Optimization of IEEE 802.11 parameters for wide area coverage

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Abstract— **Wireless mesh networks are quickly emerging as a solution for broadband wireless connectivity. The physical layer technology is making remarkable progress allowing higher bandwidth and longer distance coverage than before. While standardization efforts are going on to define new standards and paradigms for Wireless Mesh Networks, many vendors sell mesh solutions based on the 802.11b technology. This standard has been originally designed for Wireless Local Area Networks in indoor scenarios with a maximum distance between nodes up to few hundred meters. As a consequence, there are many technical challenges for adapting 802.11 to multihop networks and outdoor environments.**

This paper shows some guidelines to set the 802.11b MAC parameters in order to extend the coverage of 802.11 to long distance networks. Simulation results show that a fine tuning of MAC parameters can allow a satisfactory multi-hop wireless communication in mesh network scenario using 802.11.

Index Terms— **802.11, mesh network**

I. INTRODUCTION

Wireless mesh networks are quickly emerging as a solution for broadband wireless connectivity. The physical layer technology is making remarkable progress allowing higher bandwidth and longer distance coverage than before. While standardization efforts are going on to define new standards (e.g., WiMAX [1]) and paradigms for Wireless Mesh Networks, many vendors sell mesh solutions based on the 802.11b technology (e.g. [2], [3] and [4]). The main strength of the IEEE 802.11 standard is the fully distributed nature of the access scheme, which provides cheap and easy-to-install components that are able to operate in the unlicensed spectrum, while still guaranteeing broadband capabilities. This standard, originally designed for Wireless Local Area Networks in indoor scenarios with a maximum distance between nodes up to few hundred meters, has become the de facto standard for multi-hop networks.

In the last years a big effort has been dedicated to the optimization of the 802.11 protocol in multihop scenarios. Many works have been focused on the TCP performance optimization in 802.11 multihop networks to minimize the TCP performance degradation due to the inappropriate TCP congestion control mechanisms unable to differentiate between congestion losses and losses due to errors on the wireless channel. [5], [6] and [7], for instance, propose a crosslayer protocol design to solve the problem which is based on a feedback mechanism to differentiate between losses caused by congestion or wireless channels.

Several papers have been focused on the optimization of MAC 802.11 parameters for long distance networks. In [8], the authors show real measurements from an experimental 802.11b/g mesh network composed of 37 nodes, focusing on link-level characteristics of 802.11 such as packet loss. In [9], the authors investigate the effectiveness of RTS/CTS handshake mechanism to reduce the interference between nodes, they show that, when the interference range is larger than the transmission range, the RTS/CTS can not function properly. In [10] and in [11], the authors evaluate the spatial reuse of 802.11 links in multihop scenario when the RTS/CTS mechanism is enabled.

With respect to previous papers, we show that the 802.11 RTS/CTS is not effective with long distance link in outdoor scenarios and propose an adaptive setting mechanism of the Carrier Sensing Threshold to increase the performance of MAC 802.11b and the spatial reuse of long chair topologies.

The rest of the paper is organized as follows. In Section II, a brief description of the IEEE 802.11 CSMA/CA mechanism with its limitations is given. Section III describes the 802.11 timing parameters in relation with the length of the link. In Section IV we analyze the effect of the Carrier Sensing Threshold on the spatial reuse and propose a dynamic setting to improve the performance of multihop topology. In Section V, performance results obtained through ns-2 simulations are presented. Finally, in Section VI the main conclusions are drawn.

