ΑΛΕΞΑΝΔΡΕΙΟ ΤΕΧΝΟΛΟΓΙΚΟ ΕΚΠΑΙΔΕΥΤΙΚΟ
ΙΔΡΥΜΑ ΘΕΣΣΑΛΟΝΙΚΗΣ
ΤΜΗΜΑ ΜΗΧΑΝΙΚΩΝΠΛΗΡΟΦΟΡΙΚΗΣ

ΠΡΟΓΡΑΜΜΑ ΜΕΤΑΠΤΥΧΙΑΚΩΝ ΣΠΟΥΔΩΝ
ΕΥΦΥΕΙΣ ΤΕΧΝΟΛΟΓΙΕΣ ΔΙΑΔΙΚΤΥΟΥ - WEBINTELLIGENCE

Το πρωτόκολλο IEEE 802.11ax για πυκνά ασύρματα δίκτυα τοπικής περιοχής

ΜΕΤΑΠΤΥΧΙΑΚΗ ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

του

Αναστάσιου Βαλκάνη

Επιβλέπων : Δρ. Περικλής Χατζημίσιος
Αναπληρωτής Καθηγητής, Αλεξάνδρειο ΤΕΙ Θεσσαλονίκης

Θεσσαλονίκη, Φεβρουάριος 2017

Η σελίδα αυτή είναι σκόπιμα λευκή.

ΑΛΕΞΑΝΔΡΕΙΟ ΤΕΧΝΟΛΟΓΙΚΟ ΕΚΠΑΙΔΕΥΤΙΚΟ ΙΔΡΥΜΑ ΘΕΣΣΑΛΟΝΙΚΗΣ
ΤΜΗΜΑ ΜΗΧΑΝΙΚΩΝ ΠΛΗΡΟΦΟΡΙΚΗΣ
ΠΡΟΓΡΑΜΜΑ ΜΕΤΑΠΤΥΧΙΑΚΩΝ ΣΠΟΥΔΩΝ
ΕΥΦΥΕΙΣ ΤΕΧΝΟΛΟΓΙΕΣ ΔΙΑΔΙΚΤΥΟΥ - WEBINTELLIGENCE

Το πρωτόκολλο IEEE 802.11ax για πυκνά ασύρματα δίκτυα τοπικής περιοχής

ΜΕΤΑΠΤΥΧΙΑΚΗ ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

του

ΑΝΑΣΤΑΣΙΟΥ ΒΑΛΚΑΝΗ

Επιβλέπων : Περικλής Χατζημίσιος
Αναπληρωτής Καθηγητής, ΑΤΕΙΘ

Εγκρίθηκε από την τριμελή εξεταστική επιτροπή στις Choose a date.

(Υπογραφή)	*(Υπογραφή)*	*(Υπογραφή)*
....	....	....
Περικλής Χατζημίσιος	Αθανάσιος Ιωσηφίδης	Ευκλείδης Κεραμόπουλος
Αναπληρωτής Καθηγητής	Αναπληρωτής Καθηγητής	Επίκουρος Καθηγητής

Θεσσαλονίκη, Φεβρουάριος 2017

(Υπογραφή)

....

Click here to enter text.

Click here to enter text.

© Choose a date– Allrightsreserved

Περίληψη

Η οικογένεια προτύπων για ασύρματα δίκτυα τοπικής περιοχής IEEE 802.11, έχει απλοποιήσει τον τρόπο πρόσβασης δισεκατομμυρίων χρηστών στο διαδίκτυο. Η φιλοσοφία των προτύπων βασίζεται στη συνεχή αναζήτηση, εξέλιξη και εφαρμογή κατάλληλων τεχνολογιών με σκοπό την κάλυψη των συνεχόμενα αυξανόμενων αναγκών των χρηστών, τόσο σε ρυθμούς μετάδοσης όσο και σε ποιότητα προσφερόμενων υπηρεσιών. Οι ανάγκες αυτές οδηγούν στη συνεχή δημιουργία νέων πρωτοκόλλων, όταν τα υπάρχοντα δεν μπορούν να τις καλύψουν.

Τα τελευταία χρόνια έχουμε ραγδαία αύξηση του αριθμού των εγκατεστημένων ασύρματων δικτύων τοπικής περιοχής, γεγονός που ενώ από τη μία πλευρά προσφέρει μεγαλύτερη ευχέρεια πρόσβασης στο δίκτυο κορμού και μεγαλύτερο όγκο δεδομένων στους χρήστες, από την άλλη δημιουργεί σοβαρά προβλήματα με τις παρεμβολές που προκαλούνται όταν τα δίκτυα αυτά είναι επικαλυπτόμενα, με αποτέλεσμα τη μείωση της αποτελεσματικότητας τους. Αυτό το σημαντικό πρόβλημα οδήγησε στην ανάγκη δημιουργίας ενός καινούργιου προτύπου από την οικογένεια IEEE 802.11 με σκοπό την αντιμετώπιση του. Οι εργασίες για την δημιουργία του προτύπου IEEE 802.11ax ξεκίνησαν τον Μάρτιο του 2013 και αναμένεται να ολοκληρωθούν το 2019.

Αντικείμενο της παρούσης μεταπτυχιακής διπλωματικής εργασίας είναι αρχικά η παρουσίαση των νέων τεχνολογιών που αναμένεται να υιοθετήσει και εφαρμόσει το συγκεκριμένο πρωτόκολλο επικεντρώνοντας στην χωρική επαναχρησιμοποίηση. Ειδικότερα θα παρουσιαστεί η έρευνα που έχει πραγματοποιηθεί μέχρι σήμερα πάνω στο συγκεκριμένο θέμα τόσο από στη βιβλιογραφία όσο και στις Ομάδες Εργασίας (Working Groups) του προτύπου, όπως επίσης θα παρουσιαστούν και προτάσεις της εργασίας. Στη συνέχεια θα γίνει αξιολόγηση των προτεινόμενων λύσεων για το συγκεκριμένο θέμα μέσω εκτέλεσης προσομοιώσεων με τη χρήση του λογισμικού MATLAB.

Η δομή της εργασίας έχει ως εξής, στο Κεφάλαιο 1 γίνεται μια σύντομη γενική αναφορά στην οικογένεια προτύπων IEEE 802.11 ενώ στο Κεφάλαιο 2 περιλαμβάνει μια παρουσίαση του προτύπου IEEE 802.11ax και των νέων τεχνολογιών που αναμένεται να χρησιμοποιήσει. Το Κεφάλαιο 3 περιέχει μια αναλυτική παρουσίαση τόσο της βιβλιογραφίας όσο και των προτάσεων της ομάδας εργασίας του προτύπου που αφορά τη χωρική επαναχρησιμοποίηση. Στο Κεφάλαιο 4 παρουσιάζονται οι προτεινόμενες λύσεις, στο Κεφάλαιο 5 τα αποτελέσματα της αξιολόγησης και τέλος στο Κεφάλαιο 6 τα συμπεράσματα και οι μελλοντικές επεκτάσεις.

Λέξεις Κλειδιά: Ασύρματα δίκτυα, πυκνά δίκτυα, χωρική επαναχρησιμοποίηση, IEEE 802.11ax, παρεμβολές.

Ευχαριστίες

Θα ήθελα να ευχαριστήσω ιδιαίτερα τον επιβλέποντα καθηγητή κύριο Περικλή Χατζημίσιο για την συμβολή του στην ολοκλήρωση αυτής της εργασίας. Η ενθάρρυνση, η εμπειρία και οι γνώσεις του ήταν πολύ σημαντικές για εμένα σε όλη την περίοδο εκπόνησης της.
Επίσης θα ήθελα να ευχαριστήσω τη σύζυγο μου Γλυκερία και τα τέσσερα παιδιά μου Δέσποινα, Γαρυφαλλιά, Ευάγγελο και Χρήστο για την ενθάρρυνση, υπομονή και κατανόηση που έδειξαν κατά τη διάρκεια εκπόνησης της παρούσας εργασίας.

Η σελίδα αυτή είναι σκόπιμα λευκή.

Abstract

The family of the IEEE 802.11 protocols for Wireless Local Area Networks (WLANs) has simplified the way that billions of users connect to the internet. The philosophy of these networks is based on the continuous research, evolution and implementation of proper technologies, in order to fulfill the increased demands of users either in data rate or Quality of Service (QoS). These demands result in a continuous development of new protocols when the existing ones are not able to fulfill them.

During the last years, there is rapid increase of the number of WLANs that have been deployed . A fact that in one hand offers increased flexibility connecting to the backbone network and greater amount of data to the users, on the other creates serious problems with the interference which is provoked by the Overlapped Basic Service Sets (OBSs), resulting in a decrease of their efficiency. This serious performance issue has led to the necessity of developing a new protocol by the IEEE 802.11 family, in order to address it. The works concerning IEEE 802.11ax protocol development began on March 2013 and are expected to finish on 2019.

Subject of this M.Sc. thesis is the presentation of new technologies, which the new protocol is expected to adopt and implement, focusing on spatial reuse. Particularly the research until now in the above field will be presented, either from literature or from the protocol Task Group (TG), also thesis proposals will be presented. Afterwards an evaluation of the suggested solutions concerning spatial reuse will be conducted, using MATLAB software. The structure of this M.Sc. thesis is as follows; Chapter 1 includes a brief presentation of the IEEE 802.11 protocols family. In Chapter 2 a presentation of both 802.11ax protocol and new technologies, which are expected to adopt are included. In Chapter 3, a comprehensive presentation of the literature and TG proposals concerning spatial reuse. In Chapter 4 the suggested solutions are presented, Chapter 5 includes the results of the evaluation and finally Chapter 6 presents the conclusions and future work.

.

Keywords: Wireless networks, dense networks, spatial reuse, IEEE 802.11ax, interference

Η σελίδα αυτή είναι σκόπιμα λευκή.

Contents

1

Introduction

1.1 The IEEE 802.11 protocols family

The 802.11 which is a member of the Institute of Electrical and Electronics Engineers (IEEE) 802 family, is a series of specifications for implementing Wireless Local Area Network (WLAN) technologies. These specifications are focused on the two lower layers of the Open Systems Interconnection (OSI) model, the Medium Access Control (MAC) and Physical (PHY) layers. The MAC determines how to access the medium and the physical controls the way of transmission and reception [1].

The reason of the enormous adoption of WLANs is the number of benefits that it offers, whereas the major one is the increased mobility for users that can move, almost without restrictions and can access WLANs from nearly anywhere. The other advantages of WLANs include cost-effective network setup for hard-to-wire locations, (such as older buildings and solid-wall structures) and reduced cost of ownership-particularly in dynamic environments requiring frequent modifications (thanks to minimal wiring and installation costs per device and user). WLANs liberate users from dependence on hard-wired access to the network backbone, giving them anytime, anywhere network access.

The IEEE 802.11 Working Group has a structured method of introducing new technologies when a gap is identified in the current standard. The structured method of developing new standards has led to a long history of innovation, delivering both new PHY layers and enhancements to MAC layer in terms of security and quality of service (Figure 1.1).

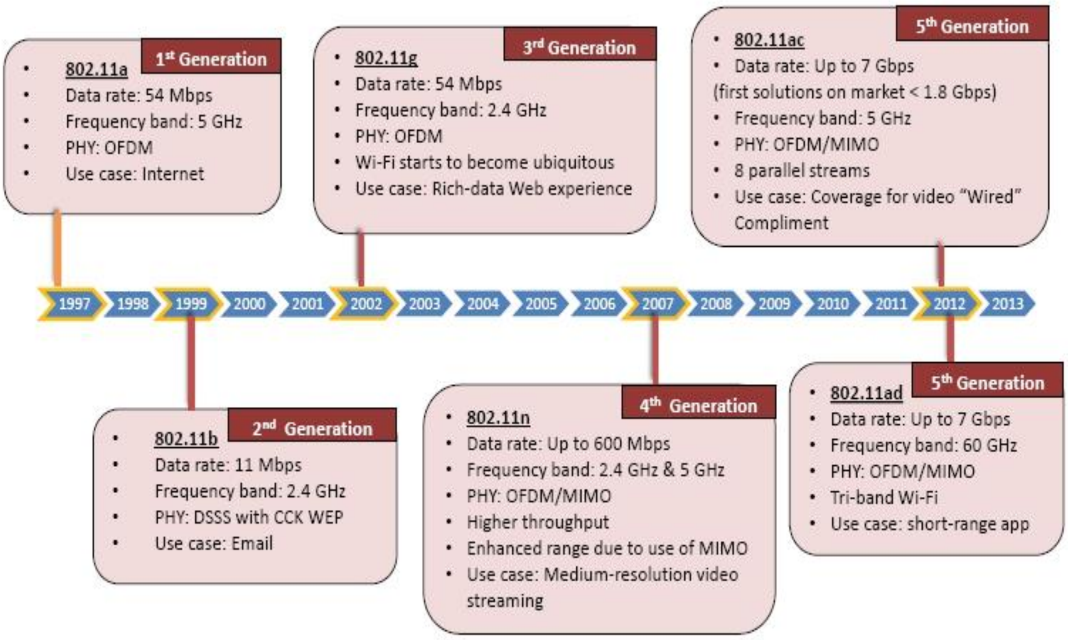


Figure 1.1 The key IEEE 802.11 amendments

The first standard for WLANs, which now is obsolete, was released in 1997 and clarified in 1999. This version was providing data rates up to 2 Mbit/s and a set of fundamental signaling methods and other services. The increasing demands for higher data rates due to utilization of demanding applications led on the necessity of the development of new standards. The first amendment IEEE 802.11b-1999 standardized the physical layer that was support of two new data rates, 5.5 Mbps and 11 Mbps in the 2.4 GHz band. Furthermore, the IEEE 802.11a-1999 defined requirements for an Orthogonal Frequency Division Multiplexing (OFDM) communication system that allowed data transmission and reception at rates of 1.5 to 54 Mbit/s in the 5 GHz band. The IEEE 802.11g-2003 raised up the data rate to 54 Mbps for the 2.4 GHz band and the IEEE 802.11n-2009 introduced Multiple Input Multiple Output (MIMO) and beam forming technologies to increase data rates up to 600 Mbps. The IEEE 802.11ac-2013 further introduced Multi-User (MU) MIMO that has the potential to change the way that Wi-Fi networks operate because it enables better spatial reuse and also increases the data rate up to 6.7 Gbps.

Next generation WLANs faces several challenges and for these reasons new amendments such as IEEE 802.11af and IEEE 802.11ah are further expanding the application scenarios of

WLANs including cognitive radio, long range communication, advanced power saving mechanisms and support for Machine-to-Machine (M2M) devices. The major challenge that WLANs are facing now is to address dense scenarios, a case that is motivated by the continuous deployment of new Access Points (APs) to cover new areas and, thus, provide higher data rates. To address this challenge, which existing protocols cannot meet, the High-Efficiency WLAN (HEW) is currently working on a new high throughput amendment named IEEE 802.11ax-2019 [2].

2

The IEEE 802.11ax protocol

The demand for very high data rate transmissions, in a dense WLAN environment, has led on the necessity of development of new protocol by the IEEE 802.11 family. This new protocol IEEE 802.11ax can offer High Efficiency WLANs and is considered as the IEEE 802.11ac successor, which cannot handle the high dense scenarios. The current Chapter analyzes both goals according to the Project Authorization Request (PAR) and the suggested enhancements on the PHY and MAC layers concerning the protocol.

2.1 Requirements and goals of the protocol

A Study Group (SG) was established on March of 2013 for the release of the PAR that was accepted on March of 2014. The Task Groups (TG) began their work on May of 2014, the first phase of standardization completed on November of 2016, the second is expected to finish on May of 2017 and the final on 2019 (Figure 2.1) [3].

The development of 802.1ax is based on the demands which are defined by the Criteria for Standard Development (CSD) [4]. These criteria are wide users' approval, compatibility with legacy devices, unique identity compared to other protocols of the IEEE 802.11 family, efficiency of new technologies that will be implied and finally commercial sustainability of the project.

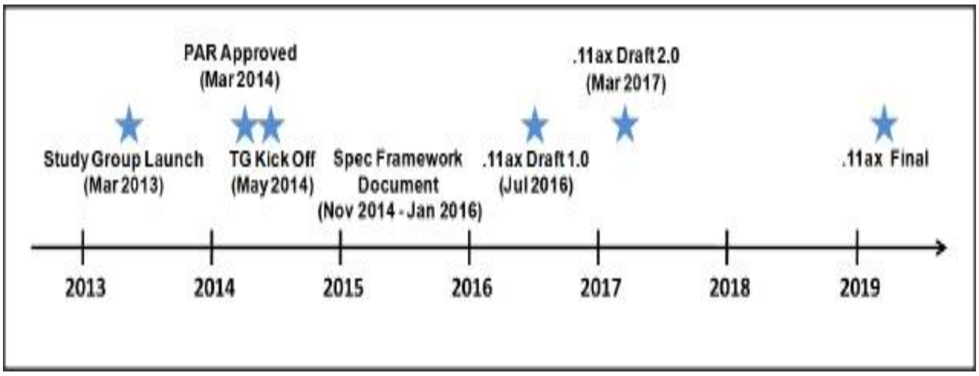


Figure 2.1 Timetable of 802.11ax development [10]

The prospects for the wide adoption of the protocol are very optimistic. Cisco has forecasted that mobile devices could have a multiplier effect on traffic [5]. An Internet-enabled HD television that downloads 45 minutes of content per day from the Internet would generate as much Internet traffic as an entire household today. With the growth of video viewing on smartphones and tablets, traffic to/from these devices is growing as a percentage of the total Internet traffic. Tablets will account for 15% of the total global Internet traffic by 2020, up from 9% in 2015. Smartphones will account for 37 % of the total global Internet traffic by 2020, up from 11% in 2015 global IP traffic is to nearly triple from 2015 to 2020 (Figure 2.2). The forecast for the sales of Internet connected devices is that the 87% will be smartphones and tablets in 2017. These types of devices are connected wirelessly to internet by utilizing the Wi-Fi technology. Another important fact is the overload of cellular networks and the effort of offloading by using WLANs.

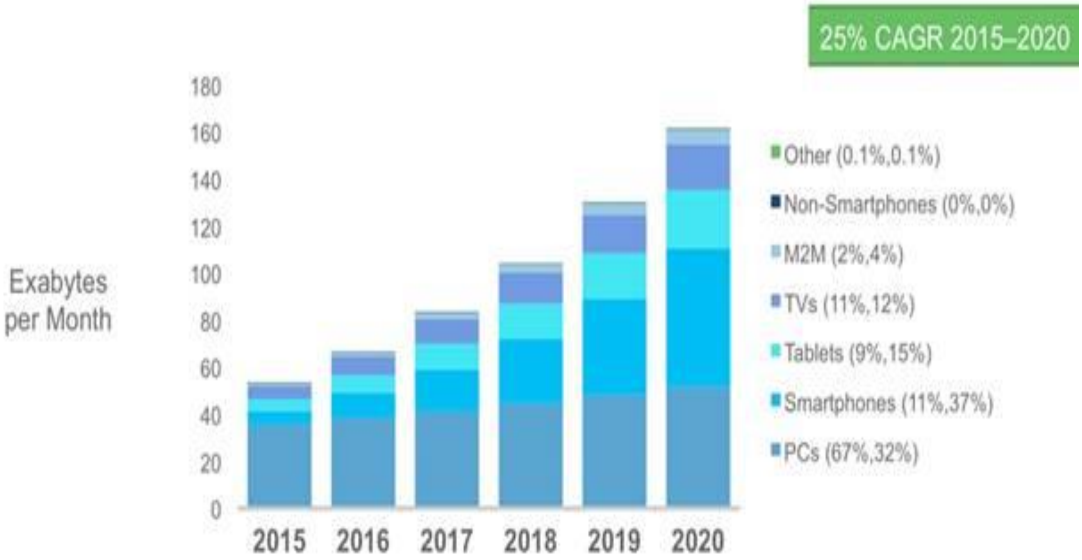


Figure 2.2 Forecasts for Global Internet Traffic by Device Type [5]

Regarding compatibility issues, we generally consider that IEEE 802.11ax is the successor of IEEE 802.11ac since it adopts many of its applied technologies and supports legacy devises. Every new amendment of the IEEE 802.11 family must contribute something new related to the existing protocols. In this case, IEEE 802.11ax focuses on the efficient support of dense networks in a way that the implemented interface will not affect user experience. This is the unique characteristic of this protocol since it is the only one that aims to increase data rate for a highly dense scenario.

The goal regarding data rate is to quadruplicate it compared to the IEEE 802.11ac in the 5GHz band and the IEEE 802.11n in the 2.4GHz band. Another goal of the protocol is the development of the appropriate mechanisms, which will allow the harmonic coexistence with heterogeneous networks and mobile devices that operate in the Industrial Scientific and Medicine (ISM) band. Finally, one major goal of the protocol is the reduction of power consumption of stations (STAs), considering the need for quadruplicating data rate and setting the target to preserve the power consumption levels of IEEE 802.11ac.

2.2 New technical features and concepts

The IEEE 802.11ax amendment may include some new technical features, which can be categorized to spatial reuse, temporal efficiency, spectrum sharing and MIMO technology. This M.Sc. thesis is about the spatial reuse and will be discussed in the next Chapter, whereas the next Sections present all the other new technical features of the new amendment.

2.2.1 Temporal Efficiency

The overhead from the packet headers, the time space between frames, collisions as well as retransmissions reduce efficiency of WLANs. The IEEE 802.11ax protocol is expected to adopt mechanisms, which will deal with the above issues and, thus, enhance transmission efficiency.

