Adaptive Transmit Power for Wi-Fi Dense Deployments

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***Abstract*—The increasing commercial success of Wi-Fi and the wireless communication industry forecast of exponential traffic growth for the next years indicate Wi-Fi dense deployments as scenarios more and more common in the future. Wi-Fi was not designed to operate in such scenarios. Because of its contention based channel access and backoff procedure, Wi-Fi presents low channel access efficiency and sensible performance degradation in terms of user throughput for dense deployments. This paper discusses the challenges of Wi-Fi operation in dense deployment scenarios and the benefits of a proposed adaptive transmit power mechanism. Wi-Fi performance is assessed by standard compliant simulations.**

Keywords*—*Wi-Fi, dense deployment, channel reuse.

I. Introduction

The demand for wireless broadband access to Internet has increased rapidly, and the proliferation of high data rate and new wireless devices leads to the forecast of exponential traffic growth for the next years [1]. Some analyses foresee, for instance, a bandwidth shortage of 275 MHz in the United States by 2014 [2]. In this context of scarce radio spectrum, the IEEE 802.11 standard for Wireless Local Area Networks (WLANs), known as Wi-Fi, has been broadly adopted. The easy and low cost deployment explains Wi-Fi increasing commercial success in residential and enterprise markets.

Wi-Fi operates in unlicensed frequency bands, as 2.4 GHz and 5 GHz, and is characterized by unplanned deployments. Wi-Fi default channel access mode is the Distributed Coordination Function (DCF). DCF implements a contention based channel access with the protocol Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA). In DCF mode, any Wi-Fi node, an Access Point (AP) or a user station (STA), listens to the channel before transmitting. This procedure is called Clear Channel Assessment (CCA). If the channel is sensed as vacant, i.e. the measured interference power is below a given threshold, then the node is able to transmit. Otherwise, when impacted by interference levels above the CCA threshold, Wi-Fi nodes defer transmissions for a random time in order to avoid transmission collisions. This is the backoff procedure.

The popularization of Wi-Fi is giving rise to scenarios with high density of communication nodes. In office or residential buildings, it becomes more and more common the operation of several uncoordinated Wi-Fi networks with overlapping coverage. Wi-Fi was not originally designed for such so called Overlapping Basic Service Sets (OBSSs) scenarios, where some STAs are under the coverage of multiple APs and the probability of transmission collisions is increased. With the increasing number of concurrent Wi-Fi nodes, conventional CCA and backoff procedures lead to channel access efficiency loss and sensible throughput degradation. In 802.11h and 802.11n standards, mechanisms as the Channel Switch Announcement are used to avoid that OBSSs operate in the same channel. Several approaches of same channel operation avoidance are available in the literature, for instance [3]. However, in case of dense Wi-Fi deployment, co-channel operation may be unavoidable.

Recognizing the need for improvement of Wi-Fi efficiency in real-world dense scenarios, the IEEE has recently created a new study group, the IEEE 802.11 High Efficiency WLAN (HEW) [4]. Dense networks with large number of APs and STAs are among the scenarios of interest. HEW aims to achieve substantial increase in data throughput per user in the considered scenarios. It specifically seeks for spatial capacity increase through physical layer (PHY) and/or Media Access Control (MAC) layer enhancements to the existing IEEE 802.11 standard. Some techniques can be considered for the improvement of spatial capacity and consequent data throughput per user. Besides antenna sectorization for OBSS mitigation and channel selection (frequency selective transmission), adaptive transmit power appears as a possible solution.

Transmit power control (TPC) for wireless networks is a consolidate research area, with foundation dating from the early 1990's with distributed power control for cellular networks [5], [6]. TPC for WLAN is also present in the literature, for instance [7]. Specifically for dense deployment scenarios, [8] presents a TPC approach where not only the transmit powers but also the CCA threshold is adapted in a BSS basis, i.e. AP and associated STAs in a BSS use the same transmit power and CCA threshold.

