On Stochastic Geometry Modeling of WLAN Capacity with Dynamic Sensitive Control

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Abstract—**Recently, wireless local area networks (WLANs) have become ubiquitous. In high density WLANs, interference resulting from neighbor cells is a challenging problem which would affect the network performance. To get higher throughput, it is important to improve spatial reuse of the channels. Since transmit power control (TPC) may cause asymmetric links unless carefully designed, we demonstrate that dynamic sensitive control (DSC) can be used to improve capacity in dense environment. In order to reduce the influence of inter-cell interference and achieve fairness, an adaptive DSC scheme is proposed to provide the edge users with higher clear channel assessment (CCA) threshold. The CCA adaptation strategy for access point (AP) is presented as well, and a stochastic geometry model is introduced in this paper. Coverage probability and average throughput derived based on the analytical model are used to measure the network performance. Furthermore, simulations show that the proposed DSC method can provide considerable performance improvement compared with the existing methods.**

I. INTRODUCTION

Wireless local area networks (WLANs) based on the IEEE 802.11 standards [1] have become ubiquitous and are expected to increase throughput in urban networks. The low cost of IEEE 802.11 based devices has caused a dramatically increase of the density of wireless networks. Meanwhile, high density wireless networks would reduce the number of users associated to each access point (AP) while providing higher data rates for each nodes, so dense deployment has been a deliberate design choice. However, the high density of APs can easily lead to poor performance due to increasing levels of interference among nodes employing the same channel. Since the number of orthogonal channels that WLAN devices can operate on is limited, the co-channel interference between neighbor cells has become one of the biggest challenges to network capacity and efficiency.

Interference modeling is important in WLANs, which can be used to optimize the performance parameters such as the clear channel assessment (CCA) threshold value, transmit power and network throughput. However, the aggregate mutual interference is not easy to predict because WLANs interact with each other in complex ways. Nodes compete with each other for the access to the medium as well as create interference. Stochastic geometry is a powerful tool that can be used to analyze and obtain the performance metrics of wireless networks in a statistical manner [2]. Dense carrier-sense multiple access (CSMA) network with aggregate interference can be analyzed by stochastic geometry [3]-[4], where some interactions via the distributed coordination function (DCF) function are simplified and the effect of interference is taken into consideration.

The aim of this paper is to provide a new approach to enhance the performance of the IEEE 802.11 WLANs in dense environment. Meanwhile, the performance should be evaluated based on a practical mathematical model. Increasing spatial reuse is an efficient way to improve capacity. Transmit power control (TPC) and dynamic sensitive control (DSC) are both useful and easy methods to reduce interference damage and to maximize spatial reuse. TPC method tunes the transmit power of APs and decrease the cover area of each AP, in order to decrease the overlapping area. DSC changes the CCA threshold which can control the sensing area and ignores some interference to improve simultaneous links.

The benefits of TPC for interference mitigation have been well-documented in the area of cellular networks. However, in WLANs, not every user has its dedicated frequency. Surveys of typical protocols have shown that the default transmission power level of AP would cause severe interference [5]. Reducing transmit power, suggested by [6], can remove the redundancy in transmit power. However, the use of different power levels of APs may lead to starvation because of asymmetric links [7]. The asymmetry influences the fairness and degrades the performance of the whole network [8], so TPC should be carefully deployed and applied on all nodes in WLANs.

Dynamic sensitive control, also called CCA adaptation, can achieve the same results as TPC without bringing in asymmetry links. Meanwhile, a DSC adopted network can work with legacy networks and reduce hidden connected stations (STAs). CCA mechanism which checks whether the channel is busy or idle is proposed by the IEEE 802.11 standard, and the decision is made based on the CCA threshold [9]. In [10], the collision prevention method is to keep the product of the transmit power and the carrier sense threshold of the sender equal to a fixed constant. The disadvantages of power control in 802.11 networks are studied in [11]. A distributed algorithm which joints optimization of transmit power and carrier sensing threshold is proposed as well [12]. However, both of the

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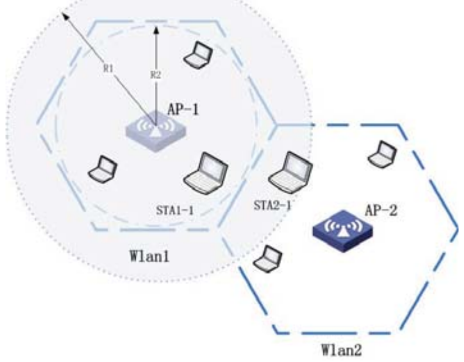

Fig. 1. The downlink relay-assisted cellular network model.

schemes take a long time to converge, and new method which is easy to implement and costs less resource should be developed.

