Association and deployment considerations in dense wireless LANs

Ali Ozyagci, Ki Won Sung, Jens Zander
KTH Royal Institute of Technology, Wireless@kth, Stockholm, Sweden
Email: {ozyagci,sungkw,jenz}@kth.se

***Abstract*—Wireless LANs based on the IEEE 802.11 standard are one of the most commonplace indoor wireless access solutions. As the ever growing demand for data consumption necessitates higher rates and volumes, it is fairly common to observe more and more WLANs being deployed in close proximity to each other. As distances between WLAN installations diminish, the access points (APs) and stations (STAs) in these WLANs create a complex interference environment, which is also compounded by the indoor propagation environment. In this paper, we investigate the impact of two important parameters related to the deployment and operation of densely deployed wireless LANs on the aggregate throughput obtained by all the nodes in these WLANs. The first such operational parameter we investigate is access point and user station association; namely, whether STAs associate with a random "strong" AP or the AP from which they obtain the strongest received power. The second operational parameter we consider is the way in which APs are placed in the indoor environment; namely, whether APs are deployed randomly or in a manner to reduce inter-AP interference. In order to account for the complex node interactions in the MAC layer, which is crucial for accurate performance estimation, we perform packet-level simulations using OPNET. Our results show that the type of node association used in densely deployed WLANs has a critical impact on the aggregate throughput. In comparison, the type of AP deployment used is not nearly as significant; varying from moderate to no impact at all.**

I. Introduction

Wireless LANs based on IEEE 802.11 standards, which usually carry the Wi-Fi trademark, are becoming ever more popular as an indoor wireless access solution in residential and office environments. This observation is also supported by recent measurement studies [1], [2], which report as many as 6103 WLANs per km^2 on all channels in the 2.4 GHz band. As WLANs are being deployed in greater numbers, the distance between these WLANs diminish, therefore they start to create contention and interference on each other. We use the term *dense* to describe a deployment of a number of WLANs in which the packet transmission activity of one WLAN influences, and is in turn influenced by, packet transmissions occurring in other WLANs.

A dense WLAN deployment implies that these WLANs have overlapping coverage areas, therefore they are potentially creating contention and interference on transmissions taking place in nearby WLANs. Thus, the way in which the AP locations are chosen in these WLANs becomes an important issue. Furthermore, overlapping coverage areas imply that the STAs in these coverage areas can receive packets from several APs. Therefore, which AP to select as the STA's serving AP becomes an important question since this choice directly influences signal power statistics, which, in turn, has an influence on the throughput performance of these dense WLANs. Although the association rule followed by STAs when they join one of the several candidate WLANs, and the method followed when AP locations are chosen are two important operational parameters related to the performance of WLANs, the impact of these two parameters on the aggregate throughput of all these WLANs is not well-investigated in the context of dense deployments.

There are numerous analyses which look into the performance of WLANs in different AP deployment regimes, e.g. [3], [4], both of which propose joint AP location selection and channel assignment methods. However, their focus in AP location selection is coverage rather than aggregate throughput maximization. Furthermore, the AP densities investigated are not large enough to represent a dense deployment. Similarly, there are various studies that investigate different STA association regimes, e.g. [5], [6], which examine the effect of STA allocation mechanisms in combination with other design parameters such as power allocation and contention window size on WLAN performance. The purpose of the allocation mechanisms in these articles are typically throughput fairness among STAs in the system. However, their results do not apply to dense settings because the investigated AP numbers are also quite small. On the other hand, theoretical models such as [7], [8], which can easily be generalized to high densities, would not be applicable to this particular question either. The reason is that the models in [7] and models derived from it do not incorporate the effect of the propagation environment. Also, stochastic geometry based models such as [8] do not take MAC protocol details into account.

