Improved Spatial Reuse for Dense 802.11 WLANs

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***Abstract*—Next generation 802.11 networks aim to significantly increase spectral frequency reuse and manage interference between neighboring Overlapping Basic Service Sets (OBSS) in scenarios with a high density of both STAs and APs . In this paper, we study the theoretical throughput gains that may be obtained by using ideal spatial reuse in a densely occupied two-BSS network operating in saturated uplink traffic conditions (i.e. the transmission queue is never empty). We then compare the theoretical throughput gains with the gains obtained by implementing a practical spatial reuse technique in a residential scenario [6] using a discrete event simulator that integrates both the PHY and the MAC [7]. Our results show that the trends identified in the simple analysis are present in the empirical simulation and demonstrate that the gains obtained may depend on the scenario. We also conclude that additional spatial re-use techniques may be needed to extract all the gains promised by the theoretical analysis.**

***Index Terms*— 802.11, CCA, DSC, TPC, hidden node, exposed node, spatial reuse node, DCF, CSMA/CA, performance evaluation**

I. Introduction

An exponential increase in the demand for data services is driving an increase in the throughput and coverage requirements for Wireless Local Area Networks (WLANs) [1] and an evolution towards high-density deployments such as residential buildings, enterprise networks and indoor/outdoor hotspots. Based on these requirements and use cases, the IEEE 802.11ax Task Group (TGax) is currently considering MAC and PHY technologies that among other things will (a) make more efficient use of spectrum resources in scenarios with a high density of stations (STAs), and (b) significantly increase spectral frequency reuse and manage interference between neighboring Overlapping Basic Service Sets (OBSS) in scenarios with a high density of both STAs and APs [2]. Within the task group, a spatial reuse Ad hoc group has been constituted to evaluate technologies to improve spatial re-use in these dense networks [3]. In this paper, we study the effect of ideal and practical spatial reuse methods on the throughput performance of dense networks.

II. Background

In WLAN networks, the 802.11 basic access DCF is based on the CSMA/CA protocol in which a Clear Channel Assessment (CCA) procedure is used by STAs to determine if they are eligible to transmit in the medium [4]. In scenarios

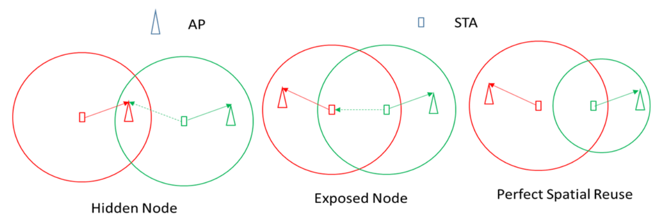

Figure 1: Hidden, exposed and spatial reuse nodes

where there is a collision due to multiple STAs simultaneously valuating the medium as idle, the STAs perform a binary exponential back-off procedure which will determine when they will retry access.

In dense networks, a STA may evaluate a channel as busy due to interference from other communication links even through the STA may be able to transmit to its designated receiver without impacting on those links. This is the exposed node problem. Alternatively, a STA may evaluate a channel as idle even when transmitting would impact the currently transmitting STA(s) negatively. This is called the hidden node problem [5]. Another set of nodes are able to transmit simultaneously without impacting the currently transmitting STA(s) negatively. These are called spatial reuse nodes. Smart CCA procedures may limit the effect of hidden and exposed nodes and enhance spatial re-use nodes in these networks.

In this paper, we compare the theoretical and empirical throughput performance gains that may be obtained by ideal and practical spatial reuse methods in high density deployments. Ideal OBSS spatial reuse occurs when a genie sets the reuse parameters to either prevent or allow all OBSS node transmission. Practical spatial reuse methods use techniques like clear channel assessment threshold adjustment to achieve the same purpose.

We study the theoretical throughput gains that may be obtained by using ideal spatial reuse in a densely occupied two-BSS network operating in saturated uplink traffic conditions (i.e. the transmission queue is never empty). We then compare the theoretical throughput gains with the gains obtained by implementing a practical spatial reuse technique in a residential scenario [6] using a discrete event simulator that integrates both the PHY and the MAC [7].

