Carrier Sensing-aware Rate Control Mechanism For Future Efficient WLANs

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***Abstract*—The rate control mechanism is an effective way to improve the overall system performance in IEEE 802.11 multi-rate networks. However, in dense environments, due to the large number of contending nodes, the packet collisions trigger unfairly the rate control mechanism to decrease the transmission data rate. In this work, we address the performance degradation problem of rate control caused by these unnecessary data rate decrements. A physical carrier sensing adaptation enhances the spatial reuse and paves the way to an adapted rate control algorithm to boost the performance of the network. Extensive simulations show a gain of 260% in achieved throughput compared to the conventional scenario.**

***Keywords*—WLAN, Wi-Fi, IEEE 802.11, MAC Protocols, Physical Carrier Sensing (PCS), Rate Control**

I. Introduction

The IEEE 802.11 Wireless Local Area Network (WLAN) is widely known as the dominant indoor broadband wireless access technology. Recently, new applications are envisioned for these WLANs such as cellular offload and other outdoor use cases. This means that the number of deployed WLANs will continue increasing in the coming years. Nowadays, the consumer services and applications are designed to be always connected to the Internet. Along with this wide proliferation of WiFi equipped mobile devices, there will be an increasing need for ubiquitous coverage. To respond to these requirements for capacity and coverage, WiFi networks are deployed more and more densely.

This dense deployment is challenging due to many factors. The contention-based access described by the Distributed Coordination Function (DCF), the core of the IEEE 802.11 MAC, is one of these factors. This medium access function is based on the Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) technique. Each device that is willing to transmit must sense the medium for potential occurring communications. If the medium is busy the current transmission is postponed. An exponential binary back-off mechanism is triggered to resolve synchronous collisions. The previous described behavior raises many questions about the performance of the overall system, especially in dense environments where the number of contending nodes is relatively large. Beside that, the operation over unlicensed frequency bands is another challenge due to the potential interferences from other systems sharing the medium.

These high density environments are not so conventional for a traditional WiFi operation. The IEEE 802.11 standard [1] is designed for cheap wireless access networks that operates simply and are easy to use and deploy. Accordingly, the MAC protocols were built to assure this simple operation with minimum interference and maximum performance. For instance, the Physical Carrier Sensing (PCS) mechanism used to sense the medium in the CSMA/CA is designed to cover a large region to protect the receiver from any potential interferer. With the increasing density of WiFi networks, the distance between co-channel networks is decreasing. In the same way, the distance separating a transmitter-receiver pair is decreasing too. Consequently, in current networks, the PCS is over-conservative since it is baning possible concurrent transmissions and hence decreasing the amount of spatial reuse. Optimizing the PCS mechanism is able to improve the aggregate system throughput by twofold as shown in [2].

The work in [2] proposes a PCS adaptation to increase the spatial reuse in a dense WLAN scenario. Authors assume a fixed data rate in their simulation setup. However in WLANs, the data rate control is an important mechanism that needs to be adapted for better performance. The interest of the present paper is to investigate and propose a PCS-based rate control algorithm relying on the work performed in [2]. The IEEE 802.11 standard [1] supports a wide variety of transmission rates. By employing different combinations of signal modulation and channel coding schemes, a large number of bit rates is possible. For example, an IEEE 802.11n [3] device is able to transmit over eight different data rates using only one single spatial stream (*e.g.* one antenna). When dealing with Multiple-Input-Multiple-Output (MIMO) systems, the number of possible data rates may reach 24. This multiple rate capability offers a wide range of supported transmission modes and hence the ability to adapt with the network environment. In other words, the transmitter is able to select the most suitable Modulation and Coding Scheme (MCS) based on the status of the transmission channel. While low MCSs can tolerate higher amount of interferences, higher MCSs can offer higher data rates.

While the standard [1] lists the supported MCSs with their associated data rates, it leaves open the issue of MCS selection. Many efforts were made to design efficient rate adaptation algorithms. The current products in the market are implementing proprietary solutions to cope with this issue. The majority of these solutions are based on the well-known Automatic Rate Fall-back (ARF) that was implemented initially by Lucent in its WaveLan-II product [4]. However, this algorithm tends often to use lower MCSs. While this may help to tolerate channel errors, using lower MCSs wont help when collisions are the major cause of packet loss (*i.e.* in dense environments). This problem is discussed in this paper and a new PCS-based rate control mechanism is proposed to cope with these unnecessary MCS decrements.