As explained above, the impact of AP deployment regime and STA association mode on the aggregate throughput of densely deployed WLANs has not been well investigated. Therefore, we extend the analysis in [9] to answer the following questions:

- What is the gain in aggregate throughput when each STA in a densely deployed WLAN associates with the AP from which it receives the strongest signal power rather than associating with a random "strong" AP?
- Can aggregate throughput of densely deployed WLANs be improved by selecting AP locations in a planned way rather than placing them randomly?

II. Models and scenarios

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

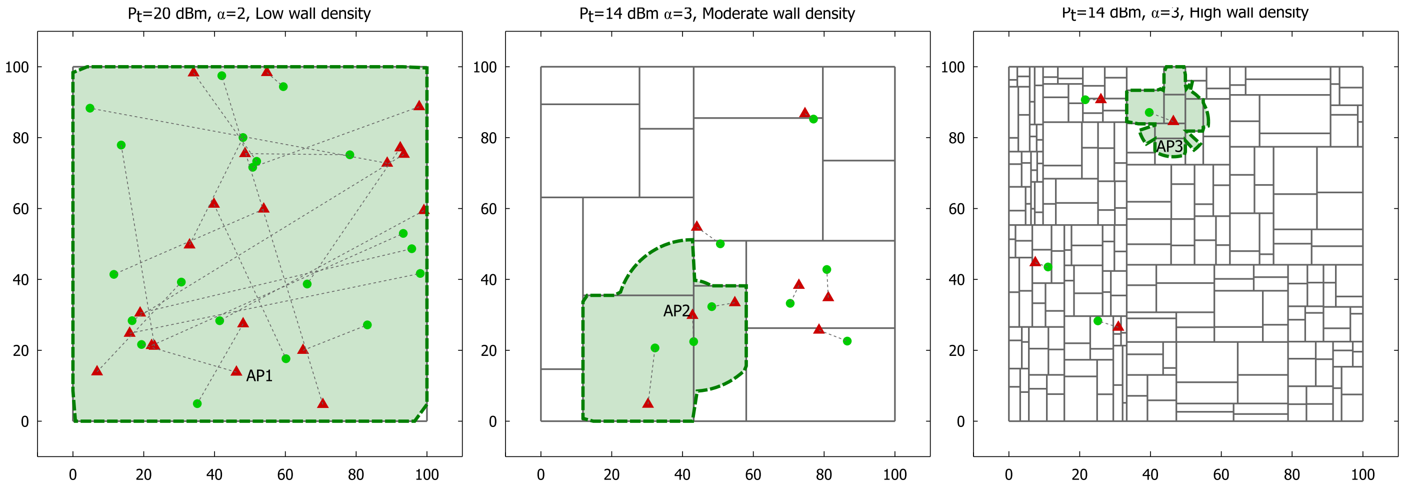

Fig. 1. Example network topologies and floor plans for various propagation environments, unplanned deployment and random association regimes. AP–STA pairs are represented by a connected triangle and circle. In all figures, the 54 Mbps coverage range of an example AP is highlighted. (a) Scenario-A: Low attenuation, high AP density ⇒ high interference. (b) Scenario-B: Moderate attenuation, moderate AP density ⇒ moderate interference. (c) Scenario-C: High attenuation, low AP density ⇒ low interference.

A. Deployment and association models

In our analysis, we compare two AP deployment regimes; unplanned and planned. In the *unplanned deployment* that we consider, AP locations are determined by users rather than wireless network engineers. This choice may be motivated by cost concerns. Users may place the APs wherever convenient; e.g. next to a power or Ethernet outlet instead of the best position in terms of SINR. We model this behavior by randomly placing the APs in our simulations.

The other deployment option, i.e. *planned deployment*, may be realized according to a number of different network planning criteria. Since we are interested in estimating the aggregate throughput, one obvious planning criterion would be to maximize this throughput. However, it is impractical and not much meaningful to plan the AP positions for throughput maximization in the system that we consider because receiver locations are not known beforehand. Therefore, to represent a planned deployment, we consider a simple planning heuristic that reduces inter-AP interference in the entire system. To be more precise, the deployment heuristic we use determines a set of AP positions such that, at each AP, the sum of interference powers from all other APs in the system is considerably reduced compared to a random deployment. The rationale is that reducing inter-AP interference will increase concurrent transmission opportunities of the APs in the system.

