Efficient MAC Protocols Optimization for Future High Density WLANS

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***Abstract*—Recently, the High Efficiency WLAN or simply HEW study group was created within IEEE 802.11 working group. This study group considers the improvement of spectrum efficiency to enhance the system's area throughput in high density scenarios. Subsequently, this led to the creation of a new task group called 802.11ax, which is expected to deliver the next Wi-Fi generation. A key perspective considered by the recent discussions is increasing the spatial reuse using Physical Carrier Sensing (PCS) adaptation. While Transmit Power Control (TPC) has always been the chosen technique when targeting spatial reuse improvements, this work investigates the weakness points in TPC especially outside centralized network architectures. On the other hand, the incentives behind adopting the PCS approach are discussed. Accordingly, a new algorithm is proposed to adapt the PCS dynamically. The performance of this proposal is compared to that of TPC using OPNET simulations. For a dense IEEE 802.11n network topology, simulation results show that PCS outperforms TPC (120% versus 66% of throughput gain respectively). Particularly, the PCS approach is more robust when there are some nodes that are not implementing the PCS nor the TPC adaptation.**

Keywords*—WLAN, Wi-Fi, IEEE 802.11, MAC protocols, Physical Carrier Sensing (PCS), Transmit Power Control (TPC)

I. INTRODUCTION

Nowadays, Wireless Local Area Networks (WLANs) are becoming more and more dense. The proliferation of Wi-Fi equipped devices will continue to drive growth in deployed WLANs. The consumer services and applications are designed to be always connected to the world wide web. This always-on trend escalates the need for ubiquitous WLAN access. Along with that, however, the data exchanged with terminals is amplified by the emerging high definition multimedia applications. According to recent forecast, by 2018, mobile data traffic has been expected to grow to 15.9 exabytes per month, nearly 11-fold increase over 2013 [1]. A large share of this traffic is carried by WLANs. Today, WLANs are often saturated with data traffic. Therefore, their capacity in terms of transported data is a key performance indicator in dense environments.

The aggregate capacity of a network is defined as the sum of all carried data per unit of time. Although this data rate can be measured at different layers, this work is interested in the data link layer measurements. While the physical layer data rate represents the peak value of the theoretical capacity, the application layer measurement involves pointless overhead that depends on the running application. This aggregate capacity is proportional to the number of transmissions that can occur simultaneously in the network. An efficient way to increase the capacity of WLANs in dense environments is to boost spatial reuse by triggering more concurrent transmissions.

Since its first release in 1997, the IEEE 802.11 standard was targeting simple, best effort and cheap local wireless communications. Almost all the previous standard amendments' objective was increasing the peak physical data rate by exploiting new modulations and coding schemes (MCS) and recent multiple-input and multiple-output (MIMO) techniques. However, the medium access mechanism is left untouched despite its vulnerabilities under certain conditions that are widely highlighted in the literature. It is true that, if enhanced, an efficient medium access mechanism will not increase the peak data rate which has been the main goal of 802.11 standardization committee, but without enhancing it, this mechanism will stay the bottleneck that makes higher data rate impossible to achieve in real networks.

In this context, the IEEE 802.11ax task group was launched in May 2014. This group is targeting ways to enhance the IEEE 802.11 physical (PHY) and Medium Access Control (MAC) layers in 2.4 GHz and 5 GHz band with a focus on improving real-world spectrum efficiency and area throughput. One of the envisioned approaches supported in the 802.11ax task group is to enhance the achieved network throughput by increasing the spatial reuse in accessing the spectrum.

The literature has brought plenty of mechanisms and approaches proper to traditional cellular technology, and tried to apply them directly to WLANs. One of these approaches was an answer to an important question: how to achieve higher spatial reuse in WLANs? Homologous to the solution adopted in cellular mobile networks, the answer was: prudent site planning and judicious channel assignment for each cell. While such basic solutions are always adequate and efficient for traditional networks, they are no more sufficient for current dense Wi-Fi environments.

