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The slow start power controlled MAC protocol for mobile ad hoc networks and its performance analysis

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ABSTRACT

We propose and evaluate the performance of a new MAC-layer protocol for mobile ad hoc networks, called the Slow Start Power Controlled (abbreviated SSPC) protocol. SSPC improves on IEEE 802.11 by using power control for the RTS/CTS and DATA frame transmissions, so as to reduce energy consumption and increase network throughput and lifetime. In our scheme the transmission power used for the RTS frames is not constant, but follows a slow start principle. The CTS frames, which are sent at maximum transmission power, prevent the neighbouring nodes from transmitting their DATA frames at power levels higher than a computed threshold, while allowing them to transmit at power levels less than that threshold. Reduced energy consumption is achieved by adjusting the node transmission power to the minimum required value for reliable reception at the receiving node, while increase in network throughput is achieved by allowing more transmissions to take place simultaneously. The slow start principle used for calculating the appropriate DATA frames transmission power and the possibility of more simultaneous collision-free transmissions differentiate the SSPC protocol from the other MAC solutions proposed for IEEE 802.11. Simulation results indicate that the SSPC protocol achieves a significant reduction in power consumption, average packet delay and frequency of RTS frame collisions, and a significant increase in network throughput and received-to-sent packets ratio compared to IEEE 802.11 protocol.

1. Introduction

Mobile ad hoc networks (MANETs) allow people and devices to dynamically self-organize into arbitrary and temporary wireless network topologies, so as to seamlessly inter-network without the use of fixed communication infrastructure. MANETs are usually multi-hop networks, where nodes, in addition to handling their own packets, also forward packets generated at other nodes.

Since nodes in a MANET are usually battery-operated, power conservation is a central issue in the MAC design of such networks. Generally, a node participating in an ad hoc network, consumes energy when transmitting, receiving or processing data, or when simply listening to the channel. Power-conservative designs for ad hoc networks face a number of challenges due to the lack of central coordination facilities [1].

We focus on the standardized IEEE 802.11 distributed coordination function (DCF) [1] contention-based protocol, which is the dominant MAC protocol for MANETs, and add new features that can improve its performance. In IEEE 802.11, a transmitter first sends a Request to Send (RTS) frame, and the intended receiver answers with a Clear to Send (CTS) frame. These control frames are used to reserve a transmission floor for the transmission of the subsequent DATA frames. 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

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approach is to some extent needed to avoid the hidden node problem, it negatively impacts channel utilization by completely disallowing concurrent transmissions over the reserved floor. For example, in Fig. 1, node A uses its maximum transmission power to send its RTS frame while node B uses its maximum transmission power to send its CTS frame. Nodes C and D hear A's RTS frame and therefore refrain for 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 the 802.11 protocol, the Slow Start Power Controlled (SSPC) MAC protocol adds two new features: (a) it introduces the slow start mechanism for the transmission power of the RTS frames, and (b) it also changes the mechanisms used by the other nodes to decide if they can transmit or not, and at which power level. 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. Instead, 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, until the receiver is reached (as indicated by its CTS reply) or until it reaches some maximum value. The CTS frames are still sent at the maximum transmission power, but, in contrast to the 802.11 approach, they do not cause a deferment of the DATA frames 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.

In the SSPC protocol, when a transmitter wants to transmit some DATA frames to a receiver it sends a RTS frame with an initial minimum power hoping that the receiver is near enough to successfully receive it. The RTS frame transmission power is increased following a slow start principle, until the receiver successfully decodes the RTS frame and replies to it with a CTS frame, or until the transmission power reaches a maximum value. The CTS frame, which is sent using the maximum transmission power, contains information regarding the minimum transmission power that the transmitter should use to guarantee the coherent reception of the DATA frames at the receiver, increased by some interference margin. The CTS frame also includes an estimate of the additional interference that the receiver can tolerate from its neighbours. This interference tolerance is used by the recipients of CTS frames to decide if they must defer or not their transmissions. This is a significant difference from the IEEE 802.11 approach, since in our scheme nodes which listen to a CTS frame are still allowed to transmit their DATA frames, provided they do not cause excessive interference to their neighbours.

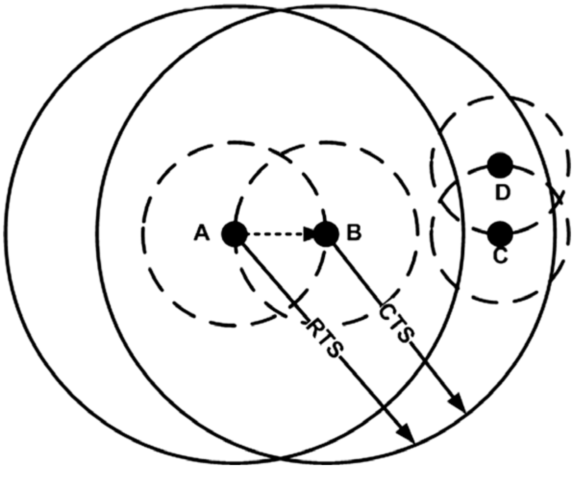

Fig. 1. The IEEE 802.11 transmission floor is illustrated with solid lines. Dashed lines illustrates that both transmissions A → B and C → D could in principle take place simultaneously.

One of the main advantages of the SSPC protocol is the use of the slow start principle for calculating the minimum required DATA frames transmission power. Nodes using the slow start technique do not have to know the topology of the network or the channel conditions, in order to compute the required DATA transmission power, while at the same time important savings are obtained in terms of energy consumption. The motivations that lead us to design a power control MAC protocol with a slow start principle were the need to minimize (i) the power consumption in the network without degrading the Quality of Service offered and (ii) the overhead required to incorporate the SSPC protocol in the IEEE 802.11 standard. As we will argue in Section 4, the IEEE 802.11 standard needs only minor modifications in the format of the RTS and CTS frames, in order to integrate the SSPC protocol.

The proposed SSPC scheme has two main advantages over the IEEE 802.11 protocol. First, since the transmission power of the RTS frame follows a slow start principle, the energy consumed and the transmission floor reserved will be close to the minimum required. 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, enlarging in this way the set of nodes that can communicate simultaneously. These two factors result in higher reuse factor, better end-to-end network throughput, less power consumption, and larger network lifetime than IEEE 802.11, as the performance results to be presented indicate. SSPC also requires only relatively mild modifications in the IEEE 802.11 operation and in the format of the RTS and CTS frames.

The rest of the paper is organized as follows: In Section 2, we review related power-aware MAC protocols for wireless networks. In Section 3, we present the main features of the IEEE 802.11 MAC protocol. Section 4 describes the proposed protocol, emphasizing its main design considerations. More specifically, Section 4.1 describes the slow start feature of the SSPC protocol and Section 4.2 describes the rules that have to be followed by nodes other than the transmitter or the receiver to decide about the power level they are allowed to use. Section 5 describes the simulation model used for evaluating the performance of the SSPC protocol, while Section 6 describes the results obtained. More specifically, Section 6.1 describes the results obtained on energy related metrics, while Section 6.2 describes the results obtained on network performance metrics. Finally, our main conclusions and future work are drawn in Section 7.