Wi-Fi standard (IEEE 802.11h) has support to a TPC procedure designated to satisfy regulatory requirements regarding the maximum interference generated by Wi-Fi in the 5 GHz band in Europe. This is related to the protection of satellite services. In spite of this TPC usage, Wi-Fi network operation conventionally has all nodes transmitting with the maximum power. This setup has the benefit of decreasing the probability of occurrence of the well known hidden node problem [9]. However, especially in dense deployments, maximum power transmissions lead to poor spatial reuse and poor data throughput per user, since they suppress other potential transmissions that could not cause harmful interference.

This paper addresses the use of adaptive transmit powers as a simple and effective measure for the improvement of Wi-Fi spatial capacity in dense deployments. Such scenarios are challenging because some STAs can be placed on the overlapping coverage area of two or more BSSs, and these BSSs have no coordination among them. Therefore, taking into account the lack of coordination among OBSSs and having in mind not to increase the signaling overhead, a mechanism to adapt the transmit power in Wi-Fi networks should be as simple as possible. With the support of standard compliant simulations, it is shown that an adaptive transmit power mechanism[1] that defines appropriate (reduced) transmit powers significantly improves Wi-Fi spatial reuse and capacity.

This paper is organized as follows. In Section II the Wi-Fi simulation model is presented, including PHY/MAC models, channel model and deployment scenarios. Section III presents the challenges of Wi-Fi dense deployments and a simple adaptive transmit power mechanism. Section IV shows the simulation results and discusses the benefits of reduced transmit powers to Wi-Fi performance in dense deployments. Section V gives the conclusions of this work.

II. Wi-Fi Simulation Model

A system level simulator developed in Matlab® is used to assess the Wi-Fi network performance. The simulator models standard compliant IEEE 802.11 (Wi-Fi) multi-user radio network, including modeling of the network layout, APs and STAs spatial distribution, radio environment, PHY and MAC layers, and traffic generation.

A. PHY/MAC Models

Wi-Fi PHY transmission is based on the Orthogonal Frequency Division Multiplexing (OFDM). The frequency resolution used in the simulator is 625 kHz.

The Distributed Coordination Function (DCF) is adopted as the basic 802.11 MAC protocol in the simulator. DCF uses the CSMA/CA mechanism, where each Wi-Fi node senses the channel to determine if it is occupied or available. In case of channel detected as occupied, the node starts a random backoff time interval. After the backoff interval, the channel is sensed again and, if it is available, the node starts the packet transmission, otherwise, the node starts an increased backoff time interval. In accordance with IEEE 802.11 standard, the power threshold for channel availability detection is -82 dBm for Wi-Fi interfering transmissions, i.e. if the measured interference is below this threshold the channel is detected as available. Acknowledge (ACK) signaling and retransmission in case of packet reception error are considered in the model. Link adaptation chooses the Modulation and Coding Scheme (MCS) for each communication link according to the last Signal-to-Interference-plus-Noise Ratio (SINR) evaluated at this link. Figure 1 shows the SINR to MCS mapping used in the simulator. Table I summarizes the main Wi-Fi MAC/PHY parameters adopted.

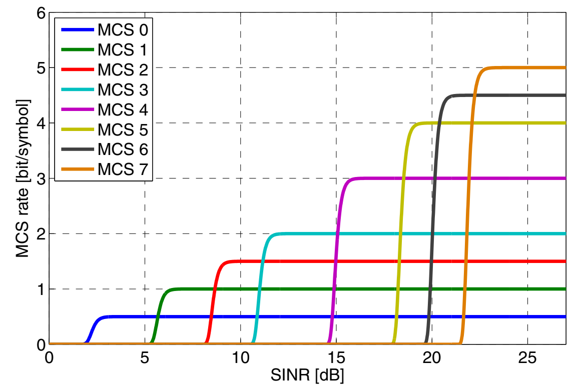


Fig. 1. SINR to MCS mapping.

TABLE I. PHY/MAC Parameters

Parameter	Value or description
Transmission scheme	OFDM
Frequency resolution	625.0 kHz
MAC protocol	DCF (CSMA/CA)
SIFS time period	16 μs
DIFS time period	32 μs
Initial Contention Window (CW) size	15 time slot intervals
Maximum CW size	1023 time slot intervals
Channel availability detection threshold	-82 dBm
Link adaptation method	SINR-based

B. Deployment Scenarios and Channel Model

The simulations performed in this work assume an indoor office environment composed of 20 single floor rooms with 10 m $\times$ 10 m area and 3 m height each room. The rooms are arranged on 2 rows with 10 rooms each, as illustrated in Figure 2.