In this paper, we propose an adaptive scheme which allows each STAs configure its CCA threshold based on the Received Signal Strength (RSS) of the associated AP beacon. Then the performance of the entire network is evaluated based on the stochastic geometry model.

The rest of this paper is organized as following. In Section II the system model is presented. In Section III, we analyze the coverage probability and estimate the average throughput obtained on each downlink and uplink. DSC algorithm is given in IV. Then, simulation results are gathered in V. Finally, we conclude the paper in Section VI.

II. SYSTEM MODEL

In this paper, we consider an IEEE 802.11 based wireless network where the APs and STAs are distributed according to independent Homogeneous Poisson Point Process (HPPP) Θ_A and Θ_S with densities λ_A and λ_S in the Euclidean plane, respectively. Each STA connects to the closest AP and has coverage of a circular area with radius R. That is to say, each STA located in the Voronoi cell of a AP is associated with the AP. In this paper, a cell represents a Basic Service Set(BSS) which contains only one AP and its associated STAs. STAs are divided into two kinds according to their positions. One is cell center STAs (CCS), i.e. those STAs which are located close to the APs and experience higher RSS. The other kind is cell edge STAs (CES), which would face severe interference from neighbor cells. The interference would significantly decrease the edge STAs throughput and even result in STA outage. The distance between the STA and its targeted AP r follows the pdf $f_r(r) = 2\pi r\lambda_A exp(-\pi\lambda_A r^2)$.

In dense environment, protocols used currently such as CSMA/CA would stop simultaneous transmissions in adjacent cells, which results in low reuse level. In this part, we take an example to demonstrate the effect of modifying CCA threshold. In Fig. 1, there are two neighbor cells WLAN1 and WLAN2, sharing the same channel. Radio signal from AP-1 arrives at STA2-1 with RSSI greater than CCA threshold and vice versa, where AP-1 is the AP in WLAN1 and STA2-1 represents one STA in WLAN2. Accordingly, AP-1 will sense the channel as being busy when AP-2 transmits to STA2-1. Since most important data is transmitted in downlink, the previous fact is very harmful for cell-1. However, if the CCA threshold of AP-1 increases (represented by the sensing range from $R1$ to $R2$), the concurrent transmissions for the two links are permitted and the spatial reuse is improved. The neglected weak transmit signals remain in the networks as interference and affect the SINR of the reception.

A. Distributions of APs and STAs

In our system, suppose the area of a AP Voronoi cell is S. From the Gamma distribution $\Gamma(K) = \int_0^\infty x^{K-1}\exp(-x)dx$ with factor $K = 3.575$ [13], the pdf of S can be approximate represented as

$$f(S) = {\lambda_A}^K \frac{K^K}{\Gamma(K)} S^{K-1}\exp(-K\lambda_A S). \qquad (1)$$

Since STAs are distributed according to a HPPP Θ_S with intensity λ_S, the STAs' number N_S in a Voronoi cell with an area of S follows the Possion distribution. Then the discrete probability density function of N_S can be written as

$$p\{N_S = k\} = \int_0^\infty \frac{(\lambda_S S)^k}{k!} exp(-\lambda_S S) f(S) dS. \qquad (2)$$

Since APs are distributed according to HPPP with density λ_A, the APs' number in the coverage area of a sensing range is given by

$$p\{N_A = k\} = \frac{(\lambda_A \pi R_{th}^2)^k}{k!}\exp(-\lambda_A \pi R_{th}^2). \qquad (3)$$

where R_{th} is the radius of sensing range and is derived in the following subsection.