2. Related work

A great deal of research on MANETs has focused on the design of power-aware protocols, where the efficiency of each protocol is interpreted in a number of different ways, using various performance criteria, techniques and algorithms. Power-aware mechanisms can be classified into MAC-layer, network-layer and higher-layer implementations. Power-aware MAC protocols can further be distinguished into the following sub-categories:

- Reservation-based power-aware MAC protocols: protocols in this category try to avoid collisions in the MAC layer, and the related retransmissions and additional power consumption. In reservation schemes a group of nodes select some type of coordinator to function as a local "base station". Since the coordinator's role consumes node resources, several schemes have been proposed where the coordinator's role is rotated among network nodes.
- Switching off power-aware MAC protocols: protocols in this category try to minimize energy consumption by forcing nodes that are not active (i.e., not sending or receiving any packets) to enter a sleep state and power up only when they have pending traffic.
- Transmission power control MAC protocols: In recent years, power control MAC protocols for wireless ad hoc networks have been the focus of extensive research as a way to reduce energy consumption and/or increase network throughput by increasing the channel's spatial reuse. A power control MAC protocol reserves different floors for different packet destinations. Both the channel bandwidth and the reserved floor constitute network resources that nodes contend for. For systems with a shared data channel (where only one node uses all the bandwidth for transmission at any time), the floor becomes the single critical resource.

The proposed protocol is a transmission power control contention-based MAC protocol that uses control packets and carrier sensing, as well as a slow start mechanism. In [4,5] the authors proposed a Distributed Contention Control (DCC) protocol, which uses information on slot utilization and on the number of transmission attempts, to estimate the probability of successful transmission before a frame is actually transmitted. If the probability of success is too low, the frame transmission is deferred to reduce the probable retransmission overhead; otherwise, the frame is transmitted immediately. Energy consumption can be reduced in this way, since by observing the channel congestion level; many energy-consuming retransmissions are avoided. In [6], a Power-Aware Multi-Access protocol with Signaling (PAMAS) is introduced for power conservation in ad hoc networks. PAMAS is a RTS/CTS-based MAC protocol with separate data and signalling channels. The signalling channel is used for exchanging RTS/CTS packets, busy tones, and probe control packets. The basic motivation for the work in [6] is that a host's energy is often wasted on overhearing packets that are not destined for it. The scheme proposed in [7] allows a station to enter a sleep mode and save energy, but a special hardware, called Remote Activated Switch (RAS), is required to receive wakeup signals. In [8], the geographical area is partitioned into smaller areas, and only one host remains active to relay frames for the stations in each sub-area. All the previous energy-aware schemes assume fixed transmission power for the nodes.

In [9], the authors proposed a power control MAC protocol for MANETs that allows nodes to vary their transmission power on a per-frame basis. The main idea in this scheme is to use different power levels for RTS/CTS and DATA/ACK frames transmissions so as to save energy. Specifically, the maximum transmission power is used for RTS/CTS frames, and the minimum required transmission power is used for DATA/ACK frames. Additionally, the source node transmits DATA frames at the maximum power level periodically, for just enough time for nodes in the carrier sensing zone to sense them, so as to avoid potential collisions between ACK and DATA frames. In [10], the authors proposed a Power Controlled Dual Channel (PCDC) MAC protocol for MANETs. To produce power-efficient routes, PCDC allows the MAC layer to indirectly influence routing decisions at the network layer by controlling the power level of the broadcasted route request packets. PCDC uses the signal strength of the overheard control (RTS/CTS) signal to build a power-efficient network topology. By allowing for a receiver-specific, dynamically computed interference margin, PCDC enables simultaneous interference limited transmissions to take place in the vicinity of a receiver. The possibility and the potential benefits of adjusting the transmission power are also considered in [11], where a Power Management for Throughput Enhancement scheme is proposed. The authors in [11] investigate the effects power adjustment has on the average power consumption and the end-to-end throughput in a wireless ad hoc environment.

SSPC is in line with the work in [9–11] in the sense that nodes use power control mechanisms to reduce power consumption and interference in the network. However, our scheme differs from the schemes in [9–11], in several aspects, which are described next. In [9], the RTS/CTS frames are transmitted using the maximum power $P_{\max}$, causing more nodes to defer their transmission than is necessary. Instead, in the SSPC protocol the source node transmits the RTS frames at power levels that follow a slow start principle, reserving a smaller transmission floor and allowing more nodes to transmit simultaneously. Also, in [9] the transmission power used for DATA frames is periodically increased from the minimum required 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. Also, in the SSPC protocol, nodes in the carrier sensing zone of a receiver have the ability to compute a (looser) bound on the maximum power they can use without causing excessive interference to neighbouring nodes, a characteristic that is not present in the protocol described in [9], where such nodes are completely prevented from transmitting. Moreover, in the SSPC protocol, the transmission power used for the DATA frames is slightly more than the minimum required, so as to allow other future transmissions to simultaneously take place over the reserved floor. This characteristic is not supported by the protocol described in [9], where simultaneous transmissions over a reserved transmission floor are not permitted. In the power control protocol described in [10], the transmission of the RTS frames is performed using the maximum power $P_{\max}$, potentially causing more nodes to defer their transmission than is necessary, in contrast to the SSPC protocol where the transmission power of the RTS frames follows the slow start principle. Also the protocols described in [10,11] do not clarify the way nodes in the carrier sensing zone of a receiver handle transmissions, an issue that the SSPC protocol deals with by calculating a looser bound on the maximum power such nodes can use. In [11], even though the proposed scheme achieves lower power consumption by using different transmission powers, it does not take into account the interference caused to ongoing and future transmissions at the receiving nodes, which may cause more retransmissions and consequently more energy consumption than the SSPC protocol.

Finally, a transmission power control mechanism is used at the random access channel (RACH) procedure in W-CDMA systems [19]. More specifically, RACH is based on random access, and increases the transmit power until correct decoding at the base station is achieved. The SSPC protocol differs from the power ramp-up procedure in RACH of a WCDMA system in a number of ways: in the SSPC protocol, the transmission power used for the DATA frames is more than the minimum required, so as to allow other future transmissions to simultaneously take place over the reserved floor, a characteristic that is not supported by the RACH procedure, which is designed for cellular-based W-CDMA systems [19]. Also, at the slow star phase of the SSPC protocol, no control frames are sent by the receiver (except the CTS frame) and the transmitter increases its power each time by a constant amount, while in the case of the PRACH procedure the terminal increases the preamble transmission power by a step given by the base station, This feature of the RACH procedure can cause higher overhead compared to the slow start procedure used by the SSPC protocol.

3. Main features of the IEEE 802.11 MAC protocol

IEEE 802.11 specifies two MAC protocols, PCF (Point Coordination Function) and DCF (Distributed Coordination Function) [3]. PCF is a centralized scheme, whereas DCF is a fully distributed scheme. The DCF standard is by far the most dominant MAC protocol for MANETs. It is based on the CSMA/CA protocol, and incorporates the RTS/CTS handshaking mechanism to overcome the hidden node problem.