We also compare two STA association modes; random and strongest-signal. In a dense deployment of WLANs, a STA will be in a position to communicate with several APs at the maximum data rate in absence of concurrent transmissions from other nodes. We define *random association* such that the STA chooses as its serving AP one of these APs with which it can communicate at the *maximum* PHY rate. Our rationale for this random association definition is that, when a user wants to associate with a WLAN, she may see several "strong" APs which have "five out of five bars" signal quality; so the user chooses one AP out of the set of APs that can provide the highest data rate.

The other association option, namely *strongest-signal association*, means that the STA simply associates with the AP from which it obtains the strongest received power.

B. Scenarios

The impact of AP deployment regime and STA association mode on aggregate throughput depends strongly on the propagation environment. In order facilitate comparisons between deployment and association regimes, we observe the aggregate throughput of these regimes in three scenarios we have selected based on different propagation characteristics. One example network topology and floor plan realization for each of the selected scenarios is illustrated in fig. 1. In the figure, we have used the unplanned deployment and random association regime for illustration purposes, which is the baseline operation regime for the comparisons we make. Note that scenario definitions are independent of the planning and association regimes.

Scenario-A represents a network in which propagation losses are small (α=2), transmit powers are high (P_t=20 dBm) and the indoor landscape is mostly open space (low wall density). When AP density realization is also high (N=20), this scenario represents a harsh interference environment.

In contrast, scn-C represents a network with very high attenuation and low transmit powers (α=3, P_t=14 dBm, high wall density). If the AP density realization is also low (N=4), this scenario represents an environment with very little interference.

Scn-B is a mixture of scn-A and scn-C. The propagation exponent is high and transmit powers are low, but also wall attenuation is quite weaker than scn-B (α=3, P_t=14 dBm, moderate wall density). Therefore, when the AP density realization is a moderate number of APs (N=8), this scenario represents an environment with moderate amount of interference.

C. Network model

AP and STA positions are modeled such that, in both planned and unplanned deployment regimes, one STA position is generated within the *coverage area* of every AP in the network. That is, no STA position is generated outside coverage areas, and no AP is left without a STA. The rationale is that if a user is in outage, then it is not relevant for throughput calculations anyway. Also, if we are simulating the throughput for a given AP density, then by definition all of these APs are occupied with serving a STA during the short time interval that we simulate. These assumptions are reasonable in order to model a high user demand.

We define a transmitter's coverage area to be the area in which the receiver can decode 1500-octet-long packets with less than 1% PER at 54 Mbps when there is no concurrent transmissions; i.e. only thermal noise is hindering packet reception. The coverage areas in different propagation conditions are depicted in fig. 1.

In our simulations, we consider the case that all APs are on the same channel; i.e. there is no adjacent channel interference or partially overlapping channels in the analysis. We investigate a WLAN density of up to 200 APs operating on the same channel. Considering a typical reuse-3 channel plan in the 2.4 GHz band, this corresponds to 3×200=600 APs simulated; i.e. 16,7 m^2 per WLAN in average.

To model different propagation conditions created by varying wall configurations, we use randomly generated floor plans. To represent the effect of different wall densities on aggregate throughput, we simulate one very large room (low wall density), 16 moderately large rooms (moderate wall density, e.g. open landscape offices) and 256 small rooms (high wall density, e.g. separate offices) as in fig. 1.

D. Propagation model

We use the same model as in [9], which is based on [10]. Pathloss increases exponentially with increasing distance, and we use different pathloss exponents ($\alpha = 2$ or $\alpha = 3$) to model different amount of clutter in the environment. If the signal crosses k walls on its path to the receiver, it further incurs an attenuation factor of $k \cdot W$, where $W = 10$ dB. The propagation model is similar in principle to WINNER II models except for the use of different constants:

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

where P_0 is the received power level at 1 m.