By the same logic, the Transmit Power Control (TPC) is suggested always as a peerless tool to manage interferences and increase spatial reuse. While TPC is very effective when applied in centralized architectures, many drawbacks are shown when applying it to distributed network architectures. This work discusses this subject and describes another efficient mechanism to optimize the MAC layer performance without suffering from the TPC's shortcomings. Instead of controlling the transmission power, the proposed scheme controls the signal detection mechanism used by Wi-Fi nodes before transmitting. For this purpose, this paper describes a new way to adapt the physical carrier sensing (PCS) dynamically at each WLAN node.

The rest of the paper is organized as follows. In the following section, the IEEE 802.11 WLAN [2] background

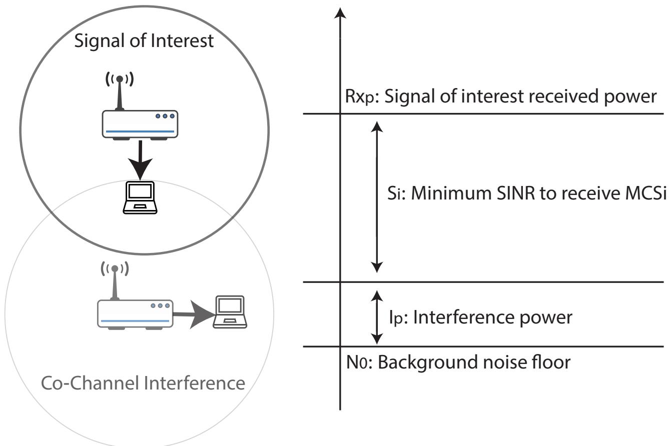


Fig. 1: Signal to Interference and Noise Ratio (SINR)

is presented and the main problems of nowadays' deployed WLANs are explained. Section III gives an overview of TPC as a way to cope with the WLANs' deficiencies and highlights its downsides. In Section IV, the concept of physical carrier sensing (PCS) adaptation is described. The communication model is detailed in Section V. Then, an adaptation algorithm is introduced in Section VI and its performance is compared to that of TPC. In Section VII, the simulation results of scenarios including legacy nodes for both TPC and PCS are shown. Finally, the last section concludes the paper.

II. Background

The basic block forming an IEEE 802.11 WLAN is termed Basic Service Set (BSS). In an infrastructure BSS, all the communications are managed by a central node referred to as an Access Point (AP). The IEEE 802.11 standard [2] describes the operation in 2.4 GHz and 5 GHz unlicensed bands. The multiple access to the medium is defined to be contention-based and is managed by the Distributed Coordination Function (DCF). The backbone of the DCF is the Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) mechanism.

The mechanism used for sensing the medium is named Clear Channel Assessment (CCA) and may take two forms: a mandatory Physical Carrier Sensing (PCS), and an optional Virtual Carrier Sensing (VCS). While the VCS only detects the IEEE 802.11 signals, the PCS senses the energy of any signal present in the channel. Keep in mind that Wi-Fi operates on unlicensed bands that may be used by many other systems. This work copes with the PCS functionality optimization and does not cover the VCS that was reported by many researches to have many drawbacks due to its overhead [3].

Depending on the data rate used to transmit, a communication is sustained only if the corresponding Signal to Interference and Noise Ratio (SINR) at the receiver exceeds certain mandatory value. As represented in Fig. 1, S_i is the minimum required SINR for a Modulation and Coding Scheme (MCS) of index i, namely MCS_i. The SINR is expressed by

$$SINR = \frac{Rx_p}{N_0 + I_P} \tag{1}$$

Where Rx_p is the power of the signal of interest at the receiver, N_0 is the background noise level and I_P is the interference power at the receiver's close vicinity. Notably, Co-Channel Interference (CCI) is one of the greatest challenges threatening wireless communications. In a dense WLAN environment, the CCI is the severest cause of performance degradation. Basing on the illustration of Fig. 1, the interference region is defined as the region around the receiver where any co-channel transmission (considered as CCI) can decrease the SINR of the signal of interest below the acceptable threshold S_i. The region around a node in which any occurring transmission is detected is termed the detection region of that node.

