Attainable User Throughput by Dense Wi-Fi Deployment at 5 GHz

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***Abstract*—Most of currently deployed Wi-Fi networks use the IEEE 802.11b/g standard and operate in 2.4 GHz ISM-band. As mobile traffic demand rapidly increases, significant Wi-Fi deployment in the still very lightly used 5 GHz band is anticipated. In combination with the recent PHY amendments, e.g., 802.11ac, such Wi-Fi in many settings emerges as a strong competitor to small cellular deployment. In this paper, we aim to quantify what total capacity and which data rates per user can be supported by high-density, the state-of-the-art 5 GHz Wi-Fi deployment. Unlike previous studies, we consider the effect of densification by explicitly modeling the different level of interference among access points for office-type scenarios with various internal wall losses. Although abundant spectrum availability at 5 GHz may compensate for system inefficiency caused by carrier sensing and contention, we find that there is a capacity limit. This capacity limit depends on propagation environments and is especially low in "open" environments or environments with low wall losses. To operate at capacities above this limit, cellular systems with their more advanced interference mitigation techniques are required.**

I. INTRODUCTION

Since smartphones have been widely spread out, Wi-Fi deployment has played an important role to offload mobile traffic in a cost-effective manner. So far, 2.4 GHz has been heavily congested due to better coverage property and the early market take-off of 802.11b/g. As traffic demand increases rapidly, it is well anticipated that the significant number of Wi-Fi access points (APs) will be deployed at 5 GHz where roughly eight times more frequency channels are available [1]. In addition, the recent PHY amendments in 802.11n/ac, e.g., higher order modulation and coding schemes or channel bonding, may further enhance capacity. Thus, using large free 5 GHz channels with the PHY layer improvement in Wi-Fi networks may be a strong competitive advantage against emerging small cellular deployment which employs more sophisticated interference mitigation schemes. In this regard, the assessment of Wi-Fi capacity in aggregate 5 GHz channels is a very crucial task since it can provide a necessary condition for the small cellular deployment.

In principle, the capacity assessment of using 5 GHz channels will be heavily influenced by AP density. Nevertheless, most of research efforts were thus far devoted to Wi-Fi performance evaluation at a given AP density and system bandwidth, e.g., see [2]. Some industry measurements were available to show the superiority of 802.11a in 5 GHz over 802.11b/g when several APs are deployed in more realistic environments [3]. There was few analytical work on dense CSMA/CA networks in homogeneous environments [4]–[6]. In reality, propagation conditions in typical indoor environments are very dependent on the types of local premises [7]. In addition, frequency channels in the standard and regulation conditions have also strong influence on the capacity of actual Wi-Fi deployment at 5 GHz. With our best knowledge, none of existing studies explicitly assessed the potential capacity of real aggregate 5 GHz Wi-Fi channels when densification is considered in the presence of internal walls.

The objective of this study is to quantify the system-level capacity and throughput per user which can be supported by the full usage of real 5 GHz Wi-Fi channels with considering densification and various indoor propagation conditions. Specifically, we aim to answer the following two questions:

- How much capacity can be ideally supported by dense Wi-Fi deployment in aggregate 5 GHz channels?
- How sensitive is this to local propagation conditions caused by different internal wall losses?

Since the performance assessment of large-scale Wi-Fi deployment itself is prohibitively complex due to contention among multiple APs in irregular indoor structures, our approach takes the best-case estimate of 5 GHz capacity. For this, we explicitly model stochastic interference and data rate of a dense Wi-Fi network based on idealized carrier sensing and contention in MAC layer. Based on a sensitivity analysis, we choose an AP density level which yields the largest network capacity. Then, mean area throughout density (Mbps/m^2) is quantified by using 802.11ac PHY parameters. It is used as an input for calculating attainable average throughput per user (Mbps/user) in three propagation scenarios. The main contribution of this study is the first attempt to estimate the potential capacity of aggregate 5 GHz Wi-Fi channels by taking densification and wall loss sensitivity into account.

The paper organizes as follows. Section II describes three representative Wi-Fi deployment scenarios according to wall density and provides a relevant propagation model. Then, MAC and PHY layer assumptions to model random interference and rate are given in Section III with a performance metric definition. Numerical results are illustrated in Section IV. Then, we conclude this study at Section V.