E. Node models

Both APs and STAs use ERP-OFDM PHY. Data packets are transmitted at 54 Mbps, whereas ACK packets are transmitted at 24 Mbps because this is the highest rate defined in the mandatory rate set of ERP-PHY [11]. Each WLAN, equivalently each BSS, consists of ERP-OFDM capable nodes, therefore slot time is 9μs. The receiver bit error rate is modeled as a function of received SINR. This receiver model is such that, when the average SINR of a packet is greater than 27 dB, then PER is less than 1% during transmission of packets with 1500 octet payloads. When a single AP-STA link is active, assuming full buffers and high received packet SNR, the maximum link capacity is 30 Mbps. This is a well known result; i.e., the link capacity is less than the peak data rate because of inter-frame spaces and backoff times [12]. The transmit power levels we consider are P_t=100 mW and 25 mW. In the simulations, we use a clear channel assessment threshold (CCA) of –76 dBm, noise figure of 10 dB and implementation loss of 5 dB as mentioned in [11]. The corresponding thermal noise power is –90.6 dBm. Finally, after a failed transmission, a packet is retransmitted for 6 times, for a total count of 7 transmissions.

When we simulate WLANs of various densities to obtain the aggregate throughput, we consider full buffers, i.e. *saturation throughput* as it is sometimes called. Considering cloud storage, video streaming services, etc. which are becoming popular, the full buffer condition can be representative of the performance of dense and fully loaded WLANs. Saturation throughput assumption may result in an aggregate throughput performance which is lower than the maximum attainable throughput for the optimum offered load. However, in the context of a dense network with many receivers, the MAC layer saturation throughput is likely to approach the maximum throughput that can be attained for the optimum offered load. Furthermore, the saturation throughput is an interesting metric in itself because it represents the performance of the densely deployed WLANs in an overloaded situation; when every STA is simultaneously trying to download as much data as possible.

In the simulation analysis, we consider only the MAC throughput. The packets to be transmitted are directly inserted to the MAC queue of the transmitter, thereby eliminating the influence of higher layers on the performance analysis. The transmitter nodes always have full buffers of 1500 octet packets, which is the maximum payload size of Ethernet packets. We define throughput as the number of bits delivered from the MAC layer of the receiver to the higher layer in unit time. Aggregate throughput is the sum of the MAC throughputs of all individual nodes in the system. Overhead of the MAC and PHY layers, retransmissions, duplicate packets are not included in the throughput results. Furthermore, only downlink is considered in order to find the limit of downlink throughput. Uplink traffic is only ACK packets transmitted from receivers back to the transmitters. We are mainly concerned with downlink performance because typical WLAN usage scenarios are downlink-heavy.

We consider the situation in which all APs and STAs are operating at the highest data rate that is possible for them. In other words, we consider that the APs and STAs do not employ rate adaptation because it is typically used in situations where the receiver is "noise limited". However, as WLANs become denser, inter-node distances become shorter, and therefore signal and interference powers get stronger. Therefore, WLAN nodes operate in an environment where SINR levels are either high enough to satisfy even the highest modulation and coding rate requirements or momentarily so low as to not be able to satisfy the SINR requirement of even the lowest data rate that the nodes can use. We further note that, by transmitting at the highest possible rate, a node will occupy the wireless medium for the shortest time. Therefore, it will occupy the channel for the shortest possible time and thereby be able to utilize many transmission opportunities.

