Effect of propagation environment on area throughput of dense WLAN deployments

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Abstract—**Indoor wireless LAN deployments have become ubiquitous. As WLAN deployments become increasingly dense, WLANs start to cause more and more contention and interference to each other, to the point that they cause significant throughput degradation to other WLANs. Since WLANs are one of the most commonplace solutions to provide indoor broadband data access, it is crucial to assess the throughput limits of WLANs in order to understand at what demand level novel broadband access mechanisms will be critically needed. The amount of contention and interference that coexisting WLANs create on each other is influenced by the indoor propagation environment such as existence of walls or clutter. Although the indoor propagation environment has a significant impact on the interaction between WLANs, and consequently on the area throughput, the relationship between the indoor propagation environment and achievable area throughput has not received much attention. In this paper, we investigate the area throughput of densely deployed WLANs in different indoor propagation environments by conducting detailed MAC layer simulations using OPNET. The results show that the propagation conditions have a profound impact on achievable area throughput; as much as several tens of times increase in highly cluttered environments compared to open areas.**

I. Introduction

Wireless LANs provide a practical replacement for wired connections in typical home and office networking scenarios. As a consequence, WLANs based on IEEE 802.11 standards, which are commonly called Wi-Fi networks, have become ubiquitous. So, it is fairly common for a given area to be covered by more than one WLAN in urban areas. For example, [1] reports that in a WLAN survey near King's Cross station in London in 2009, the node density was measured to be 749 per km^2 on a single channel. A more recent measurement study [2] which is conducted in Cologne in 2012 reports an access point density of 6103 per km^2 on all channels in 2.4 GHz band.

In addition to the denser deployment of WLANs, data usage per WLAN user is increasing due to popular Internet services such as cloud storage and video streaming. As a result, a situation in which there are many WLANs deployed in close proximity of each other, all of them simultaneously trying to deliver as much data as possible, becomes fairly probable. Yet another interesting application of WLANs is that they can be used for cellular offloading, i.e., the cellular network traffic generated indoors could be served over WLANs to relieve the cellular network of the high load. In this respect, WLANs compete as a technical solution with LTE femtocells.

For the reasons mentioned above, it is crucial to understand the outcome of increasing WLAN densities and usage on the performance of these WLANs. However, this outcome is not trivial to predict because WLANs interact in complex ways; competing other WLANs for access to the shared wireless medium as well as creating interference on other WLANs' signals, thereby causing more packet errors. This complexity is compounded by the highly asymmetric interference environment created indoors by walls and other objects. In view of this observation, we investigate the throughput limits of WLANs when a large number of WLANs are deployed in an area and all of them are trying to deliver as much data as possible at the same time.

The WLAN throughput in high load condition when all nodes always have packets in their buffers to transmit, which is also called *saturation throughput*, has been studied extensively by theoretical analysis and simulations [3]–[5] as well as measurements [6]. A theoretical model to estimate the saturation throughput of stations (STAs) operating in 802.11 distributed coordination function (DCF) under the assumption that collision probabilities are independent of the number of retransmissions, and that there are no hidden terminals or packet capture is provided in [3]. Later publications extended the results in [3] in different directions; e.g. [4] analyzed the throughput under high load by taking into account the effects of a Rayleigh fading channel and packet capture, [5] analyzed the throughput of 802.11 EDCF, which is a QoS oriented MAC mechanism. However, most of the literature on saturation throughput analysis, including those we have mentioned above, have been limited to a single WLAN. Throughput analysis of dense WLANs cannot be predicted by simply extrapolating from single-cell analysis results due to the complex interaction of transmitting nodes via the DCF function.