II. DEPLOYMENT SCENARIO AT LICENSE-EXEMPT 5 GHZ

A. Scenarios and Propagation Model

The propagation conditions are typically very dependent on indoor premises. Throughout this study, we consider three

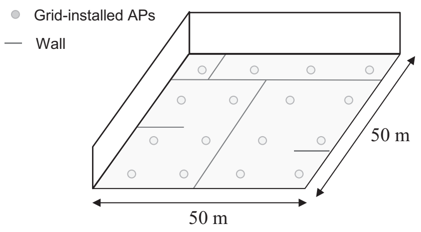

Fig. 1. An example of an indoor environment scenario.

TABLE I
PARAMETERS FOR LOCAL ENVIRONMENT SCENARIOS

Local Environments	**Average wall density α (m^{-1}) [9]**	**Mean attenuation per wall L_w (dB)** [1]
LoS	0	0
Office	0.231	5
Shopping mall	0.047	12

representative environments, categorized based on wall density α (m^{-1}): line of sight (LoS), a shopping mall, and an office. All three scenarios have square service area A with the size of 50 by 50 in meters, as shown in Fig. 1. In the LoS, α is set to zero. In the shopping mall and office cases, mean attenuation per wall L_w (dB) can be further dependent on used material types and center frequency at a given α. We use WINNER-II indoor pathloss model [8] as given in:

$$L_{ij} = 46.4 + 20\log_{10}(d_{ij}) + 20\log_{10}\left(\frac{f_c}{5}\right) + n_w L_w (\mathrm{dB}) \tag{1}$$

where d_{ij} and f_c represent the distance in meter between AP i and user j and center frequency (GHz), respectively. We assume that a wall obstructs a line of sight radio link with a probability α. Then, the average number of walls n_w between a transmitter and a receiver is estimated as $n_w = \alpha \cdot d_{ij}$. This can give us the average performance of different in-building structures with the same wall density, leading the another level of model generality. A similar approach has been taken and its validity is shown in [9]. Key parameters related to three scenarios are summarized in Table I.

B. Frequency Channel Availability at 5 GHz

Although the exact amount of 5 GHz license-exempt band varies between different countries and regions, Table II shows typical 2.4 GHz and 5 GHz frequency band candidates[2] for Wi-Fi deployment. When including guard channel overhead, maximum aggregate bandwidth W_{max} in 5 GHz channels can be up to 480 MHz as defined IEEE 802.11 standard. The 480 MHz bandwidth is divided into the different number of non-overlapping frequency channels depending on standard variants. For instance, 802.11a only supports 20 MHz channel width to create 24 non-overlapping channels. In contrast, recent amendment 802.11ac supports four options for bandwidth per channel, i.e., 20, 40, 80, and 160 MHz, based on a channel bonding technique in order to increase spectrum availability per AP. It is also noticeable that the power spectral density (PSD) limit is different according to individual frequency band in 5 GHz. In general, higher center frequency allows higher PSD p_t (dBm/MHz) to overcome coverage issues.

TABLE II
LICENSED-EXEMPT BAND FOR WI-FI AT 2.4 AND 5 GHZ

Frequency band (GHz)	**Supportable bandwidth W by IEEE 802.11 (MHz) [10]**	**PSD limit (dBm/MHz) [11]**
2.400 - 2.483	60	7
5.150 - 5.350	160	10
5.470 - 5.725	220	17
5.725 - 5.850	100	23

III. SYSTEM MODEL

In this section, we model random interference and instantaneous data rate caused by a CSMA/CA operation and provide a performance measure. We focus on downlink traffic which is the main consideration of network deployment.

A. Stochastic Interference Model for Co-channel APs

In a CSMA/CA-based IEEE 802.11 standard, there are several components that are related to arbitrating medium access and optimizing the protocol capacity: 1) predefined multiple frequency channels, 2) physical carrier sensing, 3) a binary exponential back-off, 4) data rate adjustment according to the signal quality. We in this subsection model these features for the performance evaluation of large-scale Wi-Fi deployment.