III. Methodology

In order to determine whether strongest-signal association or planned deployment provides performance gains over random association and unplanned deployment, using analytical WLAN throughput models would not be adequate because these models tend to overlook MAC protocol details and they do not incorporate the effects of indoor propagation environment such as wall attenuation. Therefore, we perform a detailed simulation study of 802.11 MAC layer aggregate throughput of multiple coexisting WLANs as a function of deployment density. In order to estimate throughput performance in varying network topologies and floor plans, we perform Monte Carlo simulations. For every combination of transmit power, pathloss exponent, wall density, number of APs, deployment regime and association mode, we randomly generate 40 network topologies and floor plans. We simulate the packet transmissions that take place within 1 second duration in the entire system, assuming that the AP and STA positions, pathgains and other parameters relevant to throughput calculations do not show much variation within this 1 second interval. We use these 40 realizations to obtain statistics to 95% confidence.

IV. Results

In [9] we analyzed the aggregate throughput of densely deployed WLANs in the unplanned deployment and random association regime. We observed that, as the WLAN density is increased, the aggregate throughput exhibits three states, which we have termed *non-congested*, *congested* and *over-congested* states. In the non-congested state, the congestion and interference between WLANs is fairly small, therefore each additional AP provides an increase in aggregate throughput which is comparable to the link throughput, which is about 30 Mbps in our simulations. As WLAN density increases, the aggregate throughput saturates because the wireless medium has become congested. As AP density increases even further, interference becomes significant and collisions dominate the outcome of packet transmissions, which characterizes the over-congested state. In the following discussion of our analysis results, we adhere to the same terminology when describing the behavior of the aggregate throughput as a function of WLAN density.

Strongest-signal association and random association modes result in approximately the same throughput performance when the amount of congestion and interference in the system is "low", which implies that these two association modes perform similarly when WLANs are in non-congested state. This can be seen in fig. 2 where the gain is close to 1 for small AP densities. In contrast, when congestion and interference increase, and consequently when WLANs move into congested and over-congested states, strongest-signal association mode always outperforms random association, as seen in all three curves in fig. 2. The reason is that, in a system which is operating in random association mode, as AP deployment density increases, interference becomes stronger due to more numerous and closer interfering APs while signal power statistics do not improve at all. As a consequence, APs end up deferring channel access for most of the time. Furthermore, when an AP eventually transmits, the outcome of the packet transmission is mostly unsuccessful due to high interference levels. In contrast, in a system which operates in strongest-signal association mode, as WLAN deployment becomes denser, the improvement in received power levels exceeds the increase in interference because of diversity in AP selection. As a result, even concurrent packet transmissions result in successful reception due to the improved SINR statistics. Therefore, the advantage of strongest-signal association mode over random association becomes most apparent in high AP densities where congestion and interference are also "high". The absolute value of "low" and "high" in this context depends on the propagation environment. That is, if attenuation is low, even few APs will lead to a high congestion and interference in the system, therefore throughput improvement due to strongest-association will be apparent sooner. Whereas, if attenuation is high, both strongest-signal and random association modes will perform similarly until much higher AP densities.

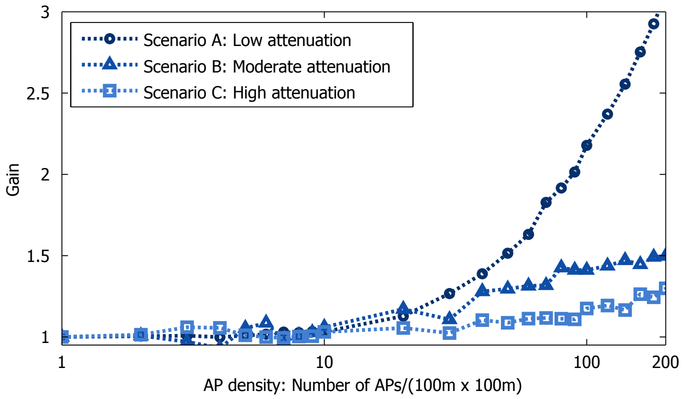

Fig. 2. Improvement in aggregate throughput in strongest-signal association mode with reference to random association mode. At high AP densities, strongest-signal association improves aggregate throughput in all propagation environments.