The rest of this paper is organized as follows. Section II depicts the work in the literature related to rate control. Then, in Section III, the communication model is evoked in details. Section IV explains the hidden and exposed node problems. The margin-based PCS is introduced in Section V as a way to cope with hidden and exposed node problems. The proposed Carrier Sensing-aware Rate Control is shown in Section VI. Finally, the simulation setup and results are discussed in Section VII before concluding the paper in Section VIII.

II. Background and Motivation

The main idea behind rate control is to fortify the communication in case of bad channel state. This is done by decreasing the transmission bit rate and using more robust MCS. On the other hand, an efficient rate control mechanism should benefit from the good channel state to increase the transmission rate opportunistically to improve the system throughput.

Rate control algorithms are implementation specific, however, generally, they are based on the measurement of the Packet Error Rate (PER). These algorithms monitor the PER to infer the status of the channel and hence to adapt the used MCS correspondingly. Although the efficiency of a MCS at a given moment depends on the receiver's channel state at that moment, almost all the rate control algorithms are sender-based. This means that the sender estimates the channel state and decides which MCS to use, not the receiver. This decision is based on the information tracked by the transmitter locally. Particularly, the Acknowledgment (ACK) history is used to deduce the current PER.

For instance, ARF [4] is one of the most implemented rate control algorithms. In its implementation, ARF defines two counters: one to count the number of successfully transmitted packets, and another that counts the number of failed packets. The success counter is incremented for every packet acknowledged by the receiver. If the ACK response is not received by the transmitter for any reason, the failure counter is incremented by one. *Two* consecutive failures reported by the failure counter result in an MCS downshift. However, the sender cannot upshift the MCS before counting *ten* consecutive succeeded packets. Yet, if the next packet (*i.e.* the eleventh one) is failed, the ARF will automatically fall back to the previous MCS without waiting for another consecutive failure. The majority of the practical rate control algorithms [5], [6], [7], [8] and [9] are based on the same principle as ARF.

It is clear that the operation of ARF-like algorithms tends always to decrease the used MCS. The reason is to protect the communication from any degradation in the channel state. However, since the packet loss is not always due to channel errors, the MCS (bit rate) decrement is not always helpful. In some situations where collisions are more likely to happen, using lower MCSs degrades the performance of the network. In dense environments, the Signal-to-Noise Ratio (SNR) is satisfied due to the close distance between the transmitter and the receiver. Nevertheless, because of the high number of contending nodes, collisions may happen frequently producing packet loss. These collisions are due to synchronous transmissions due to backoff countdown overlap or hidden node problem. In this case, reducing the MCS will increase the probability of collisions since the transmissions are occupying more channel time. Hence, instead of improving the PER, these conservative rate control algorithms will end up using the lowest MCS decreasing with that the aggregate throughput of the network.

In this context, this work proposes a new way to cope with the problem of rate control caused by unnecessary rate decrements. In a dense WLAN environment, using the PCS adaptation described in [2], the achieved SNR values are bound with certain minimum. Consequently, the rate control algorithm is prevented from using low MCSs that are more robust than needed.

III. Communication model

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

A. Path loss

In a radio environment, the generated electromagnetic signal at the transmitter suffers from variable losses before reaching the intended receiver. The propagation path loss can be expressed in dB by

$$L_P(d) = L_P(d_0) + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \tag{1}$$

Where d is the distance between the transmitter and the receiver, d_0 is a reference distance close to the transmitter (*e.g.* $d_0 = 1m$), $L_P(d_0)$ is the path loss at the reference distance d_0, γ is the path loss exponent that indicates how severely the RF signal decays as distance increases (*e.g.* $\gamma = 2$ for free-space, $\gamma = 4.5$ for closed office because of the great density of obstacles, *etc.*), and X_σ is a zero-mean random variable following a log-normal distribution with standard deviation σ. This random variable captures the shadowing effect of the wireless channel; Different receivers situated at the same distance of the transmitter receive different signals due to the variety of paths traveled by the waves and the dynamic variation of the channel with respect to time.

In this study, we will not consider the shadowing effect. Based on Eq. (1), the received power at the intended receiver will be expressed in its linear form as follows:

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

Where $Rx_p(d_0)$ is the received power at the reference distance d_0.