In [6], a Markov chain model for saturated traffic conditions in a single BSS is introduced and a throughput performance analysis is derived. This model is extended to a single BSS network in unsaturated traffic conditions and with hidden nodes in [7] and [8]. As opposed to the work in [8][9] and [10], we apply the hidden node analysis, based on saturated traffic to a dense, OBSS network model and demonstrate the gains that may be obtained through the use of ideal spatial re-use techniques.

The TGax spatial sharing group has proposed using Dynamic Sensitivity Control (DSC) and optional Transmit Power Control (TPC) to limit the occurrence of hidden and exposed nodes in dense networks [11][12][13]. Dynamic Sensitivity Control (DSC) uses STA-specific Clear Channel Assessment threshold adaptation to improve spatial re-use with TPC optionally used to improve upon this DSC gain [13]. A summary of DSC+TPC in 11ax/HEW may be found in [12] and a simulation study of DSC+TPC in residential, enterprise and BSS hotspot scenarios may be found in [11]. We implement DSC and DSC + TPC using a discrete event simulator that integrates both the PHY and the MAC [7] and compare the results to the theoretical gains.

Our results show that the trends identified in the simple analysis are present in the empirical simulation and demonstrate that the gains obtained may depend on the scenario or geometry assumed. We also conclude that additional spatial re-use techniques may be needed to extract all the gains promised by the theoretical analysis.

The paper is organized as follows: in Section III, we present the theoretical system model, introduce the analysis and obtain numerical results. In Section IV, we present the empirical system model and present simulation results. In section V, we compare the theoretical and empirical results and we conclude in Section VI.

III. Theoretical Performance Analysis

In this section, we will study the uplink throughput performance of a simple two-BSS network operating in saturated traffic conditions. In [8], a throughput analysis is derived for a single BSS in an 802.11 DCF network with saturated traffic. The work is extended in [9] to incorporate hidden and contending nodes. In this paper, we will apply the analysis to the OBSS scenarios (with different spatial reuse profiles) discussed in Section III.A and demonstrate the gains achievable by using optimal ideal spatial reuse over poor spatial reuse. The results obtained here will serve as a guideline in designing practical spatial reuse schemes.

A. System Model

We will use the term myBSS to describe the primary BSS and the term OBSS to describe the overlapping BSS. We will assume ideal myBSS CSMA/CA in which a genie sets optimal parameters to prevent multiple myBSS nodes from transmitting simultaneously. As such there are no hidden nodes within a BSS.

Two questions arise in modeling this system: (1) is there interference at the myBSS AP from an OBSS node transmission? This is based on the AP receiver sensitivity and the proximity of the OBSS nodes to the myBSS AP (2) Do the OBSS nodes defer or contend for the medium if there is a transmission in myBSS? This is based on the OBSS spatial reuse settings. We will assume ideal OBSS spatial reuse in which a genie sets optimal reuse parameters to either prevent or allow all OBSS node transmission. As an example, the genie may set the optimal values of the CCA threshold and transmit power for all nodes in the OBSS to either have all OBSS nodes defer their transmission or contend for transmission with the myBSS nodes.

Note that the interaction between the interference and the deferral behavior determines if we have exposed nodes, hidden nodes or spatial reuse nodes. We identify four distinct and illustrative scenarios (S1, S2, S2 and S4) as shown below in Table 1.

Scenario	BSS	Interference at myBSS AP	Deferral
	myBSS	Yes	Yes
S1	OBSS	Yes	No
S2	OBSS	Yes	Yes
S3	OBSS	No	Yes
S4	OBSS	No	No

Table 1: Analysis Scenarios

Scenario S1: Any UL transmission in the OBSS would cause interference at the AP in myBSS. However, any STA in the OBSS CANNOT sense the medium as busy due to transmission in myBSS (and vice versa). Scenario S1 exemplifies poor spatial reuse settings and results in OBSS hidden nodes in both myBSS and the OBSS.

Scenario S2: Any UL transmission in the OBSS would cause interference at the AP in myBSS and any STA in the OBSS CAN sense the medium as busy due to transmission in myBSS (and vice versa). Scenario S2 exemplifies perfect spatial reuse and results in myBSS and OBSS nodes contending for the channel and deferring to each other as they should.

Scenario S3: Any UL transmission in the OBSS would have no impact at the AP in myBSS. However, any STA in the OBSS CAN sense the medium as busy due to transmission in myBSS (and vice versa). Scenario S3 exemplifies poor spatial reuse and results in exposed nodes in both myBSS and the OBSS (in practice S3 may result from the CCA threshold being set too low).