The benefits of planned deployment over unplanned deployment are not as clear-cut as the difference between association modes. One interesting observation is that, planning brings most gains in moderate interference environments; that is, where attenuation and AP densities are moderate, as shown in fig 3. The reason is that, when AP densities are moderate, it is possible to find a better AP placement than a random one, which reduces the aggregate interference levels at each AP compared to the initial random AP placement by isolating APs as much as possible and thereby increasing concurrent transmission opportunities. However, when the AP density is low, and consequently the interference level from other APs is also low, then planed deployment does not improve the aggregate throughput performance substantially. The reason is that the AP location planning method that we consider aims to reduce the aggregate interference at each AP. Consequently, when the attenuation is very strong or when there are not so many interferers to begin with, then the aggregate interference is already quite low, therefore performance gain in aggregate throughput due to planned deployment is marginal. On the other hand, planned deployment is not very beneficial in high interference environments either; i.e. in low attenuation and high AP density settings. The reason is that large number of transmitters mean that throughput is degraded due to excessive interference to receivers. Therefore, reducing interference between APs to increase concurrent transmission opportunities does not improve aggregate throughput at all.

One interesting observation on the interplay between deployment regime and association mode is that planned deployment always brings some amount of aggregate throughput gain

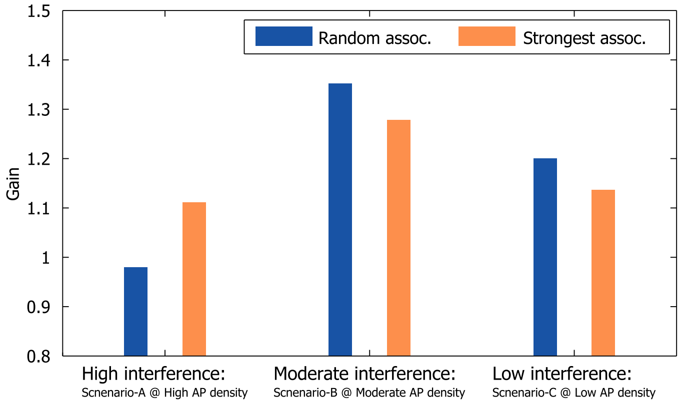

Fig. 3. Improvement in aggregate throughput in planned deployment regime in relation to unplanned deployment regime. Planned deployment brings most gains in moderate interference environments.

at high deployment densities when the WLANs are operating in strongest-signal association mode, which can be observed in all scenarios. An example for high attenuation scenarios is provided in fig. 4. The reason for this outcome is that in the random deployment regime, two or more APs may be deployed too close to each other such that even the favorable SINR statistics obtained by strongest-signal association cannot achieve the SINR requirement for successful packet reception when these two APs are transmitting simultaneously. Planned deployment eliminates such extremely poor AP location realizations, thereby improving the through performance. This gain due to planning at high AP densities is not observed in WLANs operating in random association mode.

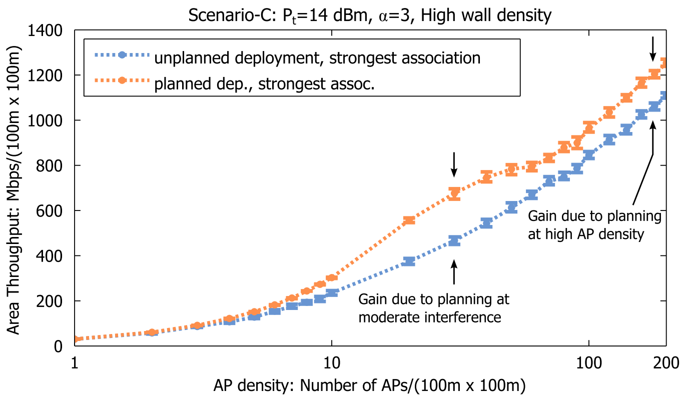

Fig. 4. Throughput improvement due to planned deployment when WLANs operate in strongest-signal association mode.