B. Signal-to-Interference-Plus-Noise Ratio (SINR) Model

We use a propagation model to simulate the attenuation of the transmitted signal [15]. The power received at y from a transmitter x is given by $P_y^x = P_{tx} l(x,y) h(x,y)$, where P_{tx} is the transmit power. In this paper, all APs are assumed to transmit with the same power P_A, while each STA has a fixed transmit power P_S. $l(x,y)$ is the path-loss which decays with the increase of distance between transmitter and receivers. Suppose that the path-loss is given by: $l(x,y) = Kr(x,y)^{-\alpha}$, where $r(x,y)$ is the Euclidean distance between x and y. $K = \frac{c}{4\pi f_c}$ represents the propagation constant where c is the radio propagation speed and f_c is the carrier frequency. [14]. α is the path-loss exponent and its value depends on the environment ($\alpha > 2$). $h(x,y)$ is a random variable accounting for the channel gain between the transmitter and receiver. In this paper, we assume the channels experience independent Rayleigh fading, i.e., $h \sim exp(1)$.

The long-term SINR is defined as the ratio between the long-term received power from a targeted transmitter and the sum of the long-term received power from all the interfering transmitters plus noise. For example, if a STA is the transmitter, the intended receiver is the associated AP (Uplink). Conversely, if an AP is the transmitter, the intended receiver is one of the STAs associated with it (Downlink).

$$\mathrm{SINR} = \frac{PhKr^{-\alpha}}{I_{agg} + \sigma^2}, \tag{4}$$

where I_{agg} is the aggregate interference power at the receiver, and σ^2 is the variance of the background noise.

C. Interference Modeling

In WLANs, transmitters contend for the access to the shared wireless channel with their neighbor nodes. In order to reduce collision, node senses the spectrum channel before transmitting its own packet. If the signal power on this channel is bigger than a given threshold γ, the channel is reported busy, and the transmit node postpones its transmission until the channel is clear. According to the assumed propagation model, the sensing range of each node can be translated into the contention domain around each transmitter where other nodes cannot transmit data simultaneously. Assume that a generic node x has a contention domain L_x from which beacon frames of APs are received. If deterministic channel gains are given, the minimum exclusion distance between the network elements using the same channel is given by $R_{th} = d_0(\frac{P_t K}{\gamma})^{\frac{1}{\alpha}}$, where d_0 is the reference distance (1 m). In this paper, we assume the nodes located in a contention domain are associated node. The associated nodes can not transmit data when the channel is occupied, so interference is caused by the un-associated nodes which are apart from the receiver with distances larger than R_{th} .

The un-associated domain Ω contains N_{BSS} BSSs. According to CSMA/CA protocol, the contention among the STAs and the AP within each BSS should be considered, which means that at most one node can transmit in one BSS at a time. We assume that all the nodes in a BSS, both APs and STAs, working on the same channel and compete to access the channel with equal probability. The only node which has accessed the channel successfully is called the active node in its BSS cell. For each receiver AP or STA in the n-th BSS, the interfering transmitters are defined to be the active nodes located in the un-associated BSSs. Therefore, the long-term average aggregate interference (received at each AP or STA at all BSSs) for uplink is explicitly defined as:

$$I_{agg\_UL} = \sum_{k=1,k\neq n}^{N_{BSS}} \frac{1}{1+N_{S\_k}} \Big(P_{AP-n}^{AP-k} + \sum_{i\in\Omega(k)} P_{AP-n}^{STA-i}\Big), \tag{5}$$

Where N_{S_k} represents the STA number in the k-th BSS. Similarly, the long-term average aggregate interference for downlink is given by

$$I_{agg\_DL} = \sum_{k=1,k\neq n}^{N_{BSS}} \frac{1}{1+N_{S\_k}} \Big(P_{STA-m}^{AP-k} + \sum_{i\in\Omega(k)} P_{STA-m}^{STA-i}\Big), \tag{6}$$

III. DYNAMIC SENSITIVE CONTROL

In order to determine whether the wireless medium is busy or not, the node which has a packet to transmit would perform CCA firstly. The goal of DSC via CCA threshold tuning is to permit simultaneous transmissions that will not violate receiver performance, in order to maximize spatial reuse.

