Improving the Capacity of Future IEEE 802.11 High Efficiency WLANs

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***Abstract*—In future's high density Wireless Local Area Networks (WLANs), to improve the overall throughput, we envision the optimization of the MAC protocols and mechanisms. Traditionally, it's clear in the literature that Transmit Power Control (TPC) is chosen as one of the most powerful tools for optimizing MAC protocols. However, the TPC is not always possible to implement due to hardware and licensing limitations on one hand, and on the other, its unbalanced use results in starvation situations. In the same context, the Clear Channel Assessment (CCA) threshold adaptation is proving its effectiveness. This adaptation is preferable to TPC that behaves aggressively towards transmitters having lower transmit power. In this paper we show that CCA adaptation mechanism may be used effectively to optimize the spatial reuse in dense WLAN deployments. For a dense IEEE 802.11n network topology, our simulations show a global gain of 190% in aggregate throughput compared to the current bound assumed by the present MAC protocol.**

Keywords*—IEEE 802.11, WLAN, Wi-Fi, Wireless MAC protocols, MAC efficiency, Spatial reuse, CCA threshold adaptation.

I. Introduction

The increasing density in deploying WLANs is due to an exponential need for omnipresent coverage. The fast evolving technology has boosted the expansion of WLAN ready devices and pushed the prices of hardware equipment down. For instance, a normal Wi-Fi network interface card is so cheap that it is embedded into almost all types of computing and communication devices such as smart phones, notebooks and tablets. With millions of hot-spots deployed around the world, Wi-Fi is rapidly becoming ubiquitous. Nowadays, urban environments are showing a huge number of deployed Access Points (APs) and connected Stations (STAs) [1].

While this massive deployment reflects the need for more capacity, it increases the amount of interference between different Wi-Fi networks. The latter results in sub-optimal user throughput due to contention [2], and therefore attenuates the global network capacity. The neighboring APs that operate on the same channel suffer from co-channel interference that may degrade severely the wireless communication quality. Since Wi-Fi operates on ISM (Industrial, Scientific and Medical) 2.4 and 5.8 GHz unlicensed radio bands, it is limited to a few number of orthogonal channels. The 2.4 GHz band includes only three non-overlapping channels, while the 5.8 GHz band contains 23 non-overlapping channels depending on countries normalization. Given the intent for omnipresent Wi-Fi, this lack of orthogonal channels quantity has made co-channel interference one of the biggest challenges to efficiency and high capacity.

Besides the need for ubiquity, nowadays applications are indeed more aggressive in terms of network resources. Gaming, high definition video, augmented reality and others are examples of daily used applications categories. To respond to these demands, the IEEE 802.11 working group [3] had always an interest in increasing the peak bit-rate. While in IEEE 802.11n it reached 150 Mbps per spatial stream, the new IEEE 802.11ac amendment is announcing almost 1 Gbps per stream. It is important to mention here that these bit-rates are theoretical; real networks never attain these upper bounds. That is due to the contention nature of the Medium Access Control (MAC) layer mechanisms of the IEEE 802.11 standard along with the interference problem discussed above.

Contrary to cellular networks, in a Wi-Fi network there is neither granted time nor dedicated frequency for each user. The IEEE 802.11 standard [4] defines a Distributed Coordination Function (DCF) to share the access to the medium. In practice, an IEEE 802.11 device uses Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) which is the backbone of the DCF. Before transmitting, a node listens to the channel to determine whether another node is transmitting. The latter mechanism is called Clear Channel Assessment (CCA). The DCF and the CCA are described in detail later in the next paragraph.

Today, the intention is to improve the efficiency of the current IEEE 802.11 WLAN on the way to support this drastic increasing need for more capacity and higher performance. It's clear that the MAC layer protocols of the IEEE 802.11 need many optimization efforts to enhance the WLAN performance in today's dense deployments. In this context, the IEEE announced the creation of a new IEEE 802.11 study group to define the scope of a future IEEE 802.11 amendment with the aim of enhancing the efficiency and the performance of WLAN deployments. The new IEEE 802.11 High Efficiency WLAN (HEW) study group [5] will consider use cases, including dense network environments with large numbers of access points and stations.