Approaches used in throughput analysis of multiple coexisting WLANs can be theoretical analysis oriented, e.g. [7], [8] or simulation oriented, e.g. [9]–[11]. The theoretical results can be applied to a large range of WLAN densities, but they mostly include highly simplifying assumptions which tend to turn the results less accurate. The analysis in [7] follows from [3]; it proposes a method which predicts the throughput of a multi-cell WLAN when the nodes have full buffers, taking into account co-channel and adjacent channel interference. However, it assumes that all transmitting STAs in a co-channel interference environment have the same transmission probability, which may not hold in an asymmetrical interference environment created by walls. In [8] the authors consider the throughput of multiple coexisting WLANs when nodes have full buffers. They consider the case in which the distance between an access point (AP) and STA is much shorter than the carrier sensing range, and transmissions that take place at a distance smaller than carrier sensing range are error-free. However, these assumptions would not hold in a propagation environment containing many walls and clutter. A combined theoretical and simulation analysis is provided in [11] for only two WLANs. However, the assumptions such as all transmissions in one WLAN being perceived as collisions by nodes in the other WLAN, and no hidden nodes are not realistic.

Another set of theoretical analyses used in literature in order to estimate the aggregate throughput of multiple nodes operating in a CSMA system is stochastic geometry based approaches, for example [12]–[14]. While a useful analysis approach to estimate the theoretical upper bound of throughput of CSMA systems, stochastic geometry based analyses typically focus on the calculation of concurrent transmitters, therefore they ignore the node interactions via the DCF function such as the significant EIFS after a collision. Furthermore, stochastic geometry based approaches typically assume a homogeneous propagation environment, thus ignoring the assymetrical interference environment in indoor deployments caused by walls and other objects. The data rate model in these analyses also tend to be simplistic, ignoring the physical layer details.

In contrast to theoretical approaches, simulation results are more accurate but they tend to be limited in their scope of investigated WLAN densities. A multi-cell WLAN system is analyzed from a coverage point of view in [9], which investigates the minimum AP density required to provide a continuous WLAN coverage in an area. Hence, in their throughput calculations, they use a fairly low density of 30 APs in a 100m $\times$ 100m area. In [10], the authors consider the saturation throughput of three DCF variants in multiple coexisting WLANs. In their analysis, at most 50 WLANs interact on partially overlapping channels, and the AP ranges considered are in the order of 100 m, therefore their analysis does not apply to a dense WLAN deployment.

The shortcomings of analytical approaches and the existing simulation studies we mentioned above highlight the usefulness of a simulation study of the 802.11 MAC performance in dense WLAN deployment scenarios. So, in this paper, we investigate the limits of WLAN area throughput for indoor propagation environments using a realistic MAC model. In particular, our contributions are taking the asymmetrical propagation environment due to walls into account, and investigating very high WLAN densities by performing detailed MAC level simulations which take physical layer details and hidden nodes into account. We perform Monte Carlo simulations to produce estimates of the area throughput; we generate random WLAN topologies and random floor plans, and simulate the MAC layer transmissions using OPNET.

II. Models

In this section, we describe the node level models, network level models and other simplifying assumptions that we have used in our analysis.

A. Network model

In our analysis, we assume that APs are deployed by users rather than wireless network engineers due to deployment cost reasons. We further assume that the users decide on AP locations based on convenience; e.g., they install an AP where there is a network plug or power outlet instead of the best position from the point of view of radio propagation. To model the effect of this deployment strategy, we place the APs randomly in the simulated environment. Although random WLAN deployment implies that the APs are not placed to maximize coverage, the STA positions are nevertheless generated within the coverage areas of their respective APs. We also note that random deployment will create a harsh interference environment, therefore the area throughput results of randomly deployed WLANs will be conservative compared to WLANs of same density which are deployed in a planned way.

