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A SLOW START POWER CONTROL MAC PROTOCOL FOR MOBILE AD HOC NETWORKS

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ABSTRACT

We propose a MAC protocol for mobile ad hoc networks that uses power control for the RTS/CTS and DATA frame transmissions in order to improve energy and capacity utilization efficiency. Unlike IEEE 802.11, in our scheme the RTS frames are not sent using the maximum transmission power to silence neighbouring nodes, and the CTS frames do not silence all receiving nodes to the same degree. In contrast, the transmission power of the RTS frames follows a slow start principle, while the CTS frames, which are sent at maximum transmission power, prevent the neighbouring nodes from transmitting their DATA frames with power more than a computed threshold, while allowing them to transmit at power levels less than that threshold. This is done by including in the RTS and the CTS frames additional information, such as the power of the transmissions, and the interference tolerance of the nodes. Moreover the DATA frames are sent at the minimum required transmission power increased by a small margin to ensure connectivity with the intended receiver, so as to cause minimal interference to neighbouring nodes and allow for future interference to be added to the receiver of the DATA frames. The power to be used by the transmitter is computed by the recipient of the RTS frame and is included in the CTS frame. It is expected that a network with such a power management scheme would achieve a better throughput performance and more power savings than a network without such a scheme.

I. INTRODUCTION

Mobile ad hoc networks (MANETs) are multi-hop wireless networks where all nodes cooperatively maintain network connectivity. Each node has embedded processors and low-power radios, and is normally battery operated. A node, in addition to handling its own packets, also forwards packets generated at other nodes. This type of networks is useful in any situation where temporary network connectivity and fast network deployment is needed.

Like in all shared-medium networks, medium access control (MAC) is important in enabling the successful operation of a MANET. One fundamental task of the MAC protocol is to avoid collisions so that two interfering nodes do not transmit at the same time. There are many MAC protocols that have been deployed for wireless voice and data communication networks. We focus on the standardized IEEE 802.11 distributed coordination function (DCF) [1] contention-based protocol, which is based on the research protocol MACAW [2], and add new features that can improve its performance.

Power control for MAC design in MANETs has recently received a lot of attention for two main reasons. As previously mentioned, wireless nodes are often powered by batteries with limited weight and lifetime. Power control can improve the overall energy consumption in a MANET, prolonging its lifetime. Furthermore, power control can reduce the interference caused to neighbouring nodes, leading to fewer retransmissions, better exploitation of the available bandwidth, and higher end-to-end network throughput.

The Distributed Coordination Function (DCF) mode of IEEE 802.11 is the most dominant MAC protocol for MANETs and is based on the CSMA/CA protocol. In CSMA/CA Request to Send (RTS) and Clear to Send (CTS) control frames are exchanged to reserve a transmission floor for the subsequent DATA frames. All mobile nodes that receive either the RTS or the CTS frame defer their transmissions for a duration specified in the handshaking frames RTS and CTS. While such an approach is to some extent needed to avoid the hidden node problem, it negatively impacts the channel utilization by not allowing concurrent transmissions over the reserved floor. This situation is described in Figure 1: nodes A and B uses their maximum transmission power to send the RTS and CTS frames, respectively. Nodes C and D hear A's RTS frame and therefore refrain from transmitting. It is clear that both transmissions A→B and C→D could in principle take place simultaneously without causing excessive interference to each other, but these transmissions are not permitted at the same time in 802.11.

To overcome this inefficiency of 802.11, which results in the unnecessary deferment of DATA frame transmissions between nodes C and D, we introduce the *slow start* principle for the transmission power of the RTS frames. With slow start, the RTS frame is initially sent using a low transmission power, which is increased by some step every time the transmitter realizes that its previous RTS transmission was unsuccessful. The transmission power of the RTS frame increases gradually until the receiver is reached (as indicated by its CTS reply) or until it reaches a maximum value. The CTS frames are sent at the maximum transmission power, but in contrast to the 802.11 approach, they do not cause a deferment of the DATA transmissions to all the recipients of the CTS frames, but only to those recipients that intend to use transmission power more that an estimated threshold. Nodes hearing the CTS frames use the information included in them to compute the maximum power they can use without causing excessive interference to their neighbours.