This article will consider a new approach to investigate the MAC aspects that could enhance the performance of the current IEEE 802.11 WLANs in dense environments. We will focus on an important mechanism that plays the main role in the medium access strategy of an IEEE 802.11 node. It's well known that increasing spatial reuse is the key for higher capacity. One of the major advantages of the CCA function is its ability to determine the amount of medium sharing. For that reason, one of our goals is to prove that optimally adjusting the CCA threshold is very efficient to improve the global (aggregate) throughput in a Wi-Fi network. Based on our

978-1-4799-5141-3/14/$31.00 ©2014 IEEE

simulations, many crucial guidelines and recommendations are proposed for the enhancement of the efficiency of the current Wi-Fi dense networks. This paper is organized as follows. We present the context and the motivations behind our work in Section II. In Section III we show the considered topology and describe our simulation setup. The obtained results are shown and analyzed in details in Section IV. In Section V, we highlight a set of guidelines and recommendations based on our analysis. Finally, we reveal our prospects and conclude the paper in Section VI.

II. Context and motivation

The used power for transmission dictates the interference projected on neighboring communication links. Therefore, to reduce co-channel interference damage and increase the amount of spatial reuse, Transmit Power Control (TPC) is suggested in the literature as a traditional solution [6]. In fact, this solution was brought from the power control adopted in cellular networks. Keep in mind that power control is applied per user basis in cellular networks without any problem since every user has its dedicated operating frequency.

Since the access to the medium in an IEEE 802.11 WLAN is based on contention between co-channel operating nodes, the node transmitting with higher power will dominate. Other nodes that transmit with lower power may lose the opportunity to gain access to the channel [7]. While reducing transmission power to decrease the amount of interference may be powerful, it creates a sort of asymmetry between nodes [8], [9], [10]. This asymmetry affects the fairness aggressively and harms the STAs who implement the TPC. Therefore, it degrades the global performance of the network. For that reason, power control is used very carefully in deployed WLANs.

Although IEEE 802.11h [11] has standardized the TPC since 2003, the latter was never used at the STA side probably to prevent asymmetric situations. Even in the recent discussions of the different IEEE 802.11 task groups, it's clear that there are no incitations to apply TPC in STAs. Accordingly, TPC is not stable if it's not applied similarly on all nodes in close proximity to avoid starvation [7], [8], [9].

Yet, another technique has proved its efficiency in managing interferences and spatial reuse. This technique consists on optimizing and adapting the CCA threshold. Compared to TPC, the CCA adaptation can bring the same results but without harming severely the symmetry of the communications. Another advantage is that a node benefits from applying CCA threshold adaptation without relying on all the neighboring nodes to do so. While TPC fails if not all the adjacent WLANs apply it, CCA threshold adaptation doesn't need their compliance.

Recalling that the DCF function described by the IEEE 802.11 standard [4] is based on a well known medium access scheme: the CSMA-CA. More details about DCF may be found in [4]. The multiple access to the communication medium is defined by CSMA-CA to be contention based. In that way, all the nodes in the same physical area compete to transmit on the half-duplex medium of a single frequency. This physical area is termed “contention domain”. While one node is transmitting, all other nodes must wait until it finishes. To check whether the channel is busy or idle a node performs a clear channel assessment, namely CCA. The decision is based on the value of the CCA threshold. If the in-band signal energy

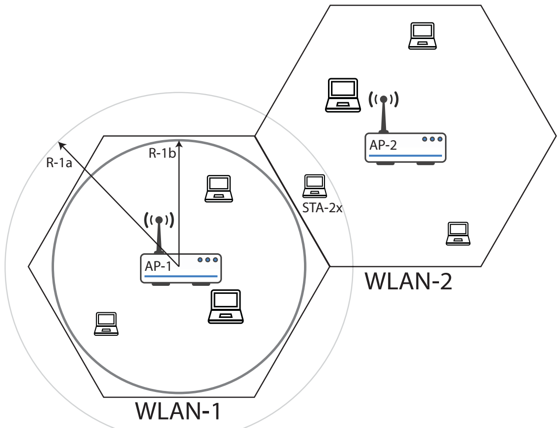

Fig. 1: Physical Carrier Sensing

crosses this threshold, CCA is held busy until the medium energy is below the threshold again. This described process is named Physical Carrier Sensing (PCS).