Each node in IEEE 802.11 maintains a network allocation vector (NAV), which indicates the remaining time of the ongoing transmissions. Using the duration information in the RTS, CTS and DATA frames, nodes update their NAVs whenever they receive a frame. IEEE 802.11 defines four interframe space durations (IFSs): SIFS (short interframe space), PIFS (PCF interframe space), DIFS (DCF interframe space) and EIFS (extended interframe space). The IFSs provide different priority levels for accessing the channel. The SIFS is the shortest of the interframe spaces and is used following the transmission of RTS, CTS and DATA frames to give priority to CTS, DATA and ACK frames, respectively. Before sending an RTS frame, a node senses the medium for a DIFS interval, and if the medium is found idle the node sends the RTS frame. Upon receiving an RTS frame, the receiver senses the medium for a SIFS interval and sends a CTS frame if the medium is free. The transmitter and the receiver send DATA and ACK frames, respectively, if the medium is free for a SIFS interval (Fig. 2). If a node that has sent an RTS or DATA frame does not receive a CTS or ACK frame before timeout, it initiates a back-off procedure [3].

4. The slow start power controlled MAC protocol

Before describing in detail the proposed Slow Start Power Controlled MAC protocol, we summarize some features of IEEE 802.11 that will be useful in our presentation.

4.1. The slow start feature of the SSPC protocol

To illustrate the operation of the SSPC protocol, consider the situation depicted in Fig. 4, where node A wants to transmit some DATA frames to node B. Node A senses the medium for a DIFS interval and if the medium is still idle, A sends an RTS frame to B using transmission power that follows the slow start principle to be described shortly. The RTS frame informs the recipients that a DATA frames transmission will occur at node B, and is sensed by all the nodes in the coverage area of node A.

The format of the RTS frame is given in Fig. 3. The common fields that are used at both the RTS frames of IEEE 802.11 [3] and of SSPC are the following:

- Frame control: It is comprised of 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.
- FCS: Frame Check Sequence used for error control.

The new field SSPC adds in the RTS frame is the field P^i_{RTS}, which is the transmission power of the current (ith) RTS transmission attempt.

At its first attempt node A sends the RTS frame with power P^0_{RTS} hoping that node B is near enough to reach it and sets a timer equal to T_{RTS}. Typical values of the power P^0_{RTS} are, for example, 15 dbm for the D-Link AirPlus™ G DWL-G630 Wireless Cardbus Adapter operating at 2.4GHz [12] and 14 dbm for the IEEE 802.11b Wireless LAN PC Card operating at 2.4 GHz [13]. The value of the timer is set to $T_{\mathrm{RTS}} = 2T_{\mathrm{PROP}} + T_{\mathrm{SIFS}} + T_{\mathrm{CTS}}$, 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

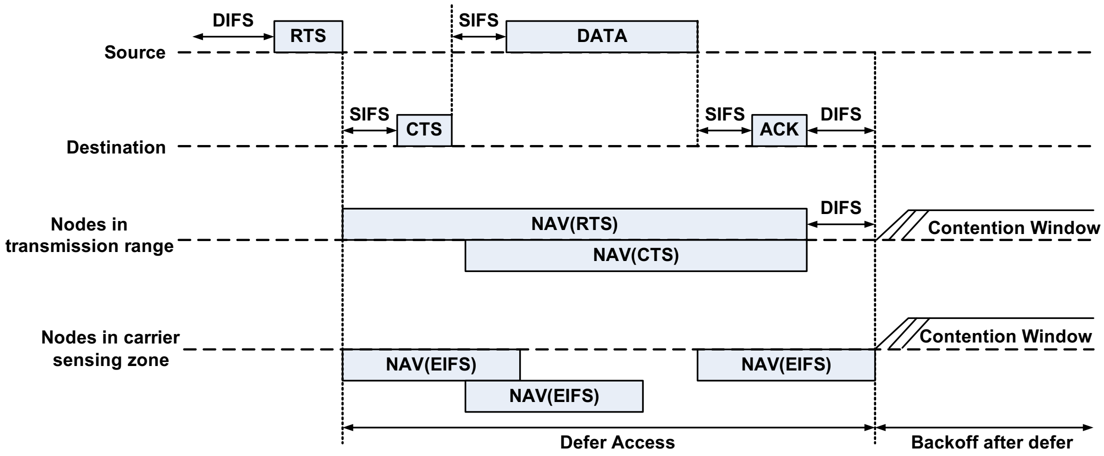

Fig. 2. IFS intervals and NAVs for the transmission of RTS and CTS frames. Nodes in the transmission range can sense and decode the signal correctly, while nodes in the carrier sensing zone receive but cannot correctly decode the signal.

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

Fig. 3. The RTS frame format in SSPC.

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 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, and retransmits the RTS frame, but now with transmission power P^{1}_{RTS} that has been increased by S dbm compared to the previous transmission power P^{0}_{RTS}.

The parameter S is referred to as the *step* of the slow start principle. 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^{i}_{RTS} 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. The minimum initial power P^{0}_{RTS} can be different for different nodes. The smaller P^{0}_{RTS} is or the larger the distance between two nodes is, the more RTS retransmissions a node may have to undertake in order to reach the intended receiver.

Most commercial IEEE 802.11 wireless adapters and access points that support automatic or manual transmit power control mechanisms use, when controlling output power, a step size varying from 1 to 3 db; see, for example, the “Alvarion BreezeAccess VL” [17] or the “Cisco Aironet 1240AG Series 802.11A/B/G Access Point” [18] datasheets. We propose the parameter S to take values between 1 and 3 db, depending on the accuracy we want to have in the estimation of P^{i}_{RTS} (and consequently P_{DATA}). The smaller the value of S, the more accurate is the computation of P^{i}_{RTS} and P_{DATA}, but also the larger is the number of RTS transmissions that may be needed before the intended receiver is reached.

All nodes that are in the transmission range of node A and correctly decode the RTS frame, set their NAV to the value $NAV^{\mathrm{TR}}_{\mathrm{RTS}} = T_{\mathrm{SIFS}} + T_{\mathrm{CTS}} + T_{\mathrm{SIFS}} + T_{\mathrm{DATA}} + T_{\mathrm{SIFS}} + T_{\mathrm{ACK}}$, as given in [3], and defer their transmissions for that period. Instead, nodes that lie in the carrier sensing zone of node A, that is nodes that detect a frame but cannot decode it, set their NAVs to the value $NAV^{CS}_{\mathrm{RTS}} = EIFS$. This is because nodes in the carrier sensing zone do not know the duration of the frame transmission. The main purpose of the EIFS is therefore to provide enough time for a source node to receive the ACK frame. 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 [3]

$$\begin{aligned} EIFS = {} & SIFSTime + (8 \times ACKsize) + PreambleLength \\ & + PLCPHeaderLength + DIFS, \end{aligned} \tag{1}$$

where *ACKsize* is the length in bytes of an ACK frame and $(8 \times ACKsize) + PreambleLenght + PLCPHeaderLength$ is the transmission time of an ACK frame at the physical layer's lowest mandatory rate. See [3] for the explanation of the other terms of Eq. (1).

Note that 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, may cause a collision with the reception of a DATA frame at the receiver [9]. This problem is also inherited by the SSPC protocol, as it also handles the hidden terminal problem using the RTS/CTS frames handshake. The use of the RTS/CTS frames in the IEEE 802.11 protocol can negatively impact channel utilization by completely disallowing concurrent transmissions over the reserved floor. In contrast, in the SSPC protocol, concurrent transmissions over the reserved floor can take place, provided that they do not use power more than a computed threshold. As a result, the negative performance impact of the hidden terminal problem is relatively limited in the SSPC protocol compared to the IEEE 802.11 protocol, as we will also see in the performance evaluation section.