This situation is described in Figure 2. Let us assume that node A wants to transmit some DATA frames to node B. Node A initially sends a RTS frame with power equal to P_{RTS}^0

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hoping that node B is near enough to successfully receive the RTS frame. If after a specific time period node A does not receive a CTS frame, it concludes that the RTS transmission has failed, invokes its back-off procedure, and sends again the RTS frame with increased power. This procedure is repeated until node B successfully receives the RTS frame and replies to it with a CTS frame, or until the transmission power reaches its maximum value P_{max}. The CTS frame, which is sent using the maximum transmission power P_{max}, includes the minimum power P_{min} that should be used by A to guarantee the connectivity between nodes A and B, increased by some margin M. The CTS frame also includes an estimate of the additional interference that node B can tolerate from its neighbours. This interference tolerance of B is used by the recipients of CTS frames (nodes C and D in Figure 2) to decide if they must defer their transmissions. For example if node C wants to transmit some DATA frames to node D with power equal to P_1, and this transmission causes interference to node B less than its interference tolerance, then both DATA frame transmissions A→B and C→D can take place simultaneously. This is a main difference from the IEEE 802.11 approach, since in our scheme nodes that listen to the CTS frame, such as node C, are allowed to transmit their DATA frames provided they do not cause excessive interference to their neighbours.

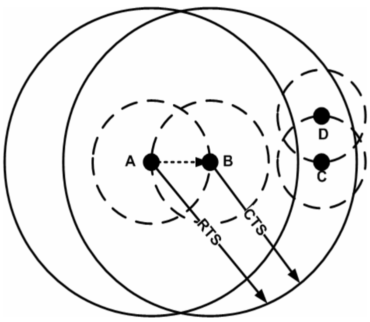

Figure 1 - The IEEE 802.11 approach. Solid lines represent the receiving areas of the RTS and CTS frames when the maximum transmission power is used, while dashed lines represent the transmission ranges of the nodes when the minimum required power for coherent reception is used.

The proposed scheme, which we call the Slow Start Power Controlled (abbreviated SSPC) MAC protocol has two main advantages. First, since the transmission power of the RTS frame follows a slow start principle, the transmission floor it reserves is close to the minimum required, and does not cause unnecessary deferments of transmissions. Second, the CTS frame silences only those nodes that are going to cause to the transmitter of the CTS frame interference greater than its interference tolerance. These two factors result in less power consumption, higher reuse factor, and better end-to-end network throughput.

The rest of the paper is organized as follows. In Section II we review related work on power control for MANETs. In Section III we present the proposed protocol, emphasizing its design considerations. More specifically, subsection A describes the slow start feature of SSPC and subsection B describes the CTS mechanism used. Finally, our main conclusions are drawn in Section IV.

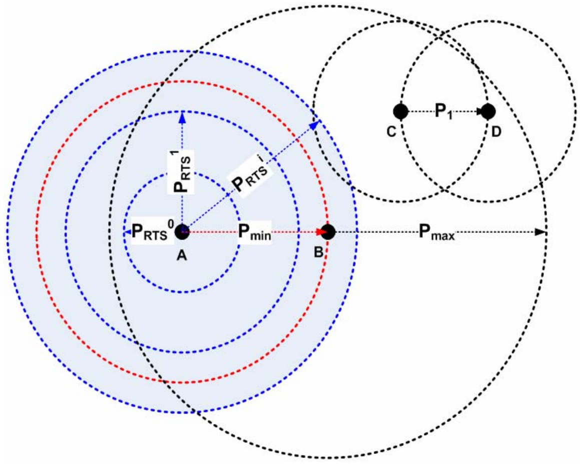

Figure 2 – Proposed power control scheme. The transmission between nodes C and D can take place, even though both nodes have received a CTS frame from node B.