In the sequel, let us take a simple example to explain the effect of modifying the CCA threshold. This example includes two neighboring WLANs depicted in Figure 1. For a CCA threshold equals to T-$1a$, the PCS range of AP-1 (R-$1a$) covers the STA-$2x$ that's associated to AP-2 of the neighboring WLAN. The previous statement means that AP-1 is not able to transmit at the same time as STA-$2x$. This fact is very harmful for the WLAN-1, since AP-1 is obliged to stay silent when STA-$2x$ is transmitting. Add to this the fact that, in almost all WLANs, the most important amount of data is directed from the AP towards its STAs. Clearly, the PCS range R-$1a$ is reducing the aggregated capacity of this network by restricting possible concurrent transmissions. Now let's consider T-$1b$ (given T-$1b > T$-$1a$) as the CCA threshold of AP-1.Now, in contrast to the previous case, the PCS range has been shrunk sufficiently (R-$1b$) to let simultaneous transmission for both AP-1 and STA-$2x$ and thus increasing the spatial reuse.

It's worth pointing out that simultaneous transmissions of STA-$2x$ are still received by AP-1, but the latter ignores them because their received power is below the new CCA threshold T-$1b$. However, these transmissions are treated by AP-1 as interferences. So, if STA-$2x$ is highly loaded, one can imagine a drop in the Signal to Interference and Noise Ratio (SINR) at AP-1. This fact brings to light the necessity of establishing a trade-off between spatial reuse and interference level. In our analysis, we will reveal that in dense environments, thanks to short distances, the SINR values stay high enough assuring successful transmissions.

As shown in the previous example, if the carrier sensing threshold is increased, more concurrent transmissions are permitted and vice versa. Theoretically, this behavior may involve more interference because the communication range of the node will decrease by becoming less aware of other concurrent transmissions. In contrast, interestingly enough, our simulations prove that in dense environments this behavior is of minor importance due to short distances between nodes.

III. Simulation setup

In our simulations, we consider a dense cellular topology formed by seven co-channel Basic Service Sets (BSSs). This

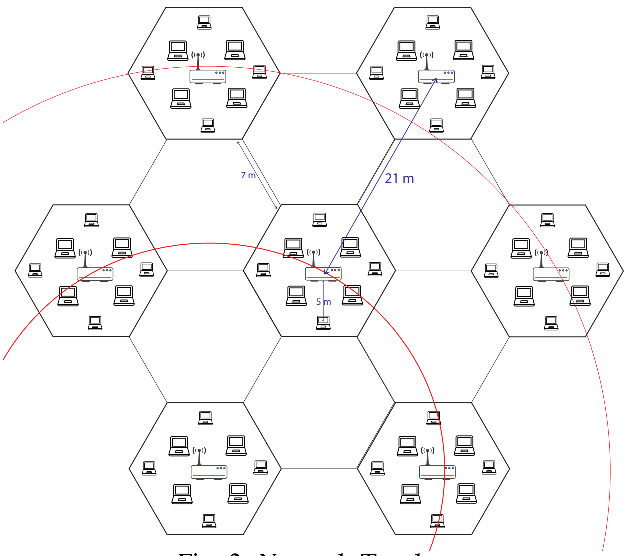

Fig. 2: Network Topology

single channel deployment aims to spot co-channel interference in a High Density WLAN environment. Each cell is an hexagon of a Radius (R) of seven meters. As depicted in Fig. 2, two co-channel cells are separated by 3R (21 meters). In other words, the value of the used frequency reuse is three. Every BSS includes the AP and eight STAs. The majority of todays consumers network traffic is in Down-Link (DL). Accordingly, the APs generate the same saturated UDP traffic towards all their STAs. Full buffer traffic takes into account the worst case where the network is always fully loaded.

OPNET Modeler [12] is used to simulate the described topology. The standard version of WLAN model under OPNET is slightly modified for the sake of our typical simulation configurations. The ITU Urban Micro (UMi) path loss model is adopted. The rate control mechanism described in [13] is implemented and used in this work. This rate adaptation is a variant of the well-known Automatic Rate Fall-back (ARF) that uses the transmission history (success/failure statistics) to select the next transmission rate. In the aim to be as close as possible to the real deployed networks, the TPC is only applied on the APs. For that purpose, the APs are transmitting with 6 dBm and the STAs with 15 dBm. Since all the traffic is in DL, the precedent configuration will not affect severely the symmetry of the communications. Detailed simulation parameters are included in Table I.