The length of packet headers can be reduced with the support of variable length in order that the minimum overhead will be incurred for every transmission. The adoption of smaller identifier is also suggested instead of the full MAC address that now is used. The piggybacking technique is suggested for packet aggregation in which the main idea of this technique is the aggregation of acknowledgment (ACK) with transmission of data packets. Such a mechanism has been proposed by [6] and [7], succeeding to increase data rates. The drawback of the piggybacking technique is the possibility of not having data to send and, thus, the transmission of the acknowledgment packet will be significantly delayed. Another field which the IEEE 802.11ax is expected to enhance is the mechanisms that handle retransmissions. Up to now, all the protocols, in a case of a packet error, have to retransmit the whole packet if there is a checksum error independently of the plurality of these errors. For this reason various mechanisms have been suggested that foresee either the retransmission only for the part of packet that is in error or the employment of appropriate algorithms that can correct the errors in the receiver side. Such a mechanism that can edit low error packets is the Zip-Tx [8]. The implementation of this mechanism achieves an average of 20% enhancement on data rate compared to the current retransmission techniques. Another mechanism that is capable of editing packet errors is the Unite platform [9], which apart from editing errors it offers the potential of damage estimation that can help for the utility of editing or even discarding the packet.

Simultaneous Transmit/Receive (STR) is an innovation in which a device can transmit and receive on the same channel at the same time, potentially doubling throughput performance [10]. The device achieves this by cancelling leakage of own transmit signal through its receive path in order to ensure an adequate Signal/Self-Interference Ratio (SIR). The ideal requirements for self-cancellation are challenging, since a device typical transmits at 10 to 25 dBm, but the thermal noise floor over 20 MHz is -101 dBm. In the noise limited case, this indicates that at least 126 dBm of cancellation is preferred, but many cases of practical interest are interference not noise limited; such as two devices in moderate proximity transmitting at 15 dBm and receiving each other at an RSSI of -50dBm (Figure 2.3). Furthermore, if self-interference can be reduced to -75 dBm, the SIR is 25 dB and only 90 dB of cancellation is required.

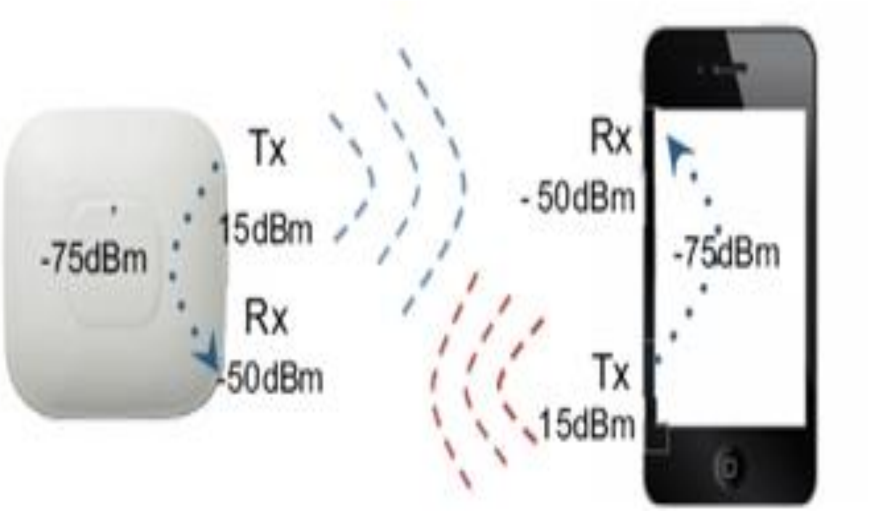


Figure 2.3 Example of STR Paired Operation [10].

STR can operate either paired or unpaired. In the paired case, two STAs are transmitting to each other. To achieve a doubling of throughput performance, the offered traffic should be symmetric (although there is a useful throughput improvement even if only acknowledgements are sent on one link within the pair). A greater concern is that both devices must support a high degree of self-cancellation, i.e. the complexity cannot be concentrated at APs. In the unpaired case (Figure 2.4), an AP transmits to STA1, while at the same time STA2 transmits to the AP. Only the AP needs a high degree of self-cancellation, since STA1 only receives and STA2 only transmits. However, while STA1 receives from the AP, STA1 may also receive interference from STA2 transmissions, degrading the SIR by ten times to 5 or 10 dB. Thus, there are many topologies in unpaired operation where throughput performance of the link to STA1 is poor. The required cancellation is achieved via a mix of antenna separation (one antenna for transmit, a different antenna for receive), analog cancellation and digital cancellation.

Self-cancellations up to 110 dB are reported in [11], whereas in [12] a mechanism that supports full duplex technology is presented and uses a technique named balun for the mitigation of self interference. This mechanism is suitable for WLANs and the results for the IEEE 802.11n show a performance enhancement of 88% for lost packets, an improvement of fairness, as well as an increase of 110% for download and 15% for upload data rates. .

.Figure 2.4 Example of STR Unpaired Operation [10].

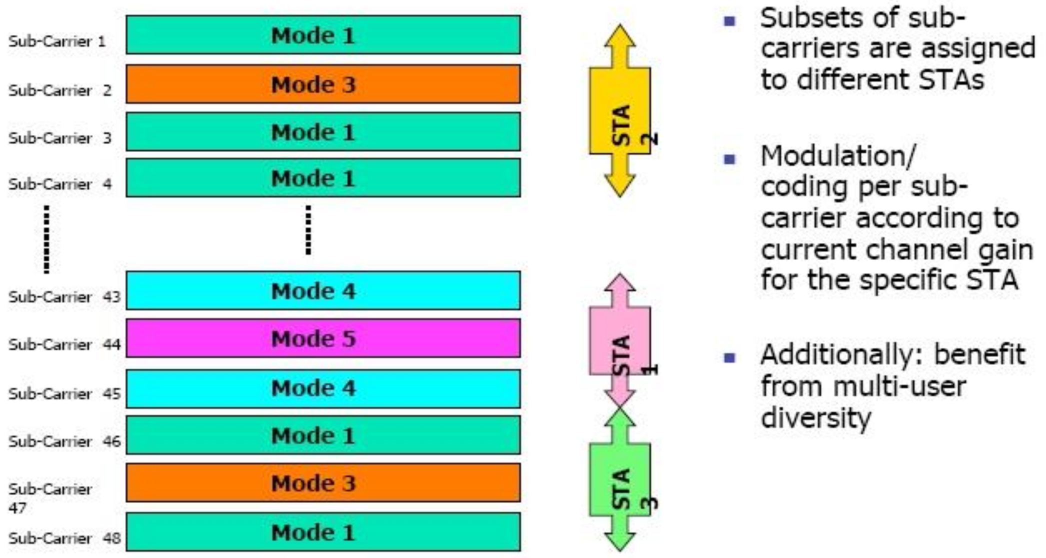
2.2.2 *Spectrum Sharing*

The scenario of various dense overlapped BSSs that IEEE 802.11ax must handle leads to the necessity of fair and efficient allocation of spectrum resources. Two are the major mechanisms that IEEE 802.11ax will implement for the above purposes; the Orthogonal Frequency Division Multiplexing Access (OFDMA) and the dynamic channel bonding.

OFDMA is a method of encoding digital data on multiple carrier frequencies for wireless networks. A large number of closely spaced sub-carrier signals are used to carry data on several parallel data streams or channels. Each sub-carrier is modulated with a conventional modulation scheme (such as quadrature amplitude modulation or phase-shift keying phase-shift keying) at a low symbol rate, maintaining total data rates similar to conventional single-carrier modulation schemes for the same bandwidth. The primary advantage of OFDM over single-carrier schemes is its ability to cope with severe channel conditions (for example, attenuation of high frequencies in a long copper wire, narrowband interference and frequency-selective fading due to multipath) without complex equalization filters.

This technique is used by other protocols of the IEEE 802.11 family by separating the channel in subcarriers of 312.5 KHz. In all cases the subcarriers that belong to the same channel have the same destination address and the same Modulation and Coding Scheme (MCS).

The enhancements that IEEE 802.11ax is expected to adopt is the potential of subcarriers direction both to multiple STAs from the AP (download) and from STAs to the AP (upload), as well as the possibility of different MCS in each subcarrier (Figure 2.5).



- Subsets of sub-carriers are assigned to different STAs
- Modulation/ coding per sub-carrier according to current channel gain for the specific STA
- Additionally: benefit from multi-user diversity

Figure 2.5 Dynamic user OFDM [13]

The benefits of the above enhancements that are described in [14] are the following: multiple access of stations to one channel, possibility of programmed spectrum sharing that can secure the required QoS for users, increase of data rate through the proper selection of max gain subcarrier from each STA and finally overhead reduction since the control information can be simultaneously aggregated to multiple destination STAs .

A major challenge for IEEE 802.11ax is the mechanism selection that will distribute the available subcarriers to STAs. There are two options; the static in which every STA will handle a specific number of subcarriers and the dynamic one in which the number of subcarriers per STA will change in relation to network conditions. Work in [15] proposes a mechanism, named Dynamic Multi User Access (MDU access), which is capable of dynamic allocation of subcarriers . This mechanism is compared against to the conventional static one and results show a 30% enhancement on the data rate that can achieved.

A survey for the OFDMA based existing protocols in [16] categorizes them into four different groups and also performs a comparison between them according to ten designing issues. These issues are important for the selection of the proper protocol that IEEE 802.11ax will implement. They include the potential of multi user channel access transmission and diversity, control and evaluation of used channels, Channel State Information (CSI), AP programming for download and upload, guaranteed QoS, exchange of control frames and compatibility.

Finally, work in [17] proposes a specific MAC protocol based on OFDM for the IEEE 802.11ax, named OFDMA based Multiple Access for IEEE 802.11ax (OMAX), which faces two major challenges, synchronization and overhead reduction. Simulation results show a performance enhancement of 160% compared to the Distributed Coordination Function (DCF) protocol.

The dynamic channel bonding mechanism was firstly implemented on IEEE 802.11ac and allowed to adjust the width of STAs assigned channel according to the state of network (Figure 2.6). Its usage enhances spectrum exploitation and fairness among STAs. In particular, work in [18] proposes such a mechanism that achieves improved efficiency for dense WLANs deployments.

In [19] a Dynamic channel Bonding (DyB) protocol is proposed, in which a node is allowed to start a transmission, as long as there are some idle narrow channels and, thus, it gradually increases channel width during transmission whenever new narrow channels become available. To enable communication over uncertain channels, a convolution method is introduced to achieve fast spectrum agreement between the transmitter and the receiver. In addition, DyB considers the severe contention in a wide band of spectrum. A compound preamble is designed to make collisions detectable in the frequency domain and a parallel bitwise arbitration is designed to quickly resolve the collisions in the time domain.

Simulations show that DyB allows a wideband device to obtain medium access opportunities even under intense narrowband interferences and the throughput is improved by 20% over current frame-based channel bonding.

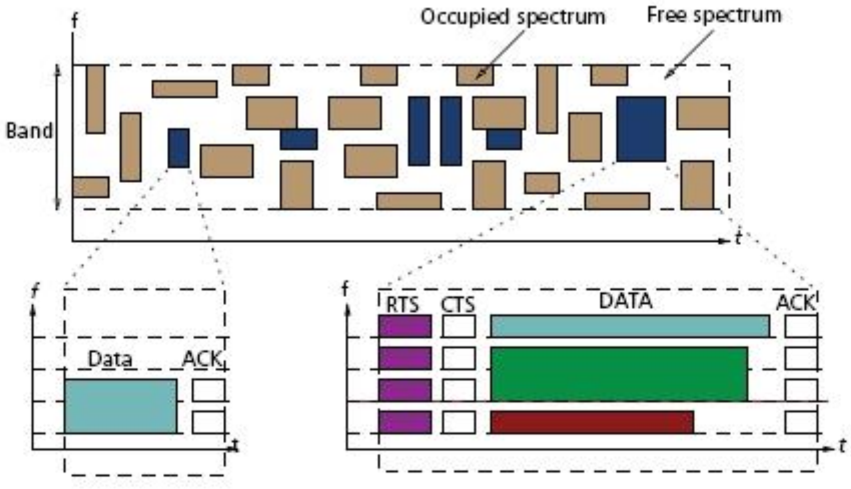


Figure 2.6 Dynamic channel bonding and OFDMA [2]

2.2.3 MIMO technology

The implementation of the MIMO technology is a major factor of data rate enhancement in WLANs. IEEE 802.11n was the first protocol of the family that adopted Single User MIMO (SU-MIMO) and IEEE802.11ac then introduced Multi User MIMO (MU-MIMO). IEEE 802.11ax is expected to extent MU-MIMO for three new fields, for uplink, massive MIMO and network MIMO.

The implementation of uplink MU-MIMO allows simultaneously transmissions from multiple STAs to AP in the same frequency channel. This is possible due to the existence of multiple receiver antennas in the Aps, however, there are many challenges for the implementation in IEEE 802.11ax. The first one is the choice of the proper mechanism that will be responsible for the separation of the received signals at AP. This problem is known as Multi-User Detection (MUD). Work in [20] proposed several schemes that address the above problem but with a complexity cost. Except complexity, another issue is the number of antennas that are installed in the AP and should be more than the associated STAs.

The selection of proper mechanism for the Channel State Information (CSI) is another challenge. Until now, there are two available choices, the implicit and the explicit [21]. Explicit offers a better accuracy on CSI with an overhead cost compared to implicit.

A major issue about the design of MAC protocols for uplink MU-MIMO is the selection of the proper mechanism that will be responsible for the planning of transmissions. Two are the major schemes that have been proposed in [22]. The first one is with the use of a coordinator (the AP take over this role) that is responsible for the grouping of STAs transmissions. The second scheme is without a coordinator in which the STAs are competing for a position to the group which will transmit in parallel. The coordinated scheme is more efficient compared to the uncoordinated one but with a complexity cost.

The massive MIMO technology is implemented in WLANs in which their architecture supports coordination and collaboration. This architecture is based on the central coordination between networks from the master AP that has increased commitments and capabilities. In this manner, multiple antennas of AP operate in coordination like an antenna array. By grouping STAs, an enhanced spectrum utilization is achieved upgrading spatial reuse and mitigating interference. Work in [23] presents a system named NEMOx that supports the above technology for the downlink. The comparison through simulation against conventional architectures shows greater efficiency and increase of data rate.

The massive MIMO technology is designed for the creation of independent wireless links between AP and STAs within a WLAN. In this case, independent links are created by the existence of more transmission and reception antennas than the number of nodes in the network. The challenges for this implementation are the high cost, complexity in processing, increased overhead and high energy consumption. Work in [24] proposes a special designed protocol for massive MIMO in WLANs. It employs massive MIMO, in which multiplexing (MUX) groups for pilot signal and simultaneous feedback are performed by an AP among users, in each MU-MIMO user group to achieve higher efficiency. Moreover, it is proposed to utilize the Long Training Field (LTF) demultiplexing scheme at each STA and the joint feedback detection scheme at the AP that considers OFDMA operation among APs. The simulation results show that the proposed protocol provides a much higher throughput compared to the conventional IEEE 802.11ac.

3

Spatial Reuse

Spatial reuse is the efficient parallel spectrum utilization from STAs using the same channel and it is a key factor that determines the performance of a wireless network, especially in dense deployment scenarios. For this reason, a special IEEE 802.11ax TG has to investigate the possible mechanisms and technologies that the protocol will adopt for the enhancement of spatial reuse. Two are the major technologies that will be used; the dynamic carrier sense and the dynamic transmit power control. In the current chapter, related work concerning the proposals of the TG is presented.

3.1 Dynamic carrier sense

DCF is a competitive technique that employs Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and a Binary Exponential Back off (BEB) algorithm. A STA wishing to transmit is required to acquire the channel status for a DCF Inter-Frame Space (DIFS) interval. If the channel is found busy during this DIFS interval, the STA defers its transmission. Medium sensing is accomplished by the comparison of signal level detection against a threshold. Up to now, all the protocols use a fixed level of threshold and this mechanism is called Clear Channel Assessment (CCA).

The dynamic CCA is the adoption of the threshold level in relation to the conditions of the network. A reduction of this level reduces the spatial reuse while an increase results in more collisions, thus, the selection of the proper level is an important challenge.

A considerable amount of work has been done to study how the physical carrier sensing mechanism affects capacity and throughput of IEEE 802.11 WLANs [25],[26].

The motivation behind these works is to improve efficiency of those networks so that requirements for increased capacity and higher performance could be fulfilled. In [27], the authors propose cognitive protocol for enabling and disabling virtual Network Allocation Vector (NAV). Their methods require additional information to be added to RTS/CTS control frames and they use a heuristic method to modify the CCA threshold.

Both hidden and exposed nodes result in a decreased overall throughput (Figure 3.1). As explained in [28], the exposed node problem creates severe scalability problems; total throughput of IEEE 802.11 network reaches a limit when the density of APs is increased. Work in [29] presents the phenomenon of the stronger frame in a collision being received successfully, known as Physical Layer Capture (PLC). PLC, along with the standardized four-way RTS/CTS transmission mode, can alleviate the effect of hidden nodes (to some extent) over the cost of fairness.

Zhong et. al [30] revisit some of the common problems faced in traditional Wi-Fi networks and show how their effects could be amplified in dense deployments, especially in co-channel scenarios. The main factors which affect spatial reuse in Overlapping Basic Service Sets (OBSs) are link suppression effect, interference amplification, STA transmissions leading to a temporary deadlock of neighboring APs and hidden/exposed nodes leading to wasted medium occupancy for a prolonged time.

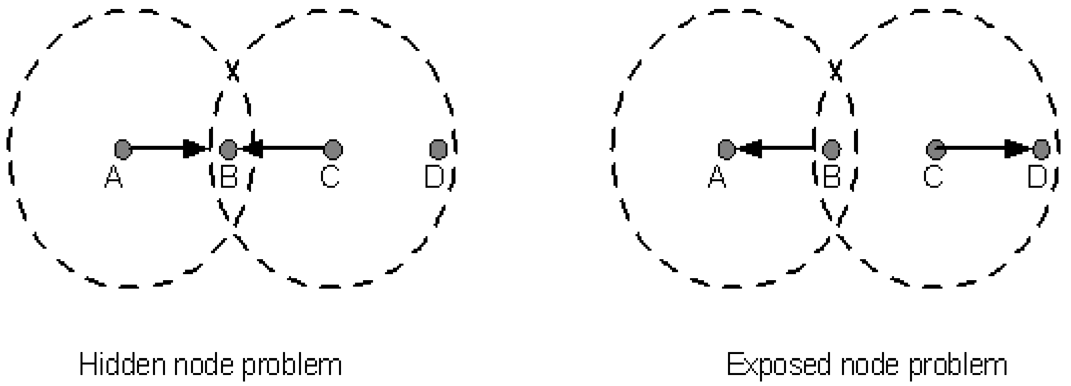


Figure 3.1 The hidden and exposed nodes problems [42]

Several mechanisms for dynamic CCA adjustment have been proposed. Work in [31] presents a dynamic carrier sense threshold that adjusts the CCA threshold in relation to the nodes density in the network. The carried out simulations using IEEE 802.11b show an enhancement of 30% compared against the fixed CCA threshold. Another approach is the proper adjustment of the received signal level and simulations in this case show an performance enhancement of 20% for IEEE 802.11n [32]. Finally, work in [33] features the advantages of dynamic CCA compared to dynamic transmit power control adjustment in spatial reuse and proposes a mechanism which shows enhancement up to 190% in data rate.

3.2 Dynamic transmit power control

Transmit-Power Control (TPC) methods are critical to reduce interference and improve network performance in wireless systems. Network devices transmit at their maximum power level, generating high interference to both co-channel and adjacent channel devices. Increasing interference entails decreasing the quality of the received signal, increasing packet loss and decreasing spectral efficiency, provided that terminals implement adaptive MCS. The IEEE 802.11 standards only define some TPC rules and functions that leave an open way for TPC implementations.

Surveys of typical deployments indicate that the default transmit power levels of the APs and the users are often set to the maximum without considering the coverage of APs and the distance of users from APs [34]. Such a default policy results in a higher interference among overlapping APs.

The major drawbacks concerning implementation of TPC will next described. IEEE 802.11 MCS and data throughput are directly related to SNR. In particular, , the reduction of the Tx power can reduce SNR, MCS and data throughput, thus, the proper adjustment is a challenge. Another issue is that in practice, such a dynamic transmit power setting may be unreliable, since the interference level in an unlicensed band where Wi-Fi operates may change frequently [35]. Finally, while reducing transmission power to decrease the amount of interference may be powerful, it creates a sort of asymmetry between nodes [36]. This asymmetry aggressively affects fairness and harms the STAs who implement the TPC. Therefore, it degrades the global performance of the network. For that reason, power control is used very carefully in deployed WLANs.