II. Related Work

We can categorize the previous research work on power-aware MAC layer design into two main categories: switching-off power-aware MAC protocols and protocols using transmission power adjustment. Switching off Power-Aware MAC protocols try to minimize the idle energy consumption by forcing nodes to enter a doze mode [5, 6, 7]. The scheme we propose belongs to the second category of power-aware MAC layer protocols, where a great deal of research has also been carried out. In [8] the authors proposed a power control MAC (PCM) protocol for ad hoc networks which consists of three phases and allows nodes to vary their transmission power on a per-frame basis. Our scheme differs from the PCM scheme at two important points. First, the transmission of RTS/CTS frames in [8] is done using the maximum power P_{max}, causing more nodes to defer their transmission than may be unnecessary. Instead in our scheme the source node transmits the RTS frame at power levels that follows a slow start principle, reserving a smaller transmission floor and allowing more nodes to transmit simultaneously. Second, in [8] the transmission power used for DATA frames periodically increase from the desired power level to the maximum transmission power P_{max}. This switching between the minimum and the maximum transmission power can cause large energy consumption. Instead, in our scheme the transmission power used for DATA is fixed and is slightly more than the minimum possible, resulting in significant energy savings.

In [9] the authors proposed the Distributed Transmission Power Control Protocol for MANETs, consisting of six phases. The transmission of the RTS frame in [9] is performed using power P_{max}, potentially causing more nodes to defer their transmission than is necessary. Instead in our scheme the source node transmits the RTS frame with transmission power that follows a slow start principle.

The possibility and the potential benefits of adjusting the transmission power are also considered in [10]. The authors proposed a Power Management scheme for Throughput Enhancement that can be applied to Wireless Ad-Hoc Networks. Even though this scheme achieves lower power consumption at the nodes, it does not take into account the interference caused to ongoing and future transmissions at the receiving node, which may cause several retransmissions and a consequent increase in power consumption compared to our scheme. Also, as in the schemes proposed in [8] and [9], each receiver transmits a beacon signal – a message like the RTS message – with power P_{max}, which can have the same negative effect described in the previous paragraph.

III. THE SLOW START POWER CONTROLLED MAC PROTOCOL

This section describes the main characteristics of the SSPC protocol. Subsection A describes the slow start feature of the SSPC protocol and subsection B the CTS mechanism used.

A. The Slow Start Feature Of The SSPC Protocol

To illustrate the operation of the SSPC protocol, consider the situation in Figure 2, where node A wants to transmit a DATA frame to node B. Node A senses the medium for a DIFS interval [1] and if it is still idle, sends an RTS frame to node B using transmission power that follows a slow start principle. The RTS frame informs the recipients that a DATA transmission to node B will take place, and is sensed by all the nodes in the coverage area of A. The format of the RTS frame (described in Figure 3) contains the following fields:

- Frame Control: It is comprised from various subfields, such as Protocol Version, Type, Subtype etc
- T_{RTS}: The RTS frame transmission duration
- RA: Address of the receiver of the RTS frame
- TA: Address of the transmitter of the RTS frame
- P_{RTS}^i: The transmission power of the current (i–th) RTS transmission attempt.
- FCS : Frame Check Sequence used at the receiver for error control.

Octets:	2	2	6	6	1	4
	Frame Control	T_{RTS}	RA	TA	P_{RTS}^i	FCS

Figure 3 - Proposed approach. The RTS frame format.