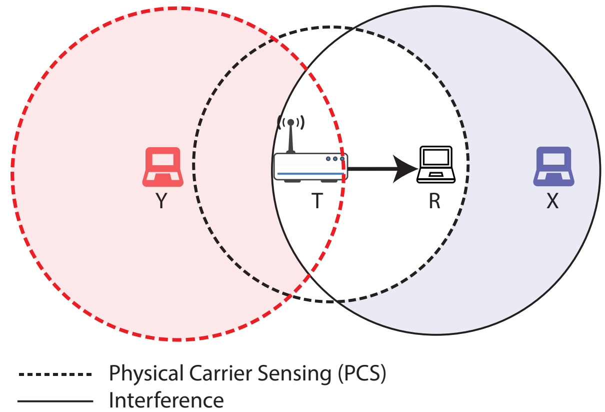


Fig. 2: Hidden and exposed node regions

In the literature, two main problems were identified to be detrimental to WLAN performance. Namely, the hidden and exposed node problems caused by the distributed nature of channel access in IEEE 802.11 WLANs [4] [5]. To explain these problems, consider the scenario shown in Fig. 2. When a potential interferer X is outside the detection range of a transmitter T, X is defined as a hidden node with respect to T. Note that, in order to threaten the transmission of T, X must be in the interference region of R, the intended receiver of X. In this case, it is impossible to achieve successful transmissions by X and T simultaneously because X transmissions will corrupt the reception at R. Otherwise, if X is outside the interference region of R, it can transmit at the same time as T without any problem.

In another situation, T may be in the detection region of the node Y. Thus any transmission initiated by T will be detected by Y and, as a consequence, the medium is inferred to be busy. Although, as shown in Fig. 2, Y is outside the interference region of the intended receiver of T (R) and therefore its transmission will not interfere with the ongoing transmission of T. In that way, Y is banned unfairly from transmitting and is termed an exposed node. This loss of possible transmission opportunities decreases the overall performance of the network. This decrease is more significant when the deployments become more and more dense.

III. Transmit Power Control

As mentioned before, the TPC is the traditional intuitive way to manage interferences and to increase the spatial reuse in wireless networks. As shown in Fig. 3a, decreasing the transmission power of the possible interferers helps to fulfill the required SINR (S_i) at the neighboring receivers. In that way, the transmission ranges in the neighboring networks are shrunk and hence more reuse is permitted.

In cellular networks, a frequency division multiplex is possible inside the same cell. Thus, the transmission power is controlled by the base station individually for each user apart from others. Such closed loop scheme is possible due to the centralized hierarchy present in cellular networks. Unfortunately, in WLANs, all the nodes of the same BSS share the same frequency and we can't always assume a centralized deployment. Despite this, TPC stays important due to two reasons: 1) Mobile nodes are energy limited devices and they have to use efficiently their power resources. TPC is a key solution to decrease the power consumption. 2) The transmission power dictates the interference power perceived at neighboring nodes.

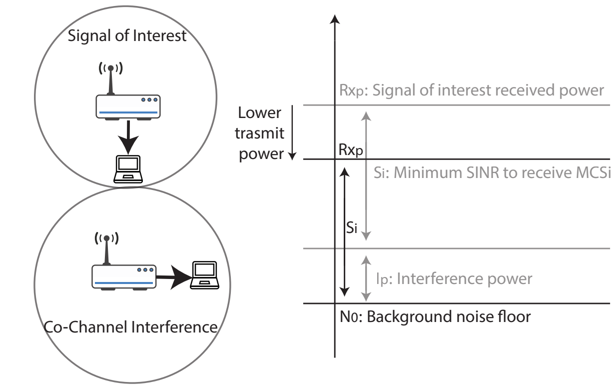
It is interesting to note that TPC is standardized since 2003 by the IEEE 802.11h amendment but it has hardly found its way to the production stage. Although, for networks with centralized controllers, the TPC is relatively simple to implement, it was only applied on APs but almost never on STAs. In such situations, the APs connected to the controller apply TPC to reduce their transmit power, however the STAs associated to these APs still transmit with their full power. The main reason behind this is related to the nature of TPC which is selfless. If a node reduces its transmission power by applying the TPC, that will promote the neighboring transmissions because they are no more bothered by the transmissions of that node. Consequently, it's the other nodes which will benefit directly and not the node that applied the TPC.