II. 802.11 MAC SUBLAYER

The 802.11 MAC supports two operation modes: the Point Coordination Function (PCF) and the Distributed Coordination Function (DCF). In this paper we focus on DCF mode, since it is the fundamental access method used to support asynchronous data transfer. The DCF is based on carrier sense multiple access with collision avoidance (CSMA/CA). Two carrier sensing mechanisms are defined in the standard: Physical Carrier Sensing (PCS) performed on the air interface, Virtual Carrier Sensing (VCS) at the MAC layer. PCS

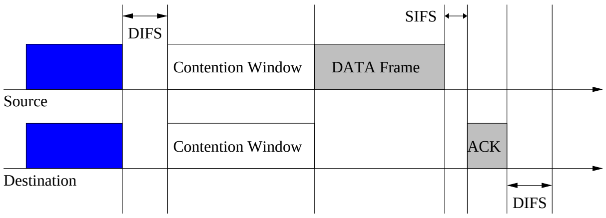

Fig. 1. 802.11 Timing diagram.

detects activity in the channel by sensing the signal strength from other sources and comparing it to the Carrier Sensing Threshold (CST). Virtual Carrier Sensing (VCS) is performed by the exchange of Request To Send (RTS) and Confirm To Send (CTS) messages. Moreover these messages are used to spread out the Network Allocation Vector (NAV) to all covered stations; the NAV indicates the amount of time that elapses until the current transmission session is complete. The VCS is designed to avoid the *Hidden Terminal Problem*, since the PCS (at source) does not suffice to avoid the interference at destination. The channel is marked busy if either PCS or VCS mechanisms indicate the channel is busy.

Priority access to the wireless medium is controlled through the use of InterFrame Space (IFS) time intervals between the frame transmissions. The IFS intervals are mandatory idle period that STAs have to wait before transmitting a packet. Three IFS intervals are specified in the standard: Short IFS (SIFS), Priority IFS (PIFS), and Distributed IFS (DIFS), where SIFS<PIFS<DIFS. Control packets (e.g. Acknowledgment packets) use the SIFS to access the channel with the highest priority. PIFS is used in the PCF mode of 802.11 standard, whereas DIFS is the time a station has to sense the idle channel before assuming that no station is transmitting. In Table I, the 802.11b standard values of SIFS, PIFS and DIFS are reported. Beyond IFSs, the 802.11 standard define two more timing parameters:

- **Slottime**: The time immediately after an idle DIFS is slotted, and a station is allowed to transmit only at the beginning of each Slottime.
- **AckTimeout**: The time each host has to wait after transmitting a frame that requires an ACK frame as a response. If no ACK is received in the AckTimeout interval, the host assumes that the transmission of the frame is failed.

Figure 1 shows the time evolution of a successful transmission without the RTS/CTS handshake. When a station has a packet to transmit, it senses the channel. If the channel is idle, it waits for a DIFS and senses the channel again. If the channel is still idle, it assumes that no stations are accessing the medium and transmits the frame. In case the channel is sensed busy, the station has to wait till the channel is free and then applies a backoff procedure. In the backoff procedure, the contention window CW is set to CW_{min} defined in the standard, the station draws a random number uniformly distributed between 0 and the value of the contention window minus one ($CW-1$) and sets the value of the backoff interval to this value. Every slottime the channel is idle, the backoff interval is decremented by 1 and when the interval value reaches zero, the station starts the frame transmissions.

When the receiving station receives the packet the checksum is computed to find out if the packet has been correctly received. Upon receipt of a correct frame, the receiving station waits a SIFS interval and transmits a positive acknowledgment frame (ACK) back to the source station, indicating that the transmission was successful. If the ACK packet is not received by the end of the AckTimeout period, the transmitting station assumes that the packet is lost and attempts to retransmit the packet till the maximum number of retransmissions allowed per packet. In this case the backoff procedure is applied increasing exponentially (doubling) the contention window value till the maximum value CW_{max} defined in the standard. Further it is mandatory that a station applies the backoff mechanism also in case of consecutive frame transmissions (even if the medium is sensed idle) to avoid the capture of the channel by the transmitting station.