The new field that we add at the RTS frame is the field P_{RTS}^i, which is the transmission power of the current (i–th) RTS transmission attempt. At its first attempt node A sends the RTS frame with power P_{RTS}^0 hoping that node B is near enough to reach it and sets a timer equal to T_{RTS}. Typical values of the power P_{RTS}^0 are for example 15dbm for the D-Link AirPlus™ G DWL-G630 Wireless Cardbus Adapter operating at 2.4GHz [3] and 14dbm for the IEEE 802.11b Wireless LAN PC Card operating at 2.4GHz [4]. The value of the timer is set to $T_{RTS} = 2T_{PROP} + T_{SIFS} + T_{CTS}$, which is the sum of the propagation delay required for the RTS frame to reach the destination (T_{PROP}), the time the receiver must wait before sending back the CTS frame (T_{SIFS}), the propagation delay it takes for the CTS frame to reach the sender (T_{PROP}), and the CTS transmission duration (T_{CTS}). We also define T_{DATA} as the time it takes for the DATA frame to reach the destination and T_{ACK} as the time it takes the ACK frame to reach the transmitter of the DATA frame. If after period T_{RTS} node A has not received a correct CTS frame, it concludes that the transmission of the RTS frame has failed, invokes its back-off procedure as is described by the IEEE 802.11 protocol [1] and sends again the RTS frame, but now with transmission power P_{RTS}^1 that has been increased by S dbm compared to the previous transmission power P_{RTS}^0. The parameter S is referred to as the *step* of the slow start principle that the transmission power of the RTS frame follows. Node A sets again the timer equal to T_{RTS} and waits for a CTS frame. Node A continues to send the RTS frame with increased transmission power P_{RTS}^i every time it does not receive a CTS frame before the timer expires, until it receives a CTS frame indicating that node B has successfully received the RTS frame, or until the transmission power reaches its maximum value. If node A sends the RTS frame with the maximum transmission power P_{max} and does not receive a CTS frame, A concludes that node B is unreachable at the present time.

All nodes that are in the transmission range of node A and correctly decode the RTS frame, set their NAVs [1] to the value $NAV_{RTS}^{TR} = T_{SIFS} + T_{CTS} + T_{SIFS} + T_{DATA} + T_{SIFS} + T_{ACK}$ and defer their transmissions for that period. Instead, nodes that lie in the carrier sensing zone of A (which cannot decode correctly the received frames) set their NAVs to the value NAV_{RTS}^{CS} = EIFS. We must mention that since nodes in the carrier sensing zone cannot decode the frame, they do not know the duration of the frame transmission. To prevent a collision with the ACK frame reception at the source node, when nodes detect a frame and cannot decode it, they set their NAVs for the EIFS duration [1]. The main purpose of the EIFS is to provide enough time for a source node to receive the ACK frame, so the duration of EIFS is longer than that of an ACK frame transmission. As per IEEE 802.11, the EIFS is obtained using the SIFS, the DIFS, and the length of the time to transmit an ACK frame at the physical layer's lowest mandatory rate [1].

However, IEEE 802.11 does not completely prevent collisions due to a hidden terminal – nodes in the receiver's carrier sensing zone, but not in the sender's carrier sensing zone or transmission range, can cause a collision with the reception of a DATA frame at the receiver [8].

Node B upon receiving the RTS frame checks the RA field to see if it is the intended receiver and the TA field to discover the address of the transmitter. It also examines the FCS field for errors. We must underline that when we say that node B received the RTS frame we mean that it received and decoded correctly the RTS frame. The ability of node B to correctly decode the received RTS frame depends on its sensitivity, which is the minimum signal level required at the receiver for adequate reception. For example, if an SNR of 9db is required to achieve sufficient signal quality and the noise floor at the receiver is -111dbm, then the minimum signal or sensitivity for good reception is -102dbm. The sensitivity is typically supplied by manufacturers, and minimum acceptable levels can be found in the technical specifications of the devices. For example, the sensitivity of the D-Link AirPlus[TM] G DWL-G630 Wireless Cardbus Adapter is -84dbm operating at 11Mbps at the band of 2.4GHz [3], while the sensitivity of the IEEE 802.11b Wireless LAN PC Card is -80dbm operating at 11Mbps at the band of 2.4GHz [4].

