two directions may cause a collision. When a neighbor of the sender (receiver) receives the RTS (CTS), it will virtually sense a busy channel in the sender's (receiver's) direction, and hold any transmission to this direction using a directional network allocation vector (DNAV) [35]. As shown in Figure 2 (b), after receiving a CTS from v, x will not transmit to the direction, but can still transmit to other directions.

This protocol suffers from the deafness problem. Suppose node y in Figure 2 (b) is sending an RTS to v. Since v is beam forming toward u, it cannot hear this RTS and will not reply. This is a viewed as a collision by y. Before v finishes its current activity and returns to the omnidirectional reception mode, y will increase its backoff delay and re-transmit the RTS several times, which leads to poor performance.

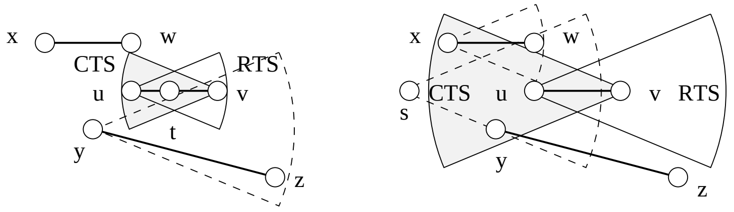
Omnidirectional RTS/CTS [17, 6]: To avoid the deafness problem, the RTS and CTS frames are transmitted to *all* directions. In this case, all neighbors of the sender and receiver are aware of the ongoing transmissions and will not initiate a transmission to these busy nodes. In Figure 2 (c), node y receives a CTS from v and will not attempt to transmit to v. Note that y can still send a packet to another node (e.g., s) in v's direction. One problem of this protocol is that omnidirectional RTS and CTS may interfere with the DATA/ACK transmissions. For example, if t in Figure 2 (c) is receiving from s, a CTS from v will causes a collision at t. The RTS/CTS shape must be tailored carefully to avoid such collisions.

In the next section, we will discuss RTS/CTS shapes that alleviate the deafness problem, and minimize the interference of control frames using the logical neighbor information.

2.2 Topology control and power control

Topology control and power control are closely related. Some literature uses these two terms interchangeably. In this paper, we use the term "topology control" to indicate the process of selecting a few logical links to form a sparsified and connected logical topology. The term "power control" represents the physical layer and MAC layer efforts to reduce the transmission power on a per packet basis.

In topology control, most links in the original networks are removed (i.e. invisible to upper layer protocols), while the remaining links still maintain network connectivity. Basically, a link (u, v) is



(a) Minimal RTS/CTS (b) Maximal RTS/CTS

Figure 3. Directional and power control MAC protocols.

removed if there is an alternative path connecting u and v, such that the total cost of this path [19, 31], or the individual cost of every link in this path [5, 20, 21, 32, 37, 38] is less than the cost of (u, v). In a typical localized topology control protocol, 1-hop information [5, 21, 32] or at least positions of logical neighbors [19, 20, 31, 38] are collected to identify alternative paths. Figure 1 (c) shows a sample localized topology control protocol [21]. A node u first builds a local minimal spanning tree (LMST) to connect its 1-hop neighbors (all nodes within the dashed circle), and then selects its first level children in the LMST as its logical neighbors.

In most existing power controlled directional MAC protocols, DATA and ACK frames are transmitted using the minimal power. The difference lies in the transmission power of RTS and CTS frames.

Minimal RTS/CTS [30]: RTS and CTS frames are transmitted using the minimal power. In Figure 3 (a), when u is transmitting to v, the CTS from v is received only by nodes between u and v (e.g., node t). In this case, node x is allowed to transmit to w and will not cause a collision. This approach suffers from the hidden terminal problem. In Figure 3 (a), the minimal power to reach z from y is larger than that from u to v. A transmission from y to z will cause a collision at v. This collision cannot be prevented because a CTS from y transmitted using the minimal power cannot be received by z.

Maximal RTS/CTS [28, 13]: RTS and CTS frames are transmitted using the maximal (normal) power to prevent the hidden terminal problem. As shown in Figure 3 (a), when v sends the CTS using the maximal power, y will be warned about the on-going transmission and hold its transmission to z. The major drawback of this approach is the reduced spatial reuse. For example, link (x, w) in Figure 3 (b) can no longer be used simultaneously with link (u, v), because a CTS from v can now interfere with an ACK from w to x. In addition, this scheme cannot eliminate the hidden terminal problem. As shown in Figure 3 (b), suppose the distance between nodes s and v is slightly larger than the normal transmission range and cannot decode the CTS from v. When s sends an RTS to s using the maximal power, this RTS will still interfere with a DATA frame sent from u to v using the minimal power, and cause a collision at

v.

In the next section, we will show how to increase the DATA/ACK power to tolerate interferences from these “invisible” nodes and, meanwhile, how to reduce the RTS/CTS power to improve spatial reuse.

3 Proposed Scheme

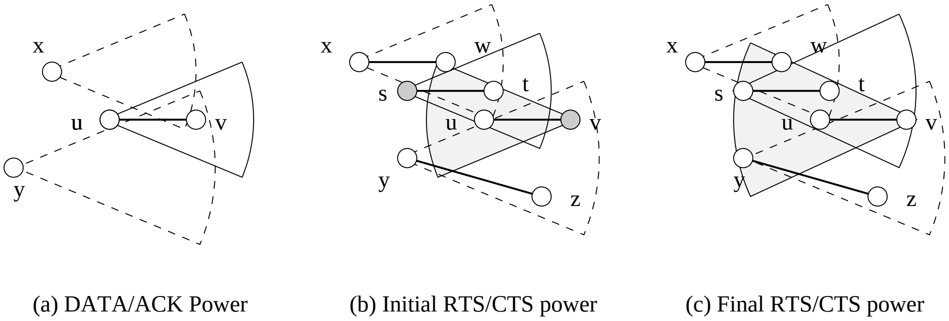
In this section, we propose two control frame shaping schemes that extend the IEEE 802.11 MAC protocol to support power control and directional antennas. In the first extension, called *adaptive power control*, an incremental adjusting process is used to find a “perfect” power assignment of RTS/CTS frames, which avoids the hidden terminal problem while maintaining high spatial reuse. The second extension, called *control frame relay*, uses multiple RTS/CTS frames to alleviate the deafness problem. It also further reduces the RTS/CTS power for higher spatial reuse.