B. 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 given by

$$Rx_R = d_0 \left(\frac{Rx_p(d_0)}{max(P_N S_0, Rx_{th})} \right)^{\frac{1}{\gamma}} \tag{3}$$

where P_N is the background noise power, S_0 the minimum Signal-to-Noise Ratio (SNR), and Rx_{th} the reception threshold that denotes the minimum power level of a received signal. Actually, the receiver can decode a received packet with high probability of success if and only if the received power exceeds Rx_{th} and the corresponding SNR is greater than S_0. It's worth to mention that both, S_0 and Rx_{th}, depend on the used coding and modulation scheme.

In dense WLANs with high spatial reuse, the transmission ranges are quite small and the Rx_{th} is greater than $P_N S_0$. Consequently, the transmission range becomes

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

C. Physical Carrier Sensing range

The Physical Carrier Sensing range (PCS_R) is defined as the distance from a transmitter within which any detected communication causes the deferral of the pending transmission. 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 expressed here in Watts, 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.

D. Interference range

The region around a receiver A where any possibly occurring transmission will corrupt the intended reception at A, is defined by the interference range and can be expressed as follows.

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

If we consider an interference limited environment where noise power is negligible (*i.e.* $P_N \approx 0$), the interference range becomes

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

IV. Exposed and Hidden 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 the channel access in IEEE 802.11 WLANs [10] [11]. To explain these problems, consider the scenario shown in Fig. 1. 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.

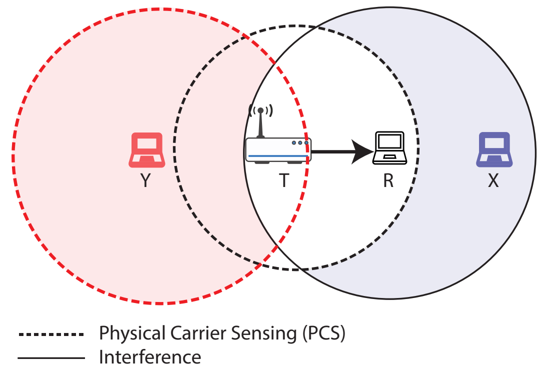

Fig. 1: Hidden and exposed node regions

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. 1, 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 network deployments become more and more dense.

As argued above, the currently adopted access method in 802.11 WLANs is not using efficiently the shared spectrum in dense environments. More precisely, the DCF suffers from an over conservative nature inherited from the way in which the medium is sensed. In today's deployed networks, it is very common to have a large number of exposed nodes experiencing performance degradation caused by neighboring co-channel networks. This problem is more pronounced in high density residential scenarios because of the totally unplanned personal infrastructure installation. For instance, in a home network, the end-user choses the location of the Access Point (AP) without caring about the possibility of overlapping with neighboring networks.

V. Physical Carrier Sensing

A. Hidden node problem mitigation

In order to mitigate the hidden node problem, the hidden region shown in Fig. 1 must be covered by the PCS as depicted in Fig. 2.

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

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

$$PCS_{th} \leq Rx_p(d_0) \left(\frac{d_0}{d}\right)^{\gamma} \frac{1}{\left(1 + S_0^{\frac{1}{\gamma}}\right)^{\gamma}} \tag{9}$$

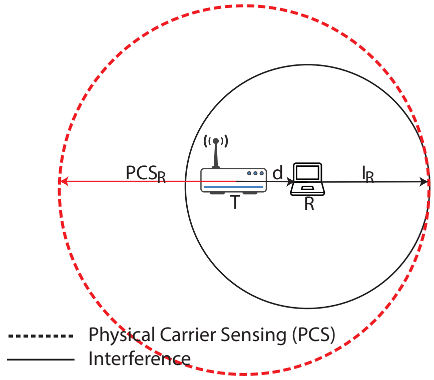

Fig. 2: Hidden node problem mitigation

Making use of Eq. (2), the linear form of the PCS threshold is given by

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

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

$$PCS_{th}[dBm] \leq Rx_p(d)[dBm] - \gamma 10 \log \left(1 + S_0^{\frac{1}{\gamma}}\right) \tag{11}$$

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

$$M[dB] \geq \gamma 10 \log \left(1 + S_0^{\frac{1}{\gamma}}\right) \tag{12}$$

B. Exposed node problem mitigation

As shown in Fig. 1, when there's a part of the PCS region that covers an area outside the interference range, this part is called an exposed region. Accordingly, 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. (12) in order to prevent exposed node situations.