Moreover, in networks which lack a central regulator, power control proves to be much more difficult to implement and to apply. Since centralized coordination between nodes is very difficult, it is necessary for each node to regulate its own transmission power autonomously. This behavior creates an asymmetric application of TPC and hence different transmission powers for different nodes. Again, the selfless feature of TPC will prevent real networks from taking this approach. The detrimental effect of this asymmetry is argued by many researchers [6] [7] [8]. It has been proved that in such situation, TPC leads to the starvation of the unprivileged nodes. Actually, the TPC is more problematic to achieve in a distributed manner because it will foster higher power transmitters, that are not applying it, at the expense of lower power transmitters that are applying TPC.

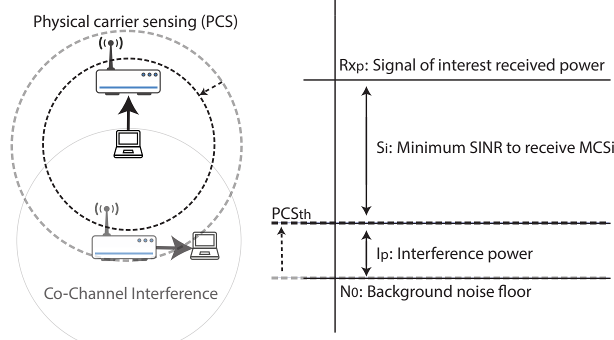
IV. Physical Carrier Sensing

Recalling the importance of the carrier sensing in accessing the shared medium, specifically the PCS, its adaptation is indeed effective in managing interferences and leveraging the spatial reuse in WLANs. Interestingly enough, the PCS adaptation is one of the solutions currently discussed in the newly created IEEE 802.11ax task group. As will be shown in the sequel, this promising solution is highly efficient in dense environments. The most important feature of this approach is that there is an incentive to adopt it in production. Contrary to TPC, the node applying PCS adaptation will benefit directly from its application.

The current PCS mechanism is over conservative in today's dense environments. An important number of nodes in these dense networks are exposed to the transmissions of the neighboring co-channel networks. Thus, the available spectrum is not efficiently exploited and the system is loosing a great amount of possible spatial reuse. In PCS adaptation, instead of decreasing its transmission power, a node will decrease its



(a) Transmit Power Control (TPC)



(b) Physical Carrier Sensing (PCS)

Fig. 3: Increasing spatial reuse using TPC and PCS

sensitivity in detecting signals in its environment. In Fig. 3b, the PCS threshold is increased so that tolerable interferences are prohibited from triggering busy channel assessments. Consequently, in situations where the signal of interest is received with a power sufficiently higher than the interference power, the reuse between neighboring networks will be possible.

V. Communication model

Before coping with any data link layer adaptation, we define a convenient propagation model for wireless communication to understand the radio channel characteristics.

1) Path loss: The received power at the intended receiver is expressed in its linear form as follows:

$$Rx_p(d) = Rx_p(d_0)\left(\frac{d_0}{d}\right)^{\gamma} \tag{2}$$

where d is the distance between the transmitter and the receiver and d_0 is a reference distance close to the transmitter (e.g. $d_0 = 1m$).

2) Transmission range: The maximum distance that a signal can travel before being successfully received by its destination is the transmission range. The latter distance is calculated in the absence of any interference, and is given by

$$Rx_R = d_0\left(\frac{Rx_p(d_0)}{max(N_0S_0, Rx_{th})}\right)^{\frac{1}{\gamma}} \tag{3}$$

where S_0 the minimum SINR, and Rx_{th} the reception threshold that denotes the minimum power level of a received signal. Actually, the receiver can successfully decode a received packet if and only if its perceived power exceeds Rx_{th} and its SINR is greater than S_0. Both S_0 and Rx_{th} depend on the MCS used for the transmission. In this work, we are interested by small transmission ranges because the aim is to increase the spatial reuse. For that, the Rh_{th} is chosen to be greater than N_0S_0. Consequently the transmission range becomes