Both schemes assume a topology control component, which selects a few logical neighbors for each node, and restricts communications to logical links. Two scenarios are considered: (1) when the MAC protocol is loosely coupled using the topology control scheme, and uses only the logical neighbor information, and (2) when the two components are tightly coupled and share the 1-hop information. The control frame shaping schemes are first introduced in the context of loose coupling. Then extensions are discussed that achieve higher performance in the tight coupling scenario.

3.1 Adaptive power control

This first control frame shaping scheme uses the standard RTS/CTS/DATA/ACK handshake sequence of the original IEEE 802.11 MAC protocol. It transmits RTS/CTS frames directionally to avoid the hidden terminal problem. Its major difference from other directional RTS/CTS schemes is the fine tuning of RTS/CTS powers on a per direction basis. Each node maintains a list of potential interferences from each direction, and adjusts its RTS/CTS powers to suppress these interferences before each DATA/ACK exchange. Two mechanisms are involved: the *detection* and *suppression* of potential interferences to DATA and ACK frames.

Let u be a sender using directional transmission, and v a receiver using omnidirectional reception. $P_{Min}(u,v)$ denotes the minimal transmission power for u to reach v. That is, when u directs its transmission beam towards v, the signal strength received by v is sufficient for a successful decoding. The value of $P_{Min}(u,v)$ can be calculated based on the distance between u and v, or estimated based on recent channel history information [30]. Let P_{Max} be the normal transmission power before power control, and $SINR_{Min}$ the minimal signal to interference plus noise ratio (SINR) for successful decoding.



(a) DATA/ACK Power (b) Initial RTS/CTS power (c) Final RTS/CTS power

Figure 4. Adaptive power control.

For a given link (u, v), the DATA and ACK frames are transmitted using the following fixed powers:

$$P_{DATA}(u,v) = \min\{(SINR_{Min}+1)P_{Min}(u,v), P_{Max}\} \tag{1}$$

$$P_{ACK}(v,u) = \min\{(SINR_{Min}+1)P_{Min}(v,u), P_{Max}\} \tag{2}$$

The non-minimal DATA/ACK powers are used for successful interference detection. In other words, the interference range (with respect to the DATA/ACK frames) of any frame is now no larger than its transmission (capture) range. If a third party RTS/CTS can affect the reception of DATA (ACK) at v (u), then v (u) must be able to decode the RTS/CTS frame to identify the source of interference. In equation (1), the coefficient $(SINR_{Min} + 1)$ provides sufficient redundancy to tolerate the interference from another node w plus the background noise, if w uses a transmission power less than $P_{Min}(w, v)$. The same protection is provided in equation (2) for an ACK frame.

In Figure 4 (a), we use an extended range to represent the extra power used by u to transmit a DATA frame to v. Since node v is outside of the transmission range of x, the corresponding signal strength at v is at most $1/(SINR_{Min} + 1)$ that of the DATA signal, which does not compromise the DATA frame reception. The transmission range of y includes v, which may cause a collision. However, v has an opportunity to receive y's message and identify y as a source of interference. The same argument also applies to the ACK frame: an interference to the ACK is either irrelevant or will eventually be detected by node u.

Based on the above interference detection mechanism, the transmission powers of the RTS and CTS frames are adjusted accordingly, as shown in Algorithm 1. To suppress interference, an RTS/CTS frame needs to be transmitted to all sources of potential interference. The minimal power of an RTS (CTS) is that of a DATA (ACK) frame (line 1). Such a power is necessary for other nodes to detect a potential interference from u (v). Once a potential interference is detected, the RTS/CTS power will be adjusted to cover the new source of the interference (lines 2 and 3). As the increased RTS/CTS power may cause

Algorithm 1 Adaptive power control (over each link (u, v))

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1: Initially, $P_{RTS}(u, v) = P_{DATA}(u, v)$ and $P_{CTS}(v, u) = P_{ACK}(v, u)$.
2: When $u$ receives an RTS/CTS from another node $x$ that lies in $v$'s direction, set $P_{RTS}(u, v) = max\{P_{Min}(u, x), P_{RTS}(u, v)\}$.
3: When $v$ receives an RTS/CTS from another node $y$ that lies in $u$'s direction, set $P_{CTS}(v, u) = max\{P_{Min}(v, y), P_{CTS}(v, u)\}$.
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new interferences and power adjusting at other nodes, the adjusting process may take several rounds to converge.

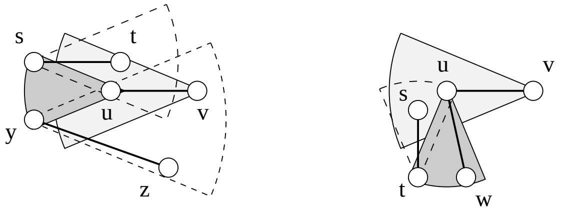
In Figure 4 (b), $P_{CTS}(v, u)$ is initially smaller than $P_{Min}(v, y)$. After v receives an RTS from y, $P_{CTS}(v, u)$ is increased to $P_{Min}(v, y)$. Then s may receive the following CTS from v, and increase its RTS power accordingly. The final assignment of involved RTS/CTS powers is shown in Figure 4 (c). Note the above RTS/CTS power assignment is for two directions only: the direction from u to v and the one from v to u. Each node maintains a separate RTS/CTS power level for each direction. Power assignments in different directions may or may not be the same.