III. TIMING INTERVAL ANALYSIS

The 802.11 standard defines the way to compute the timing parameter values. These values are derived according to the following relations:

- SIFS = RxRFDelay + RxPLCPDelay + MacProcessingDelay + RxTxTurnaroundTime.
- SlotTime = CCATime + RxTxTurnaroundTime + AirPropagationTime + MacProcessingDelay.
- DIFS = SIFS + 2 * Slottime
- AckTimeout= frameTXtime + AirPropagationTime + SIFS + AckTXtime + AirPropagationTime.

which depend on:

- *CCATime*: The minimum time the physical layer requires to determine the state of the channel.
- *RxTxTurnaroundTime*: The maximum time the physical layer requires to switch from receive to transmit mode.
- *MacProcessingDelay*: The nominal time that the MAC uses to process a frame and prepare a response to the frame.
- *AirPropagationTime*: The propagation delay.
- *frameTXtime* and *AckTXtime*: The times needed to transmit a frame and the ACK respectively at the current transmitting rate.
- *RxRFDelay* and *RxPLCPDelay*: The times needed to the physical layer to deliver a symbol to the Physical Layer Convergence Protocol (PLCP) and to the PLCP layer to deliver a bit to the MAC layer.

TABLE I
802.11B TIMING VALUES.

Slottime	$20\mu s$
SIFStime	$10\mu s$
DIFStime	$50\mu s$
CCATime	$< 15\mu s$
RxTxTurnaroundTime	$< 5\mu s$
RxTxSwitchTime	$< 5\mu s$
AirPropagationTime	$1\mu s$
MacProcessingDelay	0

The IEEE standard values for the 802.11b parameters are reported in Table I. As it can be noticed, DIFS, SlotTime and AckTimeout depend on the AirPropagationTime value. By increasing the maximum distance between nodes, the AirPropagationTime increases and all parameters have to be redefined. Many commercial products increase the transmission range (about 17-18km) by redefining these parameters. However, they are usually set based on the maximum distance between hosts defined statically.

Limitations to the maximum distance between nodes are due to the following considerations:

- *The DIFS is the minimum time that a node has to sense the channel to avoid the collision with a frame sent from the furthest node.*
  Considering the speed of light, we obtain:
  $$300m/\mu s * 50\mu s = 15km$$
  In order to avoid collision due to DIFS time, the maximum distance between two stations has to be 15km.
- *The Slottime is the time needed by any station to detect the transmission of a packet from any other station.*
  SlotTime should not end before the signal reaches the destination station.
  $$300m/\mu s * 20\mu s = 6km$$
- *The AckTimeout is the time a node waits for an acknowledgment, before assuming the frame is lost.*
  The AckTimeout accounts for all the delay in the total transmission of the frame and relative ACK. Using a propagation time of $1\mu s$, we encounter a very restrictive distance limit of 300m ($2\mu s$ has to cover the roundtrip).

The more tight limitation is due to the AckTimeout parameter, because if the distance between two nodes is more than 300m, the ACK timeout expires before the reception of ACK and the sender assumes the packet has been lost. At this point the sender, uses the exponential backoff procedure until the maximum number of transmission attempts per packet is reached. The packet is dropped and a new packet transmission starts. A simple solution to avoid the timeout expiration is to compute the timeout value according to the predefined maximum distance between two nodes. However a high AckTimeout value leads to useless delays when the packet transmission is not successful and waste of the channel capacity.

A solution to improve efficiency is to dynamically set the timing parameters according to the real distance between nodes and not to the maximum achievable distance.

TABLE II

COMPARISON OF STATIC AND DYNAMIC TIMING VALUES.

	Static	Dynamic
Slottime	$75\mu s$	$23\mu s$
SIFStime	$10\mu s$	$10\mu s$
DIFStime	$160\mu s$	$56\mu s$
AirPropagationTime	$55\mu s$	$3.4\mu s$
AckTimeout	$1729\mu s$	$1625\mu s$

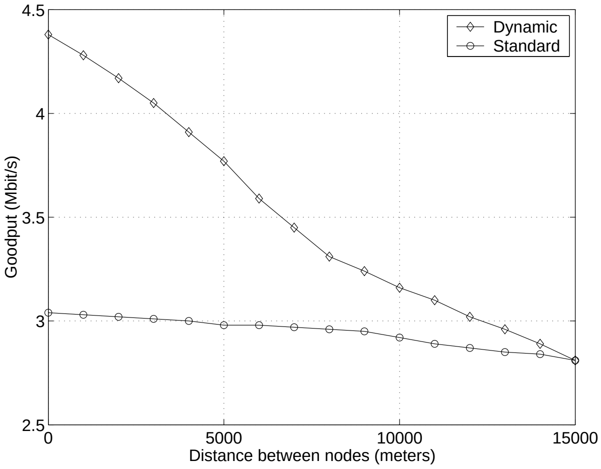

Fig. 2. Goodput varying the distance between two nodes.