Schemes which can improve the system performance through changing the carrier sensing threshold have been proposed in some literatures. However, most of them use the average duration of different states to tune the threshold, which is not easy to implement since they would take a long time to coverage and improve computation complexity. In IEEE 802.11 based WLANs, Beacon frame is one of the management frames which contains all the information about the network. Beacons are transmitted periodically by the AP to announce the presence of a WLAN. We develop a CCA adaptation method by receiving and calculating the information accompanied with the beacon frame. Furthermore, This method can be used not only on the downlink, but APs can use beacon to adjust their CCA threshold.

The CCA adaptation method is illustrated in Algorithm 1. The method begins by identifying which STAs are edge STAs and central STAs, and the threshold tuning is adopted only by the CES. The reason is that a CCS usually has a much higher SINR compared with a CES. If a CCS changes its CCA threshold according to the RSSI, the threshold value may become extreme high, and even the transmit data from the nodes located in the same BSS with the CCS will be ignored which may lead to collision and asymmetry.

Algorithm 1 The Dynamic Sensitive Control Algorithm

```
for each AP do
    Transmit Beacon at regular intervals;
end for
for each BSS $x$ do
    for each STA in the $x^{th}$ BSS do
        if $SINR > \tau$ then
            STA is a cell center STA (CCS);
        else
            STA is a cell edge STA (CES);
        end if
    end for
end for
for all CESs do
    Start a counter $N$ ;
    if $N < N_T$ then
        STA collects Beacons and calculates average RSSI $P_{RS1}$,
        $N = N + 1$ ;
    else
        STA sets its CCA threshold $\gamma_S = P_{RS} - M_1$, $N = 0$ ;
    end if
end for
for all APs do
    Start a counter $N$ ;
    if $N < N_T$ then
        AP collects Beacons from the associated APs and choose
        the minimum RSSI to calculates the average RSSI $P_{RS2}$,
        $N = N + 1$ ;
    else
        STA sets its CCA threshold $\gamma_A = P_{RS2} - M_2$, $N = 0$ ;
    end if
end for
```

To ensure coverage and link relationship, management frames such as beacons are transmitted first. Information such as link quality, neighboring relationship among APs are collected by the receive nodes. A counter is used to record received Beacons' number, and we collect N_T Beacons to calculate the average RSSI P_{RS1} (dB). Then, the CCA threshold γ is given by P_{RS} and margin M_1 (dB). The CCA tuning method for AP is similar to that for STA. Each AP records all the Beacons received from associated APs in its contention domain. It choose the minimum RSS to calculate the CCA threshold. The minimum RSS is from the farthest AP. Margin M_2 should be indicated according to the APs densities. A denser deployment of AP should be equipped with a smaller margin value. The radius of the contention domain for each node is given by

$$R'_{th} = \begin{cases} d_0(\frac{P_A K}{\gamma_S})^{\frac{1}{\alpha}} & \text{if the receiver is a CES;} \\ R_{th} & \text{if the receiver is a CCS;} \\ d_0(\frac{P_S K}{\gamma_A})^{\frac{1}{\alpha}} & \text{if the receiver is an AP.} \end{cases}$$

IV. PERFORMANCE ANALYSIS

In this part, the coverage probability is derived firstly. Then, the long-term average throughput expression is obtained to measure the effectiveness of DSC method.

A. Coverage probability

The coverage probability is defined as the probability that the SINR at the receiver is equal to or larger than a quality-of-service (QoS) threshold Γ and can be written as

$$P_c(\Gamma) = \mathbb{P}(\text{SINR} \geq \Gamma). \tag{7}$$

The coverage probability can be defined as the probability that a random receiver can reach the SINR threshold Γ, as well as the fraction of the covered area in the wireless network . In this paper, we assume a STA is in coverage when its SINR from the nearest AP is equal to or larger than the threshold Γ and vice versa.