C. Margin based PCS adaptation

According to many researchers in the field [12] [2], the current PCS mechanism is very conservative, so it produces large regions of exposed nodes. This behavior prevents possible concurrent transmissions to occur in the same channel even if it is out of the interference range of the receiver. Authors in [2] have shown that an optimized PCS is able to enhance the aggregate throughput by 190% compared to the conventional PCS case. The importance of the PCS mechanism comes from the fact that it governs the multiple access to the WLAN shared medium. So the decision of transmitting or not is made mainly based on this mechanism.

In crowded environments, the distance between the transmitters and their corresponding receivers is generally short because of the dense AP deployment. This fact means that the achieved $SINR$ values are usually enough to tolerate some additional interference. In this situation, the possible concurrent transmissions over the same channel may be useful since they increase the aggregate system throughput. Unfortunately, these transmissions are forbidden by the current PCS mechanism that tends to be over-conservative.

Inspired by Eq. (11), a simple algorithm is designed to adapt the PCS mechanism whilst mitigating the hidden node problem. Each STA tracks the power level received from its corresponding AP and sets accordingly its PCS_{th} to the value obtained by subtracting the margin M from the latest value of the received power. The margin M is a global parameter optimized for the corresponding deployment scenario. Having M, each STA updates its PCS_{th} in a periodic manner. The frequency of the adaptation is determined basing on many metrics such that the PER. While this PCS adaptation technique is not the main topic of this work, the proposed rate control algorithm is based on this margin-based adaptation as developed in the next section.

VI. Carrier Sensing-aware Rate Control

In this section, the rate control mechanism is enhanced by preventing the use of lower MCSs in situations where the channel state tolerates higher MCSs. Basing on the adaptation of the PCS, it is possible to define a lower bound for S_0. Using Eq. (11), we get

$$S_0 \geq \left(10^{\left(\frac{Rx_p(d) - PCS_{th}}{10\gamma}\right)} - 1\right)^{\gamma} \tag{13}$$

Consequently, the minimum SINR achieved by any transmission is defined by Eq. (13). Having that in mind, the usage of MCSs needed for the SINR values lower than this minimum is forbidden. In practice, the rate control algorithm is no more able to use all the supported MCS list. This list is updated so that only the reasonable MCSs that fit the situation are used. By this way, the aggregate throughput is enhanced because the rate control is deriving the maximum benefit from the supported MCSs.

As explained earlier in this paper, the currently used rate control schemes are not able to identify the cause of the packet loss. Such loss may be caused by bad channel states or by a synchronous collision due to simultaneous packet transmissions. While decreasing the MCS helps to overcome channel errors, this will never help in case of collisions. Furthermore, lower MCSs may produce more collisions because packets using these MCSs are transmitted slower than other packets using higher MCSs. For sure, the low MCSs consume more channel time and hence reduce the communication system efficiency.

The goal of our proposal is to prevent the use of low MCSs where the major cause of packet loss is collision and not bad channel state. Today, the density of WLAN networks is dramatically increasing. The APs are deployed closely to each other to tolerate the increasing number of WLAN clients as almost every house is equipped with a WiFi AP. These high density environments are suffering from a high collision probability because of the large number of contending transmitters. Since the distance between the STAs and their APs is short, the achieved SINR is normally advantageous.

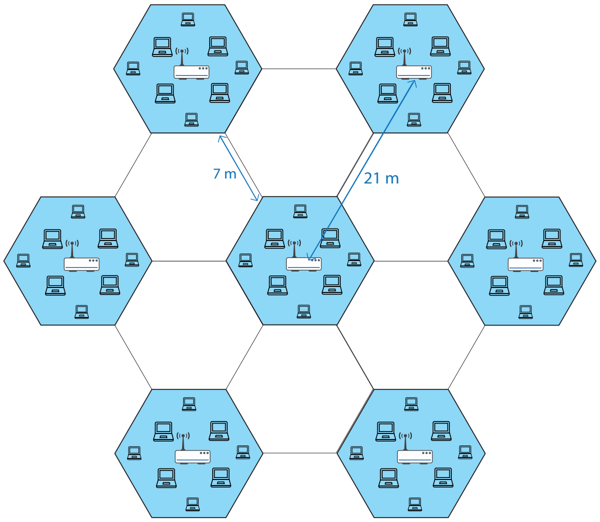

Fig. 3: Simulated network topology

In these situations, the spatial reuse is efficiently assured by a PCS adaptation as proved in [2]. However, because of the high probability of collisions between the contending transmitters, the implemented rate control algorithms will decrease their MCSs depriving the network from the possible performance improvement targeted by the PCS adaptation.