In the example of Fig. 4. Node B upon receiving the RTS frame checks the RA field to see if it is the intended receiver and the TA field to find the address of the transmitter. It also examines the FCS field to see if the received RTS frame contains errors. We must note 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 9 dbm is required to achieve sufficient signal quality and the noise floor at the receiver is -111 dbm, then the minimum signal or sensitivity for good reception is -102 dbm. The sensitivity is typically supplied by manufacturers, and minimum acceptable levels can be found in the technical specifications of its device. For example the sensitivity of the D-Link AirPlus$^{\text{TM}}$ G DWL-G630 Wireless Cardbus Adapter is -84 dbm operating at 11Mbps and at the band of 2.4 GHz [12], while the sensitivity of the IEEE 802.11b Wireless LAN PC Card is -80 dbm operating at 11Mbps and at the band of 2.4 GHz [13].

We denote by SNR^{i}_{RTS} the *SNR* at the receiver for the current (ith) attempt of the RTS frame transmission when power equal to P^{i}_{RTS} is used at the transmitter and by $SNR^{\min}_{\text{RTS}}$ the *SNR* at the receiver when power equal to the minimum power $P^{\min}_{\text{RTS}}$ that guarantees the connectivity between node A and node B is used. In other words, $SNR^{\min}_{\text{RTS}}$ 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 $P^{\min}_{\text{RTS}}$ is the minimum power that should be used at the transmitter to result in *SNR* equal to $SNR^{\min}_{\text{RTS}}$ at the receiver. The transmitter would like to know the value of $P^{\min}_{\text{RTS}}$ so that it can use it in its transmission, but of course it cannot use the definition:

$$SNR = 10\log P_{\text{received}}/N, \tag{2}$$

where P_{received} is the received signal power and N is the sum of the power of the thermal noise plus the interference noise caused at the receiver, to compute it, because it does not know N or the channel characteristics. This minimum transmission power $P^{\min}_{\text{RTS}}$ is instead estimated at the receiver and is communicated back to the transmitter through the RTS/CTS exchanged during the slow start mechanism, as explained below.

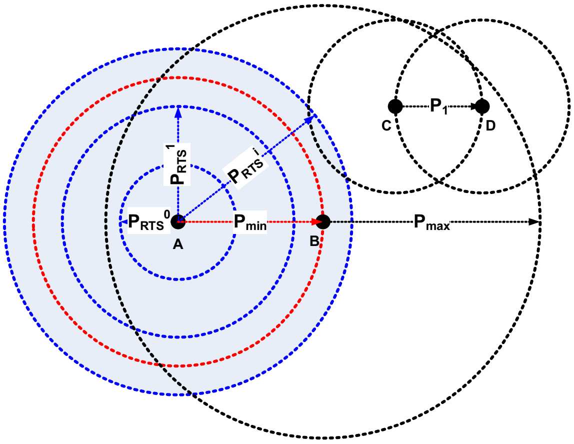

Fig. 4. The Slow Start mechanism at SSPC protocol.

Consider now the current attempt (i-1) of node A to send the RTS frame with transmission power equal to P^{i-1}_{RTS} and let SNR^{i-1}_{RTS} 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 does not receive a CTS frame, then node A invokes its back-off procedure and sends again the RTS frame with power P^{i}_{RTS}. This is node A's (ith) 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^{i}_{RTS} used by node A at its current attempt to send the RTS frame is greater than or equal to the minimum power $P^{\min}_{\text{RTS}}$ that guarantees the connectivity between nodes A and B. At the same time we know that $P^{\min}_{\text{RTS}}$ is greater than P^{i-1}_{RTS} since the $(i-1)$th attempt failed. In our protocol the receiver uses the approximations $SNR^{\min}_{\text{RTS}} \approx SNR^{i}_{\text{RTS}}$ and $P^{\min}_{\text{RTS}} \approx P^{i}_{\text{RTS}}$, where i is the first successful RTS transmission attempt. We must underline that this is only an approximation of the minimum power that guarantees the connectivity between nodes A and B and not its accurate value. The accuracy of this approximation also depends on the step size S used in the slow start mechanism. The smaller the value of S, the more accurate is the estimation of $P^{\min}_{\text{RTS}}$. Note that this estimated value of $P^{\min}_{\text{RTS}}$ takes into account all thermal and interference noise N present at B when it received the RTS frame.

4.2. 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

$$P_{\text{DATA}} = P^{i}_{\text{RTS}} + M. \tag{3}$$

Note that in order to compute the DATA frames transmission power, a node does not need to know the exact location of all the nodes in the network or the channel conditions. The DATA frame transmission power is simply derived from the value of P^{i}_{RTS}, according to Eq. (3).

The term M is used as a safety margin and also to allow for any 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 node A to increase by M the transmission power of the DATA frames. M is a design parameter and determines the future interference margin that the receiver will be able to accept from its neighbouring nodes. The larger M is, the more nodes in the vicinity of a DATA frame receiver will be allowed to transmit, but also the larger will be the interference caused by the transmitting node to nodes other than the intended receiver.

Node B sends the CTS frame using the maximum transmission power. The CTS frame format is described in Fig. 5. The fields that are common in the IEEE 802.11 [3] and in the SSPC protocol are the following:

- 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.
- FCS: Frame check sequence.

The new fields SSPC adds in the CTS frames are

- 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.
- $P_{\max}$: The CTS frame transmission power.
- P_{INTERF}: The additional interference power that each neighbour/future interferer can add to the receiver.

The interference power P_{INTERF} that neighboring nodes are allowed to contribute to the receiver B will be computed shortly.

All nodes that are in the transmission range of node B set their NAVs to the value $\text{NAV}_{\text{CTS}}^{TR} = T_{\text{SIFS}} + T_{\text{DATA}} + T_{\text{SIFS}} + T_{\text{ACK}}$. Not all these nodes, however, but only the nodes that are neighbors to node B and are going to cause to it interference power 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 $T_{\text{CTS}} = 2T_{\text{PROP}} + T_{\text{SIFS}}$. 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 $\text{NAV}_{\text{CTS}}^{CS} = EIFS$ and defer their transmissions for this duration. As already mentioned, nodes in the carrier sensing zone cannot decode the received frame, so they do not know the duration of the frame transmission (a difficulty present in IEEE 802.11 as well), and also they cannot compute the maximum power they can use. These nodes set their NAV's for the EIFS duration, to prevent a collision with the DATA frame at the receiver. Note that we do not want 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. We will present a solution to this problem later.