$$Rx_R = d_0 \left(\frac{Rx_p(d_0)}{Rx_{th}}\right)^{\frac{1}{\gamma}} \tag{4}$$

3) Physical Carrier Sensing range: The distance from a transmitter within which any detected communication causes the deferral of the pending transmission is defined to be the Physical Carrier Sensing range (PCS_R). This range is given by

$$PCS_R = d_0 \left(\frac{Rx_p(d_0)}{PCS_{th}}\right)^{\frac{1}{\gamma}} \tag{5}$$

where PCS_{th} is the Physical Carrier Sensing threshold, which is defined as the minimum power level sensed by the transmitter to infer that the medium is busy. If the sum of signals power sensed in the medium is less than PCS_{th}, then the transmitter treats the medium as idle and initiates its pending transmission.

4) Interference range: As defined before, the interference range can be expressed as follows.

$$I_R = d \left(\frac{1}{\frac{1}{S_0} - \left(\frac{d}{d_0}\right)^{\gamma} \frac{N_0}{P_r(d_0)}}\right)^{\frac{1}{\gamma}} \tag{6}$$

If we consider an interference limited environment where noise power is negligible, the interference range becomes

$$I_R = S_0^{\frac{1}{\gamma}} d \tag{7}$$

VI. Proposed Approach to Increase Spatial Reuse

The aforementioned definition of the hidden node problem leaves no doubt about the fundamental role played by the PCS in mitigating it. Simply, the interferer located outside the carrier sensing region of a given transmitter is considered as a hidden node for that transmitter. So, if all nodes located in the interference region are covered by the PCS, the hidden node problem will be resolved. The previous statement is translated by the following expression:

$$PCS_R \geq d + I_R \tag{8}$$

Using Eq. (2), (5), (7), and (8) we obtain

$$PCS_{th} \leq Rx_p(d) \frac{1}{\left(1 + S_0^{\frac{1}{\gamma}}\right)^{\gamma}} \tag{9}$$

TABLE I: Simulation parameters

Parameter	Value
MAC & PHY	802.11n
Radio band	5 GHz
Bandwidth	20 MHz
Guard Interval (GI)	Short (400 ns)
Number of antennas for each node	1
Aggregate MAC Service Data Unit (A-MSDU) max size	3839 Bytes
Aggregate MAC Protocol Data Unit (A-MPDU) max size	8191 Bytes
Up Link Traffic (UL)	full buffer
Down Link Traffic (DL)	full buffer
Default Transmit power	15 dBm
Default physical carrier sensing threshold (PCS_{th})	-82 dBm
Simulation Duration	3 min

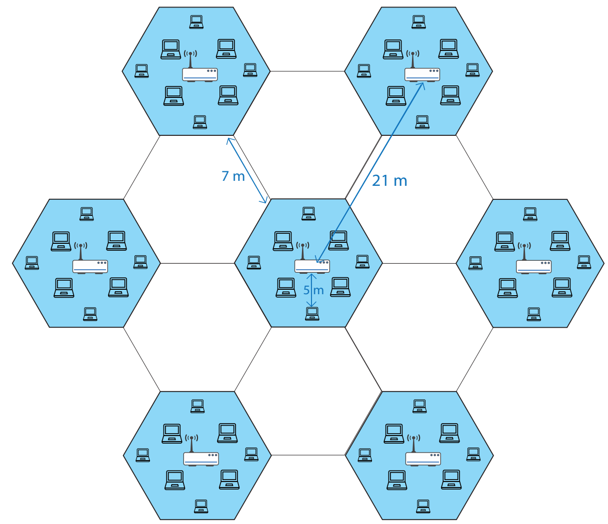


Fig. 4: Dense network topology

Supposing that the powers in the linear form are expressed in milliwatts, in logarithmic form, the previous equation is expressed as follows

$$PCS_{th}[dBm] \leq Rx_p(d)[dBm] - \gamma 10 \log\left(1 + S_0^{\frac{1}{\gamma}}\right) \tag{10}$$

Let M be the value needed to cover the hidden node region. The minimum value of this margin M is given by

$$M[dB] \geq \gamma 10 \log\left(1 + S_0^{\frac{1}{\gamma}}\right) \tag{11}$$

Increasing M more than the needed value to cover the hidden region will create the aforementioned exposed node region. As explained before, the presence of exposed nodes in the network decreases the system's spatial reuse because possible concurrent transmissions are prohibited by the conservative PCS. For that reason, the margin M must be set to the minimum value allowed by Eq. (11) in order to prevent exposed situations.