3.2 Control frame relay

The second control frame shaping considers both the hidden terminal and deafness problems. To avoid the hidden terminal problem, the interference detection mechanism described in the previous subsection is used to identify sources of potential interferences. The interference suppression scheme, however, is different. The RTS/CTS frames (i.e., *control frames*) are not sent directly to all sources of interferences.

Considering a logical link (u, v). The RTS is first transmitted from u to v with $P_{RTS}(u, v) = P_{DATA}(u, v)$. If there are interference sources outside of the range of the first RTS, v will relay the RTS to cover them. Similarly, the CTS is first sent from v to u and may be relayed by u. In Figure 5 (a), the CTS from v is relayed by u to reach a source of interference y. The transmission power of the relayed CTS is computed by v and passed to u via the first CTS frame. We assumed that u can identify y as a source of interference of v based on the signal strength of an RTS/CTS frame from y. If such an estimation is inaccurate, v can use an extra field in the CTS frame to specify the required relaying power.

Control frame relay reduces interferences caused by the RTS/CTS frames and thus achieves a higher spatial reuse ratio. As shown in Figure 4 (c), a CTS from v may interfere with an ACK frame at s, which has to increase its RTS power to cover v. When the CTS is relayed by u, as shown in Figure 5 (a), s does not increase its RTS power (or request t to relay the RTS to v), as the source of interferences (u) is already within its RTS range. Consider the situation when v attempts to initiate a transmission to u, while t is transmitting to s. Since u is aware of the ongoing transmission on link (t, s), it knows that



(a) Suppress interference (b) Alleviate deafness

Figure 5. Control frame relay.

forwarding v's RTS will cause a collision at t. In this case, u will drop the RTS and reply with a negative CTS to temporarily block v's transmission.

To alleviate the deafness problem, the RTS (CTS) is also relayed by the receiver (sender) to every direction with logical neighbors. The RTS/CTS power in these directions is set to the fixed value $P_{Min}(u,w)$, where w is the farthest logical neighbor from the receiver (sender) u in each direction. As shown in Figure 5 (b), the sender u will relay the CTS to its logical neighbor w. When receiving the CTS, w will not try to send messages to u until the end of the transmission on link (u,v). This mechanism is similar to the omnidirectional RTS/CTS scheme. The difference is that it uses multiple directional transmissions instead of a single omnidirectional one, and power control is used in every direction. In addition, an RTS/CTS will not be transmitted to those "empty" directions without a logical neighbor. The multiple relayed RTS/CTS frames can be transmitted simultaneously when the directional antenna can form multiple beams. In a single beam system, they can be transmitted in a sweeping process as in [10].

Relayed RTS/CTS frames may cause collisions in other directions. In Figure 5 (b), relaying a CTS to w may interfere with a transmission on link (s,t). In this case, using the interference detection mechanism, t will identify u as a source of interference and adjusts its (or s's) CTS power to cover u. Then u will skip the CTS relay in this direction when s is communicating with t.

3.3 Logical link estimation

In the previous discussion, we have assumed a MAC layer loosely coupled with the topology control component. Each node uses only the logical neighbor information to compute the initial powers of the RTS/CTS frames. The final RTS/CTS powers are settled in the following iterations of interference detection and suppression. In this subsection, we consider the tight coupling scenario, and discuss how each node uses the 1-hop information to speed up this learning process.

Many topology control algorithms support the action in line 1 of Algorithm 2. In these protocols, each

Algorithm 2 Smart CTS/RTS power initialization (on node u for link (u, v))

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Estimate logical links using $u$'s 1-hop information.
Emulate Algorithm 1 on these logical links.
After the emulation converges, use the resultant RTS/CTS power as the the initial power, and start Algorithm 1 from line 2.
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node u selects its logical neighbors based on its 1-hop information, i.e., positions of nodes within the normal transmission range of u. For each 1-hop neighbor v, u has the *partial 1-hop information* of v, i.e., locations of their common 1-hop neighbors. Using this partial 1-hop information, u can estimate the logical links adjacent to v. For example, the local minimal spanning tree in Figure 1 (c) is u's estimation of all logical links within its 1-hop neighborhood. This estimation is conservative. No logical link is missing, but some non-logical links may be identified as logical links, because an alternative path cannot be identified in the partial 1-hop information. However, this inaccuracy is a minor one. We expect that many nodes will use the estimated CTS/RTS powers as the final values.

3.4 Properties

In adaptive power control (Algorithm 1), the RTS/CTS power is adjusted dynamically to suppress emerging sources of interferences.

1. When does the adjusting process converge, and
2. What is the final RTS/CTS power after convergence?

The first question concerns the amount of collisions that may occur during the learning process due to the hidden terminal problem. The second question is related to the spatial reuse and bandwidth efficiency of the proposed protocols.

In the following discussion, we assume a symmetric channel (i.e., $P_{Min}(u, v) = P_{Min}(v, u)$) and non-overlapping directions (i.e. each node w appears in only one direction of another node u).

Theorem 1 *The adaptive power control algorithm converges before each node u increases its RTS/CTS power $Deg(u)$ times, where $Deg(u)$ is the number of u's 1-hop neighbors.*

Proof: In Algorithm 1, a node u increases its RTS/CTS power only if it finds a new source of interference w, such that $P_{Min}(u, w) > P_{RTS/CTS}(u, v)$ for a logical link v in the same direction of w. Since each w causes only one such increase of power at u, the number of increases is upper bounded by the number of sources of interference.