Scenario S4: Any UL transmission in the OBSS would have no impact at the AP in myBSS and any STA in the OBSS CANNOT sense the medium as busy due to transmission in myBSS (and vice versa). Scenario S4 exemplifies perfect spatial reuse and results in myBSS and OBSS nodes spatially sharing the medium.

We will estimate the throughput of these four scenarios to quantify the effect of ideal spatial reuse on system throughput.

B. Throughput Analysis

In [8], the network throughput is calculated as the number of bits transmitted in an average slot time and is given by [9]

$$S = (P_s P_{tr} E[P])/T \qquad (1)$$

where P_{tr} is the probability that there is at least one frame in the considered slot time, P_s is the probability that a transmission occurring on the channel is successful, $E[P]$ is the average packet payload size in bits and T is the average slot time. The average slot time is given by

$$T = (1 - P_{tr})\sigma + P_{tr}[P_s T_s + (1 - P_s)T_c] \qquad (2)$$

where σ is the duration of an empty slot time, T_s is the expected duration for a successful packet transmission and T_c is the expected duration of a collision. We estimate T_s and T_c for basic CSMA/CA access (shown in Figure 2 below) [8]

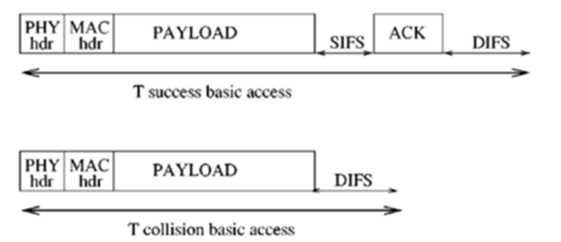

Figure 2: Basic Access Frame Exchange

Assuming zero propagation delay and equal packet lengths,

$$T_s = PHY + MAC + E[P] + SIFS + ACK + DIFS \qquad (3)$$

$$T_c = PHY + MAC + E[P] + DIFS \qquad (4)$$

In [9], P_{tr} and P_s are extended from the formulation in [8] to incorporate the presence of hidden (h) and contending (c) nodes as

$$P_{tr} = 1 - (1 - \tau)^n, P_s = \frac{n\tau(1-\tau)^{c-1+hk}}{1-(1-\tau)^n} \qquad (5)$$

where n is the total number of STAs (both hidden and contending) on the channel, τ is the probability that a STA transmits in a randomly chosen time-slot and k is the average slot decrements in period of time when another STA may start a transmission that would collide with the current transmission i.e. $k = 2T_s / T$. P_s is estimated as the probability that exactly one STA transmits on the channel, conditioned on the fact that at least one STA transmits [8].

The probability that a STA transmits in a randomly chosen time-slot, τ, is derived from the Markov chain model for 802.11 DCF in [8] as

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1)+p(W(1-(2p)^m)} \qquad (6)$$

where $W = CW_{min}$ is the minimum set for the binary exponential back-off window size in slots in the 802.11 DCF, m is the maximum back-off stage such that $CW_{max} = 2^m W$ and p is the conditional collision probability (with c contending nodes and h hidden nodes in the network). For a STA transmitting, p is dependent on there being no contending STA transmitting in a generic slot and none of the hidden STAs transmitting during an actual packet delivery and is calculated as

$$p = 1 - (1 - \tau)^{c-1}[(1 - \tau)^h]^k \qquad (7)$$

Thus, for specific parameters such as total number of STAs, number of hidden nodes, number of contending nodes, packet size etc, a non-linear equation in τ and p is solved using numerical techniques and the system throughput T is calculated. We will represent this throughput as *TP(c,h)*.

Assuming that the number of STAs in myBSS and OBSS are n1 and n2 respectively we can use the analysis above to estimate the throughput of the different networks. We assume each BSS has equal probability of transmitting data. Thus we can calculate the throughput for each BSS independently and then calculate the expected throughput.

Scenario S1: Given that myBSS is transmitting, there will be n1 contending nodes and n2 hidden nodes with $TP(n1, n2)$ and vice versa.

Scenario S2 and S3: As there are no hidden nodes, the two BSSs function as a single network with *n1+n2* contending nodes and no hidden nodes and $TP(n1 + n2,0)$ and vice versa.