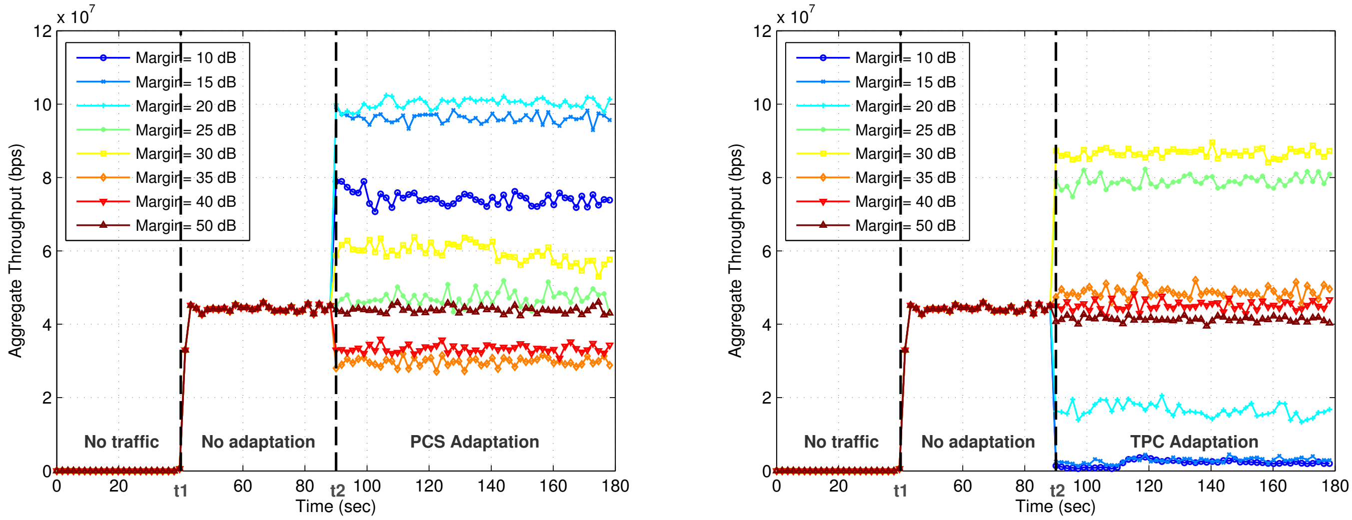
A. New Margin based PCS adaptation

Accordingly, in order to confirm the efficiency of PCS in enhancing spatial reuse and hence increasing the aggregate throughput of the network, a simple adaptation algorithm is proposed in this section. Each node adapts its PCS threshold in terms of the power received from its communication peer. For instance, in an infrastructure BSS, all communications are held between an AP and a station (STA). In such a case, the STA adapts its PCS threshold according to the power level received from its AP. This adaptation consists in adding an appropriate margin value to the received power to prevent hidden regions. Therefore the PCS threshold of each node is obtained as follows.

$$PCS_{th} = Rx_p - M \tag{12}$$

Where PCS_{th} and Rx_p are in dBm, and M is the margin value in dB.

To evaluate the performance of this adaptation, OPNET modeler [9] is used in this work. OPNET is a well-known packet level simulator widely used in the literature. Table I



(a) Margin-based PCS adaptation performance

(b) Margin-based TPC adaptation performance

Fig. 5: Aggregate throughput performance: Physical Carrier Sensing (PCS) versus Transmit Power Control (TPC)

lists the most important simulation system parameters. In the simulated scenarios, the different BSSs are deployed in an hexagonal topology shown in Fig. 4. Each BSS includes 8 STAs associated to their AP. Note that all the BSSs in the simulated network operate on the same frequency channel. With a frequency reuse equal to 3 and a cell radius of 7 meters, the distance between two co-channel APs is about 21 meters.