An important issue that must be addressed 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 (see Eq. (3)). [9] presents a method to compute the interference power. The future interference M that is allowed must be equitably distributed among the future potentially interfering users in the vicinity of B. 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 simultaneously active transmissions in its neighbourhood at time t, which we denote by $N_{\text{inst}}^R(t)$. This can be easily computed by monitoring the RTS/CTS exchange. We denote by $N^R(\text{RTS})$ the value of $N_{\text{inst}}^R(t)$ when the RTS packet is received at the receiver; the interference of these $N^R(\text{RTS})$ 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 $N_{\text{inst}}^R(t)$, denoted by $N_{\text{avg}}^R(t)$. Then $N^R(t)$ is calculated as follows:

$$N^R(t) = \max\{N_{\text{avg}}^R(t), N_{\text{inst}}^R(t)\} - N^R(\text{RTS}). \tag{4}$$

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

$$P_{\text{INTERF}} = \max\{M/N^R(t), P_{\text{INTERF}}^{\min}\}, \tag{5}$$

where $P_{\text{INTERF}}^{\min}$ is a lower bound we pose on P_{INTERF}. The rationale for posing this lower bound is the following. If the margin M is equitably distributed among a large number of neighbouring nodes then the interference power that every node will be allowed to cause to node B may be too small, and may be unusable. Also, if no lower bound on P_{INTERF} is given, then nodes in the carrier sensing zone of B, which do not correctly decode the CTS frame and therefore do not learn the accurate value of P_{INTERF}, would be prevented from transmitting since they would not be able to estimate a safe power level to use. These nodes are however at relatively large distance from B and should therefore be allowed to transmit up to a given power level, something that can be achieved by imposing the lower bound $P_{\text{INTERF}}^{\min}$, as we will see towards the end of Section 3. Therefore, P_{INTERF} is the additional interference power that each future interferer can add to a receiver, and is chosen in this paper to be the same for all the neighbouring nodes, while M is the aggregate future interference that the receiver can tolerate, which is equitably distributed to its neighbouring nodes.

The value of P_{INTERF} depends on the values of $N^R(t)$, M and $P_{\text{INTERF}}^{\min}$ according to Eq. (5). The values of M and $P_{\text{INTERF}}^{\min}$ are design parameters, while $N^R(t)$ is the number of nodes at time t that are in vicinity of the node under

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

Fig. 5. CTS frame format in the SSPC protocol.

consideration and which are to share the interference margin. In order to compute the value of $N^R(t)$, a node monitors the RTS/CTS frames exchange in its vicinity during an interval of a given duration T_{WAIT}, which is also a design parameter. The future interference allowed per node depends on the interval duration and the number of RTS/CTS frames sensed during that interval. The more RTS/CTS frames are sensed, the larger is the estimated number of neighbouring nodes $N^R(t)$ and, consequently, the smaller is the value of P_{INTERF}.

The duration for which a node must listen to collect information before making the access decision must be chosen by fine tuning the system parameters using simulation and experimental data. If nodes listen to the channel even when they do not have data to transmit, then they already have a good estimate of $N^R(t)$. If they do not listen when they are not active, then they may either wait for an interval T_{WAIT}, or use a less accurate estimate of $N^R(t)$. The parameter T_{WAIT} must be at least equal to the duration a node listens the channel before transmitting a RTS frame according to the IEEE 802.11 protocol, that is, a DIFS interval (T_{DIFS}). The value of T_{WAIT} could be chosen to be a small multiple of $T_{\text{RTS}} + 2T_{\text{PROP}} + T_{\text{SIFS}} + T_{\text{CTS}}$ that is the time a node must wait in order to receive a CTS frame. Note that an inaccurate estimate of $N^R(t)$ does not affect the correctness of the protocol; it only results in less or more allowed future interferers, each being permitted a larger or smaller, respectively, interference margin. If however, the estimate of $N^R(t)$ is close to the actual number of nodes (and therefore, to the number of potential future interferers) in the receiver's vicinity, we expect better performance results. Alternative ways to determine the number $N^R(t)$ of future interferers to be allowed, other than the one proposed in this paper, could also have been used.

As previously mentioned, node B replies to the RTS frame with a CTS frame using power equal to $P_{\max}(B)$ (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 in the coverage area of node B that a DATA frame transmission will occur to 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}.

Another issue that has to be specified is the way a neighbour node, say node C in Fig. 4, 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 strength of the received signal. There are a lot of commercial chips that among others can compute the signal strengths. Example of those chip are the Atheros AR6001X Radio On Chip which integrates the RF transceiver, baseband, MAC, central process and peripheral control functions [14], and the POLARIS™ TOTAL RADIO™ solution from RF Micro Devices which is a highly integrated transceiver that performs all the functions of a handset radio section [15].

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

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

Every node, say node C, that hears the CTS frame sent by node B at power $P_{\max}(B)$, has the ability to compute the received signal strength $P_{\text{CTS-received}}$, and consequently the channel gain between B and C by the equation:

$$G_{B,C} = P_{\text{CTS-received}}/P_{\max}. \tag{6}$$

Based on that, and assuming that the channel gain is approximately the same in both channel directions (this is a reasonable assumption when node mobility is small during the duration of a RTS/CTS/DATA transmission, so that the distance and channel attenuation do not change significantly during the control and data packets exchange) node C can compute the maximum transmission power $P_{\max}(C/B)$ that it can use without causing excessive interference at node B as

$$P_{\max}(C/B) = P_{\text{INTERF}}/G_{C,B} \approx P_{\text{INTERF}}/G_{B,C}. \tag{7}$$

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

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

$$P_{\max}(C) = \min_i P_{\max}(C/B_i). \tag{8}$$

The interference table of node C together with the NAV data structure that 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 other node D, it can increase its power up to $P_{\max}(C)$.

For example, let us consider the situation described at Fig. 6. The dashed lines represent the receiving areas of the CTS frames when the maximum transmission power

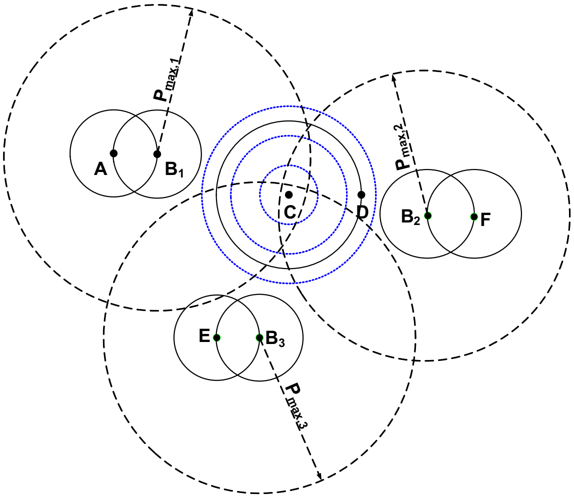

Fig. 6. Usage of the CTS frame.

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 $P_{\mathrm{INTERF},i}$ $i = 1,2,3$ 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

$$P_{\max}(C) = \min\{P_{\max}(C/B_1), P_{\max}(C/B_2), P_{\max}(C/B_3)\}, \qquad (9)$$

where

$$P_{\max}(C/B_i) = P_{\mathrm{INTERF},i}/G_{B_i,C}, \text{ for } i = 1,2,3, \qquad (10)$$

$P_{\max}(C)$ is the maximum transmission power 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. 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 $2T_{\mathrm{PROP}} + T_{\mathrm{ACK}}$ seconds [3]. 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.