Scenario S4: With perfect spatial sharing, each BSS functions as an independent BSS with n1/n2 contending nodes and no hidden nodes and $TP(n1,0)$ and vice versa.

Thus, the network system throughput is shown in the table below:

Scenario	Expected Throughput
S1	$0.5TP(n1, n2) + 0.5TP(n2, n1)$
S2	$0.5TP(n1 + n2,0) + 0.5TP(n2 + n1,0)$
S3	$TP(n1,0) + TP(n2,0)$
S4	$0.5TP(n1 + n2,0) + 0.5TP(n2 + n1,0)$

Table 2: System Throughput

C. Numerical Results

We show the throughput performances with the following parameters: MAC header size is 34 bytes, ACK size is 14 bytes, CW_{min} is 15, CW_{max} is 1023, slot time (σ) is 9 usecs, SIFS duration is 16 usec, DIFS duration is 34 usec and each BSS has 10 STAs. We sweep the results for packet sizes ranging from 0 bytes to 1500 bytes and assume a transmission data rate of 6 Mbps for both control. We show results for 6 Mbps and 65 Mbps data frames.

From the results in Figure 3 (6 Mbps data: bpsk, rate 1/2), we see a 478% gain of Scenario S2 over Scenario S1 at 1000 bytes obtained by eliminating the effect of OBSS hidden nodes. We see an 82% gain of Scenario S4 over Scenario S3 at 1000 bytes obtained by eliminating the effect of OBSS exposed nodes. From the results in Figure 4 (65 Mbps: 64 QAM rate, 5/6), we see a 600% gain of Scenario S2 over Scenario S1 at 1000 bytes and an 84% gain of Scenario S4 over Scenario S3 at 1000 bytes. This difference in gain is because the hidden nodes hurt the high throughput case more than the lower throughput case. The results show that eliminating the effect of hidden nodes results in a greater percentage gain in performance while incorporating exposed nodes to enable spatial sharing results in a greater absolute throughput.

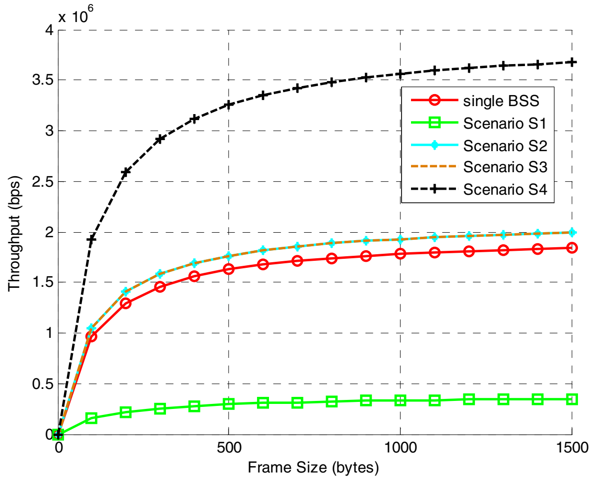

Figure 3: Saturated Throughput Performance (6 Mbps)

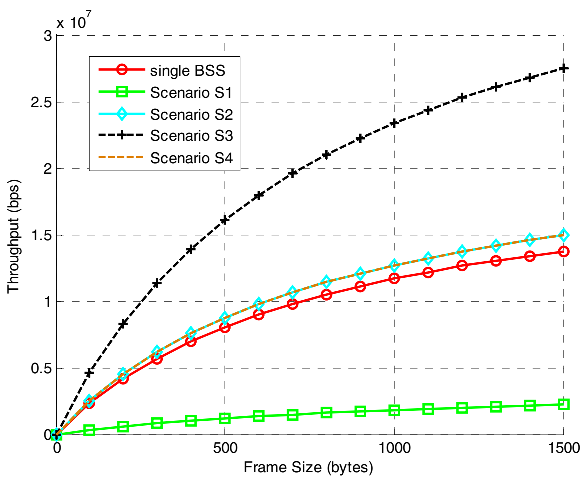

Figure 4: Saturated Throughput Performance (65 Mbps)

IV. Practical Simulation Performance

A. Practical Spatial Reuse: Dynamic Sensitivity Control with optional Transmit Power Control

In this section, we present practical spatial reuse methods based on adjusting the clear channel assessment threshold and study their performance in a realistic simulation scenario. The goal is to see if the gains observed in the analysis may be replicated in a realistic system. Note that the realistic system will have OBSS hidden nodes, exposed nodes and spatial reuse nodes. Also the real system uses realistic rate adaptation and traffic generation and so approximates full buffer traffic. As such, the results may only approximate the theoretical results from the previous section.

