Issues and Challenges in Dense WiFi Networks

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***Abstract*—The IEEE 802.11 Working Group has initiated a new study group known as IEEE 802.11ax which is aiming to devise ways to improve spectrum efficiency, in particular to enhance the system throughput in highly dense scenarios, frequently referred to as Overlapped Basic Service Set (OBSS). In this paper we revisit some of the common problems faced in traditional WiFi networks and show how their effects could be amplified in dense deployments, especially in co-channel scenarios. We then highlight our findings through a simulation based study and draw inferences from these. Some of the key insights from this study are: link suppression and deadlock effects could potentially amplify in co-channel deployments thereby significantly degrading the throughput performance. Also, increasing the concentration of APs in a given area may not always lead to better performance and therefore AP placement needs to be carefully managed in OBSS scenarios. Where AP placement cannot be controlled due to unmanaged environments, findings indicate the need for intelligent load balancing and channel selection algorithms to minimize the impact of the aforementioned effects.**

***Index Terms*—Dense WLANs, IEEE 802.11ax, Wifi**

I. Introduction & Related Work

With the ever-increasing use of portable handheld devices and the desire to be always connected, the popularity of using WiFi for accessing the Internet continues to grow. Recently the IEEE has started a new working group called 802.11ax with the focus on multi-cell deployment in a dense environment, e.g. stadiums, shopping malls, conference venues, and other outdoor scenarios. Different from previous 802.11 efforts such as 11n and 11ac in which increased point to point peak rate is the main aim, 11ax is geared more towards improved overall system efficiency, with performance metrics such as area throughput, average per station throughput, and spectrum efficiency. It tries to improve user performance by a factor of 4 in dense deployment environments with a mix of clients/AP and traffic types. In general, WiFi deployments continue to get denser with a significant increase not only in the number of stations using these, but also the number of access points. Some countries such as Korea and Japan are already witnessing this phenomenon characterized by heavily loaded APs and Overlapping Basic Service Set (OBSS) deployments wherein APs serving large number of devices also have overlapping coverage. Whilst OBSS deployments ensure good coverage, there is a potential threat in terms of degradation in performance due to inter-cell interference, for example, the inter-AP interference.

Zheng et al. in one of the related papers [1], discuss the effect of BSS proximity and end up drawing an intuitive conclusion that the closer the distance between the BSS, the higher the potential for interference. Tandai et al. propose a new interferential packet detection scheme in [2] which employs the concept of interference detection and switching the channel of the interfered BSS to a different channel. Along similar lines, Zheng et al. mention a centrally controlled colouring solution for channel allocaton in [1] and Chieochan et al. survey channel assignment schemes in WLANs in [3]. In other related work such as in [4], Anastasi et al. illustrate some scenarios wherein RTS/CTS degrade the throughput of system. To mitigate such problems, different types of MAC solutions have been proposed including a cross layer solution in [5] and a two level carrier sensing mechanism in [6]. Whilst these papers have made useful contributions, none of these papers provide a detailed analysis on the underlying causes of throughput suppression in OBSS scenarios. This paper aims to identify the reasons why OBSS may potentially lead to low overall throughput. In particular, the focus is on revisiting well known problems in WLANs to identify how these could amplify in dense deployments and, simulating and analyzing how distance between two APs of two OBSSs affects the overall saturation throughput. We make the following contributions in this paper: 1) We quantitatively show the effect on the overall throughput as the inter-AP distance changes and 2) We analyse and explain the cause of the underlying phenomenon.

The rest of the paper is organized as follows: section II analyses several different phenomenon that lead to degradation in overall performance of OBSS. Section III elaborates on the findings from the simulation study, in particular, analysing how distance between two OBSS affects overall throughput. The paper finally concludes in section IV pointing to potential future directions.

II. Factors Impacting OBSS Performance

The discussion throughout the remainder of this paper assumes an infrastructure mode deployment wherein the terms cell and BSS are used interchangeably.