When calculating the area throughput, we consider the situation that all WLANs operate on the same channel. We do not consider adjacent channel interference or use of partially overlapping channels. Therefore, the interference coming from any WLAN transmission will be co-channel interference. This assumption aims to simplify the analysis. For the case of 802.11g WLANs, if we consider that there can be three non-overlapping channels, then the area throughput of a dense WLAN deployment using 3 non-overlapping channels provided by the 2.4 GHz ISM band will be three times that of a single-channel deployment. We investigate a range of WLAN densities from 1 to 200 WLANs per channel in the 100 m $\times$ 100 m indoor environment. Considering that the same WLAN deployment density exists on three non-overlapping channels, this corresponds to a maximum density of 600 WLANs in the 100 m $\times$ 100 m area, which amounts to 16.7 m^2 per WLAN in average

We create synthetic floor plans for an indoor environment of 100 m $\times$ 100 m size. In order to model different propagation environments with respect to wall attenuation, we generate three different types of floor plans. The first type of simulated environment has no walls, which can represent an open office space. The second and third types of indoor environments have 16 large rooms and 256 smaller rooms of random sizes respectively, which correspond to a moderate wall density and high wall density. Example WLAN deployments and floor plans are illustrated in fig. 1.

B. Propagation model

To model the attenuation of the transmitted signal in the wireless medium, we use a propagation model which

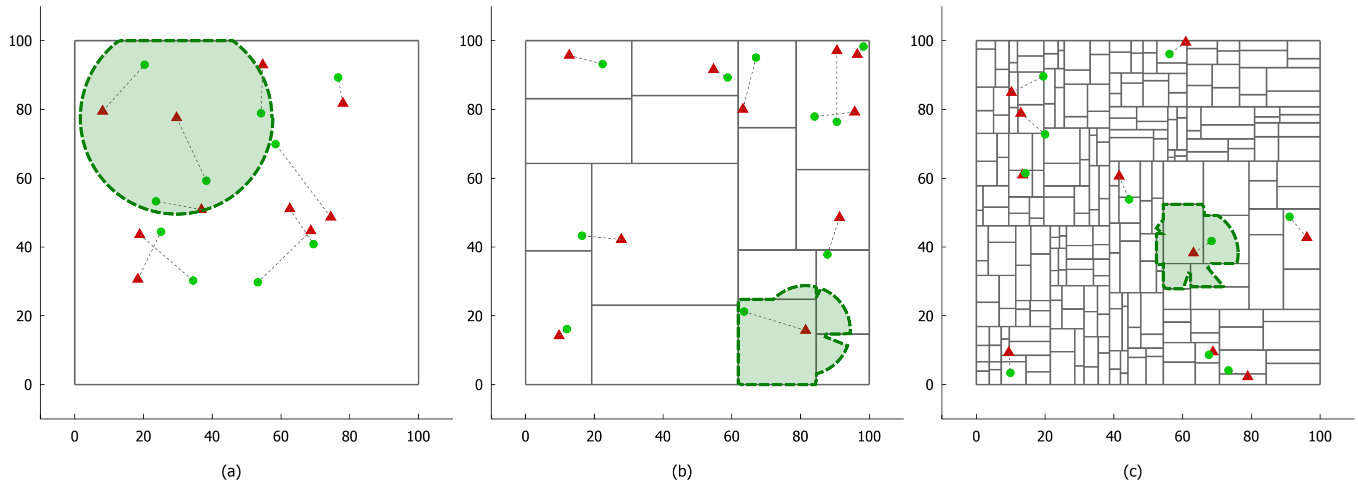

Fig. 1. Example network topologies and floor plans containing 10 links. AP–STA pairs are represented by a connected triangle and circle. For all figures, transmit power is 100 mW, pathloss exponent is 3, the 54 Mbps coverage range of an example AP is highlighted. (a) Open area. (b) Moderate wall density: 16 rooms. (c) High wall density: 256 rooms.

is based on [15]. We assume that the received power decays exponentially as distance from the transmitter increases, and each wall that lies along the propagation path attenuates the signal by a constant factor. We model the received power P_r as:

$$P_r = \frac{P_0}{d^\alpha \cdot W^k} = [P_0]_{\mathrm{dB}} - \alpha \cdot [d]_{\mathrm{dB}} - k \cdot [W]_{\mathrm{dB}} \qquad (1)$$

where P_0 is the reference received power at 1 m calculated according to free space propagation, α is the pathloss exponent, $W = 10$ dB is the constant wall attenuation factor and k is the number of wall crossings on the path from the transmitter to the receiver. Attenuation may be little or severe, depending on the amount of clutter in the indoor environment. We model this by using different pathloss exponents of 2 and 3. For simplicity, we assume wall attenuation to be the same for all walls in the indoor environment.