1) Coverage probability for the AP-STA link: We assume that STAs are distributed according to HPPP with density λ_S. If the SINR threshold at the receiver is Γ_S, and the transmit power from the AP to STA is P_A, according to equation (4), the coverage probability for a AP-STA downlink is given by

$$\begin{aligned} P_c = \pi\lambda_A \int_{v>0} & exp(-\pi v(\lambda_A(1+\rho(m\Gamma_\text{S},\alpha)))) \\ & \times exp(-\pi v \lambda_S \rho(\frac{mP_\text{S}\Gamma_\text{S}}{KP_\text{A}},\alpha)) exp(\frac{-\Gamma_\text{S} v^{\alpha/2} N_0}{KP_\text{A}}) dv, \end{aligned} \tag{8}$$

where

$$\rho(\Gamma_\text{S},\alpha) = \Gamma_\text{S}^{\alpha/2} \int_{(R'_{th}/r)^2 \Gamma_\text{S}^{-\alpha/2}}^{\infty} \frac{1}{1+t^{\alpha/2}} dt, \tag{9}$$

and $m = \frac{1}{1+N_S}$.

Beacuse of the CSMA/CA scheme, transmitters within the contention domain area would stay silence when the channel is busy. The contention domain determined by the CCA threshold can be represented by a circle of radius R'_{th}. So, the integration limits are from R'_{th} to ∞. The details of the derivation can be found in [16] and we just provide some key steps in this paper (see Appendix).

2) Coverage probability for the STA-AP link: Similarly, for the STA-AP link, the coverage probability is

$$\begin{aligned} P_c = \pi\lambda_A \int_{v>0} & exp(-\pi v(\lambda_A(1+\rho(\frac{mP_\text{A}\Gamma_\text{A}}{KP_\text{S}},\alpha)))) \\ & \times exp(-\pi v \lambda_S \rho(m\Gamma_\text{A},\alpha)) exp(\frac{-\Gamma_\text{A} v^{\alpha/2} N_0}{KP_\text{S}}) dv, \end{aligned} \tag{10}$$

where

$$\rho(\Gamma_\text{A},\alpha) = \Gamma_\text{A}^{\alpha/2} \int_{(R'_{th}/r)^2 \Gamma_\text{A}^{-\alpha/2}}^{\infty} \frac{1}{1+t^{\alpha/2}} dt. \tag{11}$$

B. Throughput Analysis

In this section, we estimate the average long term throughput obtained by a tagged STA of a typical BSS on the downlink. Meanwhile, the average throughput that can be achieved by an AP is used to measure the uplink performance. The average throughput depends on three factors. (i) The fraction of time that the AP acquires the channel which is determined by the nodes density within the contention domain. (ii) The way channel is shared among all the STAs served by the AP. (iii) The quality of the wireless link from the AP to the user, which is determined by the coverage probability.

In a BSS, STAs are assumed to transmit with equal opportunities in a long term under the CSMA mechanism, irrespective of their distance from the AP. The SINR value determines the instantaneous transmit rate and modulation scheme according to a piecewise constant function $f(x)$, which is shown in Table 1 for 802.11 a/g.

TABLE I
INSTANTANEOUS RATE FOR DIFFERENT SINR .

Index	1	2	3	4	5	6	7	8
SINR(dB)	6	8.6	9.2	12	13.6	18.2	22	24
Rate(Mbps)	6	9	12	18	24	36	48	54

AP x is assumed to be always granted transmission. The average time taken to transmit 1 bit in the BSS x is

$$t_x = \frac{\sum_{y \in V_x} 1/f(SINR(x,y))}{N_{V_x}}, \tag{12}$$

where V_x represents the STA nodes set located in the Voronoi cell of x (BSSx) and y is one of the STA node. N_{V_x} is the number of the STAs in the domain V_x. The coverage probability $P_c(\Gamma)$ can be defined as the area in which STAs can receive SINR higher than Γ. If $6 \leq \Gamma < 9$, the number of STAs that can transmit with data rate 6Mbps is given as $N_{V_x} \times (P_c(6) - P_c(8.6))$.