802.11 DCF basic access uses a clear channel assessment threshold to decide if the medium is idle or not. If a STA measures the energy in the channel and it exceeds the CCA threshold, the medium is assumed busy. However, if the energy measured is less than the CCA threshold the medium is assumed idle and the STA starts the binary exponential back-off process to transmit information on the medium.

In the current 802.11 standard [1], the CCA threshold is set to a fixed value for all STAs in the network, regardless of where they are located and regardless of the network scenario. However, it has been shown in [13] that by optimizing the transmit power and CCA threshold jointly, interference may be mitigated and network throughput increased. These ideas have also been adopted in the TGax spatial sharing group where Dynamic Sensitivity Control (DSC) and optionally Transmit Power Control (TPC) are under discussion as a method to limit the occurrence of hidden and exposed nodes and maximize the occurrence of spatial reuse nodes in dense networks [11][12][13].

The DSC algorithm used is based on ensuring that STAs close to the edge of the BSS have lower CCA thresholds while the optional TPC is set to ensure that the CCA threshold and transmit power are inversely proportional to each other as proved in [13] and shown below:

$$CCA\,(dBm) + TPC\,(dBm) = constant \quad (8)$$

We set the CCA threshold to

$$CCA = CCA_{nominal} + Margin \quad (9)$$

$$Margin = \frac{Path_{loss} - Path_{loss,min}}{Path_{loss,max} - path_{loss,min}} * CCA_{bias} \quad (10)$$

where $CCA_{nominal}$ is the minimum CCA threshold used by any STA in the network, $Margin$ is the STA specific margin that is used to modify the CCA threshold, $Path_{loss}$, $Path_{loss,max}$ and $Path_{loss,min}$ are the long term effective path loss of the STA under consideration, the STA with the largest effective path loss and the STA with the smallest effective path loss respectively and the CCA_{bias} determines the highest CCA threshold allowed in the network.

Note that with this formula, STAs far away from the edge of the BSS would have large CCA thresholds and be able to transmit with more interference in the channel, reducing OBSS exposed nodes and enhancing spatial reuse nodes while STAs close to the edge of the BSS would have low CCA thresholds and would limit their transmissions to when there is very little interference in the medium, reducing OBSS hidden nodes. This is similar to the ideal spatial reuse algorithm discussed in section III.A.

We may also use optional TPC with

$$tx_{power} = tx_{power,max} - Margin \quad (11)$$

where $tx_{power,max}$ is the maximum transmit power allowed and the $Margin$ is based on eqn (10). Note that with this formulation, the relationship between transmit power and CCA threshold is kept as proposed in [13].

We will look at the following schemes:

BSS based CCA: All nodes are set to the same CCA threshold with no TPC. In this case, all STAs set their CCA thresholds to $CCA_{nominal}$.

STA-specific CCA only: Each STA sets its CCA threshold based on eqns (9) and (10). The CCA threshold of the AP is set to the CCA threshold of the STA with the largest effective path loss.

STA-specific CCA with TPC: Each STA sets its CCA threshold based on eqns (9) and (10). The CCA threshold of the AP is set to the CCA threshold of the STA with the largest effective path loss. The transmit power of each STA is set based on eqn (11). The CCA threshold and transmit power of the AP are set to CCA threshold and transmit power of the STA with the largest effective path loss.

B. Simulation Assumptions

In this section, we present simulation results based on the three schemes discussed in Section IV.A. We use a Riverbed (OpNet) Modeler 17.5 simulator and model the residential scenario in TGax[6]. We have two scenarios:

S5: residential scenario with multiple apartments (BSSs) and no walls in-between the apartments. This models scenarios S1 and S2 in Section III.A.

S6: residential scenario with multiple apartments (BSSs) and walls in-between the apartments. This models scenarios S3 and S4 in Section III.A.