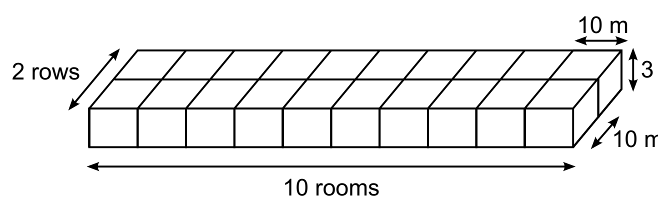


Fig. 2. Single floor office scenario: 2 rows, 10 rooms per row.

Wi-Fi frequency of operation is 5 GHz and channel bandwidth is 20 MHz. Path loss and shadowing are modeled according to TGac indoor propagation model [11], while Rayleigh fading represents multipath propagation effects over transmitted signals. The main parameters of the channel model are described in Table II.

In the simulation, a number of APs is randomly distributed among the rooms. No more than one AP is placed in a room. STAs are distributed in the rooms served by APs and are assigned to the best-serving AP. The scenarios evaluated have

[1]Other mechanisms can be used, in combination with TPC or not, to protect transmissions from hidden nodes. The utilization of Wi-Fi signaling messages as the Request-To-Send (RTS) and Clear-To-Send (CTS) is an alternative, as explored in [10] and references therein.

TABLE II. CHANNEL MODEL PARAMETERS

Parameters	Value or description
Path loss model	TGac Indoor [11]
Breakpoint distance	5 m
Wall attenuation factor	5 dB
Lognormal shadowing	μ = 0 dB
	σ = 3 dB (before breakpoint)
	σ = 4 dB (after breakpoint)
Multipath fading	Rayleigh

4 or 10 APs and 10 or 25 STAs distributed in the single floor office. In this indoor environment, low heights are assumed for both APs and STAs, and full buffer data traffic is considered. The maximum transmit power level is 20 dBm. Table III summarizes the simulation parameters.

TABLE III. SIMULATION PARAMETERS

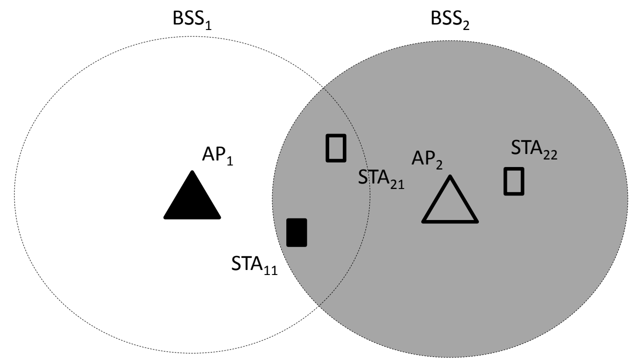
Parameter	Value or description
Scenario	Dual stripe single floor
System bandwidth	20 MHz
Operation frequency	5 GHz
Maximum transmission power	20 dBm
AP height	1.0 m
STA height	1.5 m
Number of APs in the office	4 or 10
Number of STAs in the office	10 or 25
Number of Tx/Rx antennas	1/1
Traffic type	Full-buffer data
Antenna type	Isotropic
Simulation step	8 μs
Simulation network time	2 s
Number of realizations	50