To cope with that situation, the PCS adaptation is followed by an update of the MCS list used by the rate control algorithm to prevent it from using unwanted MCSs. Once an MCS is banned, it will not be considered again until a new PCS adaptation allows it. This solution proved its efficiency by improving the performance of the network as will be shown in the sequel.

VII. Simulation Evaluation

A. Simulation setup

OPNET modeler [13] is used in this work to evaluate the performance of the proposed rate control scheme. OPNET is a well-known packet level simulator widely used in the literature. The latest standard WLAN model in OPNET is modified as follows. The rate control algorithm described in [5] is implemented. Since the basic error estimation model used in OPNET's WLAN model is not precise due to its severe abstraction, it was replaced by an implementation of a more competent model already used in Network-Simulator-3 (NS-3) [14] and that was initially described in [15]. Beside that, the PCS adaptation technique described earlier in this paper was incorporated in the WLAN model of OPNET. Accordingly, related attributes and statistics were added to assure correct operation and collect significant results.

Table I lists the most important simulation system parameters. In the simulated scenario, 7 WLANs are deployed in an hexagonal topology shown in Fig. 3. All the shown networks operate on the same frequency channel, *i.e.* $5.180\ GHz$. The topology applies a frequency reuse of 3, note that the WLANs using other channels are neither shown in Fig. 3 nor simulated because the adjacent channel interference is out of scope of this work. With this frequency reuse (*i.e.* cluster of 3) and a cell radius set to 7 meters, the distance between two co-channel APs is about 21 meters.

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 (AMSDU) max size	3839 Bytes
Aggregate MAC Protocol Data Unit (AMPDU) max size	8191 Bytes
Up Link Traffic (UL)	full buffer
Down Link Traffic (DL)	full buffer
Packet inter-arrival time	exponential
Default transmit power	15 dBm
Default physical carrier sensing threshold (PCS_{th})	-82 dBm
Simulation duration	3 min

All the nodes have the IEEE 802.11n [3] at their PHY and MAC layers. No channel bonding is permitted, so all the communications are performed on a 20 MHz channel. Each node is equipped with one single antenna, this means that 8 MCSs are possible. Both aggregation schemes are activated and the maximum aggregated data unit sizes are set to their standard default values shown in Table I. Each Station (STA) initiates an Up-Link (UL) saturated Used Datagram Protocol (UDP) flow towards its AP. On the other hand, each AP sends a Down-Link (DL) saturated UDP flow towards each one of its associated STAs. The packet size is auto-calculated by the simulator and the inter-arrival time is drawn from an exponential distribution. All the traffic flows start at $t1 = 40$ sec, the time interval before $t1$ is left for association and other initialization processes. Note that only "*data*" packets are collected via the simulation statistics to plot the throughput.

B. Results

Many simulation runs are performed, in each of which the MCS list used by the rate control algorithm is modified. Actually, the first run "*MCS All*" represents the normal operation of the rate control scheme, where all the supported MCSs are possible. This run will serve as a reference to deduce the gain when applying the proposed solution. The throughput received by each node is collected and the aggregated value is plotted with respect to time in Fig. 4. As shown in this figure, each simulation run is divided into 3 stages. In the first stage ($Time < t1$) there is no traffic generated by the flows, this stage is meant to be the initialization stage. The traffic is initiated at $t1$ but no PCS adaptation is performed until $t2$. However, in this stage ($t1 \leq Time < t2$), the aggregate throughput is shown for different MCS list configurations. The aim of showing this stage is to highlight the effect of PCS adaptation on the rate control, and hence to bring to light the efficiency of the carrier sensing-aware rate control proposed in this work.