Considering a typical commercial outdoor bridge with a maximum range of 15km, Table II reports the timing parameter values based on the maximum distance of 15 km and the settings for a link of 1 km. Obviously the larger is the difference between the maximum distance among nodes allowed and the real distance between nodes, the larger is the gap between the static and the dynamic settings. Figure 2 depicts results obtained is a ns-2 simulation [15] with two 802.11b stations, as function of the distance between nodes. The figure reports the goodput when the timing parameters are set according to maximum distance (i.e 15km) and when they are set according to the real distance between the two nodes (i.e. the abscissa value). Using the maximum distance criteria, the goodput is independent of the distance between nodes (about 3Mbps). It means that two stations 50m apart from each other, communicate at the same goodput of two stations 10km apart. When using dynamical tuning of the parameters, the goodput is optimized for every distance.

IV. CARRIER SENSING

As explained in Section II, the VCS mechanism has been designed to avoid the hidden terminal problem. In [9] the authors show that the Virtual Carrier Sensing does not solve the problem. They claim that VCS works correctly only if “Every interfering node is within the transmission range of the transmitting stations”. In fact this is the condition for receiving the RTS/CTS packets. However, normally, there are nodes outside the transmission range, but within the interference range. These nodes are still hidden nodes and the original VCS is not able to detect them. The main idea of [9] is to make the interference range equal or smaller than the transmission range. This is possible because the interference range at Receiver depends only on the distance between Sender and Receiver. So they suggest to limit the maximum distance between nodes to the value that make interference range equals to the Transmission Range. We can define three different ranges:

- **Transmission Range (TXR)**: The range within which a MAC frame can be successfully delivered and its type (RTS, CTS, DATA, etc.) field can be correctly identified assuming there is no interference from other transmissions.

- **Carrier Sensing Range (CSR)**: The range within which the power from the transmitter can be sensed indicating the busy state of the medium. This is, in 802.11, determined by a value called CST (Carrier Sensing Threshold): A transmitter starts a transmission if the noise/interference level is below that threshold.
- **Interference Ranges (IFR)**: The range within which stations in receive mode will be interfered by other transmitters.

TXR is fixed and mainly depends on the transmission power, radio propagation properties and sensitivity of receiver hardware. IFR depends on the topology of the network. CSR is evaluated by the vendors and it takes different values for every chipset. However, it should be set taking into account for the standard specification of minimum Signal to Interference and Noise Ratio (SINR). For example, the 802.11b standard specification for a transmission speed of 11Mbps does not allow a SINR below 10dB. It means that a signal arriving at the receiver is assumed to be valid only if the SINR (at receiver) is above 10dB. So we can calculate the CST according to this value.

Since we are working on the mesh network topology, we focus our analysis on an open space environment and use the TwoRayGround model as propagation model. In fact, the multipath fading and shadowing are usually neglected in an open space environment. Given d the distance between the sender and the receiver, the received power is given by:

$$P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4} \tag{1}$$

Where:

- P_r is the received power
- P_t is the transmitted power
- G_r is the gain of the receiver's antenna
- G_t is the gain of the transmitter's antenna
- h_r is the height of the receiver's antenna
- h_t is the height of the transmitter's antenna

Considering that the interference power P_i is much higher than the noise power P_n, the signal to interference and noise ratio is given by:

$$SINR = \frac{P_r}{P_i + P_n} = \frac{P_r}{P_i} = 10dB \tag{2}$$

Supposing that every node transmits at the same power and is equipped with the same antenna, the SINR is:

$$SINR = \frac{P_t G_t G_r \frac{h_t^2 h_r^2}{d^4}}{P_i G_i G_r \frac{h_i^2 h_r^2}{d_i^4}} = \frac{d_i^4}{d^4} = 10 \longrightarrow d_i = \sqrt[4]{10} \cdot d$$

Where: d is the distance between sender and receiver and d_i is the maximum distance between the interfering node and the receiver (IFR).