A. Hidden nodes and RTS-CTS

RTS and CTS have been used to tackle hidden node problem, but under multi-cell deployment, it might not be an optimum solution for spatial reuse, especially in OBSS

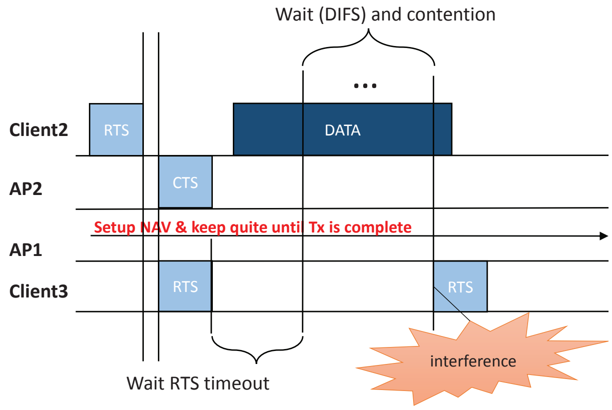

Fig. 1. Impact of RTS-CTS on data reception

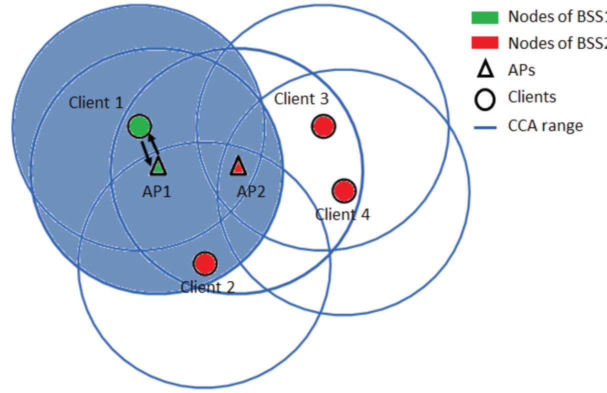

Fig. 2. Example of an OBSS scenario

environments where the number of APs in the vicinity of each other is high and there is lack of availability of non-overlapping channels as a result of which APs in the vicinity may have to resort to operating on overlapping channels. We now elaborate on how RTS/CTS is not enough to tackle the hidden node problem within multi-AP deployments in an OBSS scenario.

In Fig. 1, wherein client3 is a hidden node of client2, client3 will not set up a NAV since it will not hear the CTS from AP2 to client2. It will wait for a time out subsequent to sending an RTS and in the absence of a CTS, listen to the medium, grab it when it senses that this is free and transmits the RTS again. When AP2 is receiving a long frame (and AP1 has set its NAV accordingly), the retransmitted RTS from client3 will interfere with this communication as shown in Fig. 1. With an increase in the number of nodes being served in the OBSSs, there is increased likelihood of RTS-CTS collisions, RTS-DATA collisions and RTS-ACK collisions. In the absence of availability of non-overlapping channels to operate on, neighbouring APs may have to use channels that overlap with those used by their neighbours. In such a scenario, there are two possible ways to address the hidden node problem: 1) adapt the length of RTS or CTS e.g., longer CTS or shorter RTS, 2) increase the length of SIFS. Employing any of these will lead to an increase in overhead. However, in a dense deployment scenario, the hidden node problem is likely to show up more frequently as a result of which, it is necessary to examine the benefits that could potentially be accrued from the above amendments against the overheads that they may result in.

B. *Factors affecting throughput*

According to the findings reported in [7], the saturation throughput (total throughput) of a hidden-node-free BSS is approximately inversely proportional to the number of nodes served by the BSS. When a BSS is dense and suffering from hidden node problems as well, the saturation throughput will be much lower than the one mentioned above. We now show how the hidden node problem influences the overall throughput in the ensuing discussion assuming that the AP is located at the centre of the BSS:

1) AP-AP interference: Whilst the number of nodes being served in a BSS has an impact on the achievable throughput, this is not the only factor resulting in a lower throughput. In an infrastructure network, an AP has to coordinate with all the clients, i.e., be associated with every transmission within its BSS. When multiple APs in the neighbourhood have to resort to using the same channel, there will be only one link available for communication. When the node of one BSS is in procedure of communication, other nodes associated with other BSSs may not be able to successfully transmit, an effect termed AP-AP link suppression. Consider the scenario in Fig. 2 as an example, wherein AP1 and client1 are communicating with each other either in the uplink (UL) or the downlink (DL). Neither AP2 nor client2 (which is associated with AP2) will be able to transmit because the medium is busy. Client3 and client4 (both of whom are associated to AP2) are however free to contend and the winner will be able to transmit. Even though they will be able to transmit, there may not be a response from AP2 to acknowledge the same since it continues to sense the medium to be busy.