III. WI-FI DENSE DEPLOYMENT AND THE BENEFITS OF ADAPTIVE TRANSMIT POWER

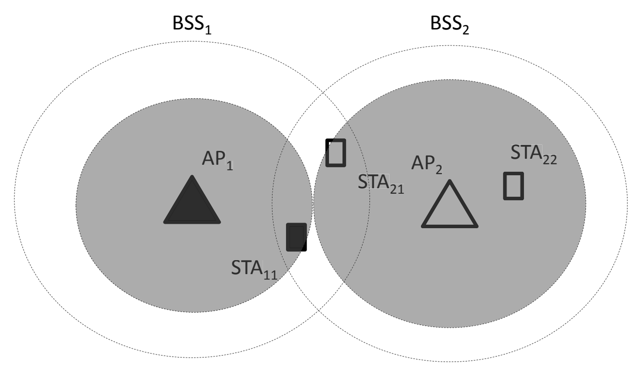
In conventional Wi-Fi operation, APs and STAs transmit with the maximum power, regardless the transmitter/receiver distance, propagation conditions, etc.. From the perspective of the transmitter/receiver communication link, maximum power transmission is not efficient. Except for a reduced number of scenarios where the maximum power is required to achieve a given QoS level (data throughput, error rate), reduced transmit powers are enough to achieve similar QoS levels, especially for short and medium distance links. Because of the limited set of MCSs, increasing the signal quality above a certain level does not provide performance gains in terms of user throughput. In other words, if the transmitter uses the highest MCS and the SINR at the receiver is appropriate for that MCS, increasing the transmit power and consequently the received SINR will not bring meaningful throughput gains, since the number of bits/symbol is not increased, as can be observed in Figure 1 for MCS7 and SINRs above 25 dB. Therefore, for a significant number of Wi-Fi transmissions the use of the maximum power leads to unnecessary high signal quality at the receiver and waste of transmitter's energy.

From the perspective of a network with multiple uncoordinated APs with overlapping coverage areas, i.e. a dense deployment scenario which becomes more common every day, maximum power Wi-Fi transmissions lead to poor spatial reuse. As mentioned, DCF operation mode is based on the CCA procedure, which determines a random waiting time (backoff) for the Wi-Fi node that detects the channel as occupied. With the increase of the number of communication nodes and the use of maximum transmit power, the number of transmission collisions naturally increases and DCF's performance in terms of throughput and latency is degraded, since backoff time increases when the channel is recurrently detected as occupied. This situation could be avoided with reduced power transmissions.

Figure 3 illustrates the Wi-Fi OBSS network behavior for a specific scenario with maximum (Figure 3(a)) and reduced (Figure 3(b)) power transmissions. For simplicity, only two OBSSs are considered. As shown in Figure 3(a), if AP_2 transmits for any of the two STAs associated to it, then BSS_1 transmissions are negatively impacted. STA_{11} transmission is blocked, since it is on the coverage of AP_2, which is currently transmitting. Also, if STA_{11} receives data from AP_1 during AP_2 transmission, this data reception can suffer from high packet error rate due to interference.



(a) Wi-Fi OBSS network with maximum power transmissions.



(b) Wi-Fi OBSS network with reduced power transmissions.

Fig. 3. Wi-Fi OBSS network behavior for a specific scenario.

Considering the same scenario, but with the use of reduced transmit powers, Figure 3(b) shows that parallel transmissions are possible. If AP_2 transmits for any of the two STAs associated to it with reduced power, then STA_{11} transmission can be possible, since the interference perceived by STA_{11} can be low enough to the CCA procedure determine the channel as available. Also, in case of STA_{11} receiving data from AP_1 during AP_2 transmission, reduced interference causes less packet errors.

The scenario and situations discussed above are only samples of the potential benefits that reduced power transmissions can provide to Wi-Fi OBSS networks. The performance gains will depend on the mechanism of transmit power adaptation and the spatial configuration of Wi-Fi nodes.

A. Transmit Power Adaptation Mechanism

In a conventional Wi-Fi operation, the transmitter uses Channel State Information (CSI) acquired from previous transmissions to adjust the next transmission parameters according to the experienced channel or network conditions. Transmit power is fixed, but link adaptation chooses the MCS according to the SINR previously perceived and reported by the receiver. Fig. 1 exemplifies the SINR to MCS mapping used for link adaptation.

The proposal for transmit power adaptation does not impact the link adaptation decision. Regardless the MCS chosen by link adaptation, instead of transmitting at the maximum power, the transmit power is set to the minimum level required to use the highest feasible MCS. From feasible MCS one must understand the one for which the minimum required SINR is achievable with transmit powers lower than or equal to the maximum transmit power. This is a useful approach for short and medium AP-STA distances, since unnecessarily high energy spent and interference generation are avoided, while still keeping the transmit power and the SINR at the receiver at appropriate levels.