We denote by SNR_{RTS}^{i} the SNR at the receiver for the current (i-th) attempt of the RTS frame transmission when power equal to P_{RTS}^{i} is used at the transmitter and by SNR_{RTS}^{min} the SNR at the receiver when power equal to the minimum power P_{RTS}^{min} that guarantees the connectivity between node A and node B is used. In other words, SNR_{RTS}^{min} is the minimum received SNR that results in a desired frame error rate FER (it depends among other things on the error correction codes used), while P_{RTS}^{min} is the minimum power that should be used at the transmitter to result in SNR equal to SNR_{RTS}^{min} at the receiver. The transmitter would like to know the value of P_{RTS}^{min} so that it can use it in its transmission. In what follows we will show how this minimum transmission power P_{RTS}^{min} can be estimated at the receiver and be communicated back to the transmitter through the RTS/CTS exchanged during the slow start mechanism.

Consider the current attempt i-1 of node A to send the RTS frame with transmission power equal to P_{RTS}^{i-1} and let SNR_{RTS}^{i-1} be the corresponding SNR at the receiver. If the timer T_{RTS} that node A sets upon sending the RTS frame expires and node A doesn't receive a CTS frame, meaning that node B could not decode correctly the RTS frame, then node A invokes its back-off procedure and sends again the RTS frame with power P_{RTS}^{i}. This is node A's (i-th) current attempt to send the RTS frame, and let us assume that this time node B decodes correctly the RTS frame. This means that the power P_{RTS}^{i} used by node A at its current attempt to send the RTS frame is greater than or equal to the minimum power P_{RTS}^{min} that guarantees the connectivity between nodes A and B. At the same time we know that P_{RTS}^{min} is greater than P_{RTS}^{i-1} since the (i-1)-th attempt failed. In our protocol the receiver uses the approximations $SNR_{RTS}^{min} \approx SNR_{RTS}^{i}$ and $P_{RTS}^{min} \approx P_{RTS}^{i}$, where i is the first successful RTS transmission attempt. This is only an approximation of the minimum power that guarantees the connectivity between nodes A and B and not its accurate value. The smaller the value of the step size S used in the slow start mechanism, the more accurate is the estimation of P_{RTS}^{min}. Note that this estimated value of P_{RTS}^{min} for the required transmission power takes into account all thermal and interference noise N present at B when it received the (i-th) RTS frame.

B. The CTS Mechanism In The SSPC Protocol

When node B correctly decodes the RTS frame, it replies with a CTS frame that includes the transmission power P_{DATA} that node A must use to transmit DATA frames to node B. This power is given by the equation:

$$P_{DATA} = P_{RTS}^{i} + M. \qquad (1)$$

The term M is used as a safety margin and also to allow for future interference at node B (interference tolerance). In other words, to allow for a number of future interfering transmissions to take place in the vicinity of node B, node B requests A to increase by M the transmission power of the DATA frames.

Node B sends the CTS frame using the maximum transmission power. The format of this CTS frame (described in Figure 4) has the following fields:

- Frame Control: It is comprised of several subfields, such as Protocol Version, Type, Subtype, etc.
- T_{CTS}: The CTS frame transmission duration.
- RA: Address of the receiver of the CTS frame.
- TA: Address of the transmitter of the CTS frame.
- P_{DATA}: The power that should be used by the transmitter to send the DATA frames, as computed by the receiver.
- P_{INTERF}: The additional interference power that each neighbour/future interferer can add to the receiver.
- P_{max}: CTS frame transmission power.
- FCS: Frame check sequence.

Octets:	2	2	6	6	1	1	1	4
	Frame Control	T_{CTS}	RA	TA	P_{DATA}	P_{INTERF}	P_{max}	FCS

Figure 4 - Proposed approach. CTS frame format.