C. Node models

We model all APs and STAs to be using 802.11 ERP-OFDM physical layer; data packets are transmitted at 54 Mbps whereas ACK packets are transmitted at 24 Mbps because this is the highest rate in the mandatory rate set of ERP PHY. Since all nodes use the ERP-OFDM PHY, we assume that they use the short (9 μs) slot time. We model the bit error rate (BER) as a function of the received SNR such that such that, for 1500 octet packets, the resulting packet error rate (PER) drops below 1% when the received SNR is greater than 27 dB. In our receiver model, when a single transmitter with full buffer is transmitting 1500 octet packets, the link throughput reaches a maximum of 30 Mbps for SNR values greater than 27 dB. Note that the maximum throughput of a single link is considerably lower than the data rate of the link, which is a well-known result [16]. In order to find the saturation throughput when all transmissions are made using the same data rate of 54 Mbps, we do not consider rate adaptation. We simulate different transmit powers levels (P_t), namely 100 mW and 25 mW in order to see the impact of transmit power levels on area throughput. As defined in [17], we use a clear channel assessment (CCA) threshold of –76 dBm, noise figure of 10 dB and implementation loss of 5 dB in our simulations. The thermal noise power in SINR calculations is taken to be –90.6 dBm. We define a transmitter's *coverage* such that a receiver can decode packets of 1500 octets sent at 54 Mbps with a PER less than 1% when only thermal noise is corrupting the received signal. The coverage range of an AP is illustrated in fig. 1 and fig. 2. In the simulations, we use a maximum retransmission count of 6, that is, a packet can be transmitted and retransmitted for a total of 7 times, after which the packet is discarded.

In order to investigate the throughput at high loads, we generate packets at the APs to be delivered to the STAs such that an AP always has packets in its buffer to transmit. This approach enables us to eliminate the impact of higher layers on the MAC layer throughput. We define *throughput* as the total number of bits delivered by the MAC layer to the higher layer in a station (STA) in unit time. Our throughput definition corresponds to the bits in the MAC service data unit (MSDU) of the MAC layer frame; the encapsulation overheads of the higher layers are included in the throughput calculations but the overhead due to the MAC and PHY layers, retransmissions by the transmitter or duplicate packets received by the receiver are not included in the throughput results. In order to investigate the limit of area throughput, we simulate transmissions of packets which are 1500 octets long, which is also the maximum payload size for Ethernet frames. As a limiting case, we only consider downlink traffic, and calculate downlink throughput in the following analysis. The uplink traffic consists solely of the ACK packets generated by the STAs.

The textbook analysis of random access systems such as

ALOHA or CSMA/CA implies that the full buffer condition is an unstable operating point for WLANs, and therefore the saturation throughput is expected to attain a lower value than the maximum throughput that the system can support for unsaturated loads. However, in the context of densely deployed WLANs, the saturation throughput has merit as a performance metric, as it represents the performance that can be expected from this system of WLANs in an overloaded condition due to densification. In other words, the saturation throughput represents the performance when all STAs in all WLANs try to pull as much data from the Internet as possible at the same time.

D. Node interactions in WLANs

In this analysis, we consider that each WLAN uses the basic access mode of DCF without the RTS/CTS frame exchange as defined in [17]. DCF dictates that all nodes listen for ongoing transmissions before they attempt to transmit a packet. In order to determine whether the wireless medium is busy or idle, the nodes which have a packet to transmit perform *clear channel assessment (CCA)*; if CCA indicates that the wireless medium is free, the node can attempt to transmit its packet, otherwise, if the CCA indicates a busy medium, the node postpones its transmission attempt, which is called the *backoff* procedure. Due to the attenuation of the transmitted power in the wireless medium, the nodes can sense transmissions from other nodes up to a certain distance, which can be called *CCA range* or *sensing range*.