The mechanism for transmit power adaptation is now described in more detail. The CSI acquired from previous transmissions provides information on the SINR at the receiver. SINR is given in dB by the expression below:

$$SINR = P_{T_x} + G - P_{I+N}, \quad (1)$$

where P_{T_x} and P_{I+N} are respectively the transmit power and the interference plus noise power (in decibel scale), and G is the transmitter/receiver channel gain (path loss plus shadowing effects) in dB. It is clear from (1) that increasing/decreasing the transmit power P_{T_x} in "x" dB produces the same effect in the SINR (considering channel and interference conditions static). Then, the transmitter is able to estimate how much increase/decrease on its transmit power will be needed to achieve a certain SINR at the receiver, since it has information on the previous SINR and own transmit power.

This ability to estimate the transmit power needed to achieve a certain SINR at the receiver allows the transmitter to determine the minimum transmit power level required to use the highest feasible MCS. The SINR to MCS mapping used by link adaptation defines the minimum required SINR to each MCS (see Fig. 1). Then, the proposed mechanism consists in the following steps:

1) Get from the SINR to MCS mapping the minimum SINR required to use the highest MCS. This is the target SINR, $SINR_t$;
2) Compare $SINR_t$ with the available estimate of SINR at the receiver, and determine the transmit power needed to achieve $SINR_t$ at the receiver.
3) If it is a feasible power (lower than or equal to the maximum power), then set the transmit power to this value; else, repeat Step 1 and Step 2 for the highest MCS immediately below.

This procedure is repeated until a feasible transmit power is reached for a given MCS. If even the lowest MCS requires an SINR not achievable, then the lowest MCS is adopted with the maximum power. This adaptive transmit power mechanism leads to significant Wi-Fi performance improvement in dense deployments when compared to conventional maximum power transmissions, as results in next section demonstrate.

IV. Simulation Results and Discussion

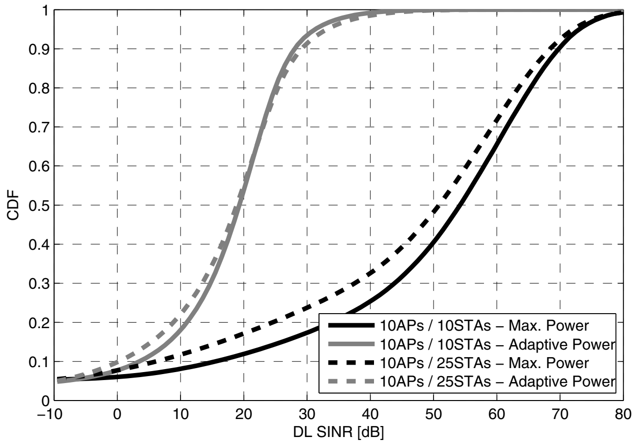
This section presents the simulation results for Wi-Fi dense deployment networks. Wi-Fi network modeling and scenarios are described in Section II. Some discussions in Section III are now enriched with simulation results.

To illustrate the fact that maximum power Wi-Fi transmissions lead to unnecessary high signal quality, Figure 4 shows the Cumulative Distribution Function (CDF) of the SINR for the 10 AP deployment. Curves obtained with maximum power and adaptive power transmissions are shown for scenarios with 10 and 25 STAs. The CDFs of downlink and uplink SINR are shown in Figures 4(a) and 4(b), respectively, and present similar values.