All nodes in the transmission range of node B set their NAVs [1] to the value $NAV_{CTS}^{RT} = T_{SIFS} + T_{DATA} + T_{SIFS} + T_{ACK}$. Not all these nodes, however, but only the nodes that are neighbours to node B and are going to cause to it interference greater than P_{INTERF}, to be specified later, defer their transmissions. To ensure node B that its CTS frame was received successfully by node A, node B sets a timer to a timeout value $T_{CTS} = 2T_{PROP} + T_{SIFS}$. If after this time node B has not started receiving a DATA frame it concludes that the transmission of the CTS frame has failed.

Nodes that are in the carrier sensing zone of node B set their NAVs to the value NAV_{CTS}^{CS} = EIFS. We would like not all the nodes in the carrier sensing zone, but only those that are going to cause to node B excessive interference to defer their transmissions. Nodes in the carrier sensing zone do not know the duration of the frame transmission and set their NAV's for the EIFS duration, to prevent a collision with the DATA frame reception at the receiver, which is a difficulty present in 802.11 as well. An additional difficulty regarding the nodes in the carrier sensing zone in the SSPC protocol is that since these nodes do not correctly decode the received signal, they cannot accurately compute the maximum power they can use for their transmissions without causing excessive interference to their neighbours. The best we can aim for regarding these nodes is as we will see later, to compute a looser upper bound on the transmission power they can use.

An important aspect that must be considered is the computation of the interference power P_{INTERF} that each neighbour node can contribute to the receiver in the future, from the total interference margin M allowed at the receiver (Eq. (1)). The future interference M that is allowed must be equitably distributed among the future potentially interfering users in the vicinity of B. [9] presents a method to compute the interference power. Let $N^{R}(t)$ be the number of nodes in the vicinity of node B at time t that are to share the interference M. Node B keeps track of the instantaneous number of active transmissions in its neighbourhood at time *t*, which we denote by $N_{inst}^R(t)$, by monitoring the RTS/CTS exchange. We denote by $N^R(RTS)$ the value of $N_{inst}^R(t)$ when the RTS packet is received at the receiver; the interference of these $N^R(RTS)$ nodes was present when the RTS packet was received and is already accounted for. In addition node B keeps track of a moving average of $N_{inst}^R(t)$, denoted by $N_{avg}^R(t)$. Then $N^R(t)$ is calculated as follows:

$$N^R(t) = \max\{N_{avg}^R(t), N_{inst}^R(t)\} - N^R(RTS). \quad (2)$$

The rationale behind the above equation is the following. When the CTS message was sent, there were $N^R(RTS)$ active transmissions in the neighbourhood of B. The future interference margin M is to be shared by future interferers, other than the $N^R(RTS)$ interferers already accounted for. The interference power that each neighbour can add to node B is given by the equation:

$$P_{INTERF} = \max\{ M / N^R(t), P_{INTERF}^{min}\}. \quad (3)$$

where P_{INTERF}^{min} is a lower bound we pose on P_{INTERF}. The rationale for this lower bound is that if the margin M is distributed among a large number of neighbouring nodes then the interference power every node will be allowed to cause may be too small, and may be unusable.

As previously mentioned, node B replies to the RTS frame with a CTS frame using power equal to P_{max} (node B does not use power P_{min} to transmit the CTS frame as it wants to inform as many stations as possible for the intended transmission that will occur). This frame informs all the nodes that are in the coverage area of node B that a DATA frame transmission will occur at node B. One important difference from the IEEE 802.11 protocol is that the CTS frame will not cause all the nodes that hear it to defer their transmissions, but only those nodes that are going to cause to node B interference greater than P_{INTERF}.