The average throughput of any user in the cell would be the inverse of the last expression. AP x competes with the active nodes in its contention domain. We take not only APs but also users that work on the same channel into consideration. Each BSS can only has at most one active node, and the active nodes access the shared medium with a frequency due to CSMA/CA. In this paper, we assume that each active node has the same

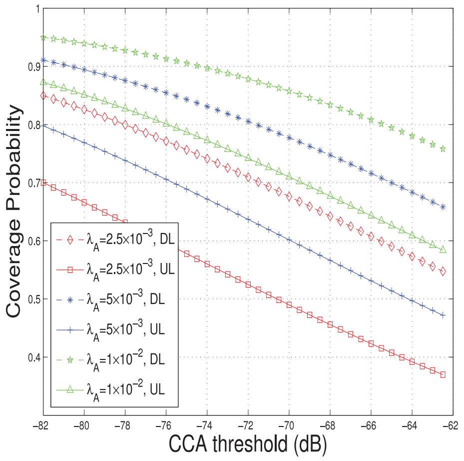

Fig. 2. Coverage Probability vs. CCA threshold for different density of APs.

access chance. Then, the throughput that can be achieved by x is given by

$$T_x = 1/\sum_{k\in L_x} t_k, \tag{13}$$

where L_x is denoted by the adapted CCA threshold.

V. SIMULATION RESULTS

In this section, system simulations are carried out to study the performance of the proposed method. Table 1 shows the default simulation parameters of the system model. According to the radio propagation fading model, the coverage probability at each node can be calculated, and the average throughput can be obtained by the derived function.

TABLE II
SYSTEM PARAMETERS

Parameter	Value
λ_A, λ_S	$2.5\times10^{-3}m^{-2}$, $10^{-2}m^{-2}$,
α	3.67
M_1,M_2	15dB,15dB
Γ_S, Γ_A,	6dB, 6dB
σ^2	-60dBm
P_{AP}, P_{STA}	25dBm, 20dBm

A. Impacts of changing the value of CCA threshold

Fig. 2 shows how the coverage probability varies with the CCA threshold for different APs' densities in different links. It can be seen from the figure that the coverage probability decreases with the increase of CCA threshold. Besides, the coverage probability of downlinks is larger.

Figure 3 shows the effect of the CCA threshold on the average throughput. As the CCA threshold increases, the average throughput also increases, and vice versa.. We observe that the average throughput increases with the density. Combined with the trend in Figure 2, we can conclude that the increase of CCA threshold would decrease the area covered by each link. However, smaller sensing range brings in less competitions nodes, and exposed nodes can transmit simultaneously which are forbidden by the DCF rules. The figure also shows that throughput of uplink transmissions grows faster than those of downlinks.

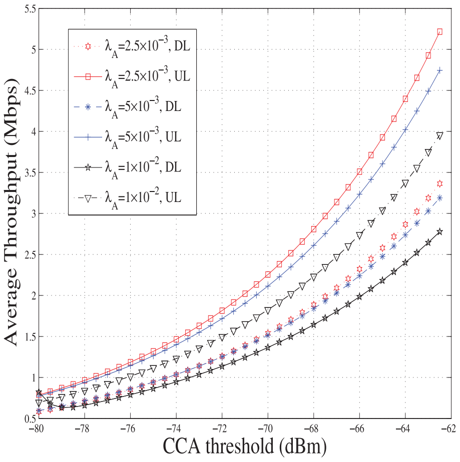

Fig. 3. Average Throughput vs. CCA threshold for different density of APs.

B. Performance Comparison

As shown in Fig. 4 and Fig. 5, increasing concurrent transmissions via DSC result in throughput improvement in both directions over the legacy network with default CCA threshold. As the density of AP increases, average throughput of legacy network remains almost static. The dense deployment with AP can lead to higher throughput in partial links, but the total transmit ability is limited according to the existing protocol. The proposed algorithm performs almost two times better compared with the default method in the uplink, and the DL transmission gets 2.5 times as much throughput as the legacy network. That is to say, the proposed algorithm creates more chances for concurrent transmissions and spatial reuse.