For the best of our knowledge, this is the first work that uses IEEE 802.11n MAC & PHY in a such study. All related papers rely on old versions of IEEE 802.11 such as a, b and g to perform simulations. The reason behind that is probably the usage of other simulation tools that does not implement the recent standard. The advantage of using this version is to take into account the new features of IEEE 802.11n such as aggregation and Enhanced Distributed Channel Access (EDCA). While these mechanisms are not present in older versions, they can obviously influence the simulation results. Having them in our simulation makes it more realistic. In the next section we will conduct a detailed discussion about our observations.

TABLE I: Simulation parameters

Parameter	Value
MAC & PHY	802.11n
Radio band	5GHz
Bandwidth	20MHz
Number of antennas	1
Aggregate MSDU max size	3839 Bytes
Aggregate MPDU max size	8191 Bytes
Guard Interval (GI)	Short (400ns)
STA transmit power	15 dBm
AP transmit power	6 dBm
Simulation Duration	5 min

IV. Results Analysis

Increasing CCA threshold does not always guarantee higher throughput, because the transmissions are initiated while other nodes are transmitting and that can result in collisions at the receiver. To overcome these collisions, the received power must be greater than the sum of all other interferences at the receiver. Thankfully, in dense environments, the distance between an AP and its client is short enough to let the receiver capture the Signal of Interest (SoI) even when multiple transmissions occur simultaneously. This conclusion and others are devised in the following sections.

A. *Feasibility*

First, we will discuss the results obtained when varying the CCA threshold between -82 and -65 dBm on all nodes. The settings depicted in Table I are used for this simulation setup. It's true that the following values are related to our simulation configurations, but their evolution shape can be generalized for all situations. In all the figures we plot the global (aggregate) throughput in terms of CCA threshold variation. In Fig. 3, one can distinguish three important parts: -82 dBm, from -81 to -75 dBm and from -74 to -65 dBm. As considered in the IEEE 802.11 standard's CCA requirements [4] and as widely used in todays WLANs, -82 dBm is the default CCA threshold value, and thus it will be used as a reference to compute the gain percentage when using other threshold values. The received signal power at the closest STA belonging to one of the BSSs of the surrounding second tier (33 m far from a considered AP) is -82 dBm. So, when CCA threshold is less or equal to -82 dBm, any considered AP affects the transmissions of the STAs belonging to the second tier of the cellular topology. Starting from -81 dBm, all the nodes of the second tier can transmit simultaneously with the considered AP, therefore the global throughput of the network increases (to 100%).

If we consider any AP in Fig. 2, let it be $AP\text{-}x$, the received power of its transmissions at the closest AP (21 meters far from $AP\text{-}x$) is -75 dBm. The maximum global throughput gain is obtained when the CCA threshold is set to -75 dBm (190%). For this value the PCS range overlaps the closest APs, meaning that the considered AP can't transmit simultaneously with the APs of the first tier. When these concurrent transmissions are permitted (CCA threshold equals to -74 dBm), the gain becomes negative. Note that at this point the majority of the STAs belonging to neighboring BSSs are prohibited from responding to their APs, thus a mass of retry attempts and unsuccessful transmissions lead to this critical decrease. The gain returns to a positive value when the CCA