Let $P_{Max}(v)$ be the maximal transmission power used by a node v to send any frame in any direction. Initially, $P_{Max}(v) \leq P_{Max}$ for all nodes v. During each increase of RTS/CTS power due to a new source of interference w, the new $P_{Max}(v)$ is set to $P_{Min}(v, w) \leq P_{Max}(w) \leq P_{Max}$. Since the transmission power of all nodes is at most P_{Max}, all sources of interference must be 1-hop neighbors of the current node u. Therefore, node u increases its RTS/CTS power at most $Deg(u)$ times. □

From Theorem 1, the number of collisions at node u caused by an inappropriate RTS/CTS power is at most $\sum_{v \in N(u)} C(v, u)$, where $N(u)$ is the 1-hop neighbor set of u, and $C(v, u) \geq 0$ is the number of the transmissions of v in u's direction before u identifies v as a source of interference.

Then we consider the spatial reuse efficiency of the proposed schemes. The following two theorems assume aligned directions; that is, all nodes use a uniform set of antenna parameters to form a set of directional beams with the same width and bearing settings. We say two links (u, v) and (x, y) are in the same direction if u uses the same (or opposite) directional beam to reach v as the one used by x to reach y.

Theorem 2 *After the adaptive power control algorithm converges, the RTS/CTS power on each link* (u, v) *is at most* $\gamma_{Min} P(x, y)$, *where* (x, y) *is the longest logical link in the network in the same direction as* (u, v).

Proof: By induction. Initially, the RTS/CTS power on each link (u, v) is

$$P_{RTS/CTS}(u, v) = P_{DATA}(u, v) \leq P_{DATA}(x, y)$$

We show that the above inequality holds after each increase of the RTS/CTS power. Let w be the newly identified source of interference that causes the RTS/CTS power increase. When w is detected by u, it must be transmitting an RTS/CTS towards a node z. Because all nodes have aligned directions, link (w, z) must be in the same direction as (u, v). In addition,

$$P_{Min}(u, w) \leq P_{RTS/CTS}(w, z) \leq P_{DATA}(x, y)$$

in a symmetric channel. Under the assumption $P_{Min}(u, w) > P_{RTS/CTS}(u, v)$, the new RTS/CTS power after adjusting is

$$P_{RTS/CTS}(u, v) = P_{Min}(u, w) \leq P_{DATA}(x, y)$$

□

Theorem 2 suggests that the topology control protocol should reduce the length of the longest logical link to achieve spatial reuse. It also shows the benefit of using directional antennas: When all logical links are classified according to their directions, the RTS/CTS power depends on the length of the longest link in each direction, which is shorter than the maximal value of all logical links. The following theorem shows that the increased DATA/ACK power in the proposed schemes does not compromise the spatial reuse efficiency.

Theorem 3 *If two links are conflicting using the increased transmission powers defined in equations (1) and (2), they are also conflicting using the minimal transmission powers.*

Proof: Let (u, v) and (x, y) be such two links. Without loss of generality, assume a DATA frame with transmission power $P_{DATA}(u, v)$ collides with a DATA frame with power $P_{DATA}(x, y)$ at the receiver v. We show that two DATA frames with transmission powers $P_{Min}(u, v)$ and $P_{Min}(x, y)$ also collide at v. Note that a minimal transmission power translates into a minimal reception power

$$P^r_{Min} = SINR_{Min} P_{Noise},$$

where P_{Noise} is the noise strength at v. Therefore, a transmission power $P_{DATA}(u, v)$ corresponds to a reception power

$$\begin{aligned} P^r_{DATA}(u, v) &= (SINR_{Min} + 1)P^r_{Min} \\ &= (SINR_{Min} + 1)SINR_{Min} P_{Noise} \end{aligned}$$

Note that a transmission with power $P_{DATA}(x, y)$ causes a collision at v, the corresponding reception power is

$$\begin{aligned} P^r_{DATA}(x, v) &> \frac{P^r_{DATA}(u, v) - P_{Noise}}{SINR_{Min}} \\ &= (SINR_{Min} + 1 - \frac{1}{SINR_{Min}})P_{Noise} \end{aligned}$$

When both transmissions use the minimal powers, the corresponding SINR at v is

$$\begin{aligned} & \frac{P^r_{DATA}(u, v)/(SINR_{Min} + 1)}{P^r_{DATA}(x, v)/(SINR_{Min} + 1) + P_{Noise}} \\ < & \frac{SINR_{Min} P_{Noise}}{(1 - \frac{1}{SINR_{Min}(SINR_{Min}+1)})P_{Noise} + P_{Noise}} \\ < & SINR_{Min} \end{aligned}$$

which implies a collision at v. □

3.5 Discussion

In the previous discussion of the control frame shaping schemes, we consider only interferences from a single node, require the support of a topology control component, and assume a static network. This subsection presents enhancements that relax these constraints. Some implementation options, such as a tradeoff between spatial reuse and collision avoidance in the proposed schemes, are also discussed.

Tolerating multiple interferences. The DATA and ACK powers in equations (1) and (2) are designed to tolerate the interferences from a transmission with a power less than $P_{Min}(w, v)$, where w is the interference source and v the receiver. To tolerate interferences from η simultaneous transmissions, the following DATA and ACK powers can used:

$$P_{DATA}(u, v) = \min\{(\eta SINR_{Min}+1)P_{Min}(u, v),\ P_{Max}\} \tag{3}$$

$$P_{ACK}(v, u) = \min\{(\eta SINR_{Min}+1)P_{Min}(v, u),\ P_{Max}\} \tag{4}$$

The value of η depends on network density and traffic volume, which is hard to estimate. For practical use, η can be set to a small constant to encourage spatial reuse while maintaining a certain margin for fault tolerance.

Neighborhood information. Although both proposed control frame shaping schemes use the logical neighbor information, it should not be viewed as a limitation of these schemes. When a topology control component is missing, or the neighborhood information is unaccessible from the MAC layer, the adaptive power control scheme can still be applied. In this case, an omnidirectional RTS [26] using the normal transmission range can be used to initialize a transmission to an unknown neighbor. The receiver uses the incoming RTS to estimate the direction and required power to reach the sender, which use the replied CTS for the same purpose. A node will not adjust its RTS/CTS power after receiving an omnidirectional RTS. The same scheme can also used in discovering logical (or active) neighbors to alleviate the deafness problem.