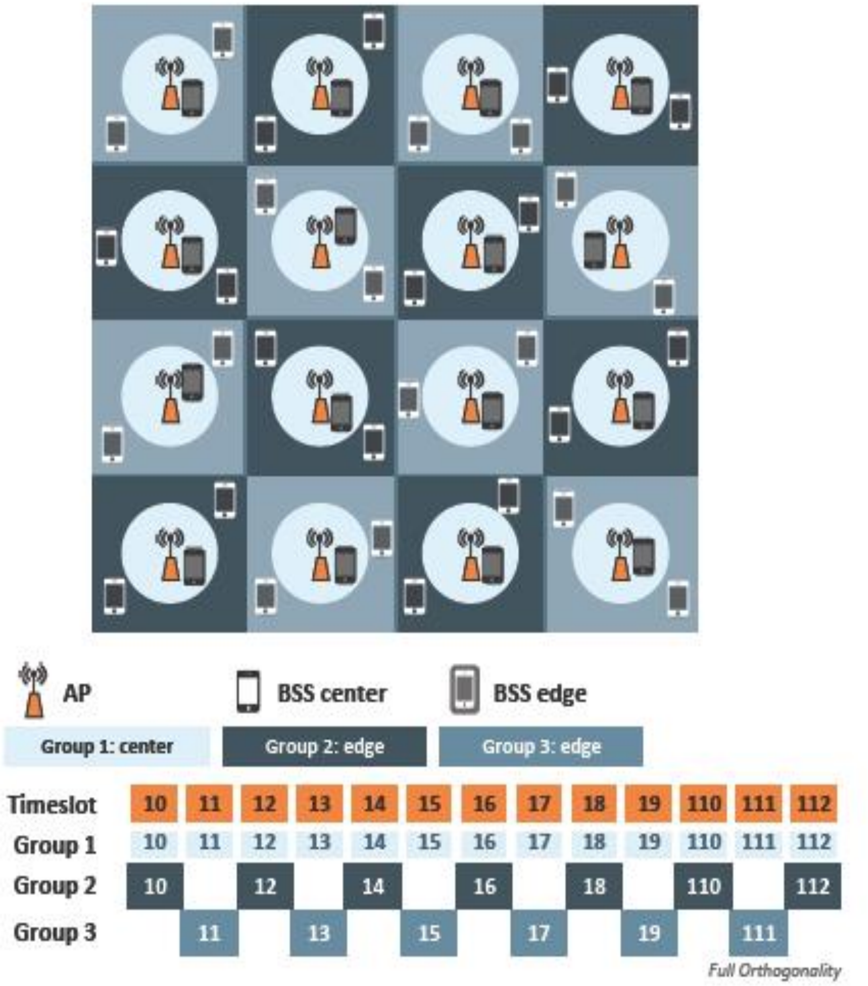
A wide range of transmit power control algorithms, each one based in different parameters, have been recently proposed in the literature in order to improve network performance and reduce interference for IEEE 802.11 wireless networks. Li et. Al. [37] proposes a power control algorithm named PCAP, which stands for Power Control for AP performance. This algorithm simultaneously considers power control and AP association for proportional fairness in multi-rate WLANs. It actually introduces the concept of the AP utility and establishes the relationship between the AP and the network utility according to proportional fairness. Based on the arithmetic geometric mean inequality, it is proved that maximizing network utility can be achieved by maximizing the average and minimizing the variance of AP utility. The PCAP is consisted of two sub-algorithms MAP and MPV. MAP, which stands for Maximize Average Performance, intends to maximize the average AP utility. MPV, which stands for Minimize Performance Variance, intends to minimize the variance of AP utility. Both MAP and MPV adjust AP utility by power control, which might trigger user-AP association changes. Simulation results show that the proposed algorithm can improve network utility, can reduce the power consumption and achieves proportional fairness.

A simple TPC scheme for IEEE 802.11n APs is presented on [38] where the adjustment of transmit power is based on the wireless link occupancy. This method runsin each AP without exchanging signaling information with other APs and STAs, seeking for transmitting with the minimum power provided that the link is not overloaded. Simulation results show that the increase of aggregate throughput in the considered scenarios was higher than 60% for networks working in adjacent channels and higher than 100% for networks far enough that share the same channel.

A TPC scheme for STAs is proposed in [39] to enhance throughput of OBSSs. Authors study four different radio ranges for IEEE 802.11systems and how OBSSs interfere with each other in a dense WLAN. The four radio ranges are transmission range, NAV set range, CCA busy range and interference range. Based on these observations, every station keeps a table for recording the path loss between itself and the neighbor BSS stations from which request to RTS/CTS frames can be overheard. Utilizing this information, those stations adjust their transmit powers and data frames are delivered using only the proper power. Simulation results show that the proposed algorithm significantly improves performance of the OBSSs.

A protocol that manages transmission power of IEEE 802.11 devices and maximizes performance of nodes within an area with a dense concentration of 802.11 networks is proposed on [40]. Authors show that it is possible to calculate the ratio between the transmit power of different nodes that maximizes overall network capacity. The proposed protocol also tunes carrier sense thresholds to ensure that simultaneous transmissions occur when possible. Nodes of network collect information about the RF environment by piggybacking signal strength and path loss information on their own transmissions and promiscuously listen for transmissions from other nodes. Using the collected data, each node executes a power control algorithm that iteratively increases the number of concurrent transmissions that can take place. Evaluation of the protocol using the OPNET simulator shows that it improves network throughput performance by 22% to 87%.

Another scheme that uses TPC in combination with fractional CSMA/CA is proposed in [41]. It is based on the grouping of STA according to their location in the network; the first group is consisted of STAs which are located at the edges of BSS and the second is consisted of STA which are located nearby APs. The first group is characterized having high interference and is in active CSMA mode during specific time slots, whereas the second group is always in active CSMA mode. Transmission schedule and power level in the network are coordinating according to the grouping of STAs (Figure 3.2). Authors claim that the proposed scheme improves performance for dense overlapping networks, reduces interference during neighboring BSS-edge transmission and is backwards compatible with CSMA/CA mode. Simulation results show an enhancement up to 100% concerning data rates.



Timeslot	10	11	12	13	14	15	16	17	18	19	110	111	112
Group 1	10	11	12	13	14	15	16	17	18	19	110	111	112
Group 2	10		12		14		16		18		110		112
Group 3		11		13		15		17		19		111	

Figure 3.2 Scheme with fractional CSMA/CA and TPC [41]

3.3 Task Group Submissions for Spatial Reuse

A special IEEE 802.11ax TG is established to investigate all the possible mechanisms and technologies that the protocol could adopt towards the enhancement of spatial reuse. In this part of the M.Sc. thesis the most important contributions for spatial reuse to this IEEE 802.11ax TG are presented in chronological order.

On September 2014, at the Athens meeting, a submission highlighted the opportunities for adaptive CCA versus the static CCA used in IEEE 802.11 amendments [42]. It also pointed the challenges that adaptive CCA brings such as (a) introduction of additional hidden nodes due to the fact that the CCA increased level would also increase collision and unfairness, (b) increased overhead due to more frequent use of RTS/CTS for all frames and unfairness toward legacy devices. It also considers SINR fluctuations due to the higher CCA threshold (Figure 3.3) and proposes more conservative MCS rate selection scheme to cope with additional SINR level fluctuation.

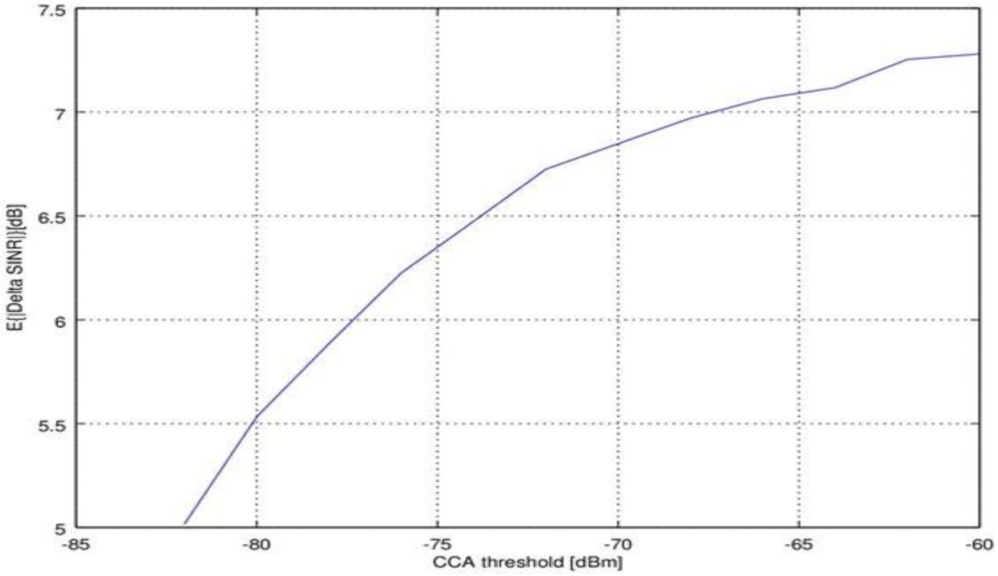
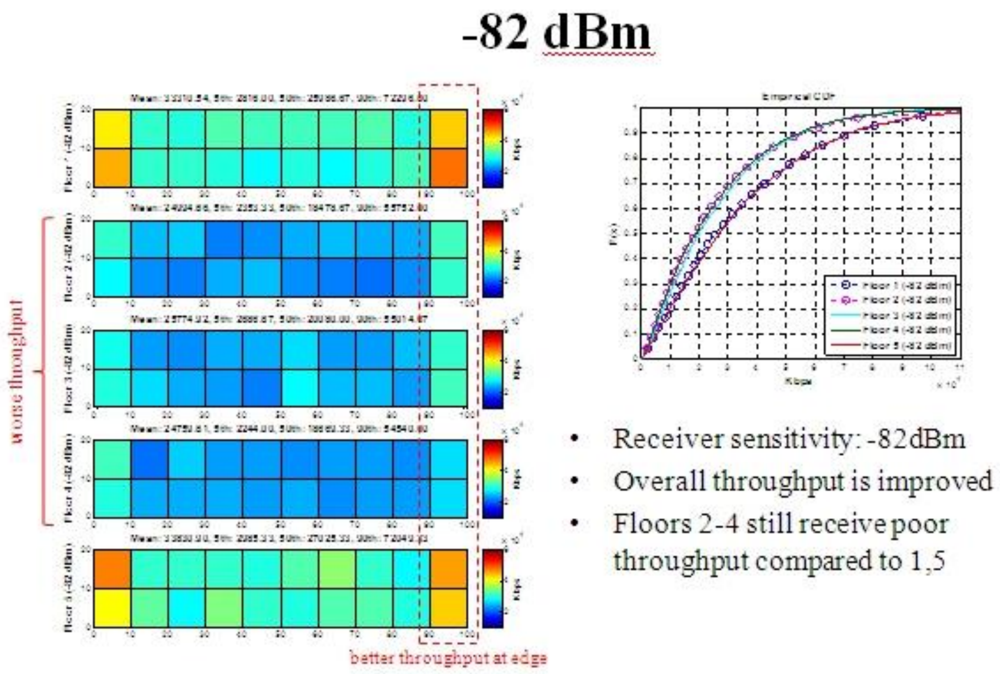


Figure 3.3 SINR fluctuations due to the CCA threshold [43]

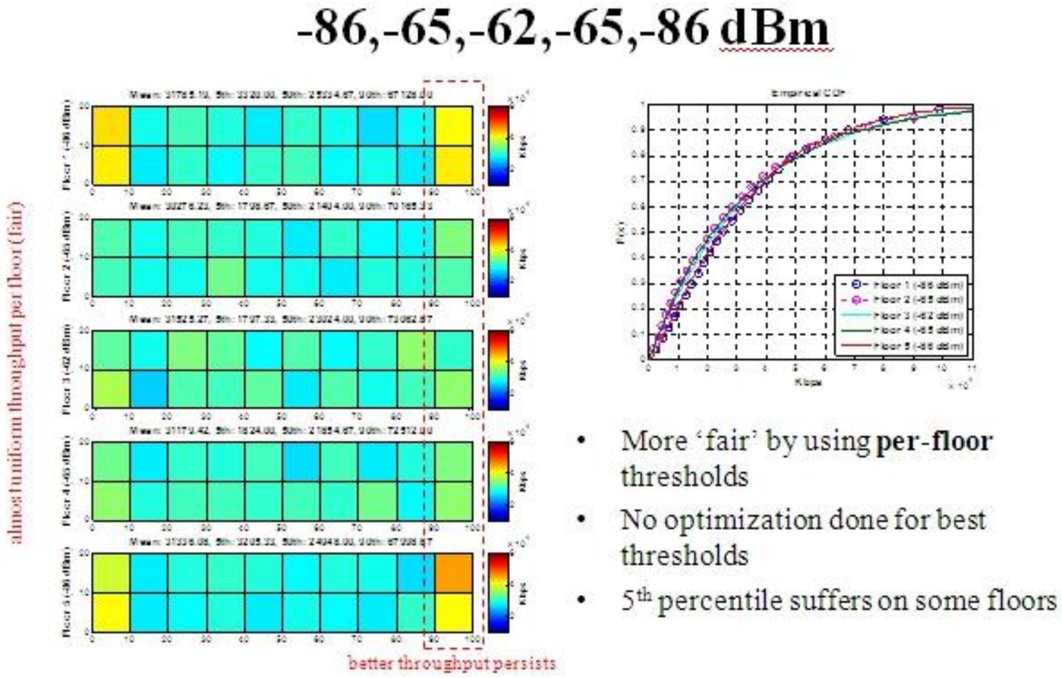
On November 2014, at the San Antonio meeting, a contribution claims that with fixed thresholds level, there is unfairness (based on location, interference, etc.) which can be mitigated by intelligent selection of thresholds level [44]. The results of residential simulation scenario show that the per floor CCA adjustment achieves a more fair performance than the fixed level adjustment for all the floors (Figures 3.4 and 3.5). The conclusion of this contribution is that adaptive configuration of CCA threshold or receiver sensitivity can help improving spatial reuse while maintaining fairness.



-82 dBm

- Receiver sensitivity: -82dBm
- Overall throughput is improved
- Floors 2-4 still receive poor throughput compared to 1,5

Figure 3.4 Residential scenario results with fixed CCA level for each floor [44]



-86,-65,-62,-65,-86 dBm

- More 'fair' by using **per-floor** thresholds
- No optimization done for best thresholds
- 5^{th} percentile suffers on some floors

Figure 3.5 Residential scenario results with variable CCA per floor [44]

On January 2015, at the Atlanta meeting, the BSS coloring mechanism that was introduced in the IEEE 802.11ah amendment and the Dynamic Sensitivity Control (DSC) mechanism were presented and compared in [45]. Simulation results show that in almost all thresholds, the gain of the DSC method is higher than the BSS color method if these methods are used individually (Figure 3.6). The authors also claimed that the possible reasons for DSC superiority are the different gain is PLCP error and that packet from legacy STA cannot be filtered by color. They also suggested that the possibilities of combination these methods in other scenarios should be considered continuously.

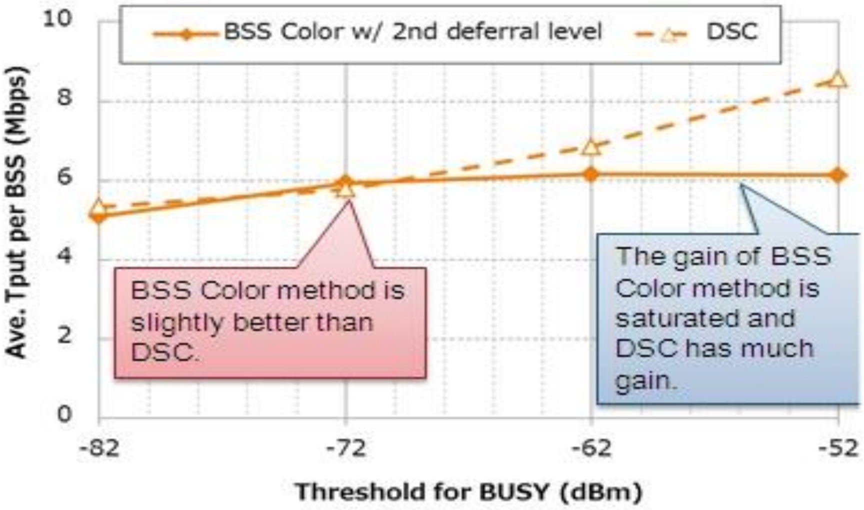


Figure 3.6 Comparison between BSS Coloring method and DSC [45]

On March 2015, at the Berlin meeting, the impact of TPC coupled to the DSC for legacy unfairness issue is presented in [46]. Authors claim that since legacy fairness is an important requirement for IEEE 802.11ax, the above scheme is considered and evaluated as a solution for recovering legacy fairness. They proposed a TPC algorithm that is linked with the DSC for STAs, in which the basic idea is to reduce Tx power by amount of raising CCA threshold by the DSC (Figure 3.7). Simulation results showed increasing system gain and maintaining fairness can be satisfied simultaneously by selecting appropriate TPC and DSC parameters.

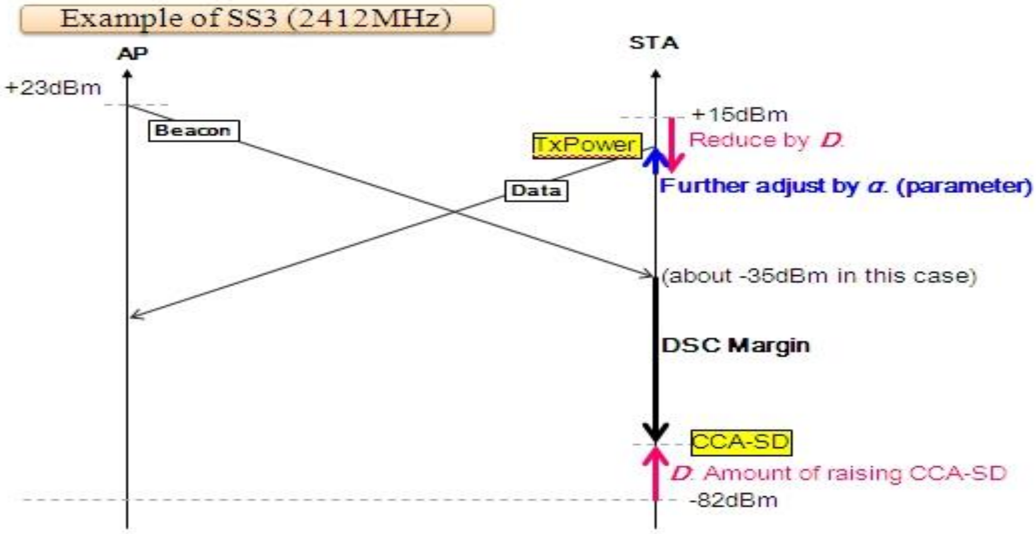


Figure 3.7 Relation of DSC/TPC parameters [46]

On May 2015, at the Vancouver meeting, [47] discussed the receiver behavior when DSC with BSS color algorithms are applied. Authors proposed the termination of receive process when the BSS color contained in the received frame doesn't match with the one used in the BSS (Figure 3.8 and 3.9). Simulation results show that the DSC technique using BSS color and termination of receive process improves system throughput.

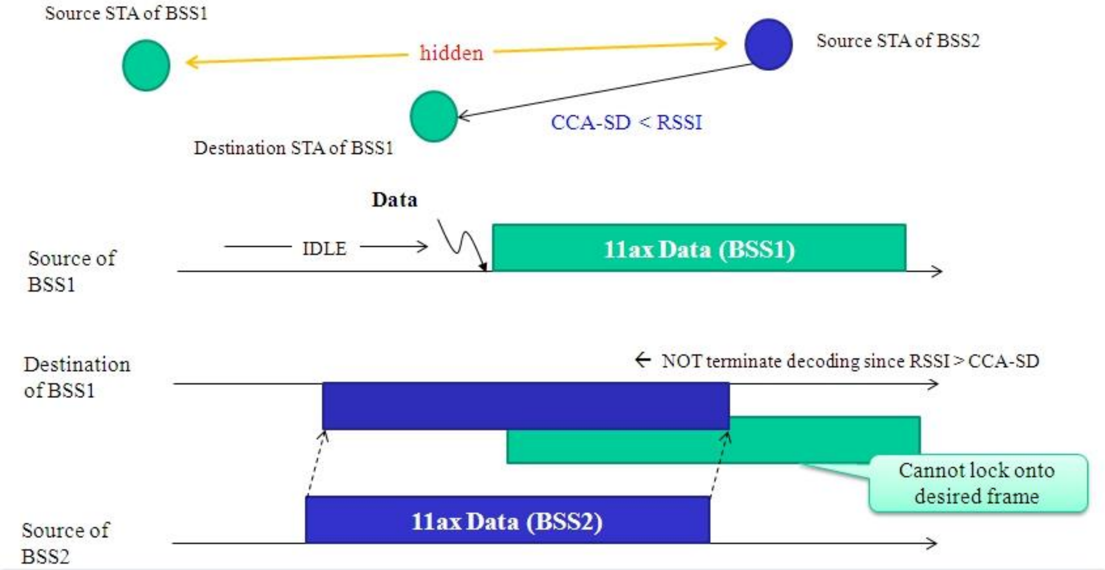


Figure 3.8 Receiver behavior without terminating decoding [47]

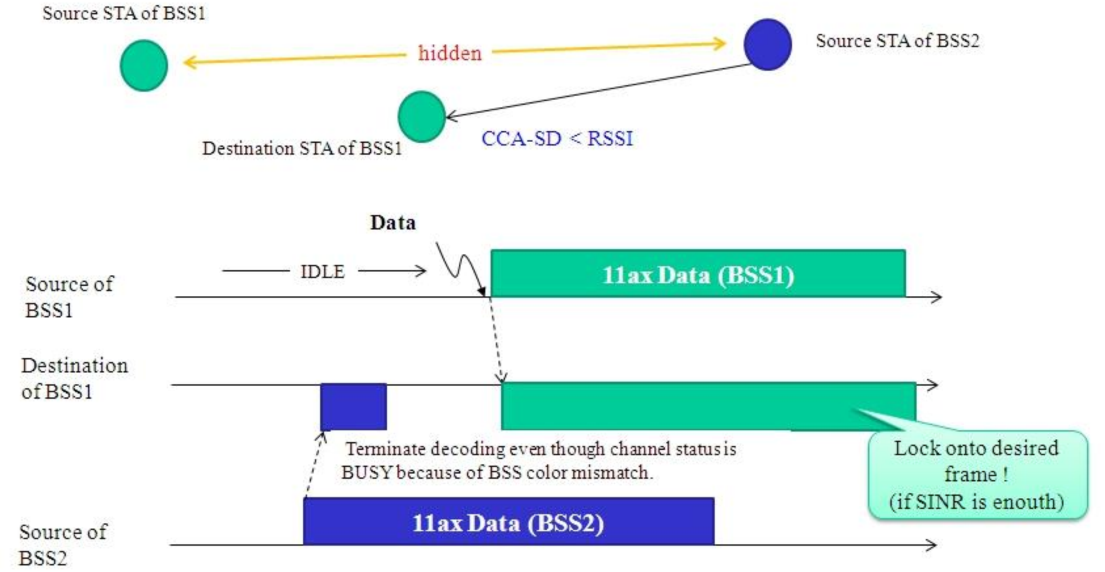
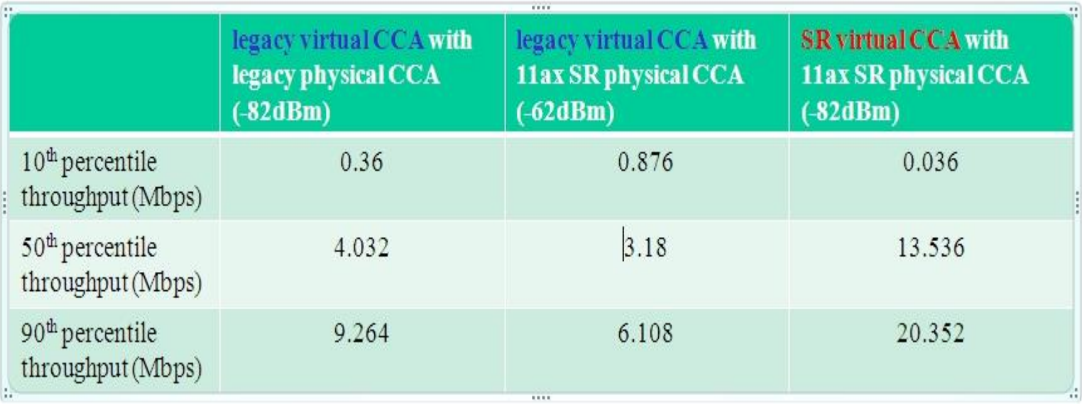


Figure 3.9 Receiver behavior terminating decoding [47]

On July 2015, at the Waikoloa meeting, [48] proposed an enhanced NAV operation for spatial reuse. Authors suggested that the current NAV operation, which states that all third party STAs receiving a RTS/CTS shall set their NAV regardless of the BSS reducing spatial reuse will not be utilized and proposed that High Efficiency (HE) STAs should have different NAV update rules depending on whether a received RTS/CTS is transmitted from OBSS. For example, a HE STA update NAV resulting from a received RTS/CTS transmitted from the BSS that is associated with but it discards a RTS/CTS transmitted from OBSS. Simulation results showed that by discarding the RTS/CTS transmitted from the OBSS, a spatial reuse gain is achieved from increasing the physical CCA threshold (Figure 3.10).



	legacy virtual CCA with legacy physical CCA (-82dBm)	legacy virtual CCA with 11ax SR physical CCA (-62dBm)	SR virtual CCA with 11ax SR physical CCA (-82dBm)
10th percentile throughput (Mbps)	0.36	0.876	0.036
50th percentile throughput (Mbps)	4.032	3.18	13.536
90th percentile throughput (Mbps)	9.264	6.108	20.352

Figure 3.10 Simulation results with enhanced NAV setting [48]

On September 2015, at the Bangkok meeting, [49] demonstrated the simulation results that evaluated coloring, DSC and TPC algorithms under different scenarios (Figure 3.11). The results showed that TPC used together with DSC and coloring is a very effective solution for dense environments. The authors also suggested that further optimization of algorithm/parameter may improve efficiency.