V. Conclusion

In this paper, we extended our investigation in [9] to AP deployment and STA association dimensions. In order to account for 802.11 MAC protocol details as well as indoor propagation environment created by walls, we performed packet-level simulation analyses of multiple coexisting WLANs. Through these simulations, we estimated aggregate throughput performance as a function of WLAN deployment density, and we identified the impact of AP deployment regime and STA association mode on system performance. We observed that both the AP deployment regime and the STA association mode used in WLANs have varying degrees of impact on the aggregate throughput. WLANs which operate in the strongest-signal association mode enjoy a performance improvement in all propagation environments; the greater the improvement as deployment density increases. On the other hand, planned deployment brings the most performance improvement in moderate interference environments, with diminishing improvement as AP density increases. Furthermore, if STAs perform random association, performance gain due to planning is insignificant. If, however, STAs perform strongest-signal association, then planned deployment can bring some throughput improvement over unplanned deployment, although this gain is not substantial. We plan to extend this performance analysis to non-full buffer situations by using realistic packet arrival models so that the results also account for the impact of higher layers on aggregate throughput.

Acknowledgment

We acknowledge that this work has been partially supported by Wireless@kth.

References

[1] S. Forge, R. Horvitz, and C. Blackman. (2012) Perspectives on the value of shared spectrum access. [Online]. Available: http://ec.europa.eu/information_society/policy/ecomm/radio_spectrum/_document_storage/studies/shared_use_2012/scf_study_shared_spectrum_access_20120210.pdf

[2] A. Achtzehn, L. Simic, P. Gronerth, and P. Mahonen, "Survey of ieee 802.11 wi-fi deployments for deriving the spatialstructure of opportunistic networks," in *Personal Indoor and Mobile Radio Communications (PIMRC), 2013 IEEE 24rd International Symposium on*, 2013.

[3] T. Vanhatupa, M. Hannikainen, and T. Hamalainen, "Genetic algorithm to optimize node placement and configuration for wlan planning," in *Wireless Communication Systems, 2007. ISWCS 2007. 4th International Symposium on*, 2007, pp. 612–616.

[4] X. Ling and K. Yeung, "Joint access point placement and channel assignment for 802.11 wireless lans," in *Wireless Communications and Networking Conference, 2005 IEEE*, vol. 3, 2005, pp. 1583–1588 Vol. 3.

[5] I. Broustis, K. Papagiannaki, S. Krishnamurthy, M. Faloutsos, and V. Mhatre, "Measurement-driven guidelines for 802.11 wlan design," *Networking, IEEE/ACM Transactions on*, vol. 18, no. 3, pp. 722–735, 2010.

[6] J. Zhang, J. Wang, and B. Bensaou, "Optimal resource sharing in multi-cell wireless lans: Joint channel assignment, association control, airtime sharing and contention resolution," in *Wireless Communications and Mobile Computing Conference (IWCMC), 2013 9th International*, 2013, pp. 317–322.

[7] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535 –547, march 2000.

[8] H. Nguyen, F. Baccelli, and D. Kofman, "A stochastic geometry analysis of dense IEEE 802.11 networks," in *INFOCOM 2007. 26th IEEE International Conference on Computer Communications. IEEE*, may 2007, pp. 1199 –1207.

[9] A. Ozyagci, K. Sung, and J. Zander, "Effect of propagation environment on area throughput of dense wlan deployments," in *Globecom Workshops (GC Wkshps), 2013 IEEE*, 2013.

[10] A. Motley and J. Keenan, "Personal communication radio coverage in buildings at 900 mhz and 1700 mhz," *Electronics Letters*, vol. 24, no. 12, pp. 763 –764, jun 1988.

[11] *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, IEEE Std. 802.11, 2007.

[12] Y. Xiao and J. Rosdahl, "Throughput and delay limits of IEEE 802.11," *IEEE Commun. Lett.*, vol. 6, no. 8, pp. 355 –357, aug. 2002.