Mobility and asymmetric channel. In a mobile network, the topology control component periodically updates its neighborhood information and logical neighbor set to reflect the movement of 1-hop neighbors. The control frame shaping process must restart after such an update for correctness. Node movement also causes inaccurate neighbor information during the time period between two updates. In this case, the estimation on the minimal power required to reach a certain destination may be insufficient. The solution is to use a fault-tolerant power as specified in equations (3) and (4) with an increased η. An asymmetric channel can cause similar problems, which can be solved in the same manner.

Another problem is an error in the estimated direction of transmission. In this case, a wider directional beam can be formed, or multiple transmissions can be used to cover neighboring directions.

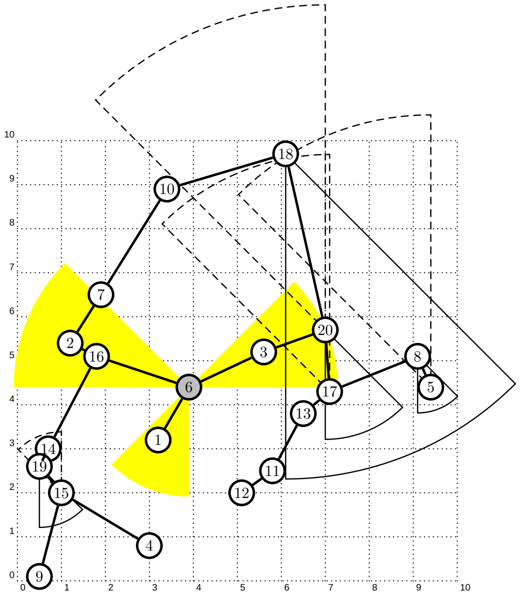


Figure 6. Control frame shapes in a sample network with 20 nodes and 8 antenna directions. The solid and dashed cones represent RTS/CTS ranges in two opposite directions. The shaded area represents RTS/CTS ranges of the gray node in all directions.

Aggressive spatial reuse. In the control frame relay scheme, the receiver cannot forward an RTS to a source of interference, if it would cause a collision with an on-going transmission. However, the receiver can still reply a CTS to the sender to continue the following DATA/ACK transmissions. In Figure 5 (a), before t transmits to s, u will be warned of this transmission. Therefore, when v sends an RTS to u, u will not relay this RTS to the direction of s. Since the transmission on link (v, u) is not conflicting with the one on (s, t), u can choose to reply a CTS to v and receive the following DATA from v.

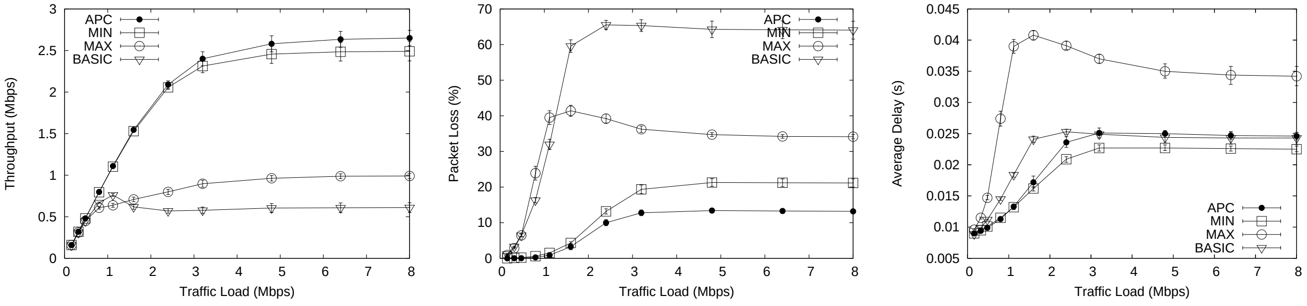
Note this option improves spatial reuse with a risk. Since node y is not aware of the transmission on link (v, u), it may send a message to z, which collides with an ACK from u to v. Here a tradeoff is involved on bandwidth efficiency and collision avoidance.

4 Simulation

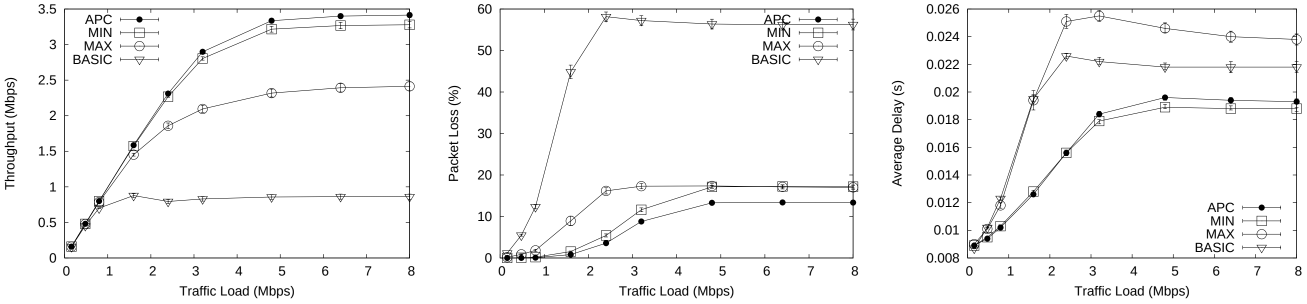
We have conducted a simulation study to evaluate the performance of the proposed scheme. Its performance, in terms of throughput, packet loss, and delay, has been compared with two existing directional MAC approaches using the maximal [13, 28] and minimal [30] RTS/CTS frames. The simulation results show that the proposed scheme outperforms these approaches.