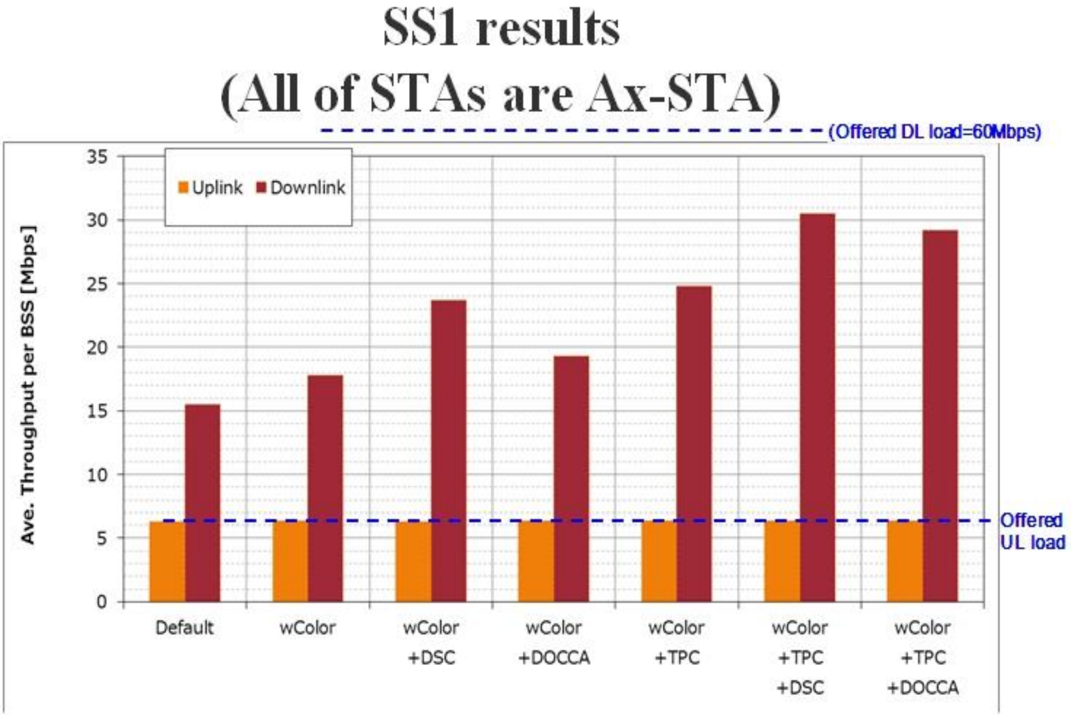
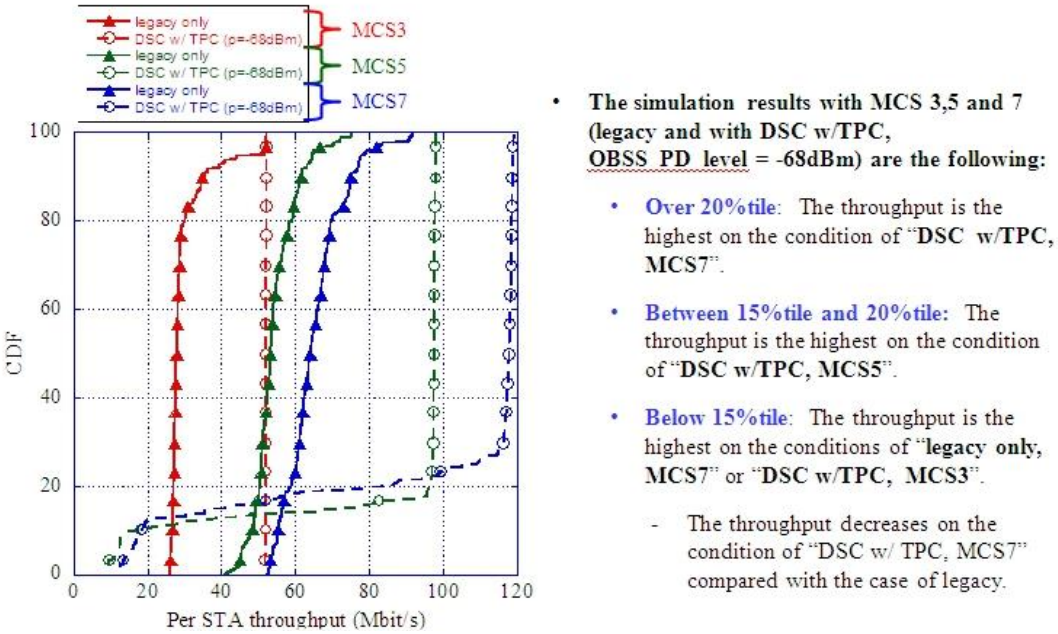


Figure 3.11 Algorithms performance [49]

On March 2016, at the Macau meeting, [50] investigated the effect of MCS selection and DSC. For this reason the proposers evaluated throughput for a residential simulation scenario in order to show the effect of spatial reuse for several different MCS parameters (Figure 3.12). The conclusions of the evaluation were that in a residential scenario SINR may be worse due to interference when adjacent APs transmit frames at the same time and throughput may be decreased by half if a STA is located far from the AP. In order to achieve higher throughput by using DSC, transmitted frames should be received successfully with a high probability. In order to improve throughput regardless of the location of STAs, one of the possible ways is the use of MCS control in conjunction with DSC, i.e., optimization of the OBSS_PD threshold.



- **The simulation results with MCS 3,5 and 7 (legacy and with DSC w/TPC, OBSS_PD level = -68dBm) are the following:**
  - **Over 20%tile**: The throughput is the highest on the condition of "**DSC w/TPC, MCS7**".
  - **Between 15%tile and 20%tile:** The throughput is the highest on the condition of "**DSC w/TPC, MCS5**".
  - **Below 15%tile**: The throughput is the highest on the conditions of "**legacy only, MCS7**" or "**DSC w/TPC, MCS3**".
    - The throughput decreases on the condition of "DSC w/ TPC, MCS7" compared with the case of legacy.

Figure 3.12 Simulation results with various MSC values [50]

On July 2016, at the San Diego meeting, [51] clarifies the parameters of spatial reuse mode. Authors proposed to define default parameters that are conservative in unmanaged environments, in contrary to the case of managed environments, the APs (usually managed by a controller) have a good knowledge of the environment and can define parameters that better suits the environment. They also proposed the structure of spatial reuse element that will contain SR_disallowed signalling in HE-SIGA to indicate whether spatial reuse operation is allowed or not.

4

Scenarios

The simulation compares efficiency of CCA and TPC adjustment by five different approaches for a WLAN environment. The first cases is the fixed CCA that uses a fixed value of CCA for both the CCA and the Tx Power levels. The second approach is the DSC method that uses the coloring rule by applying different thresholds for the intra-WLAN and inter-WLAN packets, combined with a dynamic adjustment of the CCA level (the Tx Power in this case remains fixed). The next method, which is proposal of the current M.Sc. thesis is the DSC flag that is based on the DSC with additional parameters for the CCA adjustment. The last two approaches that are being evaluated are the Adaptive Transmitter Power Control (ATPC) and the use of ATPC flag, utilizing the same algorithm for the CCA adjustment, as the DSC and DSC flag respectively, with the addition of dynamic Tx Power for these two methods.

4.1 Fixed CCA

The CCA mechanism is defined in the IEEE 802-11-2007 standard as part of the Physical Medium Dependent (PMD) and Physical Layer Convergence Protocol (PLCP) sub-layers that are part of the Physical Layer. It is composed of two related functions, Carrier Sense (CS) and Energy Detection (ED). CS refers to the ability of receiver to detect and successfully decode the preamble of any Wi-Fi signal (Fig 4.1). The level of detected signal determines CCA, according to the selected threshold, in order to report BUSY for the duration of the transmission as indicated in the PLCP length field, setting the NAV accordingly. ED refers to the ability of a receiver to detect without successfully decoding any RF energy present on the frequency band of the used channel. This energy can be noise, interference or unidentifiable Wi-Fi transmissions. Unlike CS, ED cannot determine the duration of the time that the channel will remain BUSY, so it must sample the medium for every time slot to sense if the RF energy still is present. The level of ED threshold is 20dB greater than the SD threshold.

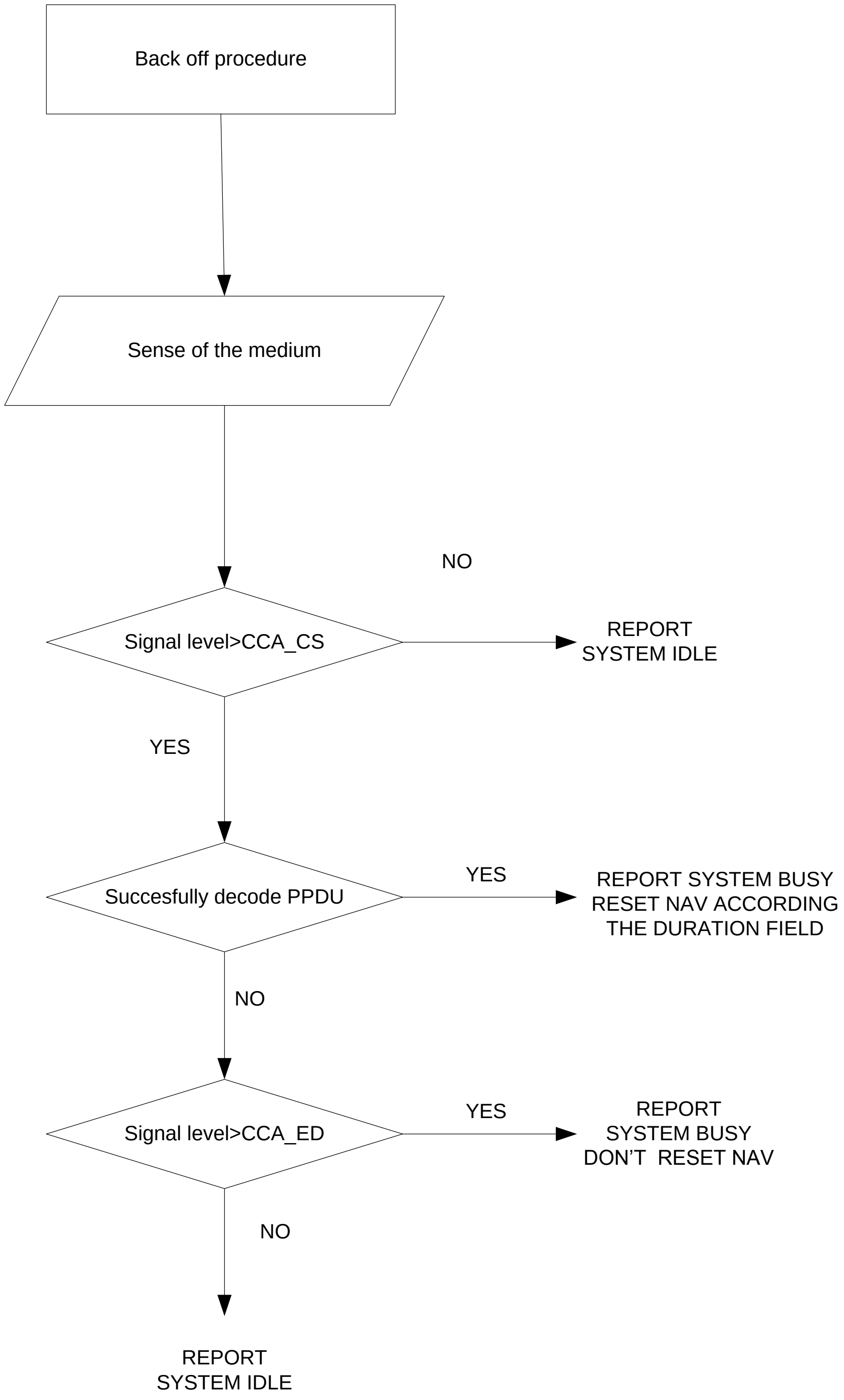


Figure 4.1 The CCA mechanism operation

The threshold levels that were implemented by IEEE 802.11ac are shown in Table 4.1. IEEE 802.11ac uses different CCA threshold levels for the primary and secondary channels. The rules that guide the development of these thresholds are (a) the required threshold doubles (+3db) when the channel bandwidth doubles and (b) the ED threshold level is 20dB greater than the primary channel threshold [52]. During the simulation scenarios the above threshold levels will be used for the fixed CCA method.

Channel width Primary	**Signal Threshold Primary**	**Signal Threshold Secondary**	**Energy Threshold Secondary**
20 MHz	-82 dbm	-72 dbm	-62 dbm
40 MHz	-79 dbm	-72 dbm	-59 dbm
80 MHz	-76 dbm	-69 dbm	-56 dbm
160 MHz	-73 dbm	-	-

Table 4.1. CCA thresholds for 802.11ac

4.2 Coloring

The coloring method is introduced in IEEE 802.11ah and it assigns a different color per BSS. The proposed TG IEEE 802.11ax draft specification issued on March 2016 [53] defines the rules for the coloring method (Fig 4.2). A station determines whether a detected frame is an inter-BSS or an intra-BSS frame by using BSS coloring or MAC address in the MAC header. The detected frame is intra-BSS frame if one of the following conditions is true:

- The BSS colour in the detected PLCP protocol data unit (PPDU) is same as the BSS colour announced by its associated AP,
- The receiver address or transmitter address of the detected frame is same as the Basic Service Set IDentifier (BSSID) or its bandwidth signalling variant of its associated AP
- Its associated AP is identified by BSSID element and the receiver address or Transmitter Address of the detected frame is same as one of the BSSID or its bandwidth signalling variant defined by Multiple BSSID element

If the detected frame is an inter-BSS frame, under condition, uses overlap basic service set preamble detection (OBSS PD) level that is greater than the minimum receives sensitivity level. A STA should regard an inter-BSS PPDU with a valid PHY header and that has receiving power RSSI below the OBSS PD level used by the receiving STA and that meets additional conditions, as not having been received at all (e.g., should not update its NAV), except that the medium condition shall indicate BUSY during the period of time that is taken by the receiving STA to validate that the PPDU is from an inter-BSS, but not longer than the time indicated as the length of the PPDU payload. The operation of coloring method is shown in Figure 4.2.

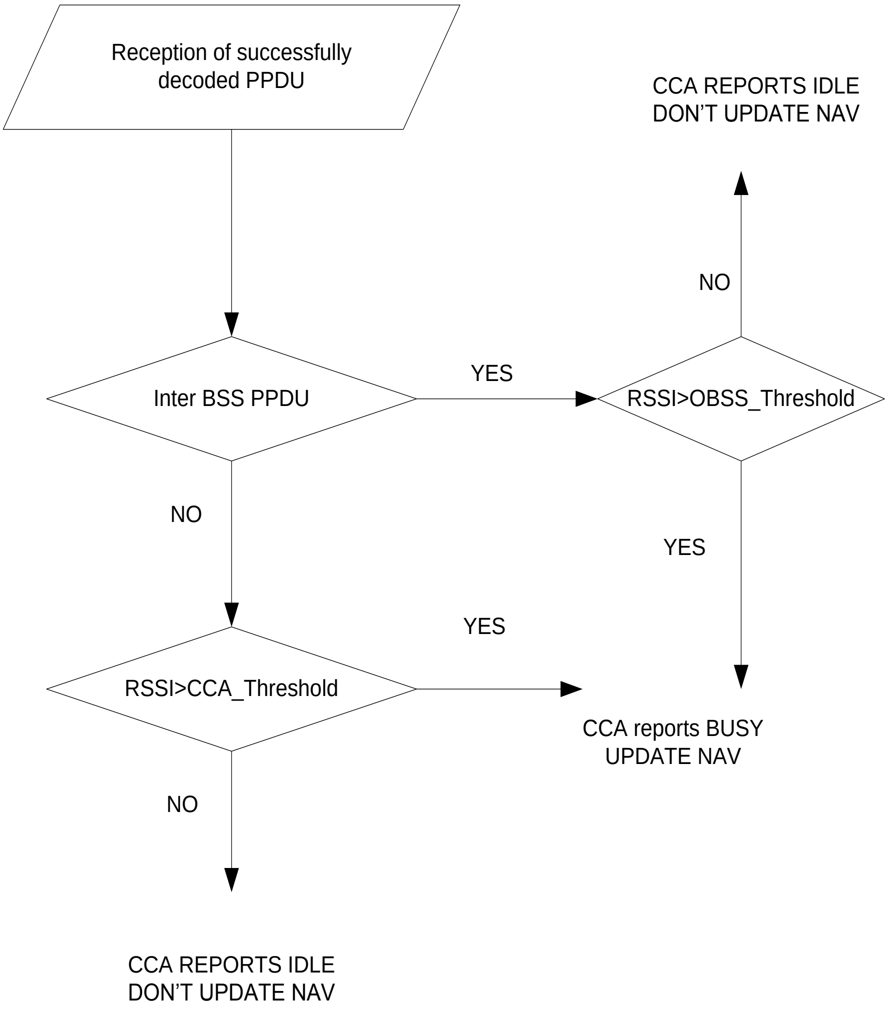


Figure 4.2 Colouring method operation in IEEE 802.11ax

4.3 Dynamic Sensitivity Control

The DSC scheme for the dynamic adjustment of OBSS_PD threshold is described in contributions [54] and [55] to the TGax. This scheme adjusts the OBSS_PD threshold of a STA or AP based upon the RSSI levels of the network AP beacons and STA probe frames. The basic idea of the scheme is to identify the type of received packet according to rules described in the coloring scheme. A DSC STA that is associated to a DSC AP shall set its effective OBSS_PD threshold, as per equation

$$\text{OBSS\_PD threshold} = \text{MIN}(\text{Upper Limit}, \text{RSSI}_{\text{beacon}}) - \text{Margin} \tag{4.1}$$

Where,

Upper Limit is the value adjusted by the AP,

Margin is the value adjusted by the AP, and

$\text{RSSI}_{\text{beacon}}$ is the received signal strength of the beacon transmitted by the DSC AP

The minimum value for effective OBSS_PD threshold is -82 dBm for any 20 MHz channel. This value is increased by 3 dB for 40 MHz channels, 6 dB for 80 MHz channels and 9 dB for 160 MHz channels.

A DSC AP may transmit the DSC Parameter element by using beacons and probe responses in order to set the values for DSC Margin and DSC Upper Limit in all associated DSC STAs. Suggested methods for the AP to determine these values are, either by pre-setting them based upon the location and environment of the network, or by a learning process. For example, if the AP is located in an apartment or house then with advanced knowledge of the dimensions or ranges required, suitable values for the DSC Upper Limit and DSC Margin could be derived and used. Similarly, for the case of an enterprise or a managed network, the values for the DSC Margin and DSC Upper Limit may be determined so as to set a desired network coverage area. Alternatively, an AP could discover the channel, overlapping situation and signal conditions by monitoring beacons and traffic from its own and overlapping networks. Based upon this monitoring, the AP could then determine the DSC Upper Limit and DSC Margin values that would suit the environment and afford an improvement in network efficiency.

The AP may set a CCA Threshold for itself that is compatible with its network and the values for DSC Upper Limit and DSC Margin that it has set. In most practical situations an effective CCA threshold setting that is equal to the DSC Upper Limit minus the DSC Margin is suggested. An alternative is to set the effective CCA threshold to be 10 dB less than the expected or actual received signal strength from a non-AP STA that is located at the edge of the network.