Various different interactions between nodes in a dense WLAN deployment can influence transmission outcomes, thus throughput. A simple indoor environment which contains three WLANs and which is partitioned by walls is shown in fig. 2. In the figure, the CCA range of AP_1 includes AP_2. Therefore when AP_2 is transmitting, AP_1 will postpone its transmission, even though AP_1's transmission would be successful and would not have harmed AP_2's transmission due to the location of their respective receivers, which is called *exposed node problem*. Another example for the sort of node interactions that degrade throughput performance takes place when AP_1 eventually transmits a packet. Note that AP_2 is in the CCA range of AP_1. Since pathgains are reciprocal and we assume that transmit powers are equal, this means that AP_2 will be aware of a packet transmission from AP_1, and it will try to decode this packet. However, AP_2 does not have enough received power from AP_1 to decode the packet that AP_1 transmits at 54 Mbps. Therefore, the packet reception will be unsuccessful. Therefore, following the DCF rules after an unsuccessful packet reception, AP_1 will have to wait for an EIFS duration. The EIFS duration is fairly long; even longer than the time it takes to transmit a 1500 octet packet at 54 Mbps. Therefore such "overheard" unsuccessful packet receptions will cause significant transmission opportunity losses. Yet another problematic situation arises when AP_3 is not in the CCA range of AP_2, but it is close to the receiver of AP_2. In such a situation, both AP_2 and AP_3 may be transmitting at the same time, but AP_3's transmission may degrade the signal quality at STA_2, causing AP_2's packet to be corrupted, which is called *hidden node problem*. Other problematic situations can arise in the transmission of acknowledgement packets (ACKs) as well. Rules of DCF dictate that receiving nodes indicate a successful transmission to the transmitting node by sending an ACK packet following the successful transmission, without sensing the channel for ongoing transmissions first. As a result, the ACK packet can be corrupted, which prompts a retransmission of the data packet.

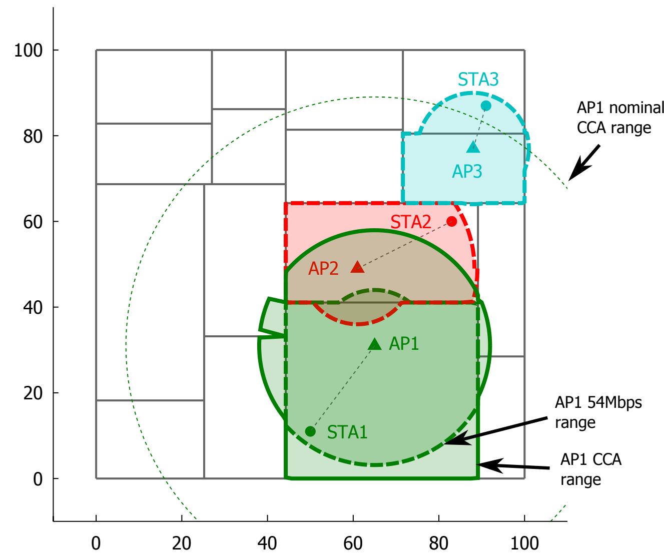

Fig. 2. Example network topology highlighting hidden node and exposed node situations.

III. Methodology

We perform Monte Carlo simulations in order to estimate area throughput of WLANs. For each combination of transmit power, pathloss exponent, wall density and WLAN density, we generate 40 random network topologies and floor plans as described above. For each network and floor plan realization, we simulate the MAC layer packet transmissions of the WLANs at high load, i.e., full buffers for 10 seconds in OPNET. The first 2-second interval is considered as the transient time for the backoff window distribution to reach its steady state. So, the results from 2 seconds of simulation time are discarded. The throughput results are calculated from the remaining 8 second interval. From the throughput results, we obtain the 95% confidence intervals of the area throughput estimates.