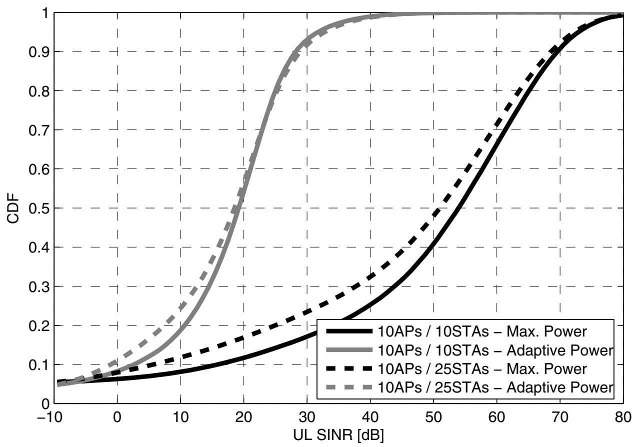
As expected, regardless the transmit power mode, increasing the number of STAs in the network leads to higher interference, which is reflected in the lower SINRs observed for 25 STA scenarios when compared to 10 STA scenarios. However, the aspect to be highlighted is the unnecessary high signal quality level achieved with maximum power transmissions. From the SINR to MCS mapping in Figure 1, it can be concluded that SINRs above a certain level, e.g. 25 dB, do not bring throughput gains. For both downlink and uplink transmissions, it is shown in Figures 4(a) and 4(b) that at least 80% of SINRs is above 25 dB for maximum power Wi-Fi transmissions. In contrast, when the proposed adaptive power mechanism is adopted, little energy is wasted with unnecessary high SINR, since only a small percentage of SINRs is above 25 dB.

Besides the energy save aspect, reduced transmit powers enable parallel transmissions in different BSSs. Figure 5 helps this understanding by showing the Probability Density Function (PDF) of MCS usage for uplink transmission in the 10 AP / 25 STA scenario (other scenarios present similar behavior). For a single BSS scenario (one AP and its associated STAs), the MCS usage with maximum power and adaptive power transmissions would be basically the same, since the adaptive power mechanism has as first target the use of the highest feasible MCS. However, the results for multiple neighboring BSSs shown in Figure 5 indicate different MCS usages. While the highest MCS has 80% probability of use for maximum power Wi-Fi transmissions, when the proposed mechanism is adopted the MCS usage is more distributed among intermediate MCSs. The reason for this behavior is that while maximum power transmissions block most potential parallel transmissions, guaranteeing high SINRs for a few concurrent links, reduced power transmissions allow more parallel transmissions with lower SINRs and MCSs, since the higher aggregate interference makes the highest MCSs infeasible.

It is important to evaluate if the trade-off stated as higher number of parallel Wi-Fi transmissions versus transmissions



(a) Downlink SINR.



(b) Uplink SINR.

Fig. 4. Cumulative distribution function of the SINR for the 10 AP Wi-Fi deployment.

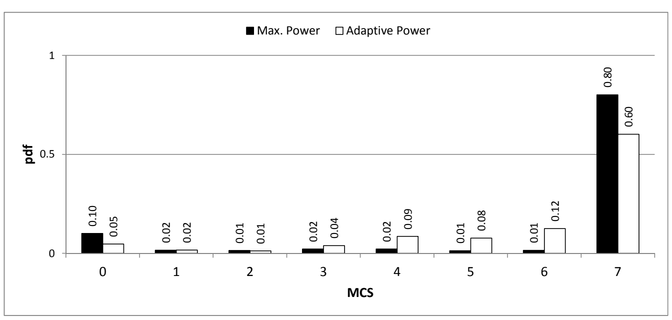


Fig. 5. Probability density function of the MCS usage for the 10 AP / 25 STA scenario.

with lower data rates (lower MCSs) is worthy. The first aspect to be considered is the net transmission/reception time per user, which gives an indication of channel access time efficiency. Figure 6 shows the mean percentage of time the user is transmitting or receiving data for all scenarios described in Section II. The remaining time is spent with signaling or wasted with backoff.

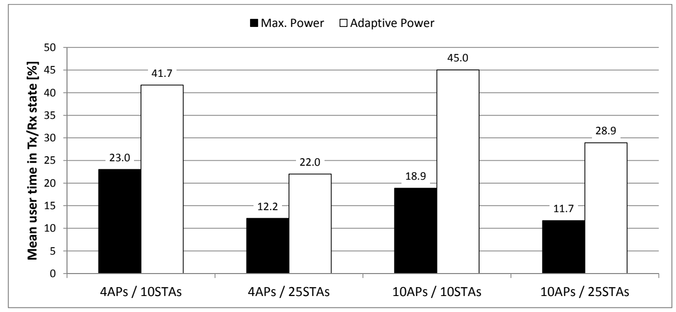


Fig. 6. Mean net transmission/reception time per user for multiple BSS scenarios.