4.4 Dynamic Sensitivity Control Flag

The current thesis proposes a method for the dynamic adjustment of OBSS_PD threshold and it is based in the DSC method that it was described before. It adds two new parameters to the algorithm that calculates the value of the OBSS_PD threshold level. These parameters are inspired of the results that arose during the simulation scenarios.

The first one is the interference flag, its purpose is to distinguish the STAs of WLANs which are placed at the edges of a dense deployment. This category of WLANs can apply an aggressive level of OBSS threshold to their AP, under certain conditions, without interfering the other WLANs and thus degrade the overall network performance. The example shown in Figures 4.3-4.4 explains the way that this parameter can enhance the spatial reuse in a dense WLAN environment. In our example scenario we have three overlap WLANs, AP1 has one associated station STA1, AP2 has two associated stations STA2 and STA3 and AP3 has one associated station STA4. AP1 and STA2 uses the same channel, the same happens with STA3 and AP3. In Figure 4.3 STA2 and STA3 uploads to AP2, AP1 and AP3 defers unnecessarily their transmissions due to conservative OBSS_PD threshold level. In Figure 4.4 AP1 and AP3 increase their OBSS_PD threshold level to maximum possible level and thus they can download simultaneously without degrading the quality of signals that the AP2 receives.

There are two conditions for an AP to increase the OBSS_PD threshold level, the first one is that the receiving STA intra beacon RSSI level is much greater than any inter beacon RSSI level received, a fact that guarantees that the station is not placed between two overlap WLANs. A STA can set its interference flag to TRUE with the following condition:

$$Intra\_RSSI_{BEACON} > INTER\_RSSI_{BEACON} + Margin \qquad (4.2)$$

The above statement can only be true for the STAs which are associated with APs that are placed at the edges of the topology, so a STA can inform the AP which is associated with via probe frames by setting the interference flag, accordingly.

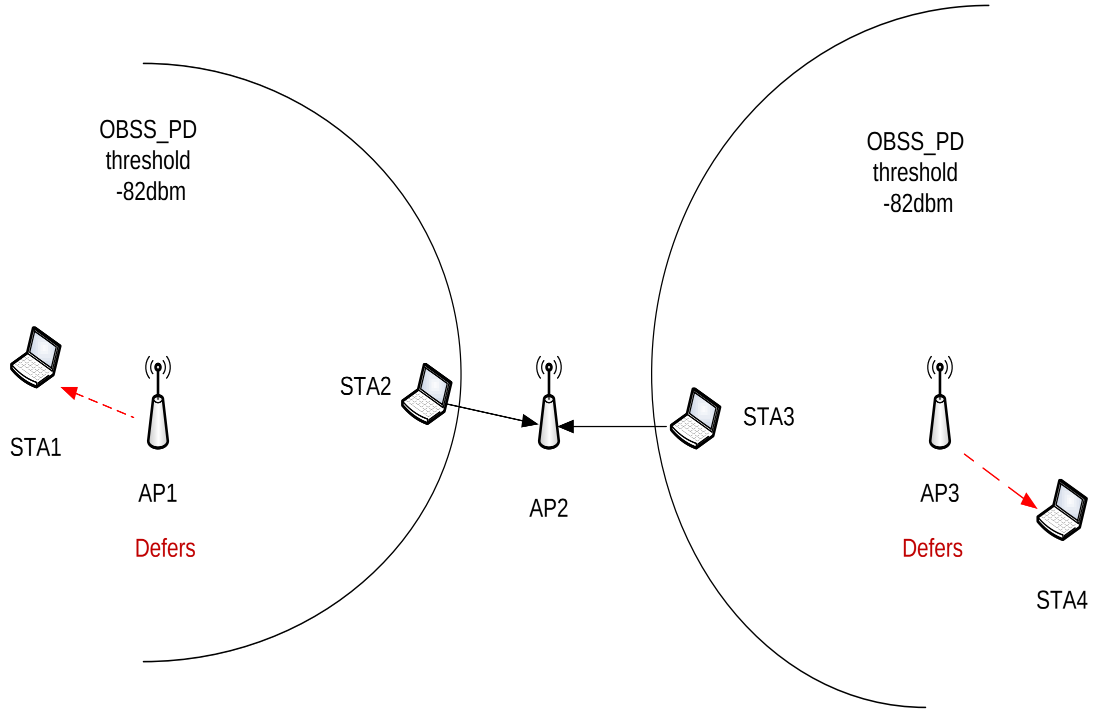


Figure 4.3 Scenario without the use of interference flag

The second condition for an AP to increase OBSS_PD threshold level to maximum is that the destination of the inter-BSS packet is an AP. If the destination of the inter-BSS packet is not an AP then it is more likely that a collision will occur, because the STA of the neighboring WLAN will be possibly affected by the AP transmission. When the two above statements are met an AP can rise up the OBSS_PD threshold to the maximum possible level.

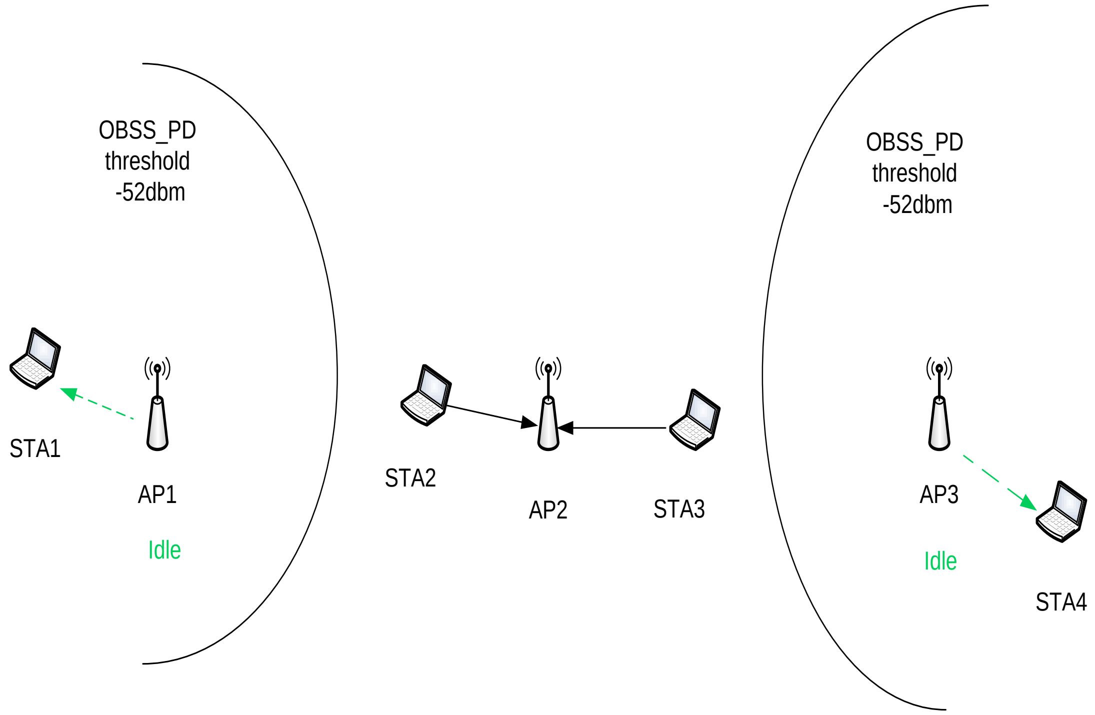


Figure 4.4 Scenario using the interference flag

The other variable is the equalizer flag, and its purpose is to balance the performance between WLANs in a dense topology. During all the simulation scenarios it was noticed that the WLANs that were placed in the middle of dense topology were underperforming compared to the WLANS that were placed to the edges of the topology , also they reveal a greater percentage of defers due to the applied OBSS_PD threshold level (Fig 4.5). This is explained by the amount of interference that these WLANs are receiving, for this reason this variable aims to boost up the performance of these WLANs by increasing their OBSS_PD threshold level. In a managed Extended Service Set (ESS) the equalizer parameter can be adjusted manually by a coordinator. Thesis proposal for the way that an AP can calculate automatically its position in a dense topology needs the exchange of information between APs. Every AP must calculate the mean RSSI value of the beacons frames that receives from the other APs, this value is sent to the other APs, with this information every AP calculates the mean value of interference of the other APs and compares it with its own mean RSSI value, if the first is lower it sets the equalize flag to TRUE. This is explained better with an example shown in figure 4.6, in this topology we have three overlap BSS, the values of RSSI beacon frames are shown for each AP. The AP-A has a mean RSSI value of -60dbm and mean value of interference -50dbm so according to the rules sets its equalizer flag to FALSE, the same happens with AP C, on the contrary AP-B which is placed in the middle of topology has a mean RSSI value of -50dbm and mean value of interference -60dbm so according to the rules sets its equalizer flag to TRUE.

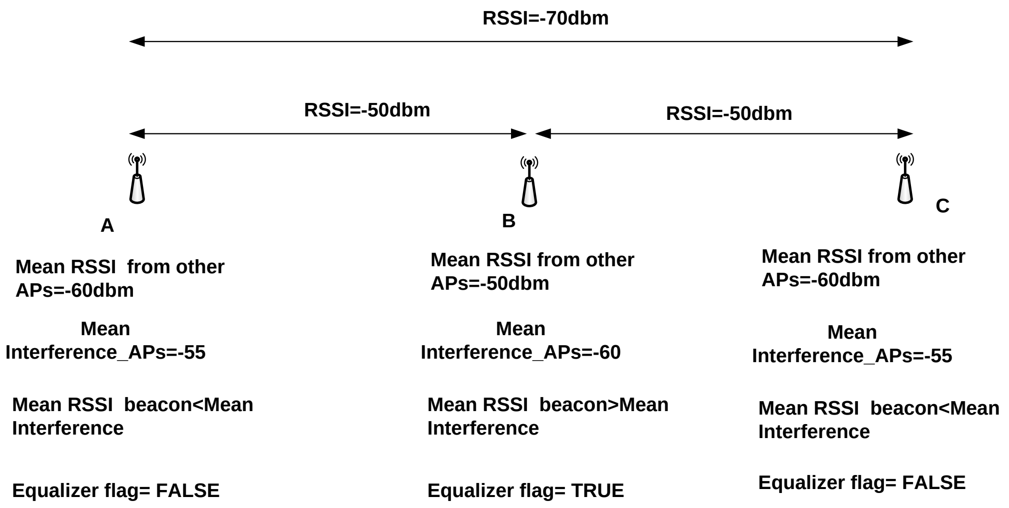


Figure 4.5 Operation of Equalizer flag

A DSC-flag AP shall set its effective OBSS_PD threshold, as per equations:

$$\text{OBSS\_PD threshold} = \text{MIN}(\text{Upper Limit}, \text{Mean}(\text{RSSI}_{\text{probe}})) - \text{Margin-Equalizer} \qquad (4.3)$$

when Interference_flag=FALSE
or

$$\text{OBSS\_PD threshold} = \text{Upper Limit} \qquad (4.4)$$

when Interference_flag=TRUE

A DSC-flag STA that is associated to a DSC AP shall set its effective OBSS_PD threshold, as per equation:

$$\text{OBSS\_PD threshold} = \text{MIN}(\text{Upper Limit}, \text{RSSI}_{\text{beacon}}) - \text{Margin-Equalizer} \qquad (4.5)$$

Where,
$\text{RSSI}_{\text{beacon}}$ is the received signal strength of the beacon transmitted by the DSC AP,
$\text{Mean}(\text{RSSI}_{\text{probe}})$ is the mean received signal strength of the probe frames transmitted by the DSC STAs.

The minimum OBSS_PD threshold value is Fixed CCA so

OBSS_PD threshold >=Fixed CCA

The proposed algorithms for the adjustment of OBSS_Threshold for the AP and STA are shown in Figures 4.5 and 4.6.

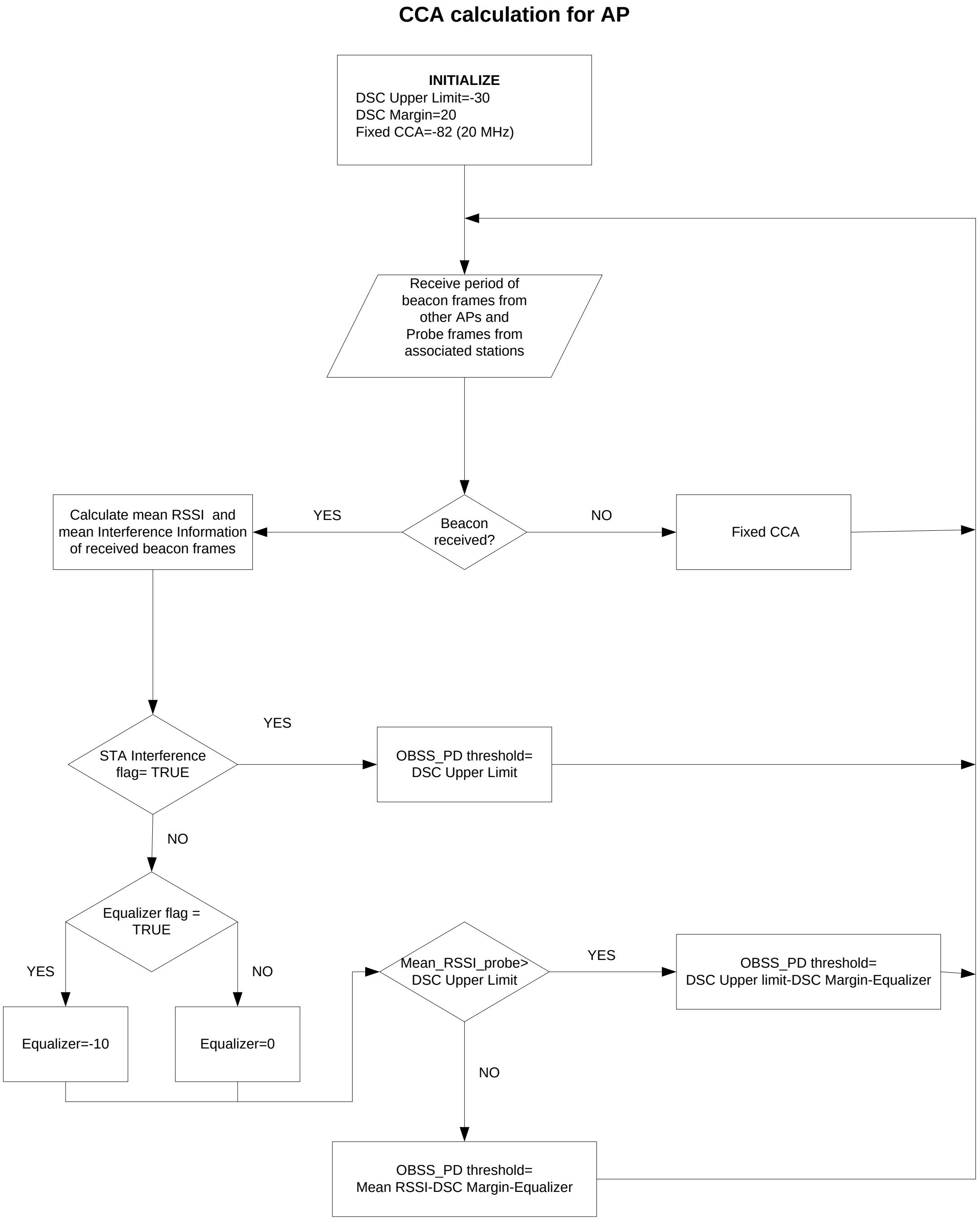


Figure 4.5 DSC flag algorithm for AP

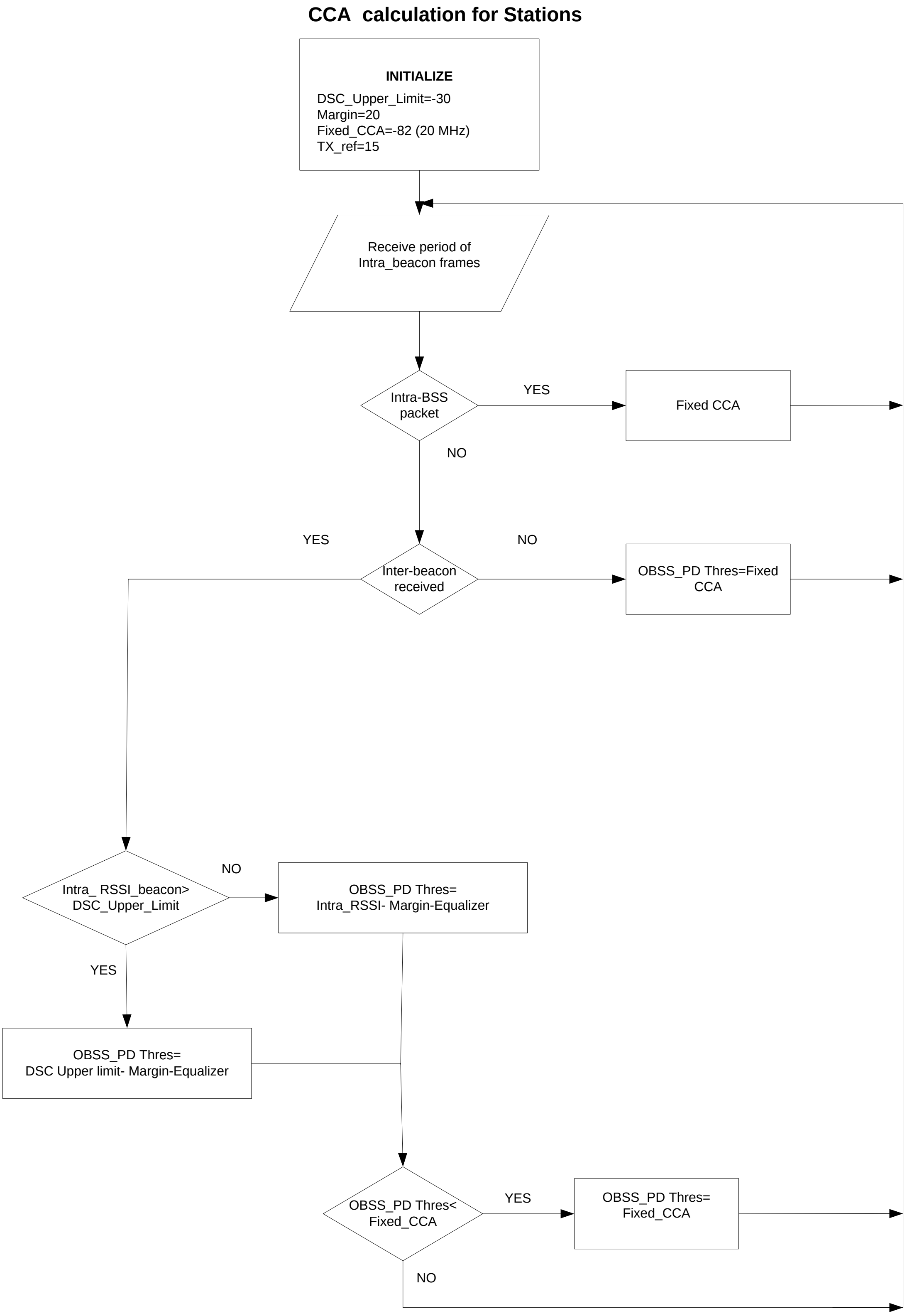


Figure 4.6 DSC flag algorithm for STA

4.5 Adaptive Transmitter Power Control

The ATPC scheme for the dynamic adjustment of transmitter power on AP and STA is described in [54] and [55]. It combines the coloring and DSC procedures previously described with dynamic adjustment of power transmission. The main rule in this scheme is that a STA or AP can increase the OBSS_PD Threshold only if it reduces its transmit power at the same time (fig 4.7). Using these values, the transmit power of a STA will be at a minimum when it is close to the AP and will increase its transmission power by 1 dB for every 1dB decrease in the effective CCA threshold up to its maximum transmit power.
The equation which linking coloring, DSC and TPC is

OBSS_PD Threshold= CCA fixed+ (TXPWRref - TXPWR)
TXPWR = (CCA fixed – OBSS_PD Threshold)+ TXPWRref (4.5)

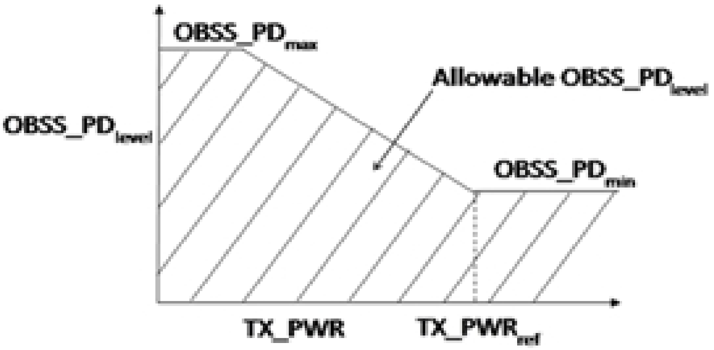


Figure 4.7 Transmit power and OBSS_PD threshold linking [54]

4.6 Adaptive Transmitter Power Control Flag

As the DSC flag the ATPC flag is thesis proposed method for the dynamic adjustment of CCA and transmit power. It uses the same algorithm with the DSC flag for the calculation of the OBSS_PD threshold and links it with the transmit power using the rules of ATPC. In the proposed algorithm the margin between minimum and maximum transmit power is 20 db. The operation of algorithm for AP and STA is shown in Figures 4.8 and 4.9.