Table 1. Simulation parameters

Parameter	**Value**
$SINR_{Min}$	10 dB
Slot Time	20 μs
SIFS Time	10 μs
DIFS Time	50 μs
CW_{Min}	31
CW_{Max}	1023
Short Retry Limit	7
Long Retry Limit	4



(a) Throughput (4 directions)
(b) Packet Loss (4 directions)
(c) Average delay (4 directions)



(d) Throughput (8 directions)
(e) Packet Loss (8 directions)
(f) Delay (8 directions)

Figure 7. Overall performance.

4.1 Implementation

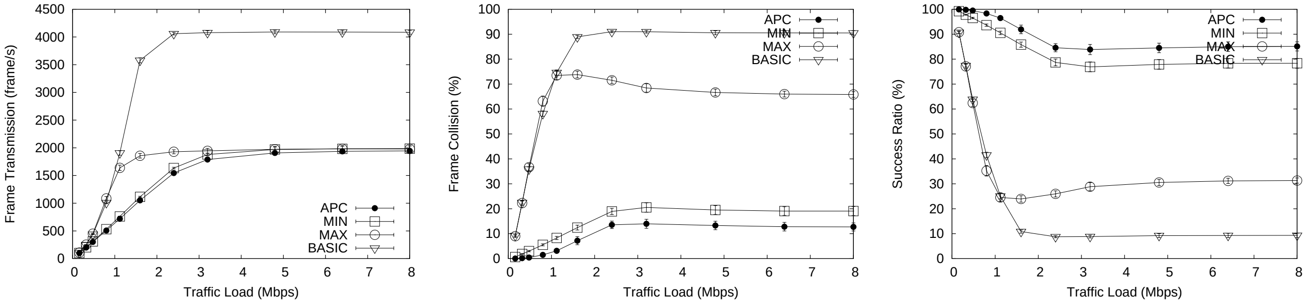
We use a discrete event simulator [11] for the simulation study. All protocols are evaluated in a static network with 60 nodes randomly deployed in a $900m \times 900m$ area. The normal transmission range P_{Max} is $250m$. Each node is capable of transmission power control and forming a single directional beam. All frames are transmitted directionally. We use a switched beam model with aligned and ideally sectorized directions [7]. We compare the performances of the following IEEE 802.11 MAC variants, using the parameters listed in Table 1:

- *Adaptive Power Control* (APC): The proposed protocol as described in Algorithm 1. Figure 6 shows a sample network using APC to determine the control frame shapes.
- *Minimal RTS/CTS* (MIN) [30]: Each node transmits all frames (RTS/CTS/DATA/ACK) with the minimal power.
- *Maximal RTS/CTS* (MAX) [13, 28]: Each node transmits the RTS/CTS frames with the normal transmission power, and the DATA/ACK frames with the minimal transmission power to reach the destination.
- *No RTS/CTS* (BASIC): The sender and receiver exchange only the DATA and ACK frames with the minimal power. It is used as a baseline protocol to evaluate the effectiveness of the RTS/CTS collision avoidance mechanism.

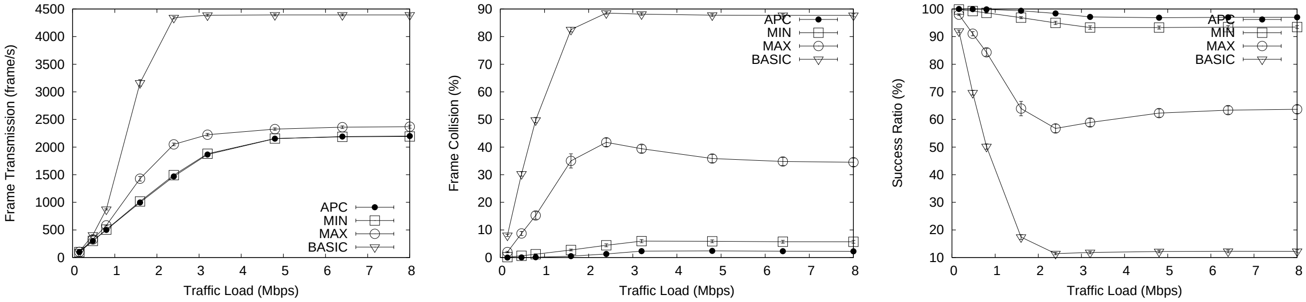
Each node uses a directional network allocation vector (DNAV) [35], such that a transmission in one direction does not block transmissions in other directions. Each node uses the LMST-based topology control algorithm [21] to determine their logical neighbors. Data traffic is randomly generated between logical neighbors. For fairness all protocols are loosely coupled with the topology control protocol; that is, each node knows the locations of its logical neighbors. That eliminates the need of a neighbor discovery scheme [28, 36]. The control frame relay scheme is not simulated.

The following measures are compared:

- *Throughput*, which is the total number of MAC layer packets delivered successfully to their destinations. This is a measure of spatial reuse and collision avoidance of each protocol. Note that a received DATA followed by a missed ACK is treated as a failure and not counted as a successful delivery.
- *Packet loss*, which is the ratio of failed transmissions to the total number of initialized transmissions. Note that the MAC layer will retransmit a packet several several times (depending on the parameter Retry Limit) before reporting a transmission failure.