As basic interference mitigation schemes, we assume that a dense Wi-Fi network employs K non-overlapping channels belonging to a channel set $\mathcal{K}$ with bandwidth $w^k = \frac{W}{K}$ (MHz). Let us define a set of APs operating in a frequency channel k as $\mathcal{A}^k$. Each AP transmits with power $P_t = p_t \cdot w^k$ (dBm) where p_t (dBm/MHz) follows the regulation PSD limit which channel k belongs to. Then, in each frequency channel, a transmitter compares its currently sensed signal strength to carrier sensing threshold CS_{thr} (mW) before a transmission attempt. We refer to the carrier sensing range of an AP as D_{cs} such that $L_{ij}(D_{cs})P_t = CS_{thr}$. D_{cs} defines the spatial reusability by allowing the concurrent number of transmissions. Fig. 3 shows the different D_{cs} for three deployment scenarios. IEEE 802.11 standard defines fixed mandatory CS_{thr} for coexistence among anonymous Wi-Fi APs in the unlicensed band. For the 5 GHz capacity estimation, we use $CS_{thr} = 10^{-8.2}$ (mW) which is defined in [1] for OFDM PHY.

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[1] We use mean wall loss corresponding for light wall and thick wall given in [8]

[2] We here also include 5.470 to 5.725 GHz band where Wi-Fi may follow more strict regulatory rules to operate in a secondary basis for existing primary radar systems.

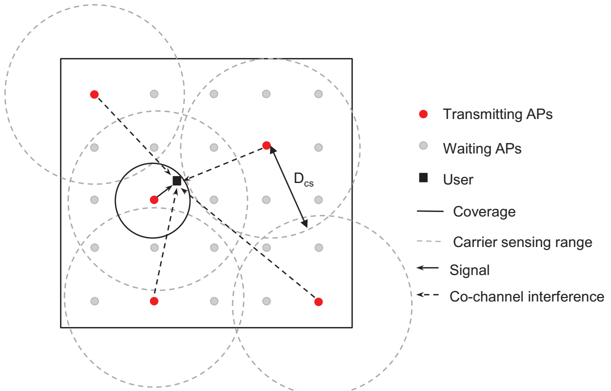

Fig. 2. The snapshot of active APs by the SSI process.

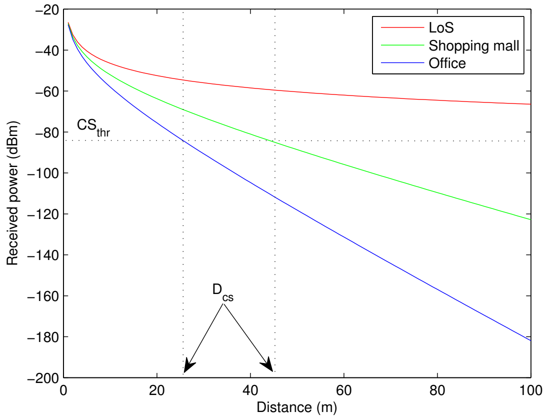

Fig. 3. Carrier sensing range D_{cs} in different propagation conditions (P_t=100 mW and $CS_{thr} = 10^{-8.2}$ mW).

Let us define the set of all co-channel APs in a frequency channel k as $\mathcal{A}^k$. Then, $\mathcal{A}_i^k$ is referred to as the set of APs which are within D_{cs} of AP i operating in a channel k. It is mathematically expressed as $\mathcal{A}_i^k := \{x \in \mathcal{A}^k, x \neq i | g_{ix}P_t > CS_{thr}\}$. We assume that all APs in $\mathcal{A}_i^k$ can perfectly detect an active AP, no causing unlucky concurrent transmission within D_{cs}. Then, the set of active APs is elected by the MAC protocol in a frequency channel k at a given time and is referred to as $\Phi^k \subset \mathcal{A}^k$. Since Φ^k plays an important role in the characteristics of interference and data rate of a Wi-Fi network, a precise and yet simple model describing this set is necessary while capturing the important features of the contending property. In addition, a simulation-based approach is inevitable to capture the various wall loss effect while existing analytical models are only applicable for idealized homogeneous environments [4]–[6].