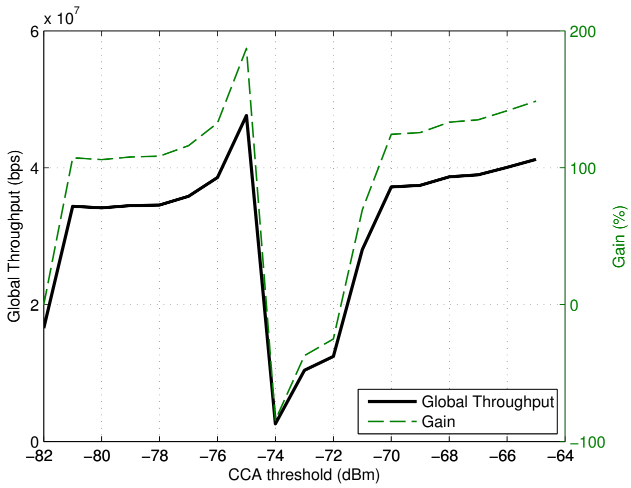

Fig. 3: Achieved global (aggregate) throughput gain in terms of CCA threshold

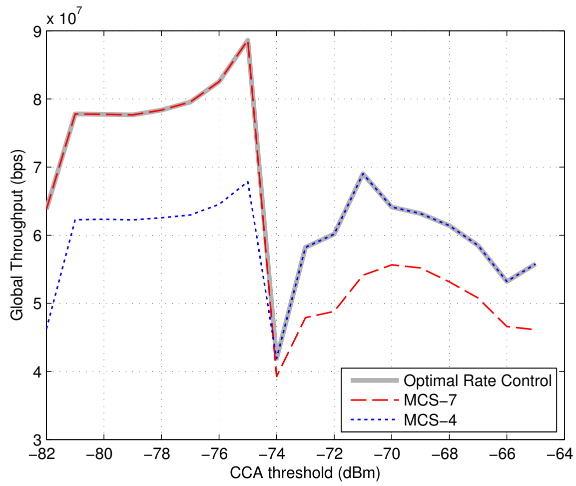

Fig. 4: Achieved global (aggregate) throughput - Rate control vs. CCA threshold adaptation

threshold exceeds -71 dBm. Recalling that the closest STA belonging to a neighboring BSS is at 16 meters from $AP\text{-}x$. At this distance, the received power of a 6 dBm transmitted signal is -71 dBm. Since the traffic is DL, the STAs only communicate management frames with their corresponding APs, mainly Acknowledgments (ACKs) frames. Since all the STAs belonging to the first tier BSSs can transmit concurrently with the considered AP when their CCA threshold is greater than -71 dBm, the throughput gain becomes positive beyond this value. After that, the gain continue it's recover because the BSSs are more and more isolated in terms of PCS range. This isolation is translated into a higher amount of concurrent transmissions.

At this stage, we showed the efficiency of choosing the appropriate value of CCA threshold to enhance the global throughput of realistic simulated network. The gain in throughput attains 190% as shown in Fig.3. It should be kept in mind that the used rate control mechanism [13] may severely affect this results. We chose to enable the rate control in this scenario to simulate a realistic use case, since currently deployed devices use similar rate control mechanisms. In the following section, we investigate the relation between CCA threshold and rate control.

B. *In relation to rate control*

For a better understanding of the implications of rate control, it's worth to mention the main causes of packet loss in WLANs. Packet loss happens for two different reasons: synchronous interferences (collisions) and asynchronous interferences. As argued in [14], [15] and others, the capability of a rate control scheme to differentiate the cause (or nature) of the interference is the key to improve the efficiency of that scheme.

In this scenario, the rate control algorithm is disabled. We perform two sets of simulations, in each one we chose a different Modulation and Coding Scheme (MCS). The global (aggregate) throughput of the network is collected and represented in Fig. 4. The first observation is that our adopted rate control algorithm [13] is not optimal. Hence, it's not able to adapt to the changing CCA threshold. Another deduction is that the distance between two neighboring co-channel APs plays a fundamental role in the effectiveness of the used MCS. In our simulations, this distance is 21 meters. The received signal power at this distance is -75 dBm. As shown in Fig 4, the maximum throughput is observed when using the higher MCS (MCS-7) at a CCA threshold that covers these neighboring APs (-75 dBm). For the lower MCS case, the maximum throughput is achieved for a CCA threshold that equals to -71 dBm. In our simulation, this belongs to the case where the PCS range of each AP does not include any node from other BSSs. Next, we analyze the above observations in detail and highlight the appropriate emerged conclusions.

If we want to use high data rates, the first tier of neighboring co-channel APs most be covered by the PCS. We found that the transmissions of the closest co-channel APs are very detrimental for the central AP and thus they must be covered. Actually, these transmissions are treated as interference signals at the central AP and thus the SINR of the Signal of Interest (SoI) inside the central BSS is lowered. Not covering these surrounding APs increases the amount of interferences significantly and expanding the carrier sensing range further than needed may raise the probability of collisions. That's because more nodes are included in the same contention domain. In this case, the packet loss is due to synchronous back-off time where the channel status may be sufficiently fine for successful transmissions. As shown in Fig. 4, lower data rate does not perform better in this case because the SINR values at the receivers are high enough. In contrast, shrinking WLANs by contracting the physical carrier sensing range must be accompanied with lower transmission rates to tolerate the increasing amount of interferences caused by concurrent transmissions. Here a robust MCS can ameliorate the received SINR and thus the achieved global throughput (Fig. 4).

So, an efficient rate control algorithm must operate jointly with the CCA threshold adaptation algorithm. When the latter threshold is increased (the PCS range is contracted), the used rate must be decreased to maintain an acceptable SINR values. An algorithm that's able to behave properly and optimally with the CCA threshold adaptation will be the subject of a further study.