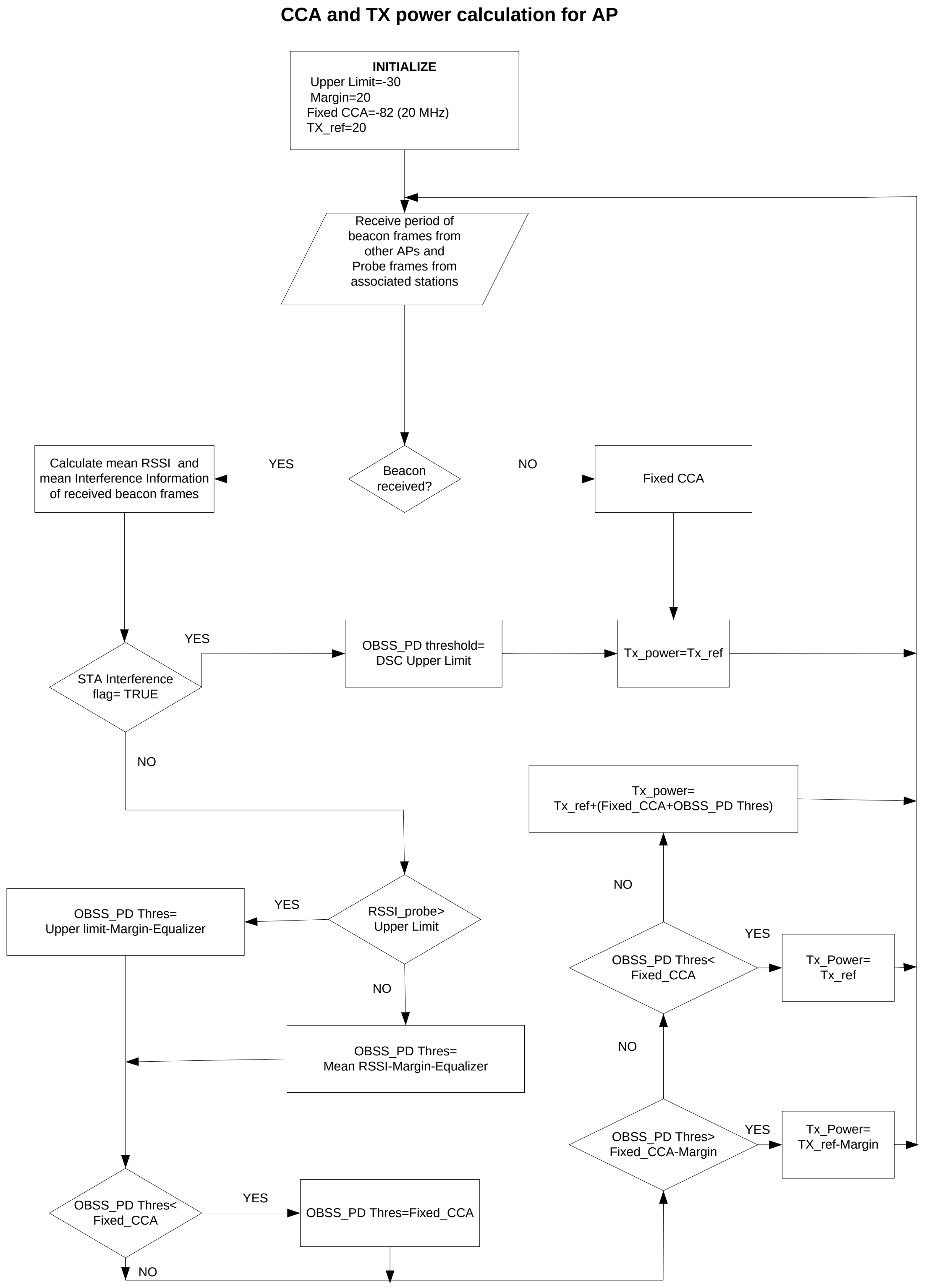


Figure 4.8 TPC flag algorithm for AP

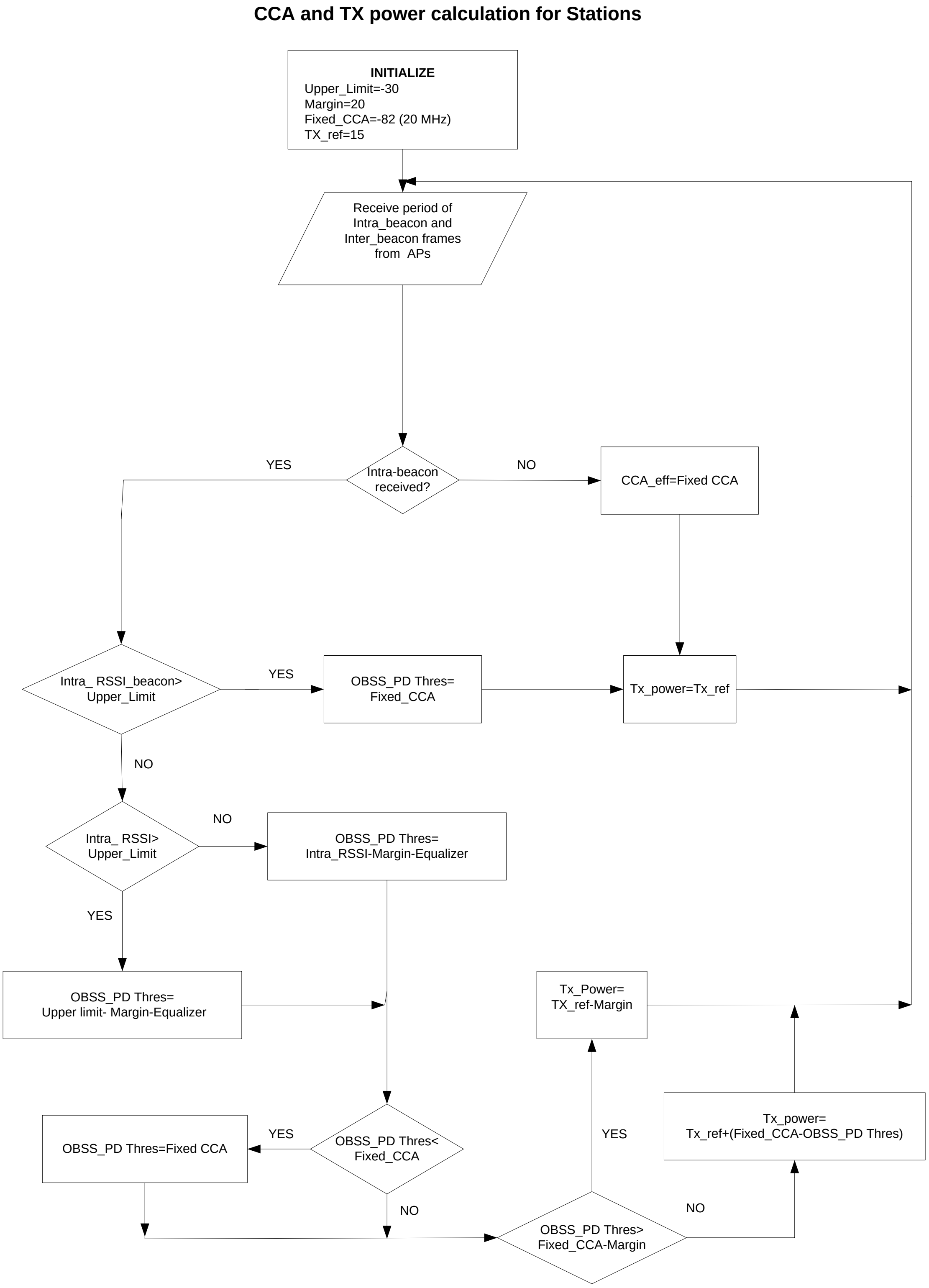


Figure 4.9 TPC flag algorithm for STA

5

Simulation results

The performance evaluation of the schemes was conducted with the use of MATLAB software. The simulation considers many scenarios in which each scheme was evaluated for certain characteristics for a dense WLAN topology.

5.1 Technical Characteristics

The simulator is based on the creation of separate links between every node, AP or STA, within the area that the WLANs are deployed. The log-distance path loss model was adopted for the calculation of these links, in this model received power (in dBm) at a distance d (in meters) from the transmitter (Pr(d)) is given by the equation:

$$P_r(d) = P_{ro} - 10\log\alpha(d) + X\sigma \tag{5.1}$$

where

P_{ro} is the signal strength 1 meter from the transmitter,

α is known as the path loss exponent, and

$X\sigma$ represents a Gaussian random variable with zero mean and standard deviation of σ dB

The parameters (α,σ) define the statistical model and are viewed as heavily dependent on the environment. Measurements in the literature have reported empirical values for α in the range between 1.8 (lightly obstructed environments with corridors) and 5 (multi-floored buildings), while values for σ usually fall into the interval 4-12 dB [56]. Based on experiments with off-the-shelf IEEE 802.11 hardware, Faria [57] have shown that the log-distance path loss model, with log-normal shadowing, can be used to estimate signal attenuation both inside and outside a building, with moderate accuracy. Measurements produced a model with a path loss exponent α of 4.02 and a standard deviation σ of 7.36 dB. These values of α and σ were used for the path loss calculation during all the simulation scenarios.

The SINR value is crucial for the calculation of Data rate in our simulation. According to [58] the long-term SINR is defined as the ratio between the long-term received power from a desired 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; if an AP is the transmitter, the intended receiver is one of the STAs associated with it. The interfering transmitters are defined in each test.

The long-term SINR of the receiver node-RX with the desired transmitter node-TX is defined as:

$$SINR_{RX}^{TX} = \frac{P_{RX}^{TX}}{\sum\limits_{\{k:N(k)>0\}} \frac{1}{N(k)} \sum\limits_{i \in \Omega(k)} P_{RX}^{TX_i} + N_0}$$

P_{RX}^{TX} : the long-term received power at node-RX from node-TX

$\Omega(k)$: the set of interfering transmitters in the k^{th} BSS

$N(k)$: number of interfering transmitters in the k^{th} BSS, *i.e.*, $N(k) = |\Omega(k)|$

N_0 : noise floor (and noise figure)

The summation of interference is over every BSS which contains at least 1 interfering transmitters. The number of interfering transmitter in the BSS that the receiver belongs to is always 0.

The simulation concerns the Physical layer and the calculated data rate corresponds to the capabilities of this layer. The BSS deployed in the simulation are operating in 5 GHz band and all the nodes are using 20 MHz wide channels. The MCS used by the nodes is dependant from the value of SINR in the used link. All the simulation scenarios are worst case, which means that all nodes transmit in the same frequency, all nodes uses one antenna for reception and one for transmission and the level of reference transmission power is 15dbm for STA and 20dbm for AP. Each BSS consists of one AP and one associated STA and randomly chooses Download or Upload with p=0.5. The transmitter and the receiver will be the AP and the selected STA depending on the Download or Upload. All the technical characteristics of simulation are shown in Table 5.1.

Frequency band	5GHz
Num of Channels	1
Channel BW	20MHz
MCS	Dynamically selected due to SINR
Tx Power AP	20dbm
Tx Power STA	15dbm
Download possibility	0.5
Upload possibility	0.5
Path loss exponent α	4
Standard deviation σ	7
Num of Antennas STA and AP	1
Antenna AP gain	0 dBi
Antenna STA gain	-2 dBi
Spatial Streams	1

1.1 Technical characteristics of simulation

5.2 Topology of WLANs

The dimensions of the area where the WLANs were deployed during the simulation are 100X100 meters. In this area, several deployments of different density simulated, these deployments were consisted of 2,3,4,6,8,12,16 and 24 WLANs. The topology of these deployments are shown in Figure 5.1.

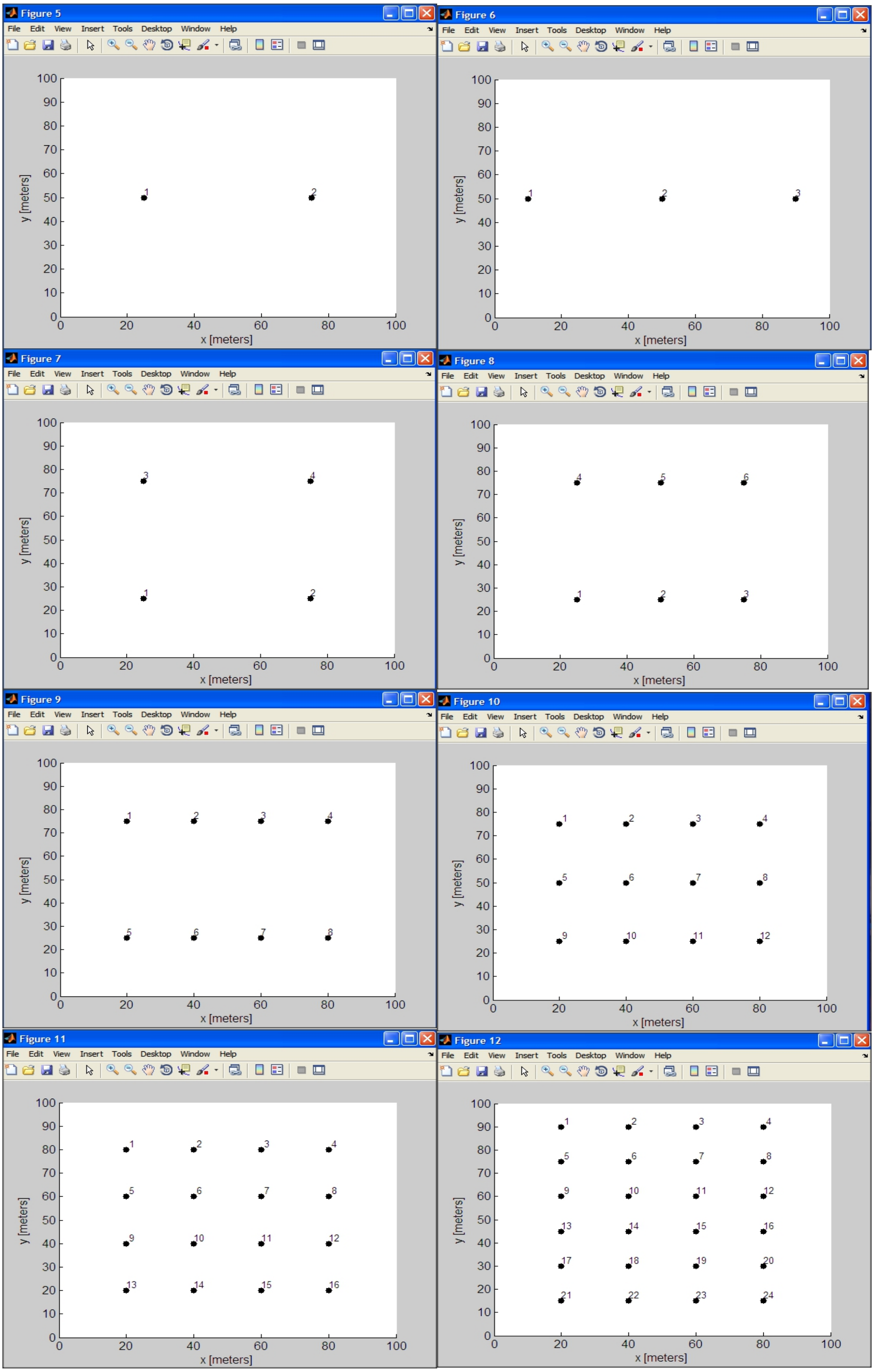


Figure 5.1 Simulation topologies

5.3 WLANs performance with static OBSS_PD threshold

This simulation evaluates the performance of WLANs using different static values of OBSS_PD threshold, the levels of these thresholds are -82, -72, -62 and -52 dbm. The scenarios of evaluation includes various density deployments of WLANs and the metrics are data rate and the percentage of deferred transmission. Every WLAN is composed of an AP and one associated STA placed in a certain distant from AP .The bandwidth of channels for the STA during simulation is 20 MHz and the number of iterations per topology is 100.

The first simulation shows the data rate performance of the static OBSS_PD threshold levels in different WLAN deployments. The independent variable is the number of WLANs and the dependent variable is data rate, the simulation is iterated for different distances between STA and AP, the distances are 5, 10, 15, 20, 25 and 30 meters respectively. The results of simulation (Fig 5.2) shows that for every OBSS_PD threshold level the data rate is reduced with the increase of WLANs deployment density. The main observation from that simulation is that the optimal level selection is heavily dependent upon the distant of STA from APs. In near distances the aggressive selection of OBSS_PD threshold level optimizes the performance compared to conservative one, in contrary conservative levels performs better than the aggressive ones as the distance arises.

The next simulation shows performance (in particular deferred transmission) of the static OBSS_PD threshold in the same scenario as the previous one (fig 5.3). Results show that the aggressive selection of OBSS_PD threshold reduces the amount of defers in all cases as expected but with bad results in the performance of the network in the more scenarios as shown before. Additionally shows that for every OBSS_PD threshold level the percentage of defers arises with the increase of WLANs deployment density In contrary conservative OBSS_PD threshold selection results increasing of defers with beneficial results in the performance of the network in many cases.

In third simulation the dependent variable is the distance and the independent variable is the data rate, the simulation is iterated for different number of WLANs deployed. The performance results for all the scenarios confirms the relation of optimum level selection with the distance between STA and AB and the density of deployed WLANs.

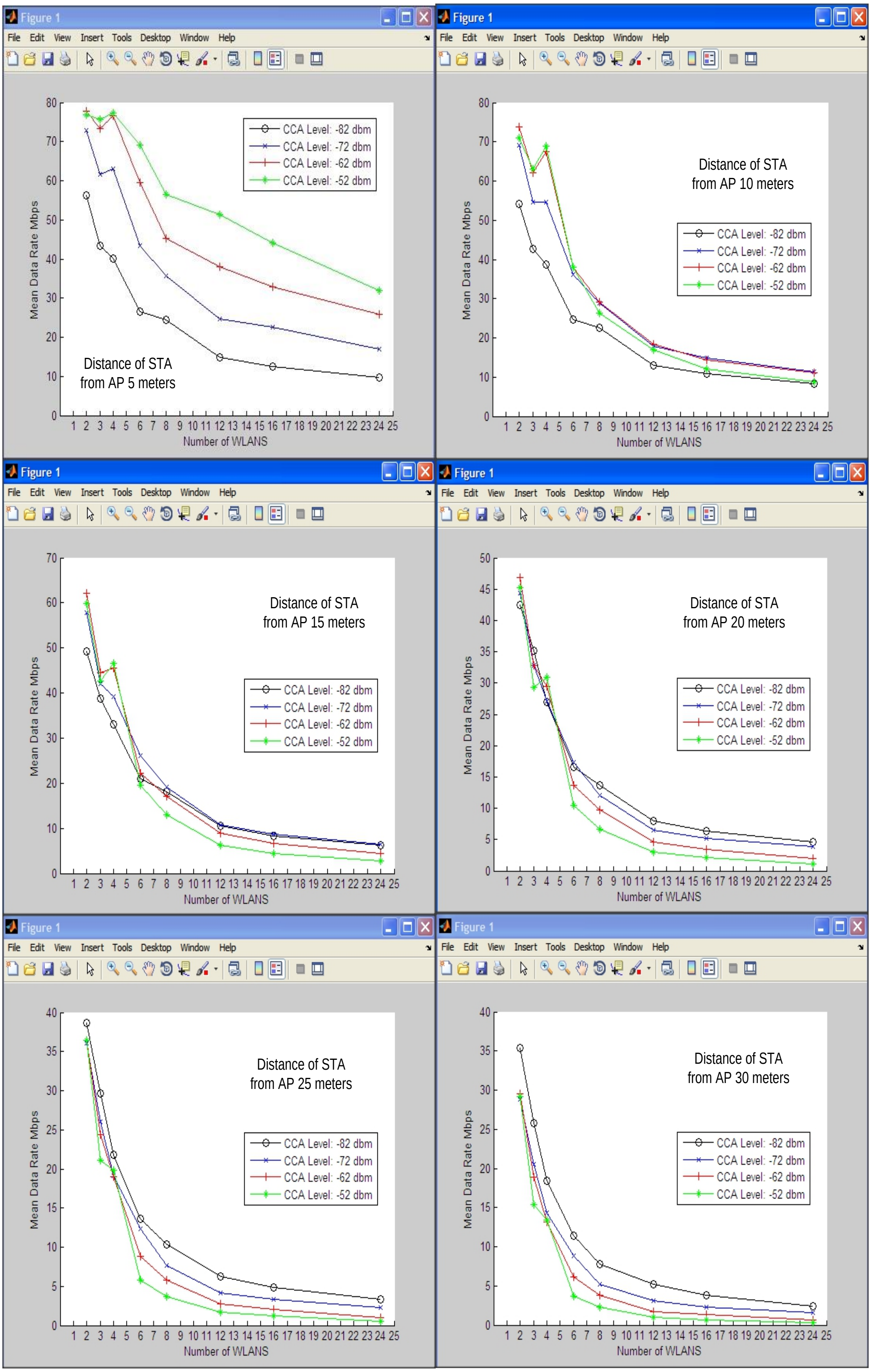


Figure 5.2 Data rate performance for various topologies in different distance scenarios between STA and APs

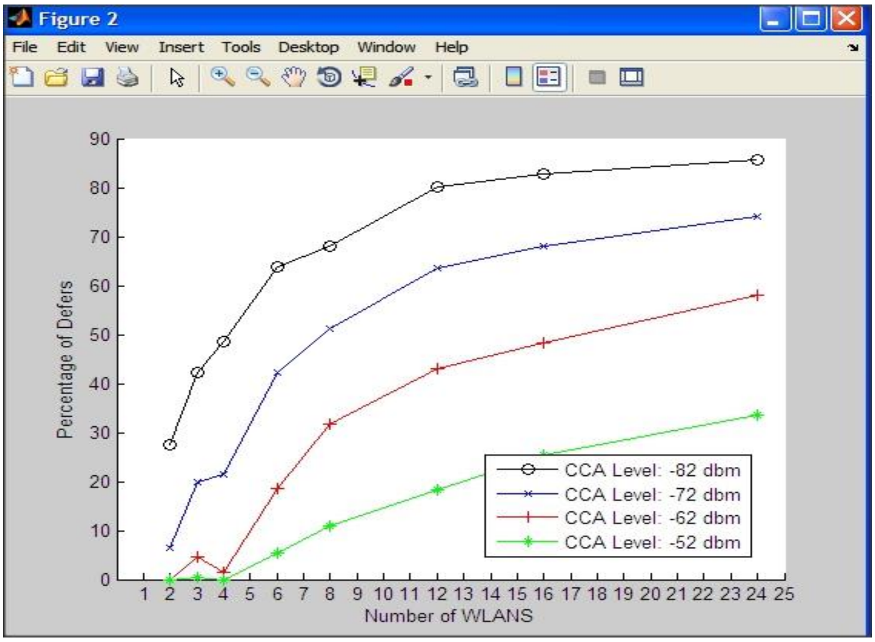


Figure 5.3 Percentage of defers per topology with static OBSS_PD threshold levels

The final simulation shows the performance of each WLAN for every deployment scenario including data rate and number of defers. During this simulation the OBSS_PD threshold level is -82 dbm , which is the default CCA value of 802.11ac for the 20Mhz channel, also the STAs are placed randomly within a distance of 30 meters from the associated AP. The results indicate the unbalanced performance of WLANs, especially for the more dense scenarios. The WLANs that suffer are the ones that are placed in the middle of topology since they receive more interference that results in the increase of defers and decrease of the SINR in received packets.