A node updates its interference table every time it senses and decodes a new CTS frame originated from one of its neighboring nodes or every time an interference source is gone. For example, in Fig. 6, when the DATA frame transmission from node A to node B_1 is completed, node C removes from its interference table the record related to node B_1. Node C knows when the transmission of the DATA frame from node A to node B_1 is completed by using its network allocation vector which indicates the remaining time of an ongoing transmission. More specifically, node C knows that after time $\mathrm{NAV}_{\mathrm{CTS}}^{TR} = T_{\mathrm{SIFS}} + T_{\mathrm{DATA}} + T_{\mathrm{SIFS}} + T_{\mathrm{ACK}}$ from the time instance at which it sensed the CTS frame from node B_1, the DATA frame transmission from node A to node B_1 will have been completed. Another scenario is the case where a node B_i in Fig. 6 aborts (probably under some abnormal conditions) an ongoing transmission (which has been indicated by the exchange of the RTS/CTS frames), while node C is in the slow-start phase of sending an RTS frame. In that case node C cannot update its transmission power $P_{\max}(C)$ dynamically, so the interference power P_{INTERF} corresponding to node B_i remains unused. Of course, it will be unusual, or rare for a node B_i to cease its transmission given that it has already transmitted an RTS frame to the receiver and has received a CTS frame from it.

Consider, finally, a node G that is in the carrier sensing zone of node B (Fig. 7) and receives its CTS frame. Since this node cannot correctly decode the received CTS frame, it does not know the values of the interference power P_{INTERF} it is allowed to cause to node B, or the transmission power of the CTS frame it received. We assume, however, that node G can still compute the received signal strength $P_{\text{CTS-received}}$ of the CTS frame. Even though node G cannot compute the exact value of the maximum transmission power it is allowed to use, it can compute a looser bound on the maximum power allowed to it as follows:

$$\begin{aligned} P_{\max}(G/B) &= P_{\mathrm{INTERF}}/G_{G,B} = P_{\mathrm{INTERF}} \cdot P_{\max}/P_{\text{CTS-received}} \\ &\geqslant P_{\mathrm{INTERF}}^{\min} \cdot P_{\mathrm{RTS}}^{0,\min}/P_{\text{CTS-received}}, \end{aligned} \qquad (11)$$

where $P_{\mathrm{RTS}}^{0,\min}$ is the minimum initial transmission power used in the slow start mechanism for the RTS transmission. In other words, node G uses Eq. (7) together with the upper bound

$$G_{G,B} \leqslant P_{\text{CTS-received}}/P_{\mathrm{RTS}}^{0,\min}, \qquad (12)$$

on the channel gain between G and B, for which we assume the approximation $G_{G,B} \approx G_{B,G}$. The upper bound on the channel gain is obtained from the received signal strength $P_{\text{CTS-received}}$, since we know that any transmission of an RTS frame must have used power at least equal to $P_{\mathrm{RTS}}^{0,\min}$. Recall that $P_{\mathrm{INTERF}}^{\min}$ is the lower bound on the interference power P_{INTERF} and is also a known design parameter. So although nodes in the carrier sensing zone cannot compute the exact

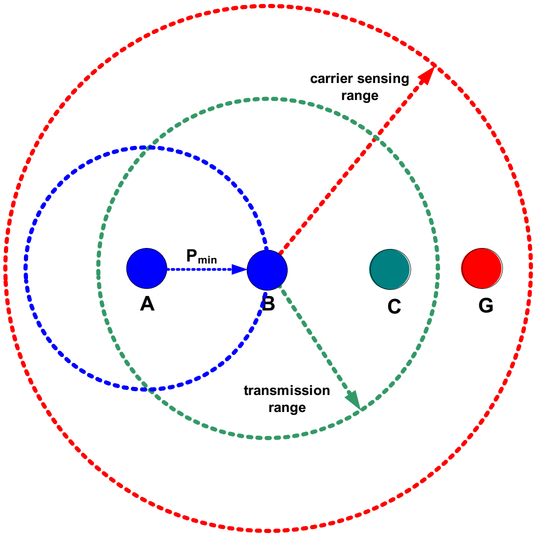

Fig. 7. Transmission and carrier sensing zone of node B.

value of their maximum allowable transmission power, they can still compute a lower bound [namely, the right hand side of inequality Eq. (11)] on the power they can safely 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 of a collision with the ACK frame at the source. Instead, in the SSPC protocol, nodes in the carrier sensing zone can compute a threshold on the maximum allowable transmission power and defer their transmissions for an EIFS duration only if they intend to use power more than that threshold. Note that as the number of terminals that cannot correctly decode the CTS frame increases, the performance of the SSPC protocol will degrade, since such terminals will use a rather pessimistic upper bound on the maximum power they can use; however, performance will still be better than that of IEEE 802.11 protocol, where all nodes in the carrier sensing zone of a CTS frame are prevented from transmitting.

Many current MAC protocols support rate adaptation, where multiple rates are served, each corresponding to different minimum required *SNR* at the receiver [Eq. (2)]. A different required *SNR* value corresponds to a different minimum power level at the receiver, and therefore a different required transmission power. In our description of the SSPC protocol we assumed that the rate is given and is the same for the RTS, CTS and DATA frames transmitted. Since in the SSPC protocol a node knows the maximum power it can use and can increase its transmission power only up to that level, it may not be able to reach the intended destination, in the sense that its RTS packet may not be correctly decoded at the intended receiver at the desired rate. In that case, the transmitter may reattempt to send the RTS packet (using the slow start principle, or, probably preferably, using directly its maximum allowed transmission power), using a smaller rate for the RTS packet and in case of success, for the CTS and DATA packet transmission that will follow. The RTS and CTS packets will then have to be modified to also include a field recording the rate at which the impending transmission is requested each time.

5. Simulation model

In our experiments we used the Network Simulator ns2 [2] to simulate a wireless multi-hop network of 36 nodes distributed according to a two dimensional uniform distribution in a $500 \times 500\ \mathrm{m}^2$ area. To obtain results that are easier to interpret, we mainly focused on the performance benefits that can be obtained through the use of power control, and not on the protocol overhead involved. Therefore, we assumed in our simulations that nodes have global knowledge of the network topology [16] and other information they need for adjusting their transmission power and no control packets and related overhead were included. Note that the SSPC protocol's overhead is somewhat larger than that of IEEE 802.11, due to the repetitive RTS frame transmissions of the slow start mechanism and the additional fields used in the RTS and CTS frames.

The received signal power at distance d from the transmitter was assumed in our simulations to be

$$P_r(d) = P_t \cdot G_t \cdot G_r \cdot \lambda^2/(4\pi)^2 \cdot d^a \cdot L, \tag{13}$$

where P_t is the transmitted power, G_t and G_r are the antenna gains of the transmitter and the receiver, respectively, L ($L \geqslant 1$) is the system loss factor, λ is the wavelength and a is the path loss constant. In our experiments we set $G_t = 1$, $G_r = 1$ and $L = 1$. Parameter a is typically between 2 and 4 depending on the wireless channel. In our experiments we assumed $a = 2$, corresponding to the Free Space propagation model without multi-path phenomena, where there is always a clear line-of-sight path between sender and receiver. Note that the SSPC protocol does not assume any knowledge of the radio propagation model, and the model of Eq. (13) is used only for performance evaluation purposes. A different propagation model would naturally result in different performance, even though we believe that the performance effects of the model used would be similar for both the SSPC and the IEEE 802.11 protocol.

The MAC protocol we used is a power controlled version of IEEE 802.11. The amount of energy expended for a packet transmission was taken to be equal to its transmission power multiplied by the duration of the packet transmission. Some constant (independent of the distance) energy was also consumed for packet reception and processing. When a node is idle we assume that it consumes no energy.