The aggregate throughput is increased up to 260% with the proposed adaptation scheme. It is worth noticing the worst case is when all the supported MCSs are allowed (*i.e.* "*MCS All*"). The scenario "*MCS 5-7*" where only the MCSs of index 5, 6 and 7 are used is the best performing scenario in terms of aggregate throughput. Certainly, the set of MCS performing the best depends on many criteria, one of them is topology. Accordingly, for other topologies we may have a different

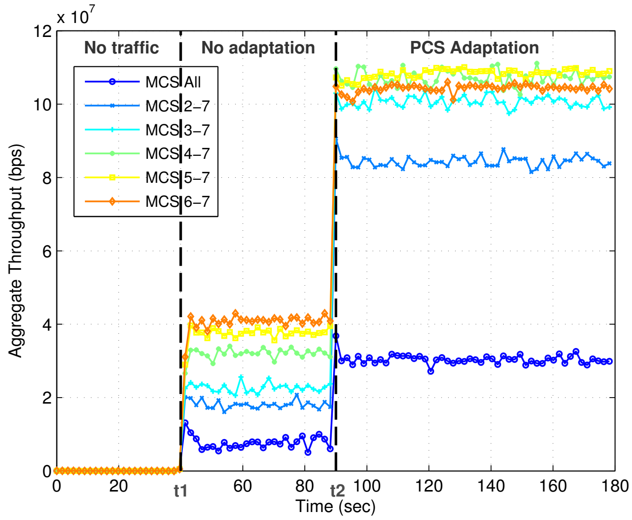

Fig. 4: Aggregate throughput performance

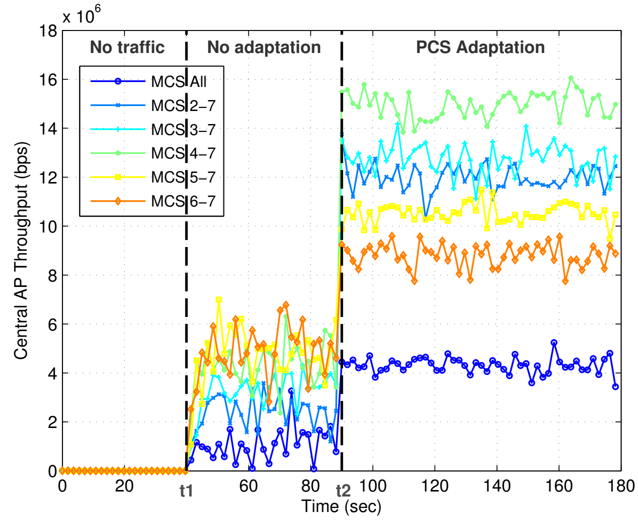

Fig. 5: Central AP achieved throughput

MCS set that brings the maximum aggregate throughput. An important thing to notice in Fig. 4 is the difference in maximum aggregate throughput achieved in the situation where no PCS adaptation is applied ($t1 \leq Time < t2$) and the other one where it is applied ($Time > t2$). Although, the PCS adaptation is not sufficient alone because the provided spatial reuse is neutralized by the unnecessary MCS downshifts performed by the rate control mechanism. By limiting the used MCS set, as previously described, knowing that after the PCS adaptation a certain minimum SINR is almost always achieved, the network will highly benefit from the additional spatial reuse.

The aggregate throughput only tells half the story. It is interesting to take a look at the worst case receiver represented by the central AP in the simulated topology (Fig. 3). This AP belonging to the central WLAN experiences the greater amount of interference from the surrounding WLANs. Fig. 5 plots the total throughput received by this AP in terms of time. The same previously described logic of simulation stages is applied here. In spite of the bad situation of this AP, the achieved gain in the adaptation stage ($Time > t2$) is almost the same gain brought to the aggregate throughput. While the highest aggregate throughput is achieved with the MCS configuration *"MCS 5-7"*, for the central AP the best MCS configuration is the*"MCS 4-7"*. This is due to the fact that this AP is the receiver the most exposed to the interference and hence a more robust MCS (*i.e.* MCS 4) enhances the achieved throughput.

VIII. Conclusion and Perspectives

This paper shows that achieving more spatial reuse in high density WLANs is more efficient with an adaptive rate control algorithm. The latter is able to benefit from the variety of the modulation and coding schemes defined in the standard. However, in dense environments, due to unnecessary decrements in the transmission bit rate, the currently adopted rate control schemes do not achieve the best performance. To cope with this problem, this work proposes a carrier sensing-aware rate control mechanism that adapts the minimum used bit rate following a physical carrier sensing adaptation. Simulation results show that the proposed scheme is able to achieve a gain of 260% in the perceived throughput.

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