C. *The effect of legacy devices*

Wi-Fi deployment is somehow chaotic [2] in terms of diversity in authority and lack of planning [16]. Therefore, any

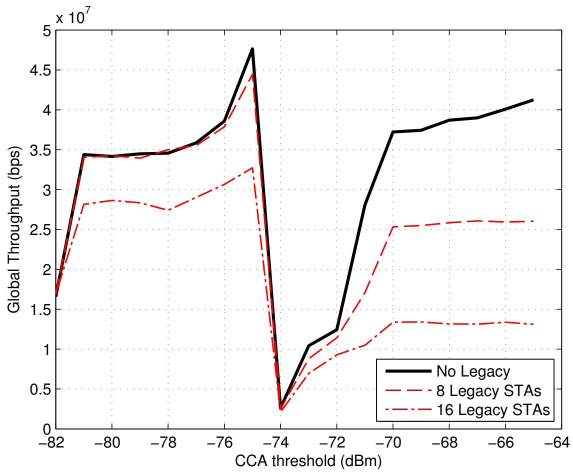

Fig. 5: Achieved global (aggregate) throughput - The effect of legacy devices

proposed enhancement must take into account the possibility of coexistence with other devices that are not adopting the same solution. To investigate the effect of these legacy devices, we conducted a test where the CCA threshold adaptation is not applied on N STAs. These N STAs are selected randomly from the different BSSs. We ran two simulation sets for N = 8 (14% of STAs) and N = 16 (28% of STAs). The key question is: how much throughput will be affected by the presence of these legacy STAs?

In Fig. 5, we plot the global (aggregate) throughput achieved in each situation. We can clearly observe the effect of the presence of the STAs that are not modifying their threshold. However, this effect is more severe when the CCA threshold exceeds -74 dBm. Above this value, the PCS of each node does not cover other nodes belonging to other BSSs. In such a situation, the presence of STAs behaving differently will be more noticeable. The legacy STAs, having their CCA threshold fixed to -82 dBm, will be prohibited from gaining access to the channel by the transmissions of the neighboring APs. Thus, they will not be able to acknowledge their APs. Therefore, their destined traffic will experience higher losses, which results in the decrease of the throughput. As depicted in Fig. 5, the legacy devices representing 14% and 28% of the total number of STAs result in throughput losses up to 37% and 68% respectively. But in both cases, we still have important gains in global throughput when the CCA threshold is optimally adapted.

From the above, it's clear that the growing heterogeneity nature of the present wireless networks can't be ignored. This diversity challenge necessitates flexible and autonomous solutions. In other words, centralized schemes are not envisioned as suitable solutions except in specific cases where a single authority is responsible of all the co-located WLANs.

V. Guidelines and Recommendations

Basing on our observations, we believe that any future work aiming at enhancing the capacity of IEEE 802.11 WLANs must take into account the following guidelines: a) In dense environments, because of short communication links, CCA threshold adaptation has a great advantage for global network throughput. As we proved, it can be used to increase the volume of spatial reuse on the one hand, and maintain a sufficient separation distance to minimize interferences on the other hand. b) An optimal trade-off must be considered between the amount of concurrent transmissions and their possible consequent interference level. Since the latter level is related to the density of the considered network topology, it's suggested to design a distance aware adaptation of the CCA threshold. c) An optimal rate control algorithm must behave coherently with the adaptive CCA threshold. For instance, this algorithm must be able to differentiate between interferences and collisions. d) Any optimization solution must take into account the coexistence with legacy devices that are not applying the same optimization scheme. e) Distributed adaptation algorithms are more adequate for todays networks, because they are able to adapt to the unplanned and unmanaged deployment growth of current WLANs.

VI. Conclusion and Perspectives

In this paper, we took a new approach in exploring the possibilities to improve the capacity of the IEEE 802.11 WLANs. We proved that by optimizing physical carrier sensing, we can increase the global network throughput in dense WLAN environments. By exploiting the MAC protocol mechanisms, we argue that there is a need to optimize the access method scheme in the IEEE 802.11 WLAN. We showed that an optimal CCA threshold adaptation can provide up to 190% of gain in throughput. Preparing the way for a further work that studies an optimized adaptation algorithm, we conducted a newly deep analysis of the impacts of such optimization. Finally, we summarized our observations and proposed a list of essential guidelines and recommendations.

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