We considered the following two cases:

- Static power case: Each node uses static transmission power for its transmissions (as in IEEE 802.11).
- Adjustable power case: Each node adjusts its transmission power to the minimum required value that guarantees the reliable reception of the frames at the sink nodes (as is done by the SSPC protocol). This minimum power can be estimated by the nodes via the slow start mechanism described in Section 3.

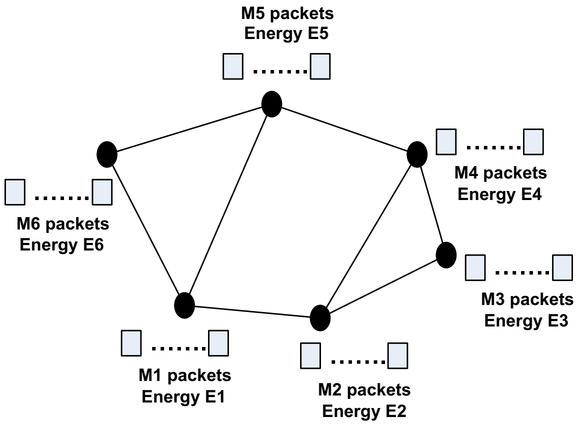

Fig. 8. The packet evacuation problem. There is a fixed number of packets per node that have to be delivered to their destinations. The objective is to serve the packets in the smallest number of steps and/or using the minimum amount of energy.

The performance of these two approaches was evaluated in the setting of the evacuation problem illustrated in Fig. 8. In this problem, there is a fixed number of packets per node that have to be delivered to their destinations. The objective is to serve the packets in the smallest number of steps and/or using the minimum amount of energy. In our experiments, the number of packets evacuated from the network varies from 100 to 1000 (at steps of 100) packets per node. Packet destinations are taken to be uniformly distributed over all remaining nodes of the network. The threshold for the received power required for correct reception (that is, the receiver sensitivity) is the same for all nodes. Other parameters used in the simulation are showed in Table 2.

The routing protocol used, is the minimum hop algorithm. To compare the two approaches the same paths were chosen for the packets delivery from the source to the sink nodes. We must note here that if the SSPC protocol is adopted, the routing algorithm could be improved to better exploit the advantages of SSPC over the usual IEEE 802.11. We chose to use the same (minimum hop) routing algorithm in our performance results for both protocols so that the results can be directly comparable; further performance benefits could have been obtained for the SSPC protocol using energy-aware or interference-aware routing algorithms, as a link transmission using SSPC expends less energy and causes less interference to other nodes. However, our focus is on the MAC layer, and routing, even though important, is outside the scope of this work. Finally, we did not consider node mobility or adaptation rate mechanisms in our simulations.

6. Performance results

In the experiments conducted for the static power and the adjustable power cases we measured:

- The average energy E consumed by the nodes at the end of an evacuation period.
- The variance σ_E^2 of the energy consumed by the nodes.
- The average packet delay D, defined as the average time between the beginning of an evacuation instance and the time a packet reaches its destination, averaged over all packets delivered to their destinations.
- The network throughput over an evacuation period.
- The number of collisions of RTS frames, due to the MAC protocol and the hidden terminal problem and.
- The received-to-sent packets ratio RS.

The first two performance parameters are related to energy considerations, while the remaining four are directly related to network performance.

Table 2
Simulation parameters.

Parameter	Value
Data packet size	500 bytes
Transmission rate	0.1 packets/s
Carrier sense threshold	1.92278e–08 Watt for 250 m
Reception threshold	1.92278e–08 Watt for 100 m

We choose to compare the performance of the SSPC protocol to that of the usual IEEE 802.11 protocol, as is done in most other related works, which also use IEEE 802.11 as a reference point. We believe that the results would be harder to interpret if comparisons were made to other (not equally used in practice) protocols.

6.1. Energy related parameters

In this Section, we present the measurements conducted on the energy related performance parameters. The energy consumption due to RTS/CTS frames exchange is not accounted for, since we focus on the performance benefits that can be obtained through the use of power control, and not on the protocol overhead involved.

Fig. 9 illustrates the average energy consumed per node (measured in Joules) after all packets have been evacuated from the network, for the adjustable and the static power case. It shows that using adjustable power results in considerably smaller energy consumption than using static power. The energy savings increase (linearly) with the number of transmitted packets. This is because in the adjustable power case every node adjusts its transmission power, via the slow start mechanism of the SSPC protocol, to the minimum required level for coherent reception at the receiving node, so that nodes consume only the necessary amount of energy. Instead, when static power is used, and the desired recipient is at a smaller distance than the static transmission range used, a node may expend an unnecessarily large amount of energy and cause unwarranted interference to other nodes. Also in the case of adjustable power, the number of frames retransmissions due to collisions and the average consumed energy in the network are both smaller, compared to the case of static transmission power.

The variance of the energy consumed by each node is shown in Fig. 10. The variance of the consumed energy indicates how the power consumption in the network is distributed among the various network's nodes. This is an important parameter, since we want power consumption

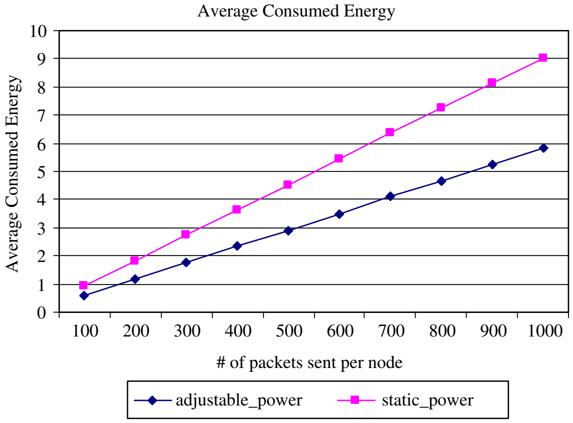

Fig. 9. Illustrates the average consumed energy per node at the end of an evacuation period for the static and the adjustable power case. The number of packets evacuated from the network varies from 100 to 1000 (at steps of 100) packets per node.

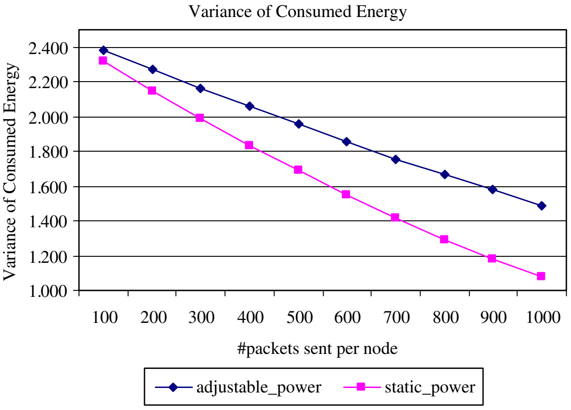

Fig. 10. Illustrates the variance of the energy consumed at the nodes for the adjustable power and the static power case. The number of packets evacuated from the network varies from 100 to 1000 (at steps of 100) packets per node.

to be uniformly distributed among the nodes of the network. From Fig. 10, it can be seen that static power approach results in smaller variance in the energy consumed per node than the adjustable power approach. This indicates that SSPC tends to spread energy consumption more uniformly among the nodes.