Therefore we have found that the interference range depends on the distance d. Generalizing, the interference range is given by the following formula:

$$d_i = \sqrt[n]{SINR_{th}} \cdot d$$

Where n is the signal attenuation coefficient and $SINR_{th}$ is the threshold defined in the specification. Using n=4 (TwoRayGround model for long distance link), the relation becomes:

$$d_i = 1.78 \cdot d \tag{3}$$

In [9], authors use equation (3) to limit the interference range. In fact, using $d = TXR \cdot 0.56$, IFR is equal to TXR. It means that, limiting the distance between nodes using equation (3), help to avoid the hidden nodes problem. This solution completely solves the problem, but with some severe limitations for our kind of scenarios:

- Maximum distance between nodes is decreased.
- Mandatory VCS (Onerous overhead for long distance link).

A. Dynamic Physical Carrier Sensing

There are several proposed schemes for dynamic Physical carrier sensing, but each solution uses the VCS and it is not recommended for outdoor environments or long-distance link [10], [11].

Due to the necessity to switch off the VCS (RTS/CTS mechanism), we try to find an optimal solution using the PCS and modulating the CST in order to obtain the correct CSR.

In the PCS, a station senses the channel and starts with the transmission only if the received power is below the CST. The CST is generally static, and its value depends on the hardware implementation (providing the CSR). However, a static CST, severely limits the carrier sensing. We want to find an optimal CST to make VCS useless, and to avoid its overhead. In [9] the authors propose a value of CSR that covers all the VCS area. Since the IFR of the receiver is given by equation (3), CST on the sender node has to be set to cover the distance between sender and receiver and the distance between receiver and interfering node:

$$CSR = d + d_i = 2.78 \cdot d$$

However, authors don't suggest a mechanism to dynamically modify this value, thus d has to be set at the maximum distance between nodes, causing the exposed nodes problem (nodes which are in the CSR but not in the interference range).

We propose a scheme for the dynamical tuning of CST. Furthermore we perform some simulations to confirm the improvement of our scheme in comparison to other schemes.

Let us consider two communicating stations A and B. If we assume a symmetric medium, the same Transmitted Power and the same hardware at every station, then:

$$P_{AB} = P_{BA}$$

Where P_{AB} is the power received in B from A and P_{BA} is the power received in A from B.

Thus station A knows the theoretical power received in B by sensing the power of received frames. The goal is to find an optimal CST in A covering the whole IFR in B. Using the TwoRayGround Model, we obtain:

$$P_{AB} = P_{BA} = P_t G_A G_B \frac{h_A^2 h_B^2}{d^4}$$

We want to find a relation between this known power and an optimal CST. Considering equation (3), we can state that the power received in A from any interfering station (which interferes in B), should be at least:

$$P_i = P_t G_A G_i \frac{h_A^2 h_i^2}{(\sqrt[4]{10} \cdot d + d)^4}$$

Since station A knows P_{AB}, we can evaluate the relation between the two powers:

$$P_i = P_t G_A G_i \frac{h_A^2 h_i^2}{(\sqrt[4]{10} \cdot d + d)^4} = \frac{P_{AB}}{(\sqrt[4]{10} + 1)^4}$$

Generalizing we can write:

$$CST_S = \frac{P_r}{(\sqrt[n]{SINR_{th}} + 1)^n} \tag{4}$$

Where n is a generic signal attenuation coefficient, CST_S is the optimal CST on the sender and P_r is the Power received at Sender (the same at Receiver). In the remainder of this work, we refer to this mechanism as Dynamic Physical Carrier Sensing (DPCS).

As an example we show the case where five nodes (A,B,C,D and E) are displaced on a straight line as depicted in Figure 3.