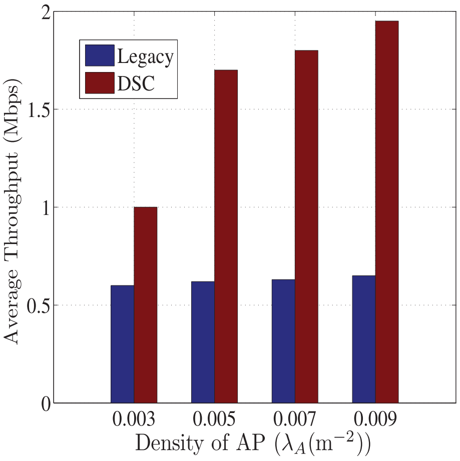

Fig. 4. Comparison of uplink average throughput.

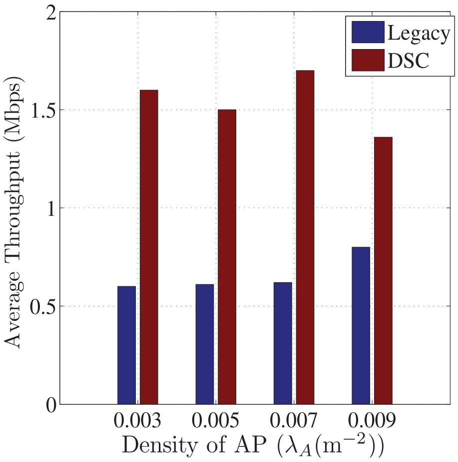

Fig. 5. Comparison of downlink average throughput.

VI. CONCLUSIONS

In this paper, we investigated a dynamic sensitive control method. It has been shown that the proposed CCA tuning method can improve spatial reuse via reducing the contention range. In addition, a stochastic geometry model was used theoretically to analyze the performance of 802.11 network and indicate the influence of CCA adaptation. Analytical expressions of coverage probability and average throughput were both derived based on the model. Numerical results showed that a DSC adopted WLAN can provide up to almost 300% of gain in capacity. The work in this paper sheds a useful insight into the practical design of high density WLANs.

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APPENDIX

The coverage probability of downlink is given by

$$\begin{aligned} p_c &= \mathbb{P}(\frac{KP_{\mathrm{A}}h_0 r^{-\alpha}}{I_r+\sigma^2} \geq \Gamma_{\mathrm{S}}) \\ &= \int_0^\infty \mathbb{P}(h_0 \geq \frac{\Gamma_{\mathrm{S}} r^\alpha (I_r+\sigma^2)}{KP_{\mathrm{A}}}|r) f_r(r)dr \\ &= \int_0^\infty exp(\frac{-\Gamma_{\mathrm{S}} r^\alpha \sigma^2}{KP_{\mathrm{A}}}) \mathcal{L}_{I_r}(\frac{\Gamma_{\mathrm{S}} r^\alpha}{KP_{\mathrm{A}}}) f_r(r)dr, \end{aligned} \tag{14}$$

where $L_{I_r}(s)$ represents the Laplace transform of I_r. In our system, interference received by one STA is from all un-associated active nodes. $L_{I_r}(s)$ can be derived from the definition of Laplace transform, evaluating at $s = \Gamma_{\mathrm{S}} r^\alpha / P_{\mathrm{A}}$. Hence,

$$\begin{aligned} \mathcal{L}_{I_r}(s) &= \mathbb{E}_{I_r}(\exp(-sI_r)) \\ &= \exp(-2\pi\lambda_A \int_{R_{th}}^\infty (1 - \frac{1}{1+smP_{\mathrm{A}}v^{-\alpha}})vdv) \\ &\times \exp(-2\pi\lambda_S \int_{R_{th}}^\infty (1 - \frac{1}{1+smP_{\mathrm{S}}u^{-\alpha}})udu), \end{aligned} \tag{15}$$

where $m = \frac{1}{1+N_S}$. We assume $l = \frac{P_{\mathrm{S}}}{P_{\mathrm{A}}}$. The last step can be derived from the probability generating functional(PGFL) of the PPP, which for some function such as $g(x)$, there exists

$$\mathbf{E}[\prod_{x\in\Theta} g(x)] = \exp(-\lambda \int_{\mathbb{R}^2} (1-g(x))dx), \tag{16}$$

where λ represents the density of the interference node.