IV. Results

The area throughput of dense WLAN deployments at high loads in any given environment exhibits the general behavior illustrated in fig. 3. The area throughput initially shows an almost linear increase with the number of deployed WLANs, which we refer to as a *non-congested* deployment. This almost linear increase indicates that each WLAN can attain a throughput which is close to the link throughput of 30 Mbps. As the WLAN density increases, the area throughput reaches a plateau where deploying more WLANs does not increase the area throughput. This regime is where the WLAN deployment has become *congested*. As the WLAN density increases further, the number of collisions increase significantly, thus the area throughput falls below that obtained in the dense regime; we call this an *over-congested* deployment.

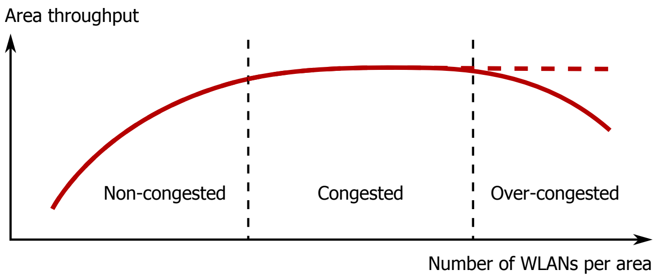

Fig. 3. Abstract plot of area throughput as a function of AP density.

The AP densities corresponding to the non-congested, congested and over-congested deployment regimes depend on the propagation environment, particularly on the amount of attenuation of interference between the coexisting WLANs. In topologies with little attenuation, the congested regime is reached even for small WLAN densities, as seen in the "low attenuation" curve in fig. 4. If the attenuation is very small such that all APs exert strong interference on each other, then high WLAN densities push the system into the over-congested regime, where area throughput degrades with increasing WLAN density. This trend can be observed in the "low attenuation" curve in fig. 5 at higher WLAN densities. In contrast, in topologies with strong attenuation, the WLANs operate in the non-congested regime even for high WLAN densities, which can be observed in the "strong attenuation" curve in fig. 5. For lower transmit power values, the throughput results become even higher than the curves in fig. 4 and fig. 5. This means that, for all practical WLAN densities of up to 200 APs per 100 m $\times$ 100 m per channel, there is always improvement in area throughput by densification in environments with strong attenuation. Note that for small WLAN densities, the "strong attenuation" curve is very close to the "interference-free throughput" line, which indicates that the WLANs in the strong attenuation environment can obtain a throughput that is close to the link throughput of 30 Mbps. In topologies with moderate attenuation, high WLAN densities reach the congested regime, however the over-congested regime where throughput degrades is never reached for all practical AP densities of up to 200 APs per 100 m $\times$ 100 m per channel. This trend can be observed in the "moderate attenuation" curve in fig. 5. Again, for lower transmit power values, the throughput results are even higher. As the figures show, the transition between different regimes is gradual; i.e., there is no clear breakpoint. Therefore we have labeled the non-congested, congested and over-congested regions qualitatively.

In an indoor environment with lots of clutter, which corresponds to a pathloss exponent of 3 in our simulations, the ratio of area throughput obtained in a very dense

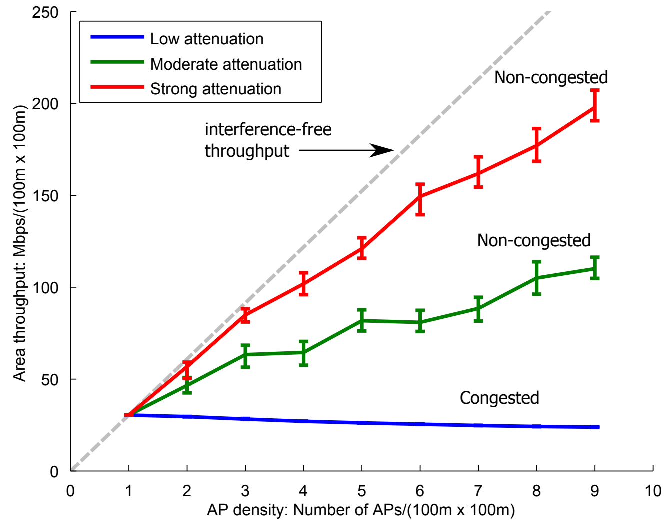

Fig. 4. Area throughput for single channel deployment, 1 to 9 WLANs. Low attenuation: No walls, $\alpha = 2$, $P_t = 100$ mW. Moderate attenuation: Moderate wall density, $\alpha = 3$, $P_t = 100$ mW. Strong attenuation: High wall density, $\alpha = 3$, $P_t = 100$ mW.