(a) DATA transmission (4 directions) (b) DATA collision (4 directions) (c) DATA/ACK exchange (4 directions)



(d) DATA transmission (8 directions) (e) DATA collision (8 directions) (f) DATA/ACK exchange (8 directions)

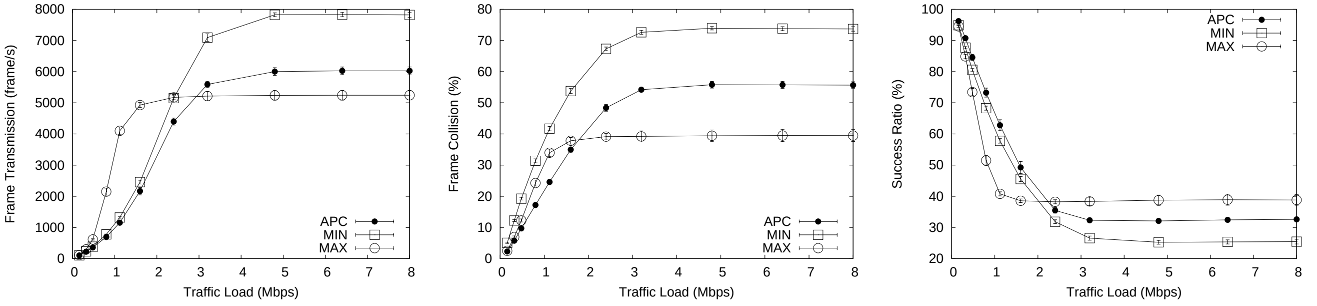
Figure 8. Data frame transmission.

- *Average delay*, which is the average time between the transmission of the first RTS and the reception of the last ACK in a successful transmission. Delays of failed transmissions are not calculated.

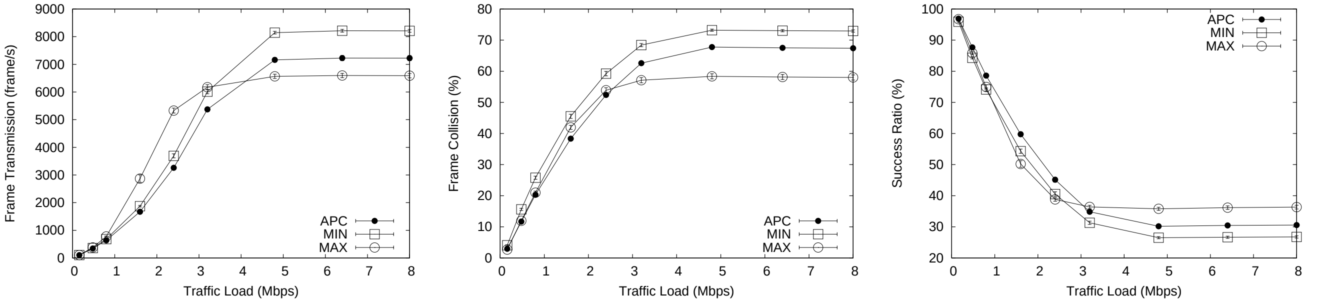
Each simulation takes 100 seconds and is repeated 20 times. The confidence level of all simulation results is 95%. The channel bandwidth is $2Mb/s$. We use a packet size of 2000 bytes and a average traffic load of 100-5000 packets per second (pps). The data arrival rate at each node follows the Poisson distribution.

4.2 Results

Figures 7 (a) shows the throughput of the four protocols using 4 directional beams, respectively. The sequence from the highest to lowest throughput is APC, MIN, MAX, and BASIC. All protocols have similar throughput under a low traffic load ($< 1Mbps$). BASIC is slightly better than MAX in this case. It suggests that the benefit of the RTS/CTS-based collision avoidance is overridden by the spatial reuse penalty of the maximal control frame shape. Under high traffic load, the throughput of APC and MIN is significantly (150%) higher than MAX and BASIC. APC has a slightly (5%) higher throughput than MIN. Figures 7 (d) shows the throughput using 8 directional beams. The performance of MAX improves



(a) RTS transmission (4 directions) (b) RTS collision (4 directions) (c) RTS/CTS exchange (4 directions)



(d) RTS transmission (8 directions) (e) RTS collision (8 directions) (f) RTS/CTS exchange (8 directions)

Figure 9. Control frame transmission.

significantly compared with the 4 direction case, but is still lower than that of APC and MIN.

Compared with other protocols, APC shows significant improvement in packet loss ratio. As shown in Figures 7 (b) and (e), the packet loss of APC is no higher than 70% that of MIN, 30% that of MAX, and 20% that of BASIC in the 4 direction case. The corresponding ratios are 80%, 80%, and 30% in the 8 direction case. That means APC is very effective at avoiding transmission failures. Figures 7 (c) and (f) compare the average delays of four protocols. In the 4 direction case, APC has the same delay as BASIC, which is much smaller than that of MAX, and only slightly larger than that of MIN under a high traffic load. When using 8 direction beams, the average delay of APC is still slightly larger than that of MIN, but much lower than those of BASIC and MAX.

For a better understanding of the above results, we also investigate the transmission of each frame type. The transmission of DATA and ACK frames are shown in Figure 8. Under a low traffic load, MAX and BASIC transmit much more DATA frames than APC and MIN (Figures 8 (a) and (d)). Since all protocols have a similar throughput in this scenario, this difference is explained by their high percentage of DATA frame collisions (Figures 8 (b) and (e)) and low percentage of successful DATA/ACK exchanges (Figures 8 (c) and (f)). That shows using no control frame causes a large amount of collision. On the other hand, using very large control frame shapes has the same effect.

APC has a very low percentage of DATA frame collisions and high percentage of successful DATA/ACK exchanges under a low traffic load, which means that APC provides very effective collision avoidance. Under a high traffic load, it is at least 20% better than MIN, which has the second best performance, in the 4 direction case, and 50% better in the 8 direction case.

Figure 9 shows the transmissions of RTS and CTS frames. Generally speaking, the protocol using a larger RTS/CTS power transmits more RTS/CTS frames, has a higher percentage of RTS/CTS collisions, and has a lower success ratio of RTS/CTS handshake. That is, APC experiences more RTS/CTS failures than MIN and less than MAX. Note that several consequent failed RTS/CTS handshakes are treated as a link failure and packet loss. A larger number of RTS re-transmissions also implies longer backoff delays. This partially explains why APC and MIN have the similar packet loss ratios under a low traffic load, even if APC has a much lower DATA collision ratio in this case.