In order to model the random variable Φ^k in more realistic indoor environments, we adopt Simple Sequential Inhibition (SSI) process which is a family of a random packing process [12]–[14]. Let us define a SSI process Ψ in a constructive manner on a finite and discrete set $\mathcal{A}^k$. $\Psi(n)$ is composed of a sequence of n random variables denoted by X_1, ..., X_n which are independently and uniformly distributed in $\mathcal{A}^k$. Initially, X_1 is added to $\Psi(1)$. Then, X_i is systematically added to $\Psi(i)$ if and only if it does not belong to the contention domain of any APs in $\Psi(n-1)$, i.e., $X_i \notin \cup_{X_j \in \Psi(i-1)} \mathcal{A}_{X_j}^k$. The process stops whenever entire APs in $\mathcal{A}^k$ are either active APs or in the contention domain of any other active APs. This process always lets APs transmit unless it is in the range of D_{cs} of other active APs, i.e., no idle time slots which may occur due to random backoff in IEEE 802.11 MAC. It is also noticeable that $|\Phi^k|$ is random variable due to random sequential selection at a given deployment density λ_a (AP/m^2). Unlike a deterministic simulation-based model in [15], this reflects more realistically instantaneously-varying interference and the number of active links which are hard to be characterized analytically and is also applicable in any general indoor environments.

B. Data Rate Model

Each user associates with an AP with the highest signal strength. We assume that both an AP and a user have single antenna stream configuration for the analysis simplicity[3]. For a given realization Φ^k, each active AP $i \in \Phi_k$ randomly selects one user to transmit data. Then, instantaneous signal to interference and noise (SINR) ratio of the served user by AP i can be given as

$$\widehat{SINR}_i = \frac{g_{ii}p_t}{\sum\limits_{x \in \Phi^k \setminus i} g_{xi}p_t + \sigma^2}, \qquad (2)$$

where σ^2 accounts for noise PSD (mW/Hz). Then, the instantaneous data rate[4] of the selected user, namely $\hat{R}_i$, can be ideally achieved as

$$\hat{R}_i = w^k \min\left\{\zeta_1 \log_2(1 + \zeta_2 \widehat{SINR}_i), \eta_{max}\right\} \text{ (Mbps)}, \quad (3)$$

where η_{max} (bps/Hz) represents the maximum link spectral efficiency. ζ is the bandwidth efficiency coefficient which captures the protocol overhead of MAC and PHY layer, e.g., packet header or control signaling. In this regard, the rate model implicitly assumes the perfect rate adaptation without any quantization loss unlike a practical discrete rate model. Note that the rate adaptation in practical Wi-Fi is imperfect due to the lack of explicit channel information feedback.

C. Deployment Model and Mean Area Throughput Density

For a given λ_a, we assume that APs are deployed in a grid basis [9]. Instead of assuming realistic random deployment, this model indeed provides optimistic performance. Specifically, n_x by n_y APs are equally placed to maintain equal sub-square areas whose size is $\frac{50}{n_x} \times \frac{50}{n_y}$ (m^2). For the sake of simplicity, we assume $n_x = n_y$. Let us define mean area

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[3] Ideally, our results can be easily extended to MIMO enabled applications by simply scaling the capacity with the number of antenna.

[4] We here refer to the effective data rate at MAC layer.

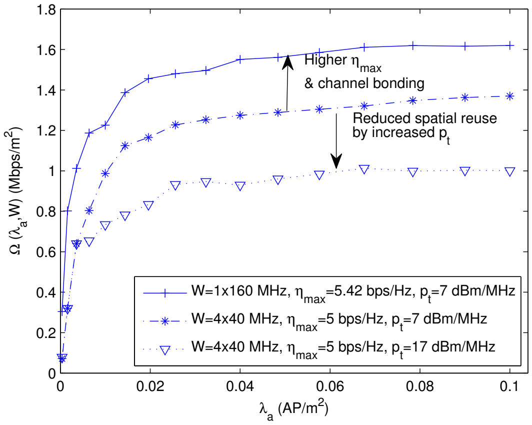

Fig. 4. Mean area throughput density Ω as a function of deployment density λ_a.