The key point we would like to drive home here is that adding more and more APs may not necessarily lead to better performance. This will be further elaborated upon in section III.

2) STA-AP interference: In addition to inter-AP interference, STAs may also affect the APs of other BSSs in different ways, the most common being to suppress the link of other BSSs.

Deadlock effect: Two APs operating on the same channel may deadlock each other because of the presence of hidden node in each BSS. As an example, consider the scenario in Fig. 2. Client1 sends an RTS which is received by both AP1 and AP2 but not heard by client2 since it is out of Clear Channel Assessment (CCA) range of Client1. AP2 then sets its NAV so as not to interfere with client1s impending transmission. If client2 transmits an RTS to AP2 right after client1s RTS transmission to AP1 is completed and both client1 and AP1 are in their SIFS (AP1 has not yet had a chance to reply with

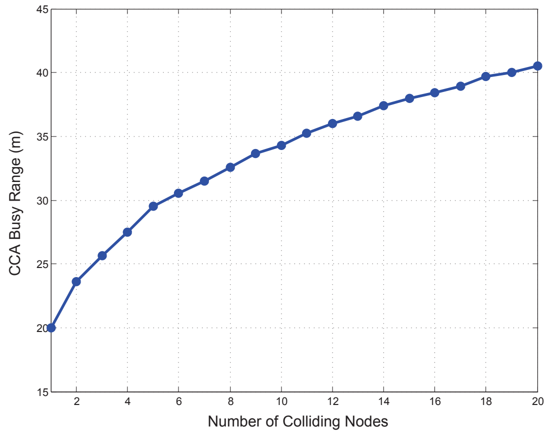

Fig. 3. CCA threshold for different distances between the receiver and the nodes with colliding transmissions

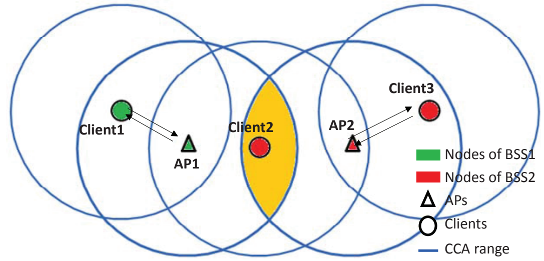

Fig. 4. Scenario depicting STA-AP link suppression

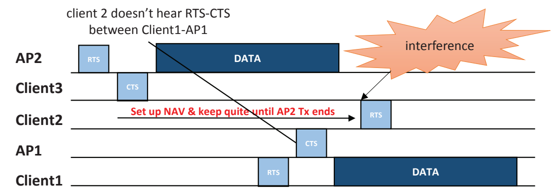

Fig. 5. Example showing STA-AP exposed node issue

a CTS to client1s RTS), AP2 wont respond with a CTS as it is waiting for an impending transmission from client1. This RTS from client2 will force AP1 to remain silent (AP1 will set up its NAV so as to wait completion of an impending transmission from client2). In this kind of scenario, AP1 and AP2 are both waiting for the potential transmission from client2 and client1 respectively and therefore cannot respond with a CTS to the RTS they previously received from their associated nodes (client1 and client2 respectively). Thus, the APs will be in a deadlock for a while before they start sensing the medium again. Such a deadlock state is caused by at least two non-interfering nodes belonging to two adjacent BSSs but they can interfere all the APs at the same time.