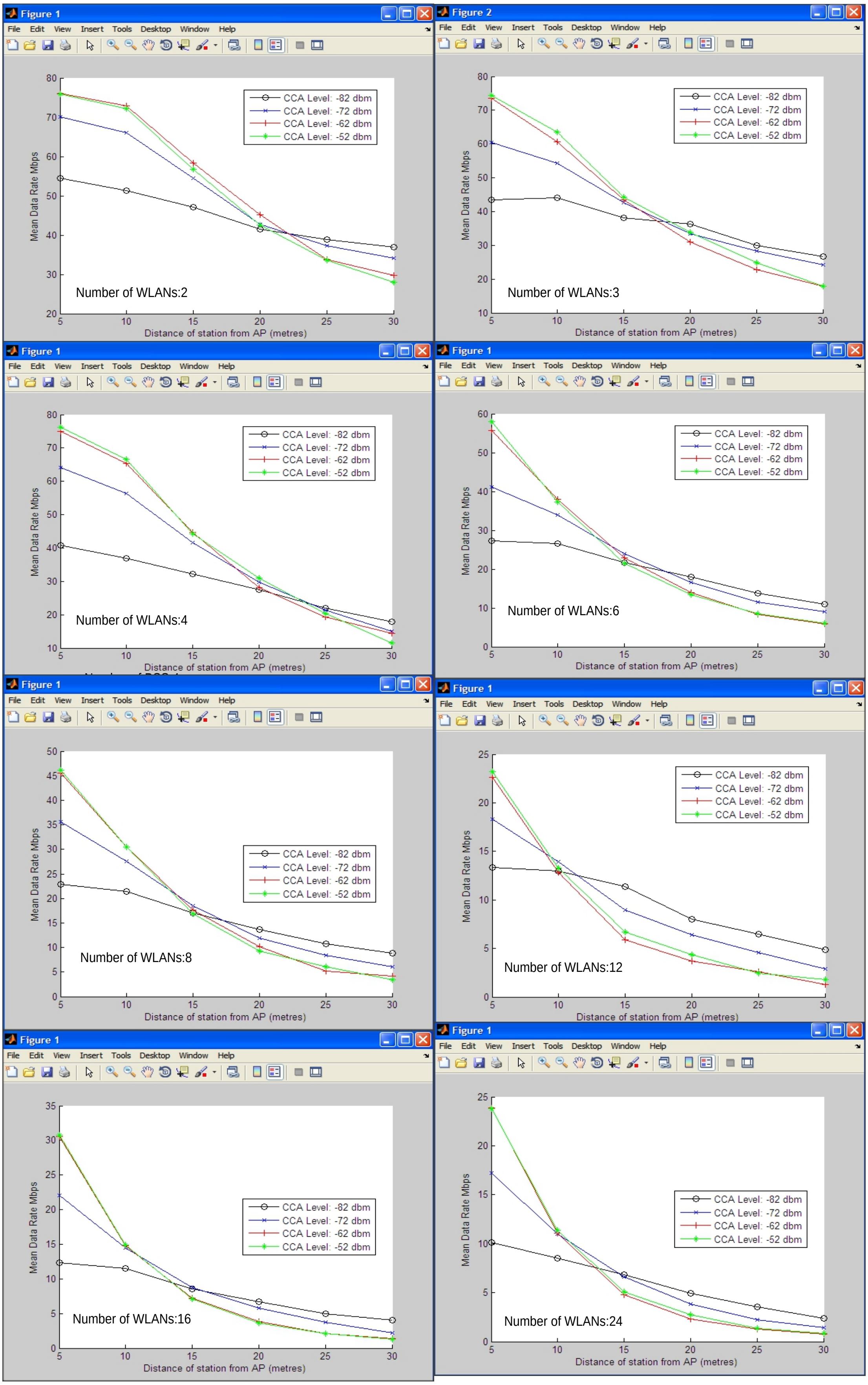


Figure 5.4 Data rate per distance between STA and APs in different topologies scenarios

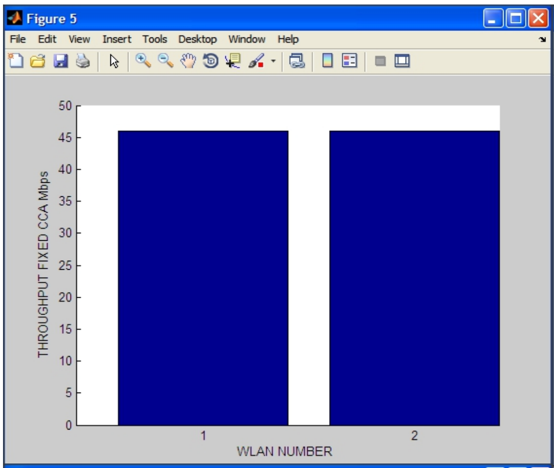


Figure 5
File Edit View Insert Tools Desktop Window Help
THROUGHPUT FIXED CCA Mbps
0
5
10
15
20
25
30
35
40
45
50
1
2
WLAN NUMBER

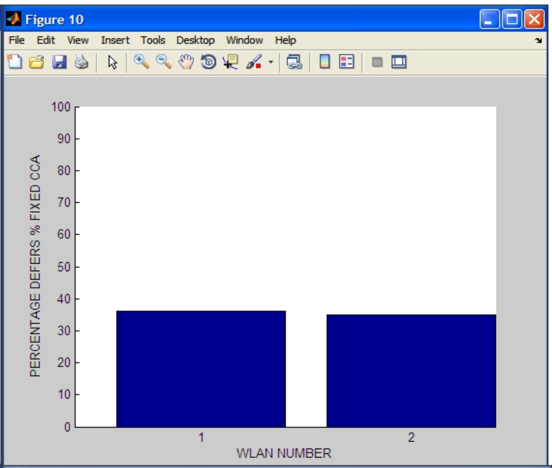


Figure 10
File Edit View Insert Tools Desktop Window Help
PERCENTAGE DEFERS % FIXED CCA
0
10
20
30
40
50
60
70
80
90
100
1
2
WLAN NUMBER

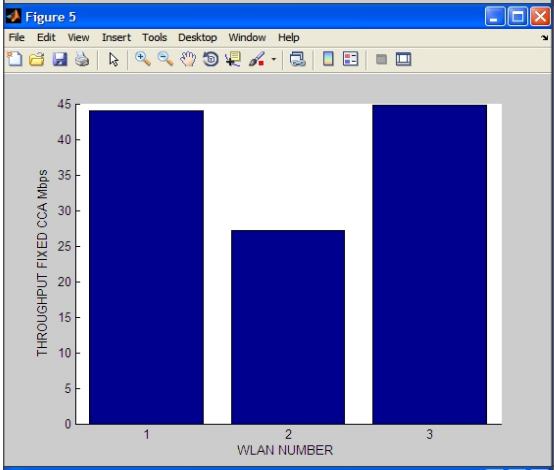


Figure 5
File Edit View Insert Tools Desktop Window Help
THROUGHPUT FIXED CCA Mbps
0
5
10
15
20
25
30
35
40
45
1
2
3
WLAN NUMBER

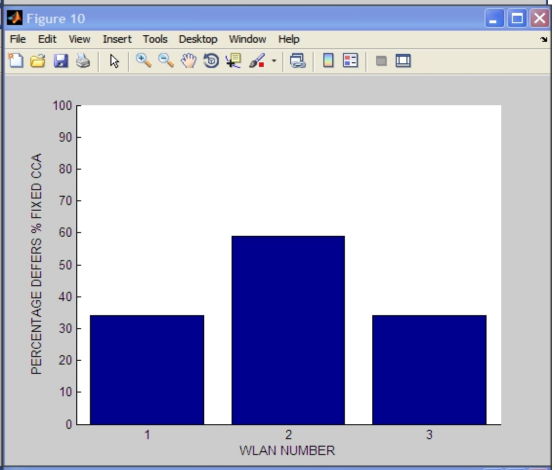


Figure 10
File Edit View Insert Tools Desktop Window Help
PERCENTAGE DEFERS % FIXED CCA
0
10
20
30
40
50
60
70
80
90
100
1
2
3
WLAN NUMBER

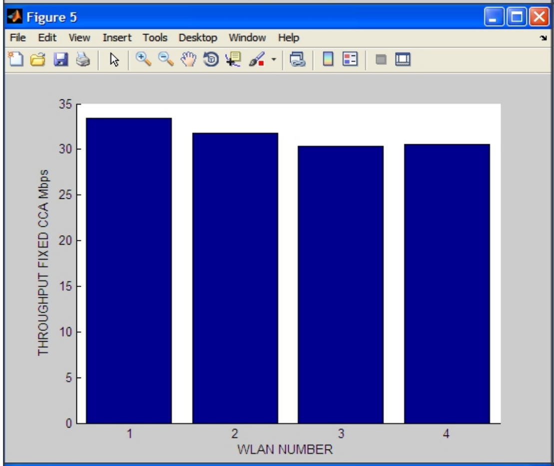


Figure 5
File Edit View Insert Tools Desktop Window Help
THROUGHPUT FIXED CCA Mbps
0
5
10
15
20
25
30
35
1
2
3
4
WLAN NUMBER

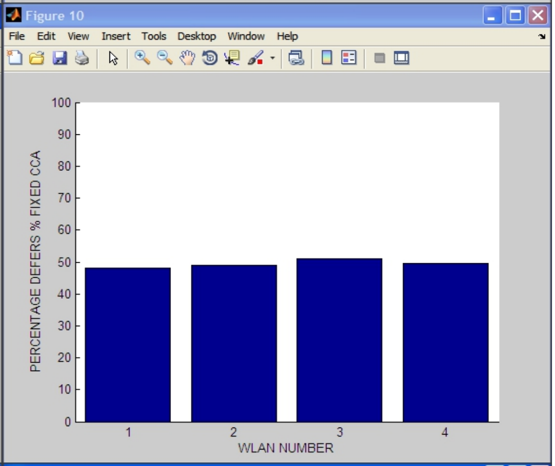


Figure 10
File Edit View Insert Tools Desktop Window Help
PERCENTAGE DEFERS % FIXED CCA
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
WLAN NUMBER

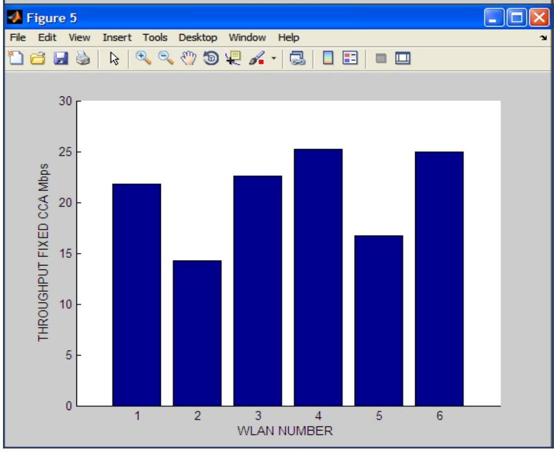


Figure 5
File Edit View Insert Tools Desktop Window Help
THROUGHPUT FIXED CCA Mbps
0
5
10
15
20
25
30
1
2
3
4
5
6
WLAN NUMBER

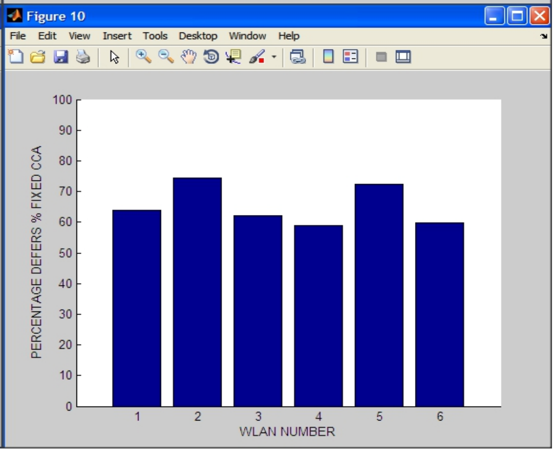


Figure 10
File Edit View Insert Tools Desktop Window Help
PERCENTAGE DEFERS % FIXED CCA
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
5
6
WLAN NUMBER

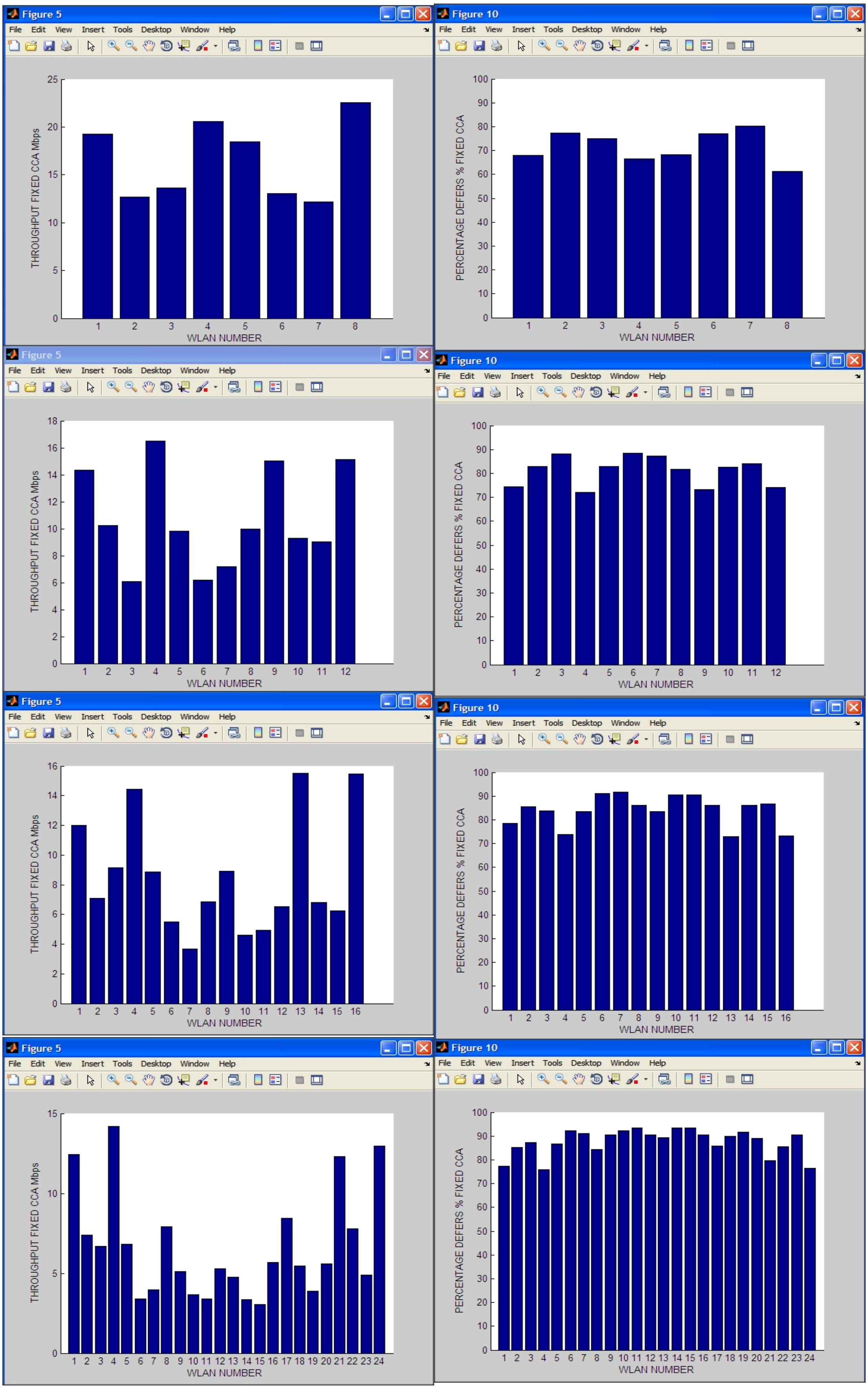


Figure 5.5 WLANs data rate and percentage of defers in different topologies scenarios

5.4 *Evaluation of algorithms*

The performance evaluation of the considered algorithms is carried for three different topology scenarios; the first with three deployed WLANs, the second with eight and the third with sixteen. During all the mentioned scenarios every WLAN is consisted of an AP and one associated STA which for every iteration is placed randomly within a distance of 20 meters from AP. Each of the scenarios is simulated for a number of 10000 iterations.

The first simulation investigates the performance of each algorithm concerning the percentage of transmission defers due to the Inter-WLAN packets. The results (Fig. 5.6) shows the preeminence of TPC flag and DSC flag algorithms, also we can see the poor performance of fixed CCA algorithm compared to the others which is a major obstacle for an effective spatial reuse in dense WLAN deployments.

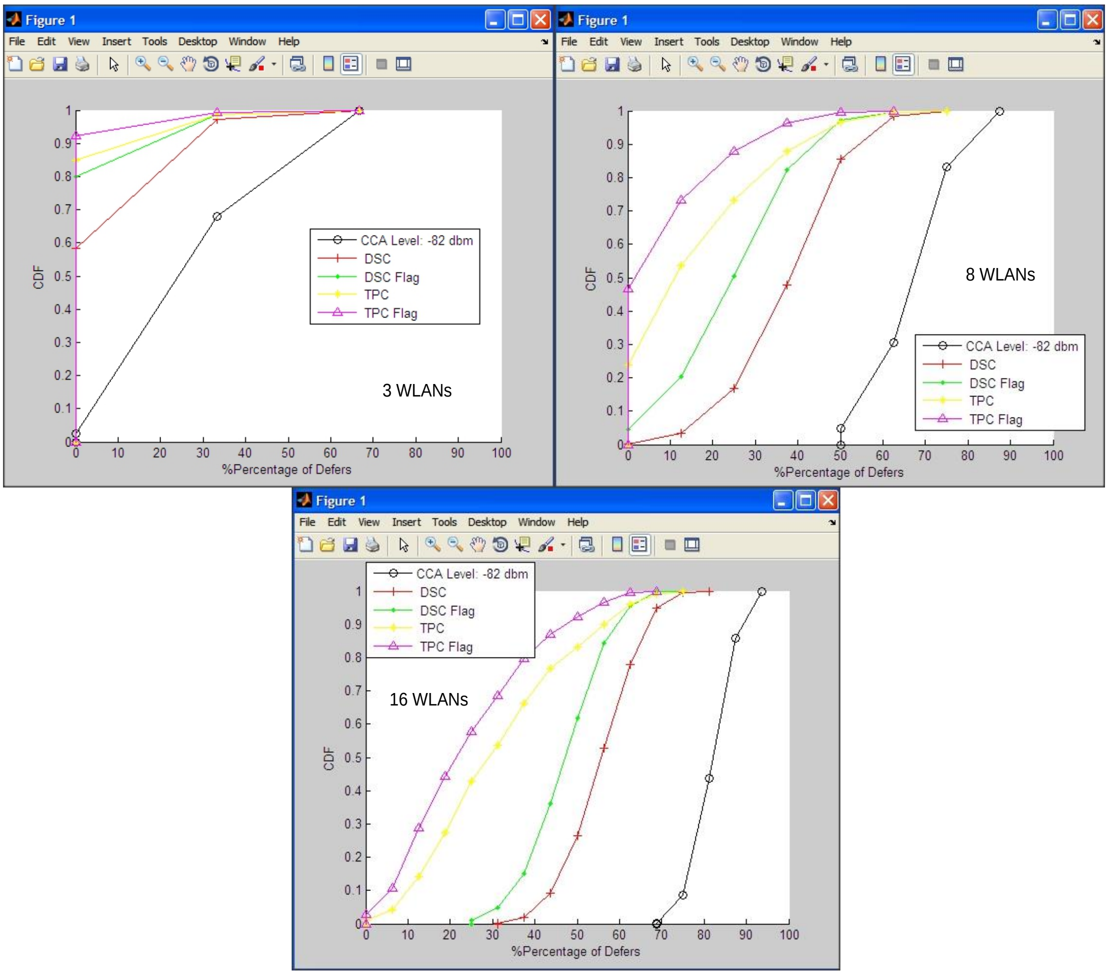


Figure 5.6 CDF of transmission defers on simulated scenarios

Next simulation investigates the performance of each WLAN on the selected scenarios concerning again the percentage of transmission defers due to the Inter-WLAN packets. Figures 5.7-5.9 show the results of the simulation for each algorithm on deferent topology scenarios. In all cases we can see the impact of the applied algorithm to the WLANs performance, first observation is the unbalanced performance of fixed CCA, DSC and TPC algorithms due to the high interference level that the WLANs, which are placed in the middle of dense topology, receive. The next observation shows the opposite effect when DSC flag and TPC flag are applied, in this case the WLANs which are placed in the middle of topology face reduced percentage of defers compared to the WLANs which are placed at the edges. This is explained by the equalizer parameter which the two algorithms apply for the balancing of the WLANs performance.