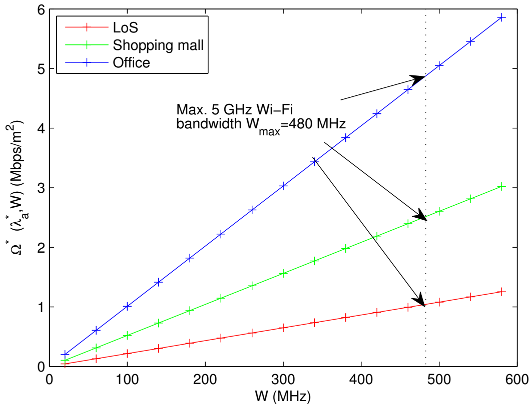

Fig. 5. Mean area throughput density Ω^* at the saturation AP density λ_a^* as a function of system bandwidth W.

throughput density Ω for λ_a and W which is feasible during a busy hour as:

$$\Omega(\lambda_a, W) := \frac{1}{A} E\left[\sum_{k\in\mathcal{K}} \sum_{i\in\Phi^k} \hat{R}_i\right] \ (\mathrm{Mbps/m^2}) \tag{4}$$

The expectation reflects a long-term average over the random variable Φ^k and user locations when the system is fully utilized. By assuming that all users have statistically same channel access opportunity and link capacity in long-term, the average throughput per user $\bar{R}$ (Mbps/user) can be approximated for a given average user density $E[\lambda_u]$ (user/m^2) by

$$\bar{R} \simeq \frac{\Omega(\lambda_a, W)}{E[\lambda_u]} \ (\mathrm{Mbps/user}). \tag{5}$$

IV. NUMERICAL RESULTS

A. *Simulation Methodology and Parameters*

Recall that our objective is to estimate Ω and $\bar{R}$ in 5 GHz Wi-Fi channels. For this, we facilitate a snapshot based Monte-Carlo simulation. In each snapshot, users are uniformly and independently dropped. The channel gain matrix is generated when each AP randomly selects one user to be served. The realization of Φ_k is produced by the SSI process. Then, we evaluate one sample value of $\sum\limits_{k\in\mathcal{K}} \sum\limits_{i\in\Phi^k} \hat{R}_i$. We estimate Ω by averaging independent sample values in different snapshots. For K frequency channels, we employ a heuristic channel assignment algorithm where each AP chooses randomly and sequentially a frequency channel generating the minimum aggregate interference. We conducted 1000 different channel and contention realizations. σ^2=-174 dBm/Hz is assumed with noise figure 5 dB. $f_c = 5.5$ GHz is used. We consider $CS_{thr} = 10^{-8.2}$ mW at 20 MHz which is a requirement from 5 GHz OFDM standard [1]. We use $\zeta_1 = \zeta_2 = 1$ for ideal PHY and MAC efficiency.

B. *Selection of λ_a and Key PHY Parameters*

Fig. 4 illustrates Ω according to λ_a in an office scenario where the lowest interference and the largest spatial reuse among three scenarios are expected. We found that Ω hardly increases after certain λ^a. This is mainly because CS_{thr} limits spatial reuse. Let us define saturation deployment density λ_a^* at which extra deployment density Δ (AP/m^2) has the marginal capacity increment. It can be mathematically expressed as

$$\frac{\Omega(\lambda_a^* + \Delta) - \Omega(\lambda_a^*)}{\Delta} < \epsilon \ (\mathrm{Mbps/AP}), \tag{6}$$

where ϵ is sufficiently small constant. We use ϵ as 0.01 (Mbps/AP). We observe from Fig. 4 that PHY advances in 802.11ac by better η_{max} and channel bonding yield limited improvement in an average system-level capacity. In order to perform the best case estimate, we assume the full channel bonding of whole available W, i.e., $K^* = 1$. η_{max}^*=5.42 (bps/Hz) is also used which is equivalent to the highest achievable data rate 866.7 Mbps at w^k=160 MHz of 802.11ac [16]. In addition, the figure shows that lower transmit power limit is helpful since it increases more concurrent APs, i.e., reduced D_{cs}. Thus, we use conservative p_t^*=7 dBm/MHz although higher frequency channels may allow more aggressive transmit power as shown in Table II. With the 802.11ac PHY parameters, Fig. 5 plots $\Omega^*(\lambda_a^*, W)$ in λ_a^* according to W in three scenarios. Since noise effect is marginal, $\Omega^*(\lambda_a^*, W)$ almost linearly increases with W. We can finally assess *attainable* mean area throughput density of 5 GHz $\Omega_{max}^*(\lambda_a^*, W_{max})$ in three scenarios when using the maximum channel bandwidth $W_{max} = 480$ MHz. However, the slope of three lines is significantly different due to distinct propagation conditions. For instance, the office has five times more capacity than LoS due to increased spatial reuse and reduced interference by walls.