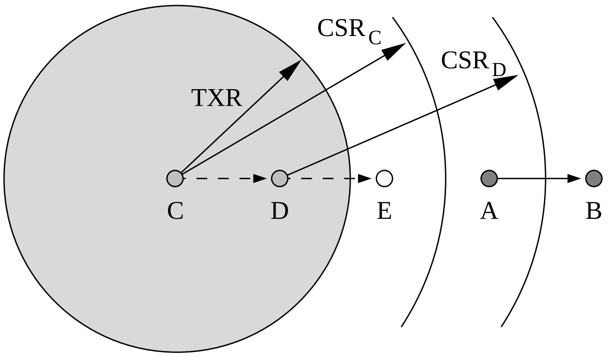

Fig. 3. DPCS example.

The ratio between the Carrier Sensing Thresholds in C and D and the received power transmitted from A depends on the number of hops between A and C and A and D:

$$\frac{CST_C}{P_{AC}} = \frac{3^n}{(\sqrt[n]{SINR_{th}} + 1)^n}$$

$$\frac{CST_D}{P_{AD}} = \frac{2^n}{(\sqrt[n]{SINR_{th}} + 1)^n}$$

which are equal to 1.3561 and 0.2679 when $n = 4$ and $SINR_{th}$ is 10dB as in the 802.11b specifications. This example shows that CST_C is greater than P_{AC} and that CST_D is lower than P_{AD}, indicating that during a communication between A and B, station C can transmit to D and station D is interdicted to transmit to E, respecting the IEEE802.11 standard SINR specification.

V. RESULTS

In order to analyze the performance of the DPCS scheme, we compare the behaviour of three CST settings:

- **CSR=2.2TXR**: The setting of 802.11b WLAN cards provided with the Lucent Orinoco Wavelan chipset [12] as implemented in 802.11 module for ns-2.
- **CSR=TXR**: The setting used by the widespread Intersil [13] based WLAN cards.
- **DPCS**: The CST as computed using equation (4).

Before showing numerical results we discuss the behaviour of the three settings in some particular scenarios. In the following examples an ongoing communication between stations A and B takes place. During this communication, another station, C, senses the channel in order to start a transmission to D. All the nodes are displaced on a straight line and every node is l meters far away each other.

A. Overestimation

The first scenario we consider is depicted in Figure 4. In this scenario A is $2l$ far from D and $3l$ from C.

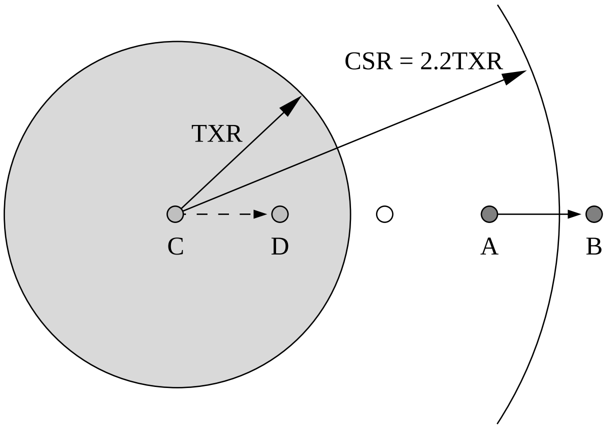

Fig. 4. Overestimation example.

In this case the CSR=TXR rule and the DPCS rule would allow the contemporaneous transmission of A to B and C to D. In the CSR=2.2TXR case the transmission is interdict because the CSR is too large. Computing the SINR with the TwoRayGround model, we obtain:

$$P_{CD}/P_{AD} = d_{AD}^4 / d_{CD}^4 = (2l)^4 / l^4 = 16 = 12.04dB$$

where P_{CD} and P_{AD} are the received power of the signal received in D from C and A respectively and are given by:

$$P_{CD} = P_t G_C G_D \frac{h_C^2 h_D^2}{d_{CD}^4}$$

$$P_{AD} = P_t G_A G_D \frac{h_A^2 h_D^2}{d_{AD}^4}$$

In this case the obtained SINR is greater than 10dB meaning that power transmitted by A does not interfere with the transmission from C to D and is able to decode frames. In spite of the computed SINR, the CSR=2.2TXR rule does not allow the transmission because it overestimates the carrier sensing range.