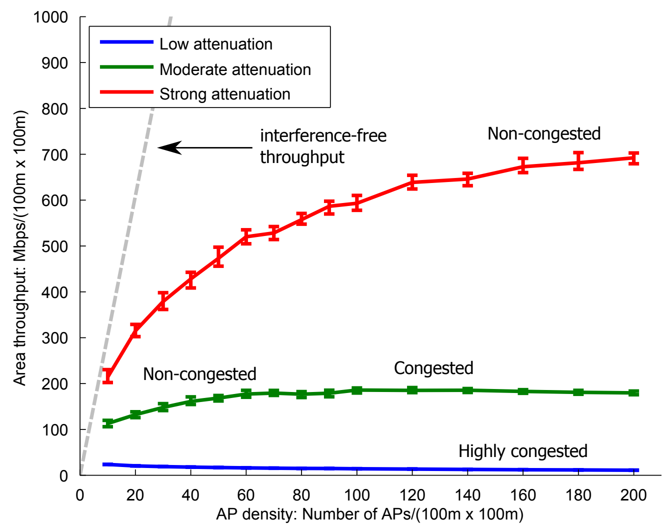

Fig. 5. Area throughput for single channel deployment, 10 to 200 WLANs. Same parameters as fig. 4.

deployment (200 APs) in a topology with many walls to a topology with no walls is between 6-12 times, depending on the transmit power. The difference is more prominent in an indoor environment with little clutter. When pathloss exponent is 2, the ratio of area throughput in a very dense deployment (200 APs) in a topology with many walls to a topology with no walls is between 30-48 times, depending on the transmit power. The numerical results for the highest simulated AP density of 200 APs per 100m $\times$ 100 m simulation area for all different sets of simulated parameters are presented in table I.

TABLE I. AREA THROUGHPUT RESULTS FOR MAXIMUM SIMULATED AP DENSITY OF 200 AP/(100m× 100 m)

Propagation conditions		Transmit Power 100 mW	25 mW
No Walls	$\alpha = 2$	11.1 Mbps	11.3 Mbps
	$\alpha = 3$	56.2 Mbps	101.8 Mbps
Moderate wall density	$\alpha = 2$	69.1 Mbps	111.1 Mbps
	$\alpha = 3$	179.7 Mbps	276.2 Mbps
High wall density	$\alpha = 2$	411.4 Mbps	549.6 Mbps
	$\alpha = 3$	692.3 Mbps	912.1 Mbps

V. CONCLUSION

In this paper, we have investigated throughput limits of dense WLANs in indoor environments by modeling different propagation conditions. We have shown that the propagation environment has a profound impact on the performance of very dense networks. This means that, even though the general behavior in fig. 3 is predicted in previous works, e.g. [3], the "simplistic" distance dependent models used in most previous works do not predict network performance very accurately. Our results also highlight the big difference in AP densities that lead to non-congested, congested or highly congested regimes for various propagation environments. We also observe that in high attenuation environments, densification can always bring area throughput improvement within the range of AP densities we investigated. Furthermore, in moderate and strong attenuation environments, unplanned AP deployments, which represent a worst-case interference scenario, exhibit non-decreasing area throughput trends with increasing WLAN density in the range we investigated. Therefore, in such environments, a planned deployment is not as critical as it would be in low attenuation environments. Although this analysis has been done using 802.11g physical layer parameters, the conclusions can easily be generalized to 802.11a; the higher frequencies will lead to less interference compared to the 802.11g case, which will lead to increased area throughput performance.

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