Initially, it is interesting to show the effect of this adaptation on the aggregate throughput of such a dense network. For this part of simulations, the transmission bit-rate is fixed. Specifically, all transmitters are configured to transmit using the MCS 7 (64-QAM modulation scheme and 5/6 coding rate). For different margin values, Fig. 5a depicts the aggregate throughput with respect to time. This throughput includes all traffic successfully received by the MAC layer of all nodes. All the nodes start their transmissions at $t1 = 40s$ but they don't apply the PCS adaptation until $t2 = 90s$. In the interval between $t1$ and $t2$, the PCS_{th} is set to the traditional over-conservative value of -82 dBm.

After adapting the PCS threshold using equation (12), the carrier sensing range is contracted. Thus, more concurrent transmissions are permitted, and as a consequence, as shown in Fig. 5a, the aggregate throughput is largely increased for some margin values. It is worth noting that the aggregate throughput is not increased for all margin values. The performance of each value is related to the number of co-channel nodes covered by the sensing region. For instance, large margin values lead to carrier sensing ranges smaller than the minimum PCS_R and thus create detrimental hidden nodes regions. For that reason, in the results shown in Fig. 5a, the margins greater than 40 dB lead to lower aggregate throughput. Furthermore, the best aggregate throughput is achieved with a margin equal to 20 dB. This adaptation leads to a gain of 120% in throughput.

B. Comparable Transmit Power Control scheme

This section introduces a new TPC algorithm that is fairly comparable to the PCS adaptation described above. Each node adapts its transmit power so that its transmission is received at a margin above the traditional PCS threshold (-82 dBm) by the intended receiver. In that way, the shrinking ratio of the sensitivity range is maintained the same as the PCS adaptation case. This simple adaptation algorithm is used to compare the performance of TPC versus PCS adaptation.

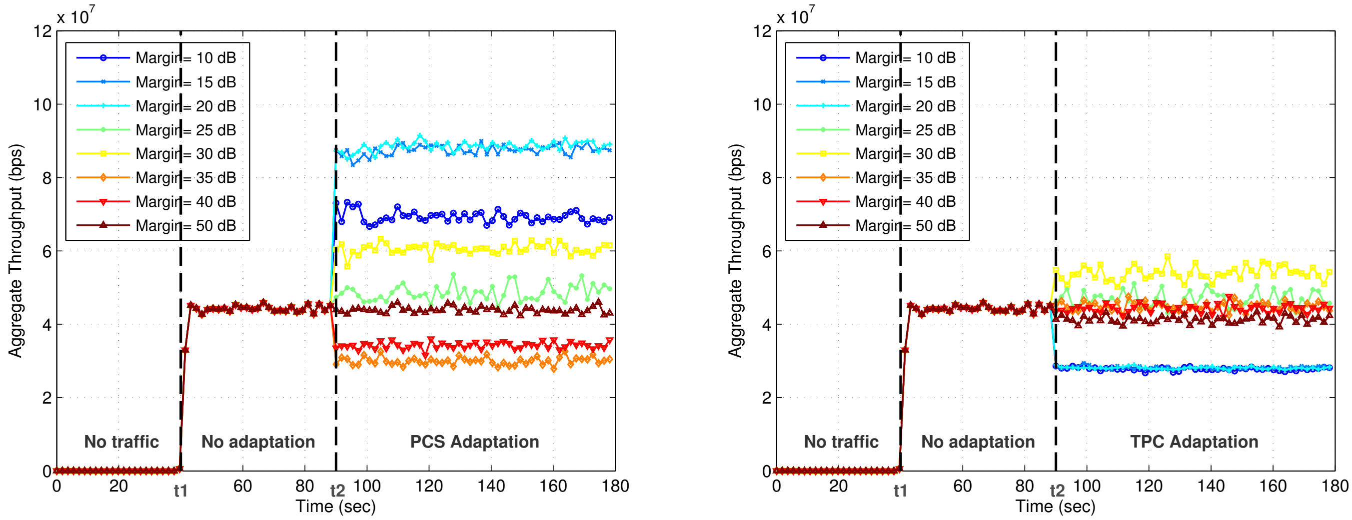
Fig. 5b shows the aggregate throughput obtained before applying TPC ($t1 < t < t2$) and after its application ($t > t2$) for different margin values. For the simulated topology, the highest aggregate throughput is obtained with a margin equal to 30 dB. Furthermore, when using lower margin values, the TPC adaptation leads to inconsiderable aggregate throughputs. This is due to the very low transmit power that doesn't succeed in satisfying the required SINR (S_i). Interestingly enough, the PCS adaptation outperforms the TPC which achieves around 66% of maximum gain in aggregate throughput.