We simulate an apartment building with 1 floor and 2 rows of 10 apartments per floor. Each apartment is 10m x 10m with 1 AP placed in each apartment. 5 STAs are randomly placed within each apartment in each 1 of 10 drops. We will assume a TGn Channel B path loss model, and a wall / floor penetration loss model given by

$$PL(d) = 40.05 + 20 * log10(fc/2.4) + 20 * log10(min(d,5)) + (d > 5) * 35 * log10(d/5) + 18.3 * F\hat{}((F + 2)/(F + 1) - 0.46) + WL * W \quad (11)$$

where d = max(3D distance [m], 1), fc = center frequency [GHz]; F = number of floors traversed, W = number of walls traversed in x-direction plus number of walls traversed in y-direction and WL = wall loss in dB. We set the wall loss to 0 dB in S5 (without walls) and 5 dB in S6 (with walls).

Log-normal shadow fading with 5 dB standard deviation, iid across all links is used with 2x2 11n and a 20 MHz bandwidth in 5 GHz band. We assume a reuse 1 channel allocation. An AWGN PHY Abstraction is used and the traffic modeled is full buffer traffic with Adaptive Auto Rate Fallback (AARF) rate adaptation. The simulation is run for 80 seconds after a 40 second warm-up period.

We sweep the $CCA_{nominal}$ from -90 dBm to -50 dBm with CCA_{bias} set to 5dB. Throughput is TP(CCA_{nom}, CCA_{bias}).

C. Simulation Results: BSS Based CCA Adaptation

Figures 5 and 6 below show the throughput achieved with BSS-based CCA only and with the CCA threshold values ranging from -90 dBm to -50 dBm for scenarios S5 and S6. At a CCA threshold value of -90 dB, myBSS hidden nodes become a problem and the throughput drops drastically. At the other extreme, at a CCA threshold level of -50 dBm, OBSS hidden nodes become a problem and the throughput also drops. An optimal CCA threshold maximizes the throughput (Tmax).

Figure 5: Throughput with no walls (S5)

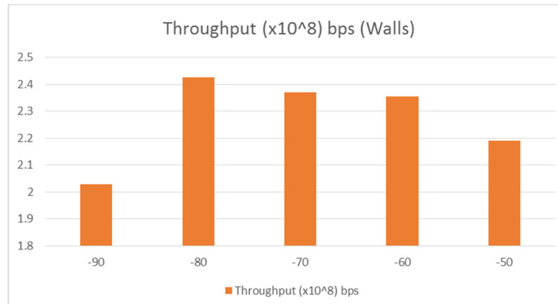

Figure 6: Throughput with walls (S6)

Comparing TP(-50, 0) to Tmax, we see that with no walls (scenario S5), we are able to get a gain of 18.5% but with a 1.2x10^8 bps throughput at TP(-70, 0). With walls (scenario S6), we are able to get a gain of 10% over TP(-50, 0) and 2.4x10^8 bps throughput at TP(-80,0).

This behavior mirrors the behavior seen in the theoretical analysis with ideal spatial reuse where the S2/S1 gain is equivalent to the gain seen in S5 and is greater than the S4/S3 gain. The S4/S3 gain is equivalent to the gain seen in S6.

D. Simulation Results: DSC with Optional TPC

Figures 7 and 8 below show the gains achieved over a BSS-based threshold of -80 dBm (which approximates the CCA threshold required by 802.11). This illustrates the gains different spatial reuse schemes may have over a legacy 802.11 with fixed CCA threshold.

In scenario S5 with no walls, BSS based TPC at TP(-70,0) shows some gain over the legacy CCA level while STA specific CCA at TP(-70,5) shows roughly the same gain. In scenario S6 with walls, BSS based TPC is best at TP(-80,0) while STA specific CCA at TP(-80,5) shows a gain of 4%.. Adding TPC at TP(-70,5) results in a 16% gain over the legacy CCA level. The results demonstrate that in these scenarios, with this version of STA-specific CCA threshold adaptation, TPC may be needed to extract the spatial reuse gains in the channel. Note that gains are scenario and geometry dependent. We anticipate more gains in denser environments e.g. outdoor BSS or residential with multiple floors [6]. We also observe that the current 802.11 threshold has been optimized for separate BSSs (Tmax = TP(-80,0) for scenario S6 with walls) while additional scenarios may need to be able to adjust their CCA thresholds to maximize their performance (Tmax = TP(-70,0) for scenario S5 without walls).