C. *Wall Sensitivity and Attainable User Throughput $\bar{R}_{max}^*$*

Indoor partition materials and dielectric properties vary widely as well summarized in [7], making it difficult to generalize the indoor wall loss. Thus, the mean wall loss is one of important study parameters to be investigated since it may strongly influence the interference emission. Fig. 6

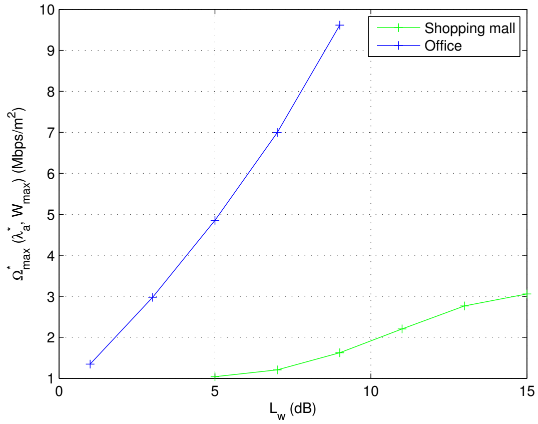

Fig. 6. Attainable mean area throughput density $\Omega^*_{max}(\lambda^*_a, W_{max})$ according to mean wall loss L_w.

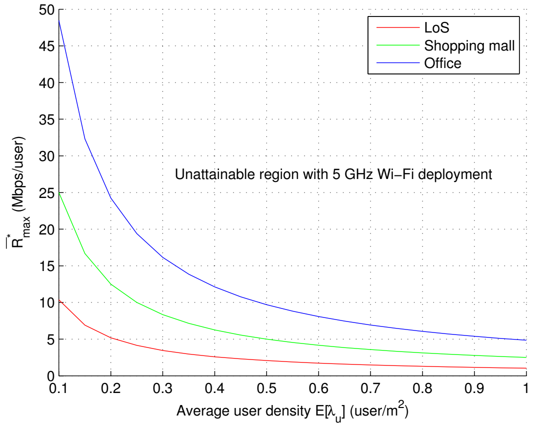

Fig. 7. Attainable throughput per user $\bar{R}^*_{max}$ as a function of average user density $E[\lambda_u]$ (user/m^2) in three scenarios.

provides the sensitivity of Ω^*_{max} according to L_w. It shows that even a few dB difference considerably changes Ω^*_{max}. For instance, 3 dB reduction in the office makes 40% drop of Ω_{max}. Similarly, 4 dB increase in the shopping mall makes 50% of capacity rise. For a given 5 GHz capacity Ω^*_{max}, actual user experience depends on the number of users who share the capacity. From Eq. (5), we can calculate *attainable* average throughput per user, namely as $\bar{R}^*_{max}$, from the estimated Ω^*_{max}. Fig. 7 shows $\bar{R}^*_{max}$ as a function of user density $E[\lambda_u]$. Due to the fundamental limit on dense Wi-Fi network capacity, we can find that there is an unattainable user throughput region above each curve in the figure.

V. CONCLUSION

We quantified attainable capacity and average throughput per user by fully exploiting Wi-Fi 5 GHz channels when both 802.11ac PHY features and Wi-Fi densification are considered. For this, we estimated ideal mean area throughput density as a function of deployment density and available channel bandwidth. Results showed that the substantial level of user data rates can be ideally supported by 5 GHz Wi-Fi deployment mainly due to large spectrum availability, especially in an office scenario with many walls. However, densification did not much contribute the capacity expansion because of limited spatial reuse enforced by carrier sensing mechanism in unlicensed band. This implies that small cellular deployment based on more advanced MAC is indeed required at the end for high-capacity services. Due to the prohibited complexity of dense network performance evaluation, we assumed perfect carrier sensing and no idle APs which led the optimistic estimate. As a next step, we need to validate our estimates by comparing them with packet-level simulations.

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