B. Underestimation

The second case shown in Figure 5 depicts the situation where A and C have the same distance from D. In this case the SINR at node D is basically 0 dB because the interference power at the receiver (D) is equal to the useful power transmitted by C. Observing Figure 5 it is possible to notice that the CSR=TXR setting would allow A and C to transmit simultaneously, leading to packet collision and to a steep goodput decrease. In this case the CSR=TXR setting is not able to work correctly without the RTS/CTS handshake mechanism (VCS), whereas DPCS and CSR=2.2TXR modes interdict the simultaneous communication.

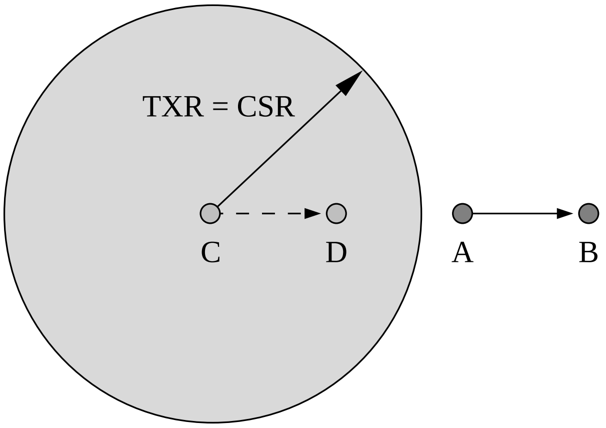

Fig. 5. Underestimation example.

C. Long chair topology

The effect of the incorrect CST settings is underlined by the long chair topology, depicted in Figure 6. The topology consists of 10 hops. If we set a communication between A and M, after some milliseconds every node will be competing to use the channel. Using an inaccurate CST value leads to the spatial underutilization (lower throughput) or spatial overutilization (higher throughput, many retransmissions, lower goodput). Figures 7, 8 and 9, depict the spatial reuse in the cases of CSR=2.2TXR, CSR=TXR and DPCS respectively.

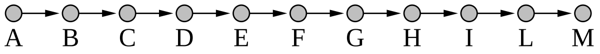

Fig. 6. Long chair topology.

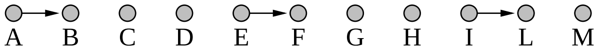

Fig. 7. CSR=2.2TXR spatial reuse.

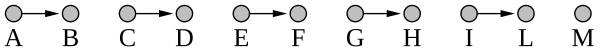

Fig. 8. CSR=TXR spatial reuse.

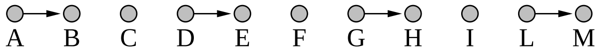

Fig. 9. DPCS spatial reuse.

It is worth noticing that the CSR=2.2TXR rule leads to underutilization of the links, whereas the CSR=TXR rule leads to an overutilization of the links. With DPCS, the reuse factor is 1:3, which is the optimal for the depicted scenario.
Drawing on the last example, we show simulation results. The simulation topology consists of n nodes displaced on a straight line and transmitting on the same physical channel. The communication takes place between the first node (the sender) and the last node (the receiver), hopping on the intermediate nodes. The distance between every node is l=500m and the number of nodes n varies between 3 and 14. Figures 10 and 11 depict the throughput and the retransmission probability respectively at the MAC layer.