Another potential inconvenient for the TPC is related to the transceiver hardware aspect. Actually, with lower margins, the resulting transmit powers are extremely low. Unfortunately, for hardware limitations, it is difficult to transmit or receive using these insignificant power values. The applicability of TPC on the existing 802.11 network interface cards is questionable as shown in the work carried out in [10]. Inevitably, this problem must be considered when comparing TPC to other solutions like PCS adaptation. Moreover, the evolving technology may be able to cope with this limitation.

VII. Interoperability with Legacy Nodes

In this part, the performance of the two approaches is studied in the presence of legacy nodes that do not implement, either the PCS or the TPC adaptation algorithms. WLAN deployment is somehow chaotic in terms of diversity in authority and lack of planning. Therefore, any proposed enhancement must take into account the possibility of coexistence with other entities that are not adopting the same solution. To investigate such a situation, a test is conducted without applying the adaptation algorithms on 7 STAs (12.5% of total STAs). These legacy STAs are selected randomly, one from each BSS. The key question is: how much the aggregate throughput will be affected by the presence of these legacy STAs?

Fig. 6a and Fig. 6b show the resulting aggregate throughput when applying the PCS and the TPC adaptation, respectively.



(a) Margin-based PCS adaptation performance with legacy nodes

(b) Margin-based TPC adaptation performance with legacy nodes

Fig. 6: Aggregate throughput performance in presence of legacy nodes: Physical Carrier Sensing (PCS) versus Transmit Power Control (TPC)

It is clear that the PCS adaptation shows greater ability to tolerate the presence of legacy nodes than the TPC adaptation. For the PCS approach, the maximum aggregate throughput is decreased by 10% compared to the case where there are no legacy nodes. On the other hand, in the case of TPC, the presence of 7 legacy STAs causes more than 35% of aggregate throughput decrease. While all other STAs are decreasing their transmit power according to the previously described algorithm, these 7 STAs continue transmitting using their highest power. Therefore, as described earlier in this paper, the STAs transmitting with higher power dominate the channel access. The other STAs that apply the TPC remain exposed to the ongoing dominating transmissions.

So the nodes that don't apply TPC will have more chance to transmit. However, in the PCS case, the advantage is for the nodes that apply the adaptation because they will be able to transmit simultaneously with others. Actually, to cope with the increasing density of WLANs, the medium access mechanism must be somehow aggressive. Thanks to the short distances between the transmitters and their receivers, the SINR condition is satisfied even with some simultaneous communications. The aim is to adapt the PCS mechanism properly to the density of the environment in a way to increase the spatial reuse.

VIII. Conclusion

This paper showed that the IEEE 802.11 MAC protocols' efficiency is indispensable in order to cope with the increasing density of WLAN environments. The importance of spatial reuse has been presented as a key to improve the network capacity. Subsequently, the TPC is introduced as one of the solutions that affects the level of spatial reuse. However, due to its vulnerabilities, another technique is proposed as a promising solution. Specifically, it was argued that the PCS must be optimized because of its fundamental role in medium access. A new adaptation algorithm is proposed to verify the impact of the PCS and the TPC on the aggregate throughput. Using OPNET, the simulations are conducted in a high density scenario. It has been shown that PCS adaptation achieves 120% of gain in aggregate throughput versus 66% of gain achieved by TPC. Furthermore, the PCS approach is able to coexist with legacy devices without substantial performance degradation (10% versus 35% of throughput performance degradation for PCS and TPC respectively). A future study will extend the current work by investigating the possible combination of the two approaches to improve the overall system performance.

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