A final issue that has to be specified is the way a neighbour node, say node C, determines the maximum transmission power that it can use without resulting in interference greater than P_{INTERF} at the receiver B. We assume that every node has the ability to compute the signal strength of the received signal. There are a lot of commercial chips that among others can compute the signal strengths. Those chips include typical Radio Frequency Transceivers and are characterized by low power consumption. Example of those chip are the Atheros AR6001X Radio On Chip [11], and the POLARIS™ TOTAL RADIO™ [12]. So node C that hears the CTS frame sent by node B at power P_{max}, has the ability to compute the signal strength of the received signal $P_{CTS\text{-}received}$, and consequently the channel gain between B and C by the equation:

$$G_{B,C} = P_{CTS\text{-}received} / P_{max}. \quad (4)$$

Based on that, and assuming that the channel gain is approximately the same in both directions, C can compute the maximum transmission power $P_{max}(C/B)$ that it can use without causing excessive interference at B as:

$$P_{max}(C/B) = P_{INTERF} / G_{C,B} \approx P_{INTERF} / G_{B,C}. \quad (5)$$

Every node like node C, maintains an interference table, where he records for each of its neighbours, say nodes B_1, $B_2,\ldots,B_N$, from which it has received a CTS frame, the information about the maximum transmission power it can use without causing excessive interference to that neighbour (Table 1).

Table 1 - Description of the interference table that node C maintains

B_1 $P_{max}(C/B_1)$	B_2 $P_{max}(C/B_2)$	…	B_N $P_{max}(C/B_N)$	$P_{max}(C)$

The maximum power at which node C can transmit is then found as:

$$P_{max}(C) = \min_i P_{max}(C/B_i). \quad (6)$$

The interference table of node C together with the NAV data structure it maintains (to record the durations of the ongoing transmissions in its neighbourhood) is used to dynamically update the maximum transmission power $P_{max}(C)$ that node C can use. When node C uses the slow start mechanism to transmit to some node D, it can increase its power up to $P_{max}(C)$. When a neighbour node B_i ceases a transmission or when a new neighbour starts transmission, $P_{max}(C)$ is updated. For example, let us consider the situation described at Figure 5. The dashed lines represent the receiving areas of the CTS frames when the maximum transmission power is used, the solid black lines represents the transmission range of the nodes A, C, E and F when the minimum required power for coherent reception of DATA frames is used, and the solid blue lines represent the receiving areas of the RTS frames from node C when the slow start principle is applied. Nodes A, F and E have already gone through the RTS/CTS procedure and have started transmitting some DATA frames to nodes B_1, B_2 and B_3, respectively. During the RTS/CTS exchange that preceded these DATA transmissions, nodes B_i, i = 1,2,3 have computed the future interference power $P_{INTERF,i}$ i = 1,2,3 that each of their neighbours is allowed to cause to them, and transmitted it in the CTS frames they have sent at power $P_{max,i}$, i = 1,2,3, respectively.

Node C wants to compute the maximum transmission power that it can use without causing excessive interference to its neighbours. Node C has received three CTS frames from nodes B_1, B_2, B_3. Using the received signal strength of each CTS frame, it computes the maximum transmission power it can use without causing excessive interference to its neighbours as:

$$P_{max}(C) = \min\{P_{max}(C/B_1), P_{max}(C/B_2), P_{max}(C/B_3)\}, \quad (7)$$

where

$$P_{max}(C/B_i) = P_{INTERF,i} / G_{Bi,C}, \text{ for } i=1,2,3. \quad (8)$$

$P_{max}(C)$ is the maximum transmission power that node C can use to transmit its DATA frames without causing excessive interference to its neighbours. So when it invokes the slow start mechanism to transmit to node D, it will increase its transmission power in steps of S dbm up to that power level.

Assuming that the power required for C to reach node D is less than the maximum power $P_{max}(C)$ that C is allowed to use, node D replies with a CTS frame informing C about the power level P_{DATA} it should use.