Interference amplification effect: This occurs when collisions result in the colliding signals combining in a single signal. This combined signal, which may be stronger than the individual colliding signal, causes interference over a longer range than what would be possible in the case of the individual colliding signals. As an example, as seen from Fig. 2, when client1 is transmitting to AP1, client3 and client4 are free to contend. If transmissions from client3 and client4 collide, the combined signal could potentially reach AP1 which may lead to a failed reception at AP1 (for data sent from client1). Such interference amplification effect may not be obvious when 1) BSSs are far away from each other, 2) the number of STAs is low. However, this effect is likely to be noticeable in dense OBSS deployments. To validate the existence of this effect, we ran a simple experiment. Two or more nodes were made to transmit at the same time and the distance between the receiver and these nodes was increased during each run of the experiment and the corresponding range when the receiver senses the channel to be free was recorded. This value is the CCA threshold. Fig. 3 shows the CCA threshold as the distance between the receiver and the nodes with colliding transmissions is increased. As evident from this figure, when two or more nodes are transmitting simultaneously, the range of their transmission, which makes other nodes to sense the channel as busy, does not linearly increase with the number of colliding nodes. Intuitively, given the probabilistic nature of the CSMA/CA mechanism, one would expect the probability of large number of nodes colliding at the same time to be low.

STA-AP link suppression effect: This effect is manifested when neighbouring APs operate on the same channel (e.g. AP1 and AP2 in Fig. 4), are out of the CCA range of each other and the nodes in the OBSS area are exposed to the interference from neighbouring cells. For example, nodes like client2 in this area will contend with nodes from other BSSs and their transmission will lead to both AP1 and AP2 sensing their channel as busy. Thus, only one link is active while the other is suppressed even though there are two neighbouring cells (which should normally have one link in each cell active) thereby leading to reduced link utilisation.

STA-AP exposed node effect: Fig. 5 shows an embodiment of the exposed node problem based on the topology shown in Fig. 4. AP2 starts data transmission to client3 subsequent to a successful RTS-CTS exchange. Client1 sends an RTS to AP1 which is acknowledged with a CTS by AP1. While client1 receives the CTS, client2 fails to receive the same because the CTS collides with the DATA frame being heard at client2. Consequently, there will be no NAV update for client2. client2 will start transmitting if it wins the contention over other STAs in OBSS area from BSS1 subsequent to completion of transmission of AP2 as shown in the figure. Such a transmission from client2, an exposed node of BSS1, will interfere with the ongoing frame reception at AP1 and cause a collision. Whilst exposed node problem is a well known problem in WLANs, the objective here is to emphasise that this problem is likely to be amplified in OBSS environments.

3) STA-STA interference: STA-STA suppression effect: The way how STAs suppress the transmission and reception of each other is similar to that described in the AP-AP interference (link suppression) section.