As general remark, it is observed a poor channel access efficiency for maximum power Wi-Fi transmissions. No more than 23% of Wi-Fi node time is effectively used for data transmission or reception in the considered scenarios. Also, regardless the transmit power mode, increasing the number of STAs in the network strongly reduces the channel access efficiency, since the number of same BSS nodes contending for the channel increases, and consequently the number of transmission attempts and collisions too. On the other hand, the comparison between maximum power and adaptive power Wi-Fi transmissions reveals that the use of reduced transmit powers and the consequent higher number of parallel transmissions improves the mean channel access efficiency per user. For 4 AP deployments, the net transmission/reception time percentage per user is around 1.8x higher with adaptive transmit power for both 10 and 25 STA scenarios. For 10 AP deployments, it is around 2.4x higher than for maximum power Wi-Fi transmissions.

Although the enhanced mean channel usage time per user, the more numerous parallel transmissions enabled with reduced transmit powers lead to lower data rates. The ultimate metric to evaluate the effectiveness of the proposed adaptive transmit power mechanism for Wi-Fi in the considered OBSS scenarios is the data throughput. Figure 7 shows the mean throughput per user for all scenarios described in Section II. The behavior of throughput is shown to be similar to the net transmission/reception time in Figure 6, with significant gains being obtained with the adoption of adaptive transmit power. For 4 AP deployments, where the OBSS interference is moderate, the mean throughput gains for 10 and 25 STA scenarios are, respectively, 70% and 66%. For higher density deployments like the considered 10 AP scenarios, the mean throughput gains achieve approximately 113% and 138% for 10 and 25 STAs, respectively.

As a final evaluation of adaptive transmit power benefits for Wi-Fi dense deployments, Figure 8 illustrates the 10^{th} percentile throughput per user for all scenarios described in Section II. It is important to note that expressive throughput gains are also observed for less favored users, especially for the most interfered scenarios with 10 APs.

V. CONCLUSIONS

The commercial success of Wi-Fi makes dense deployment scenarios more common every day. Wi-Fi is recognized to

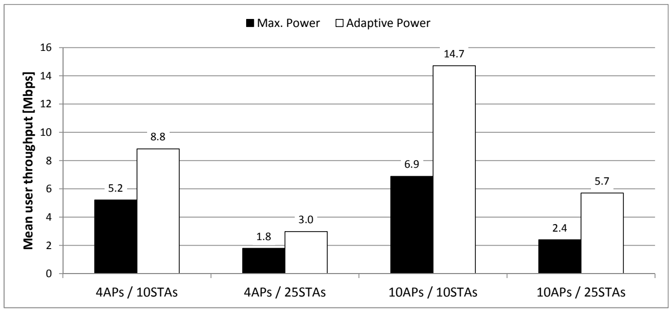


Fig. 7. Mean user throughput for multiple BSS scenarios.

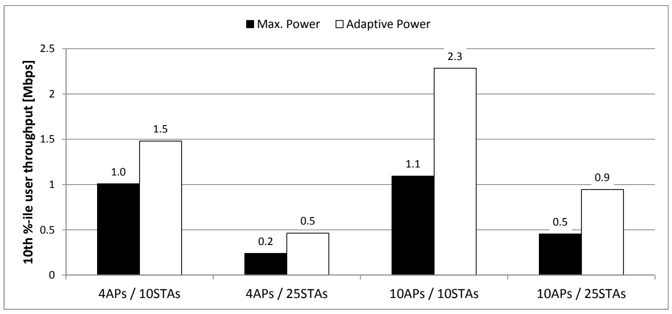


Fig. 8. 10th percentile user throughput per user for multiple BSS scenarios.

present inefficient channel usage and low spatial capacity in such scenarios, resulting in low user throughput. This paper discusses the benefits that adaptive (reduced) transmit power can provide to Wi-Fi in dense deployments. Besides the energy save, reduced transmit powers allow more concurrent transmissions in Wi-Fi networks with multiple uncoordinated APs. These simultaneous transmissions have lower data rate, but it is shown by simulations that the increased spatial reuse with reduced power transmissions compensates this fact, and significant throughput gains per user can be obtained with the implementation of the proposed adaptive transmit power mechanism for Wi-Fi dense deployments.

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