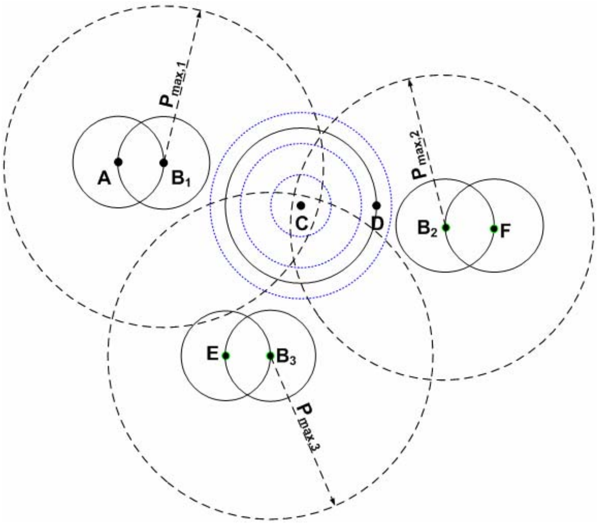

Figure 5 - Usage of the CTS frame.

Consider now a node G that is in the carrier sensing zone of node B and receives the CTS frame. Since this node cannot correctly decode the received CTS frame it does not know the values of the interference power P_{INTERF} that it is allowed to cause to node B, and also it does not know the transmission power of the CTS frame it received. Nevertheless, it can still compute the received signal strength $P_{CTS\text{-}received}$ of the CTS frame. Clearly, node G cannot use Eq. (5) to compute the exact value of the maximum transmission power it is permitted to use, but it can still compute a looser bound on the maximum power it can use as follows:

$$P_{max}(G/B) = P_{INTERF} \cdot P_{max} / P_{CTS\text{-}received} \geq P_{INTERF}^{min} \cdot P_{RTS}^{0,min} / P_{CTS\text{-}received}. \quad (9)$$

where $P_{RTS}^{0,min}$ is the minimum initial transmission power used at the slow start principle for the RTS transmission and is assumed to be the same for all nodes. Recall that P_{INTERF}^{min} is the lower bound on the interference power P_{INTERF} posed by Eq. (3) and is also a known design parameter. So although nodes in the carrier sensing zone cannot compute the exact value of the maximum transmission power they can use, they can compute a looser bound on the maximum power they can use without causing excessive interference to node B. Note that in the classic IEEE 802.11 standard nodes in the carrier sensing zone defer their transmissions for the EIFS duration. The EIFS is the largest of all the IFSs, and is used to reduce the probability that a collision will occur with the ACK frame at the source node. Instead, in our protocol nodes in the carrier sensing zone can compute a bound on the maximum transmission power they can use.

Finally, when node C receives D's CTS frame, it waits for SIFS duration and transmits the DATA frames with power level P_{DATA}. After transmitting the DATA frame node C sets a timer to $2T_{PROP} + T_{ACK}$ seconds. If after this period node C has not received a correct ACK frame, it concludes that the transmission of the DATA frame has failed, and hence it invokes its back-off procedure.

From the above it is obvious that several transmissions can take place simultaneously if every node that receives CTS frames adjusts its transmission power at the appropriate value using the information included in the CTS frames.

IV. Summary And Conclusions

In this paper we proposed a Slow Start Power Control MAC protocol for wireless ad hoc networks. In SSPC, the RTS frame transmission power follows a slow start principle, while the DATA frames are sent with the minimum transmission power that guarantees the connectivity between the nodes plus some margin used to allow for future interference. Moreover, the CTS frames are sent at the maximum transmission power and include information that is used by the recipients to compute the maximum transmission power they can use for their DATA frame transmissions. It is expected that ad hoc networks using the SSPC protocol can achieve higher end to end throughput and less power consumption than networks using the standard RTS/CTS mechanism of 802.11. Our future work will focus on investigating the performance of the proposed protocol under various scenarios and a possible improvement at its design principles.

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