STA-STA exposed node effect: This situation occurs when

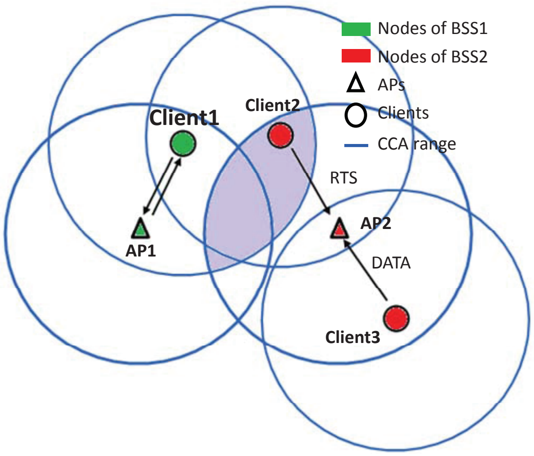

Fig. 6. Example showing STA-STA exposed node issue

exposed STA-STA pairs belonging to different BSSs can overhear each other. When one of the STAs of this pair is a hidden node of another STA of its own BSS, problems appear. The example shown in Fig. 6 highlights the STA-STA exposed node problem and is explained as follows: client1 starts its transmission to AP1 subsequent to a successful RTS-CTS. client2 sets up its NAV after hearing the RTS from client1 and stays silent until the NAV timer expires. During this time, client3 sends an RTS to AP2 which is acknowledged with a CTS by AP2. However, this CTS fails to be received at client2 due to ongoing transmission from client1 to AP1 in the vicinity. Once client2 is free to contend for the medium, it will transmit to AP2 as soon as it grabs the medium. We observe that once the inter-BSS STA-STA (client2-client1) exposed node problem occurs (e.g. when CTS of AP2 for client3 is garbled at client2 due to data transmission from client1 to AP1), the later the CTS from AP2 is transmitted to an intra-BSS STA (client3 in this case), the higher the possibility that transmission of client3 will be interfered. A potential fix to this problem could be to extend the NAV as follows: $T_{extend} = T_{DATA} + T_{ACK} + T_{SIFS} - T_{remainder\_of\_NAV}$.

III. Impact of Inter-AP Distance on Performance

When increasing the concentration of APs in an area, it is of great interest to identify the impact that this may have on the overall throughput. Another objective of this study is to investigate if adding APs to the deployment would lead to improved performance. Simulations were carried out to test how the distance between two APs affects overall throughput in saturation scenario of two BSSs. Basic version of 802.11 standard was considered in these simulations. Table I shows the different parameters and the values chosen for these during the simulation study.

Fig. 7 shows how the overall throughput varies as the inter-AP distance is increased for a number of different scenarios each with different number of nodes per BSS. We can see that the overall throughput gradually increases with increasing distance (upto 20m) between the APs. In general, the throughput is low up to this point due to the various effects (such as link suppression, temporary AP deadlock, interference amplification, exposed nodes etc.) described in the previous section. These effects become less pronounced as the inter-AP distance further increases as evident from the sharp rise which is seen after 20m. This distance is the CCA threshold range for each AP (based on the log-distance path loss model). This is the range at which neighbouring APs are outside of the carrier sense range of each other. Since the number of nodes per BSS in each scenario is constant, increasing the inter-AP distance implies a relative decrease in the node deployment density. The throughput continues improving as the inter-AP distance is increased until saturation conditions are reached. This happens when moving the APs any further from each other (beyond 40m in this case) wont have any significant effect on the interference.

To assess how a single AP would perform instead of the

TABLE I
Parameters used in simulations

Parameter	Value
SIFS	$28\mu s$
Slot time	$50\mu s$
DIFS	SIFS + 2*Slot time ($128\mu s$)
Propagation delay	$1\mu s$
CTS Timeout	$300\mu s$
ACK Timeout	$300\mu s$
Carrier Sense threshold	-76dBm
Data header	(2+2+6+6+6+2+6+4)bytes = 272 bits
CW backoff index	[5, 10] equivalent to CW [31,1023]
RTS	(2+2+6+6+4)bytes = 160bits
CTS	(2+2+6+4)bytes = 112bits
ACK	(2+2+6+4)bytes = 112bits
Control frame header	(2+2+6+6)bytes = 128 bits
Data rate	1 Mbps
Constant transmit power	70mW (-18dBm)
Operating frequency	2.4GHz
CCA range	20m (approx. calculated using log-distance path loss model)
Antenna gain	0dBi
Path loss exponent	2.2