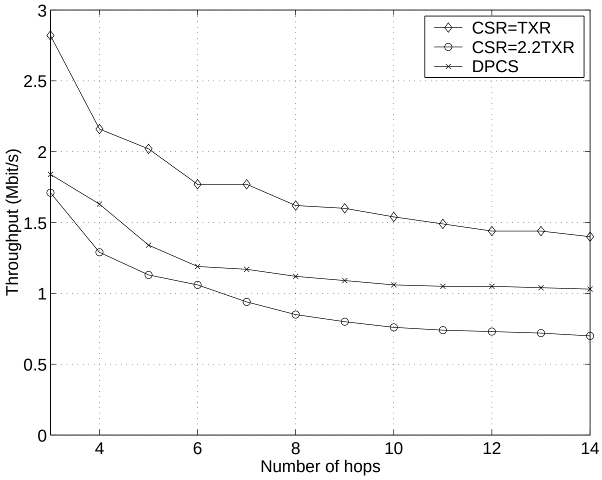

Fig. 10. Throughput vs. number of hops.

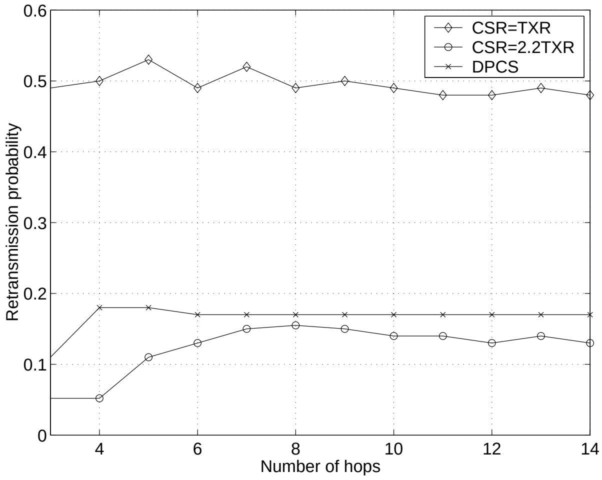

Fig. 11. Retransmission probability vs. number of hops.

It is possible to observe that the CSR=TXR model gives the highest throughput, because the CST allows nodes to access the channel more frequently. However the frame retransmission probability is very high indicating that the most of the transmitted packets collide and are not decoded at the receiver side. With the CSR=2.2TXR setting, the throughput as well as the number of retransmissions are the lowest one, while the DPCS setting is a trade-off between the two solutions. Finally,

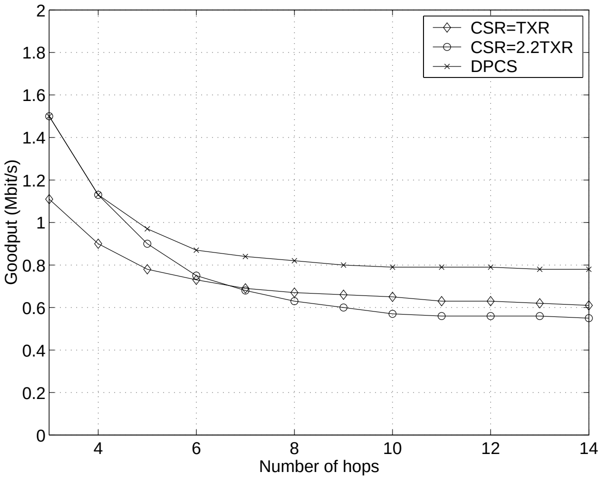

Fig. 12. Goodput vs. number of hops.

Figure 12 depicts the goodput obtained with the three different settings. As the number of nodes increases, the gap between the performances is more visible. When the number of hops increases DPCS gives an improvement of 41% and 27% in comparison to the other two settings.

VI. CONCLUSIONS

This paper focuses on the performance of multihop 802.11b based mesh networks. It is shown that the performance of the whole system depends on several factors such as the spatial reuse of the links and the use of the RST/CTS handshake mechanism.

The main findings of the paper are: i) the use of RST/CTS handshake is not effective in multihop outdoor scenarios because the mechanism is prone to the exposed node problem. Turning off the mechanism leads to an increase of link utilization; ii) the proposed dynamic mechanism (DPCS) to set the Carrier Sensing Threshold improves the performance of the system. The mechanism is based on the assumption of homogeneous hardware and sets the CST according to the received power level estimation and minimum SINR acceptable according to the 802.11b standard. It is shown that the mechanism improves the link spatial reuse factor while respecting the SINR constraints.

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