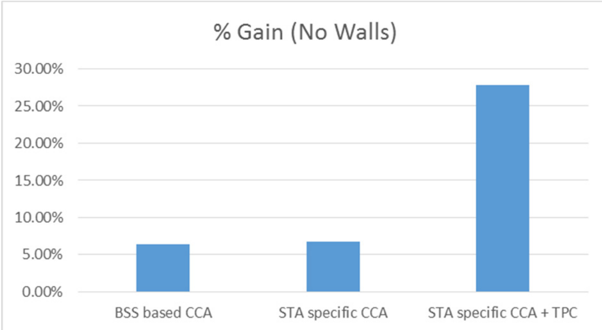

Figure 7: % Gain with TP(-80,0) as reference: no walls (S5)

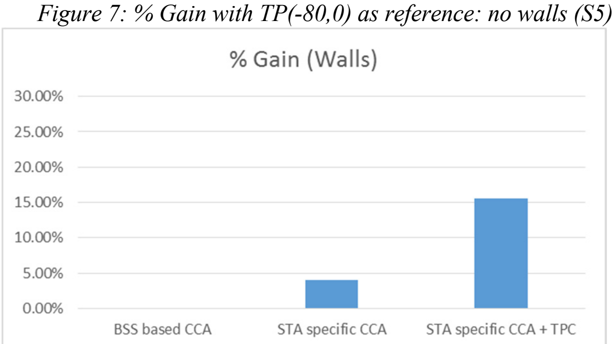

Figure 8: % Gain with TP(-80,0) as reference: walls (S6)

E. Theoretical vs Simulation Results

To compare the theoretical analysis results with the simulation results, we show the gains compared with TP(-50,0) from using the BSS-based CCA threshold adaptation. This is because the TP(-50,0) results approximate the non-deferral scenarios in the theoretical model.

In Figure 9, we see that when the OBSSs are not isolated (modeled by S5 with no walls), using good spatial reuse techniques as opposed to poor spatial reuse techniques result in a 42% gain. This is similar to the trend in S1/S2 that returned a gain of 478%/600%.

In Figure 10, we see that when there is some isolation between the OBSSs (modeled by S6 with walls) good spatial reuse techniques as opposed to poor spatial reuse techniques result only in a 28% gain. This is similar to the trend in S3/S4 that returned a gain of 82%/84%.

In summary, we see that the gain trends are similar to the results obtained from the theoretical analysis.

V. Conclusions

In this paper, we compare the theoretical and empirical throughput performance gains that may be obtained by ideal and practical spatial reuse methods in high density deployments.

Our results show that the trends identified in the simple analysis are present in the empirical simulation and demonstrate that the gains obtained may depend on the scenario or geometry present. We also conclude that additional spatial re-use techniques may be needed to extract all the gains promised by the theoretical analysis.

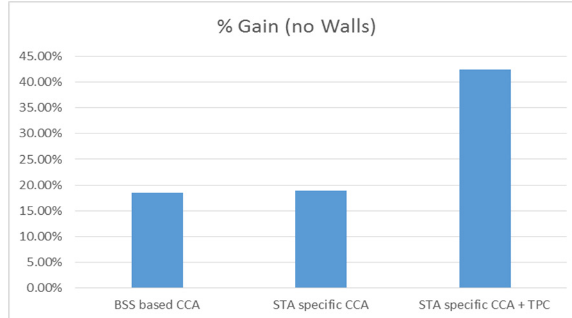

Figure 9: Reference OBSS hidden node case with TP(-50,0) as reference: no walls (S5)

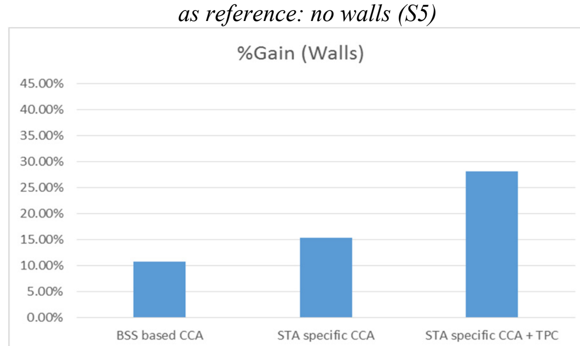

Figure 10: Reference OBSS hidden node case with TP(-50,0) as reference: walls (S6)

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