The simulation results can be summarized as follows:

1. Among all simulated protocols, APC achieves the highest throughput and the lowest packet loss ratio.

2. The average delay of APC is lower than that of MAX, and similar to that of MIN.

3. Under a low traffic load ($< 1Mbps$), APC achieves almost perfect collision avoidance of DATA/ACK frames, which is significantly better than MAX and MIN.

5 Related Work

5.1 Power control MAC

Many existing power control protocols use busy tones and additional channels to avoid the interference between a control frame and a data frame and achieve a high spatial reuse ratio [23, 24, 39]. As indicated in [25], these protocols suffer from interoperability problems with existing standards and hardware. Among single channel solutions, ELPCM [12] transmits RTS/CTS frames using the minimal power and suffers from the hidden terminal problem caused by the heterogeneous transmission power. The focus of [15] is on energy efficiency. It transmits RTS/CTS via the maximal power and does not improve spatial reuse. POWMAC [25] also transmits RTS/CTS with the maximal power, but achieves spatial reuse by inserting an idle period (called the access window) between an RTS/CTS handshake and the consequent data transmission. Multiple RTS/CTS handshakes are allowed during an access window to initial concurrent transmissions among neighbors. During the RTS/CTS handshake, the sender and receiver negotiate on a transmission power that is strong enough to tolerate the existing interference at the receiver's side, but not too strong to cause a collision at the sender's neighbors. In the power control scheme proposed in this paper, the transmission power of RTS/CTS frames is adjusted to achieve spatial reuse while avoiding collision. An access window is not necessary.

Although some TDMA schemes [3, 34] have been proposed, the majority of directional MAC protocols are CSMA schemes that extends the IEEE 802.11 standard. Early directional MAC protocols use omnidirectional RTS/CTS [2, 28] for channel reservation, and transmits the data frame directionally for lower interference and higher signal quality. Then directional RTS/CTS [9, 17] have been combined with a directional network allocation vector (DNAV) [35] for higher spatial reuse. It is assumed that the sender can obtain the direction of the receiver from a higher layer protocol. If that is not the case, an omnidirectional RTS [27, 18] or a directional neighbor discovery scheme [28, 36] can be used to locate the receiver.

5.2 Directional MAC

The deafness problem in directional RTS/CTS schemes has been identified in [9, 17]. A scheme combining omnidirectional and directional RTS was proposed [17]. An omnidirectional RTS is used to avoid deafness, if it will not interfere with a ongoing transmission; otherwise, a directional RTS is used. Deafness at the receiver's side was not considered in this scheme. This scheme has been improved in [14], where neighbors of both the sender and the receiver are notified via circular directional transmissions (i.e., sweeping) of RTS/CTS. This sweeping process skips those directions with ongoing transmissions to avoid interference. Each node maintains a list of busy neighbors and will avoid sending RTS to these neighbors. A similar scheme is used in this paper to avoid deafness, with two major differences: (1) the sweeping process skips empty directions with no logical neighbors, and (2) power control is applied at each direction to reduce interference. The above schemes attempt to prevent the deafness problem in advance. Another solution is to control the damage after the problem happens. In [8], an out-of-band tone is used to notify victims of the deafness problem, such that they will not be punished by an increased backoff delay window. The drawback of this method is that it requires a second channel, which introduces extra complexity and overhead.

Power control has been applied in several directional MAC protocols [28, 30, 6, 13] for energy and channel efficiency. In [13, 28], RTS/CTS frames are transmitted via the maximal power, but the data frame is sent via a reduced power. As fewer nodes will sense the data transmission, more nodes can send RTS frames to initiate new transmissions and thus improve the spatial reuse. These schemes do not reduce the interference of RTS/CTS frames. In [6], RTS/CTS frames are also transmitted via the maximal power, but the transmission beam is adjusted to avoid interfering with ongoing data transmissions.

In [30], all frames (including RTS/CTS) are transmitted using the minimal power. This scheme allows the maximal spatial reuse, but cannot prevent the hidden terminal problem caused by the heterogeneous transmission powers.

5.3 Topology control

Most topology control protocols [5, 19, 20, 21, 31, 32, 37, 38] attempt to minimize two properties of each node: degree (i.e., the number of logical neighbors) and transmission power (i.e., the minimal power to reach the farthest logical neighbor). Both are essential for achieving high spatial reuse in the MAC protocol proposed in this paper. Some advanced schemes try to achieve other desirable properties such as low message cost, constant stretch ratio [33], and low weight [22]. However, MAC layer issues, such as spatial reuse and collision avoidance mechanisms, are not considered. There is no attempt to share neighborhood information with MAC layer for effective directional beam forming and power control. An exception is the interference aware protocol in [4], where the link interference under the omnidirectional transmission model is considered in link removal. This protocol can be extended to use an interference model using directional transmissions to achieve a higher MAC layer throughput.

6 Conclusion

We have proposed two CSMA/CA MAC protocols for the efficient application of power control and directional antenna techniques in MANETs. Both protocols extends the IEEE 802.11 standard for backward compatibility. The first protocol uses a single channel scheme to avoid the hidden terminal problem in power control. The second uses multiple RTS/CTS frames to alleviate the deafness problem in directional media access control while minimize the interference of the RTS/CTS frames.

Both proposed protocols assume the existence of a topology control scheme, which reduces the MANET into a small set of logical links, and restricts data traffic to these logical links. By exploiting the information of adjacent logical links, each node can determines in an iterative process an optimal RTS/CTS power for each direction that maximizes spatial reuse while depressing interference from neighboring logical links. When 1-hop information (i.e., locations of nodes within the normal transmission range) is available, which is the case in many localized topology control schemes, each node can estimate logical links among 1-hop neighbors and speed up the iterative adjusting process. The performance of the proposed protocols has been evaluated via analytical and simulation study. Our future work includes analysis of the proposed protocols in mobile networks with unstable channel conditions.

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