6.2. Network performance related parameters

In this subsection we present the results obtained on the network performance related parameters. Fig. 11 illustrates the average packet delay *D* of the packets delivered to their destinations for the adjustable power and the static power case, as a function of the number of packets evacuated per node. The delay is defined as the average time that elapses between the beginning of an evacuation instance and the time a packet reaches its destination, averaged over all packets delivered to their destinations.

For both approaches, the average packet delay increases as the number of packets that are evacuated increases. It can be seen that the adjustable power approach used in SSPC outperforms the static power approach used in standard IEEE 802.11. This is because the SSPC protocol allows more concurrent packet transmissions as long as they do not cause excessive interference to ongoing transmissions.

Fig. 12 depicts the network throughput (in bits per second) achieved during an evacuation period computed as

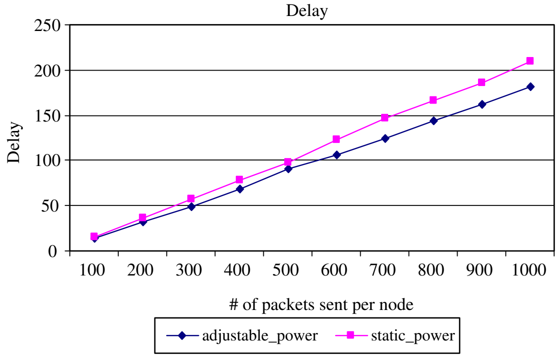

Fig. 11. Illustrates the average packet delay for the adjustable and the static power cases. The number of packets evacuated from the network varies from 100 to 1000 (at steps of 100) packets per node.

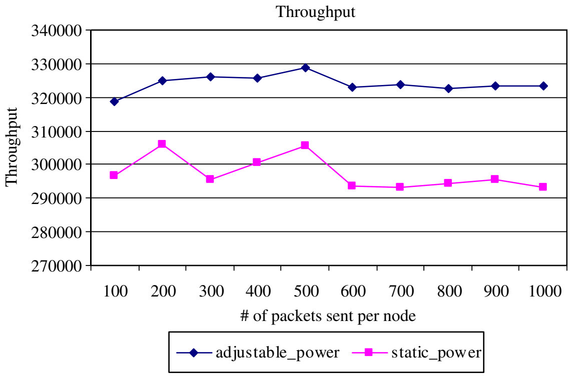

Fig. 12. Illustrates the network throughput for the adjustable and the static power cases. The number of packets evacuated from the network varies from 100 to 1000 (at steps of 100) packets per node.

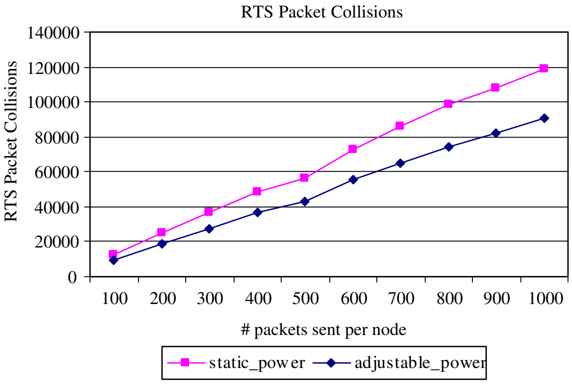

Fig. 13. Illustrates the number of the RTS frames collision for the adjustable and the static power cases. The number of packets evacuated from the network varies from 100 to 1000 (at steps of 100) packets per node.

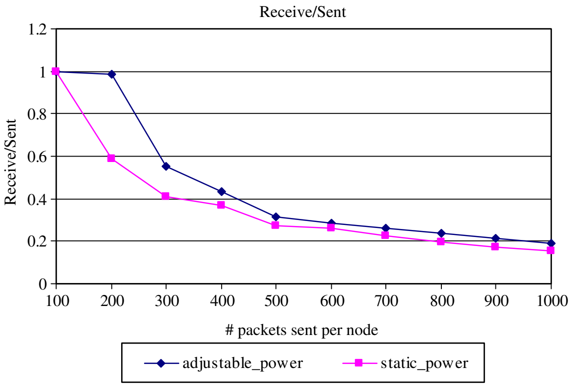

Fig. 14. Illustrates the received-to-sent packets ratio for the adjustable power and the static power case. The number of packets evacuated from the network varies from 100 to 1000 (at steps of 100) packets per node.

the number of bits transferred by the network divided by the time period the network is active. As shown in Fig. 12, adjustable power results in higher network throughput than static power. When nodes use static power $P_{\max}$ a larger number of neighbouring nodes defer their transmissions, upon hearing a RTS or CTS frame, resulting in lower network throughput. In contrast, in the adjustable power case, more simultaneous transmissions can take place. The performance difference between the two cases is almost the same for the different values of the number of packets evacuated per node.

The number of the RTS frames collisions due to the MAC protocol and the hidden terminal problem is illustrated in Fig. 13, which shows that the frequency of RTS frame collisions is smaller when adjustable power is used. This is because, in the case of the static power approach every node sends its RTS frame with maximum transmission power, while in the case of the adjustable power, the transmission power of the RTS frames is adjusted at the minimum required, resulting in fewer RTS collisions The performance difference between the adjustable power and the static power approach increases (linearly) as the number of packets evacuated increases.

The received-to-sent packets ratio is shown in Fig. 14. We observe that more packets are delivered to their destinations in the adjustable power case than in the static power case. This is because nodes spend less energy by using the minimum required power for their DATA frames transmissions, prolonging in this way the lifetime of the network. Since the nodes remain alive for longer time, the network capability of delivering packets to their destination is increased.

Even though no simulations have been performed on the effects network density has on performance, we believe that the benefits of the SSPC protocol over the IEEE 802.11 protocol will be more significant for dense networks. When the IEEE 802.11 protocol with constant transmission power is used, RTS frame collisions in the network will increase when network density increases, In the case of the SSPC protocol, the negative impacts of increased network density will be limited compared to the classic IEEE 802.11 protocol, because of the slow start principle used for RTS transmissions and the better channel reuse factor it achieves, both of which are more important for dense networks.

7. Conclusions and future work

We proposed and evaluated a new MAC protocol for ad hoc networks, called the Slow Start Power Controlled (SSPC) protocol. In SSPC, RTS frame transmission power follows a slow start principle, while DATA frames are sent using the minimum transmission power that guarantees the connectivity between the nodes plus some margin that allows for future interference. CTS frames are sent at the maximum transmission power and include information that is used by the recipients to compute the maximum power they can use for their DATA frame transmissions. Rate adaptation mechanisms can also be combined with the SSPC protocol. We obtained performance results in the setting of the evacuation problem, for the case of static transmission power and for the case where nodes adjust their transmission power to the minimum required level via the slow start mechanism of the SSPC protocol. Our performance results show that power adjustment results in smaller power consumption, delay, and number of RTS collisions and higher network throughput and packet delivery ratio.

Our future work will focus on the performance of the SSPC protocol under various mobility scenarios. We also plan to evaluate quantitatively the effects the overhead inserted by the SSPC protocol has on performance and compare it to that of other power control MAC protocols.

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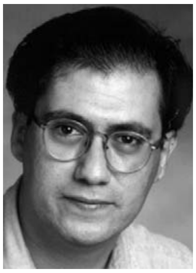

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