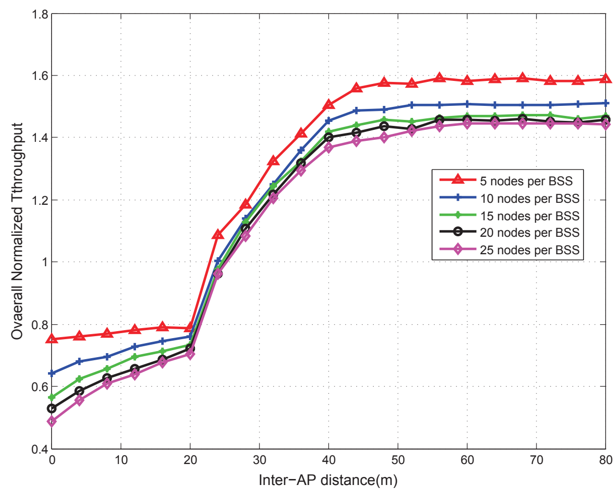

Fig. 7. Overall normalised throughput v/s. inter-AP distance

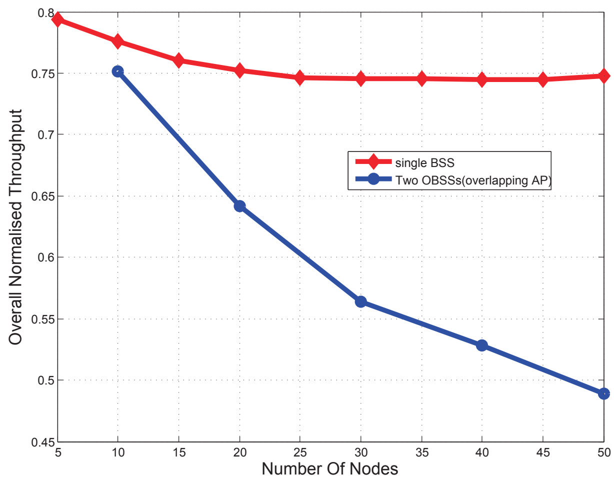

Fig. 8. Single AP scenario

two considered in the above scenario, we ran simulations for different number of nodes (10, 20, 30, 40, 50). Each of these scenarios corresponds to the 2 AP scenario with 5, 10, 15, 20 and 25 nodes per each AP. Fig. 8 depicts the performance in the single AP case and the two AP case. The comparison clearly shows that in the OBSS case (wherein AP1 and AP2 have overlapping coverage areas), inter-AP distance $<= 20m$ in this case, the overall throughput attained is better in the single AP scenario as compared to the two AP scenario. It is only when APs go out of range of each other that the overall throughput improves considerably and is better in the two AP scenario (almost 50-100% higher) as compared to the single AP scenario. These findings suggest that merely increasing the concentration of APs in an area may not necessarily bring performance improvements. If these APs have to operate on co-channels (which is an assumption of the simulation study described above), their placement should be decided carefully. This may not be a problem in a planned deployment scenario such as an enterprise deployment or one where a single administrative entity is responsible for deploying the APs. This may however be an issue in unplanned deployments where neighbouring APs may not have any mechanisms to coordinate with their neighbours. This also points to the need for enabling the APs with autonomous channel selection algorithms which can help to avoid/minimise potential interference in scenarios where OBSS deployment may be unavoidable.

IV. Conclusion

The IEEE 802.11 Working Group has recently started work under the auspices of the '11ax' group focusing on dense WiFi deployments. Such dense deployments are characterized by an increase not only in the number of stations that are served but also an increase in the number of APs, often referred to as Overlapped Basic Service Set (OBSS) deployments.

This paper detailed some of the commonly occurring phenomenon in wireless LANs which are known to degrade performance and showed how the effects of these could potentially amplify in OBSS deployments. A simulation based study was also elaborated on which aimed at uncovering insights that could be useful in terms of feeding considerations while designing a solution. In particular, the effect of inter-AP distance on the overall saturation throughput (both DL/UL) was studied. It was found that in a co-channel OBSS deployment, several effects such as, link suppression effect, interference amplification, STA transmissions leading to a temporary deadlock of neighbouring APs and hidden/exposed nodes leading to wasted medium occupancy for a prolonged time, are pronounced and therefore lead to lower link utilization.

It was also found that in such deployments, merely increasing the concentration of APs in an area may not necessarily bring performance improvements. The AP placements have to be carefully managed to mitigate the aforementioned effects. Whilst this is achievable in planned deployments, this throws challenges in the unplanned deployment scenario. The findings from this study motivate the need for designing intelligent load balancing and autonomous channel selection algorithms for OBSS operation in unplanned environments where there may not be much coordination amongst the neighbouring APs. Additionally, it would also be of interest to study analytically (e.g. using the Bianchi's model) the OBSS problem to confirm the findings of the simulations reported in this work. These are interesting problems for further work in this area and should help to overcome some of the challenges thrown by densification of these networks.

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