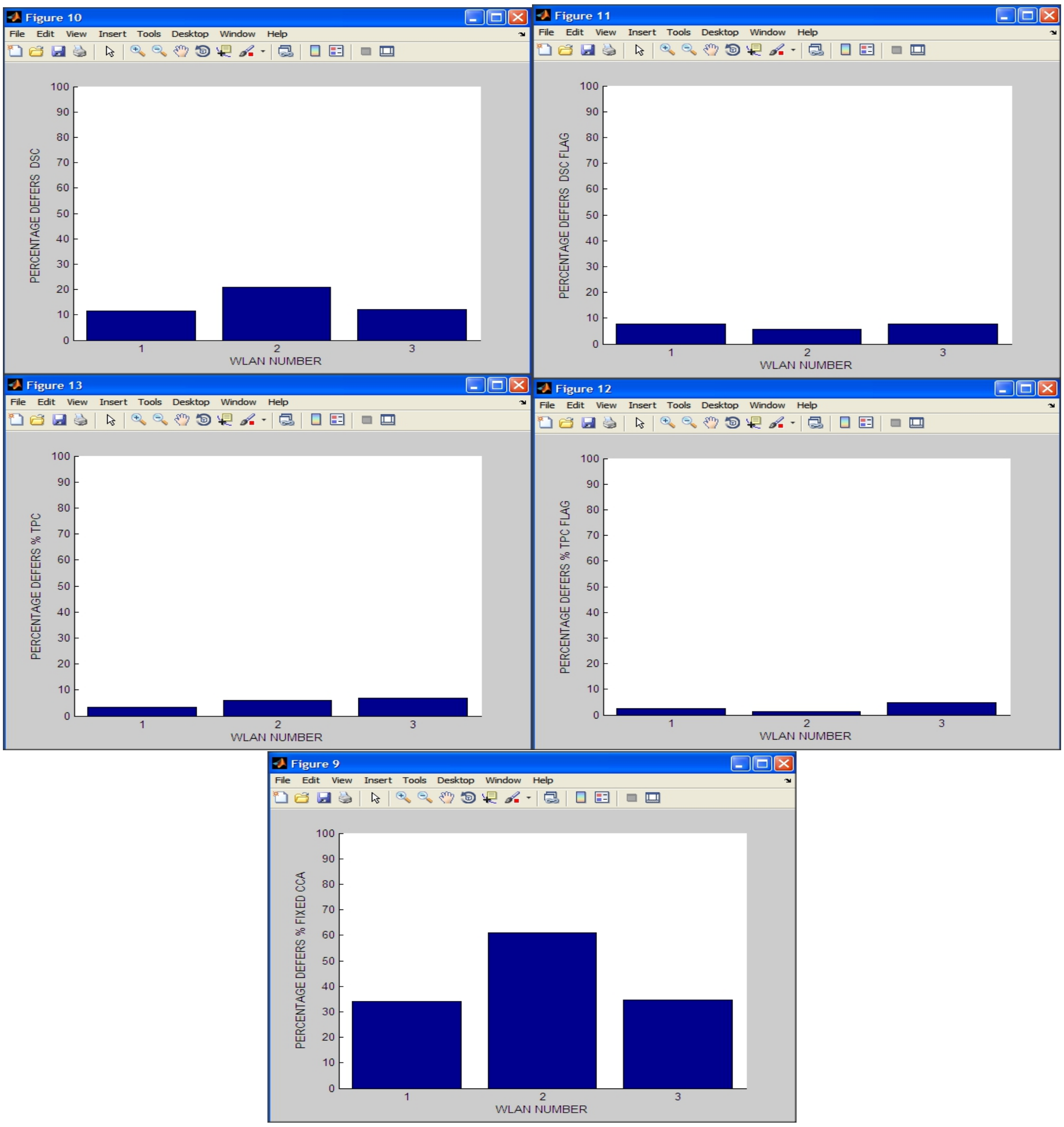


Figure 5.6 Percentage of transmission defers per WLAN for each algorithm in 3 WLANs scenario

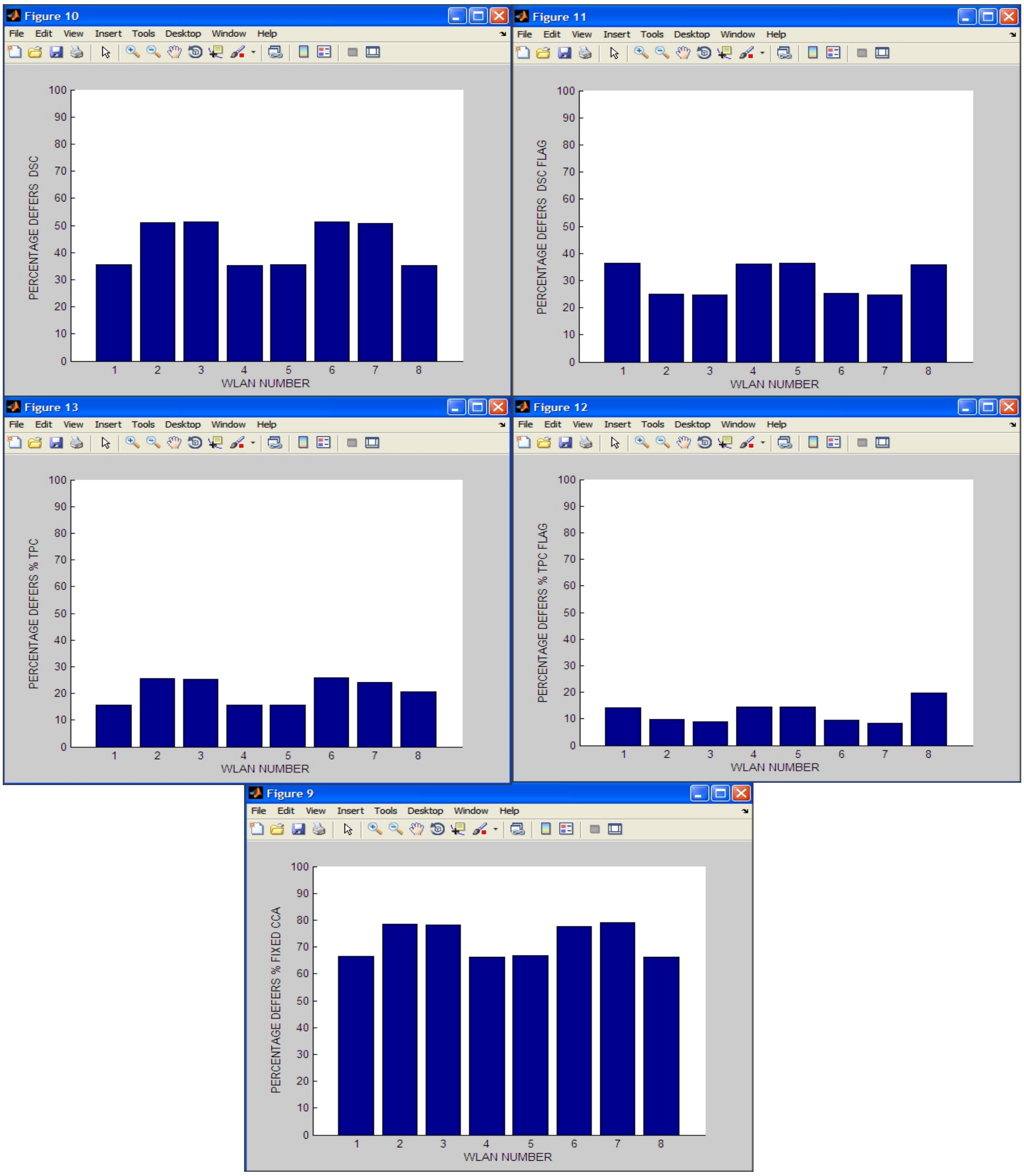


Figure 5.7 Percentage of transmission defers per WLAN for each algorithm in 8 WLANs scenario

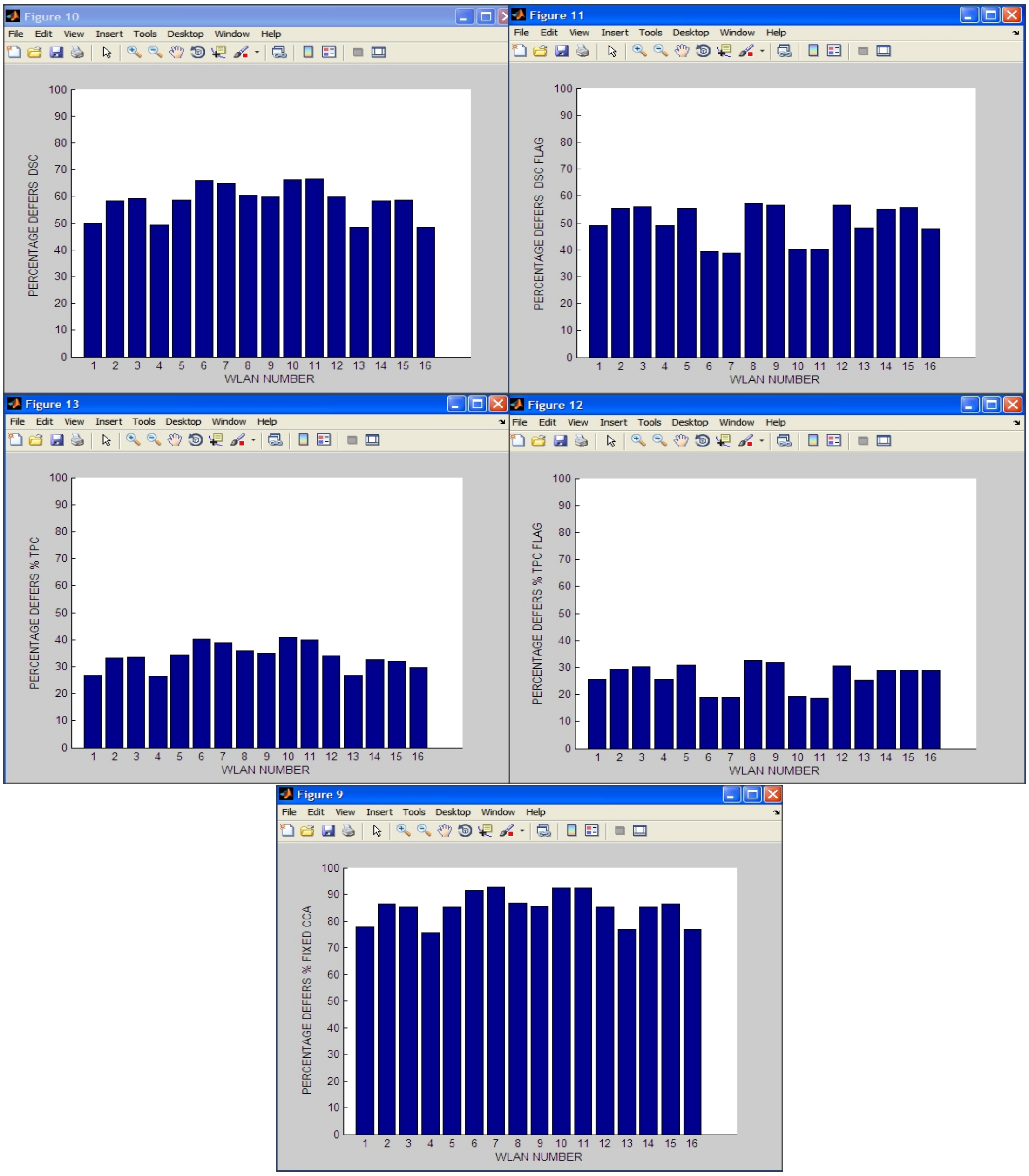


Figure 5.8 Percentage of transmission defers per WLAN for each algorithm in 16 WLANs scenario

The third simulation concerns the data rate performance of the selected algorithms. Results show (Fig. 5.9-5.10) that the fixed CCA performance is poor for all the scenarios compared to the other algorithms, the reason for this is the conservative CCA level selection which rises the percentage of transmission defers and degrades the spatial reuse. The level of enhancement for the other algorithms increases in relation with the topology density (Fig 5.11). All the other algorithms have almost the same performance with a light preeminence of TPC and DSC flags.

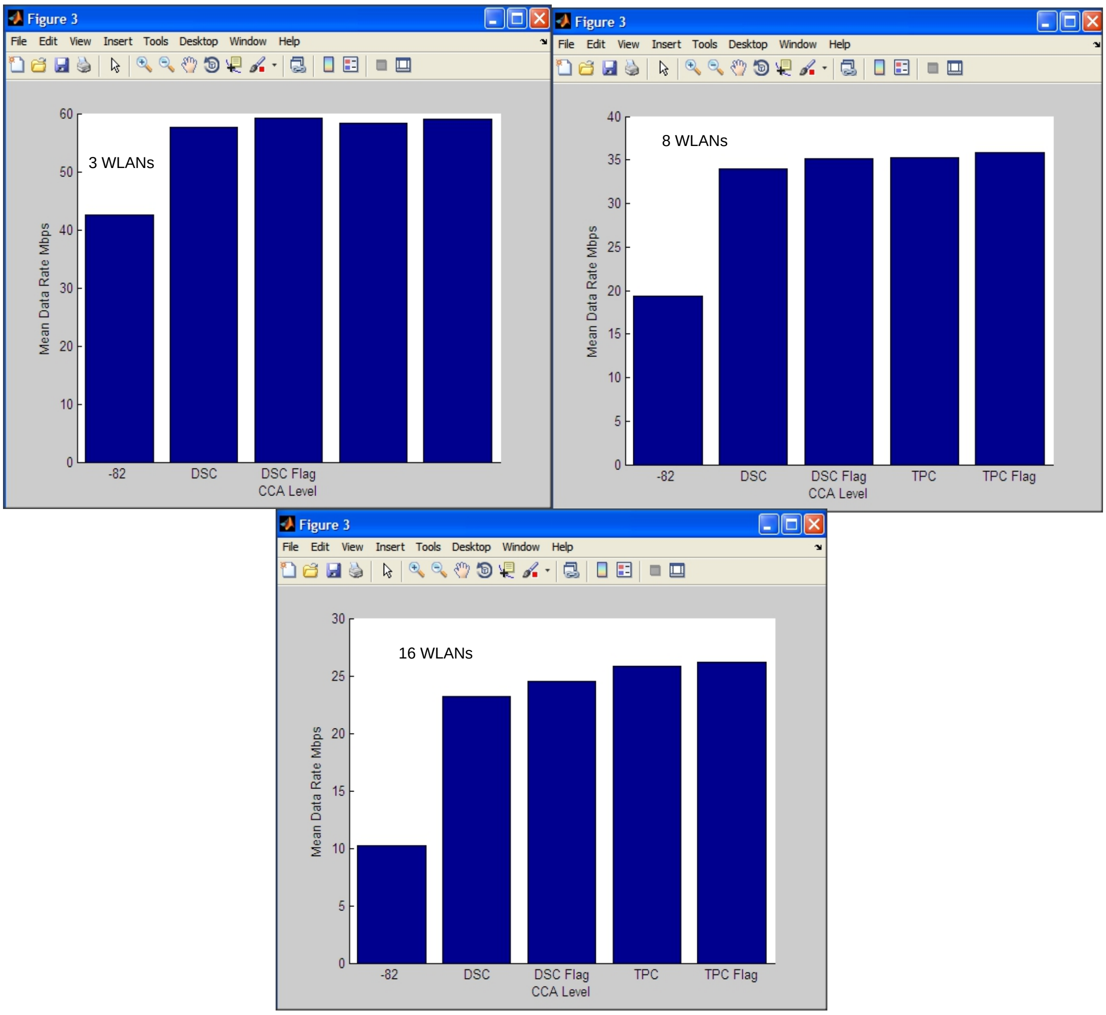


Figure 5.9 Data rate performance per algorithm on simulated scenarios

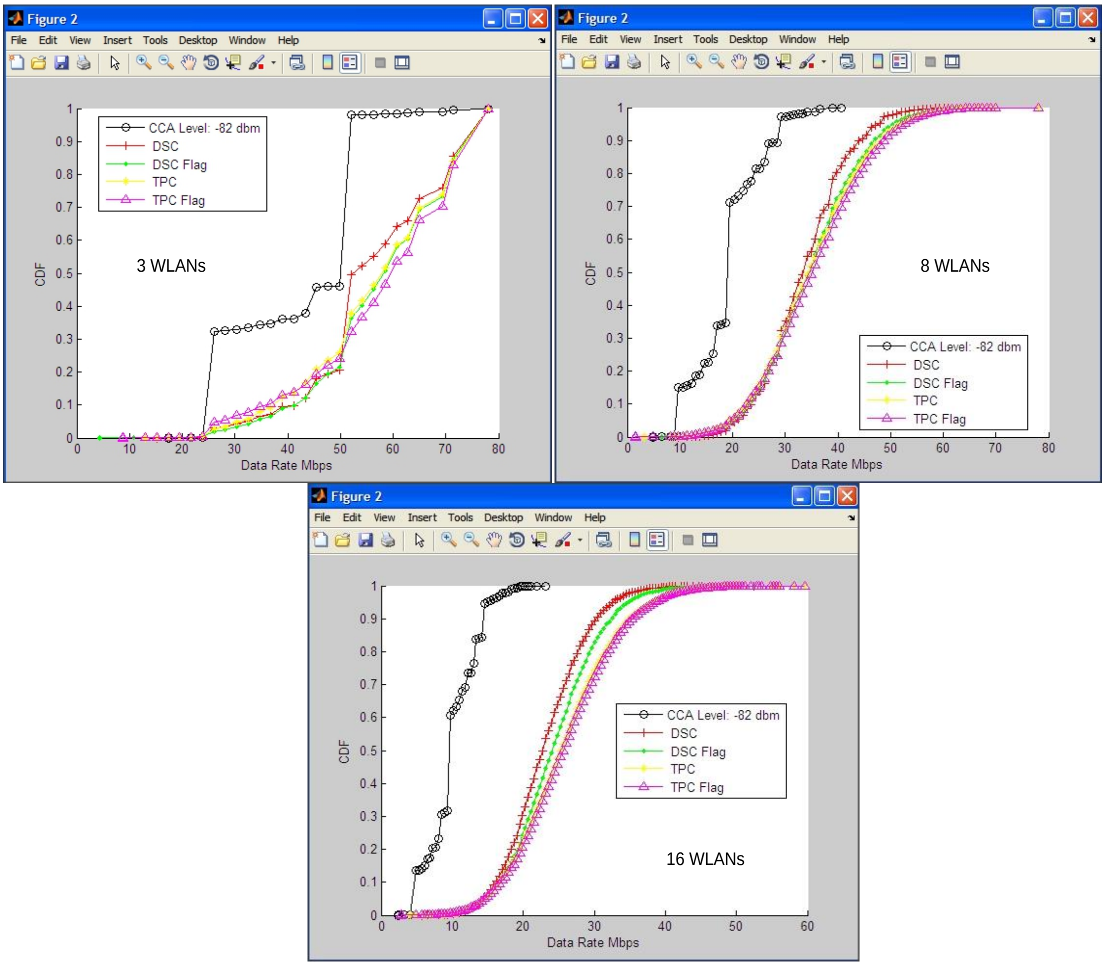


Figure 5.10 CDF of data rate on simulated scenarios

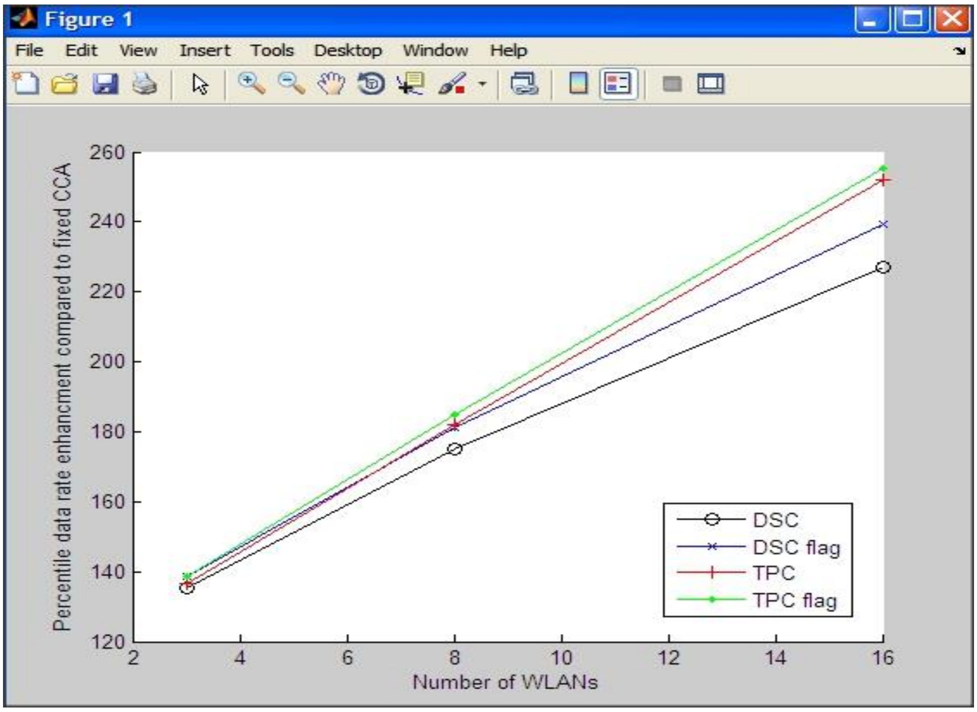


Figure 5.11 Percentile data rate enhancement compared to fixed CCA

Next simulation investigates the performance of each WLAN on the selected scenarios concerning the data rate. Figures 5.11-5.13 shows the results of the simulation for each algorithm on deferent topology scenarios. The appliance of fixed CCA, DSC and TPC algorithms produces unbalanced results, the WLANs that are placed in the middle of topology underperform compared to the WLANs which are placed at the edges. The DSC flag and TPC flag algorithms enhance the performance of the suffering WLANs without degrading the overall performance of the network, this is achieved by the equalizer and interference flag parameters that the algorithms uses.

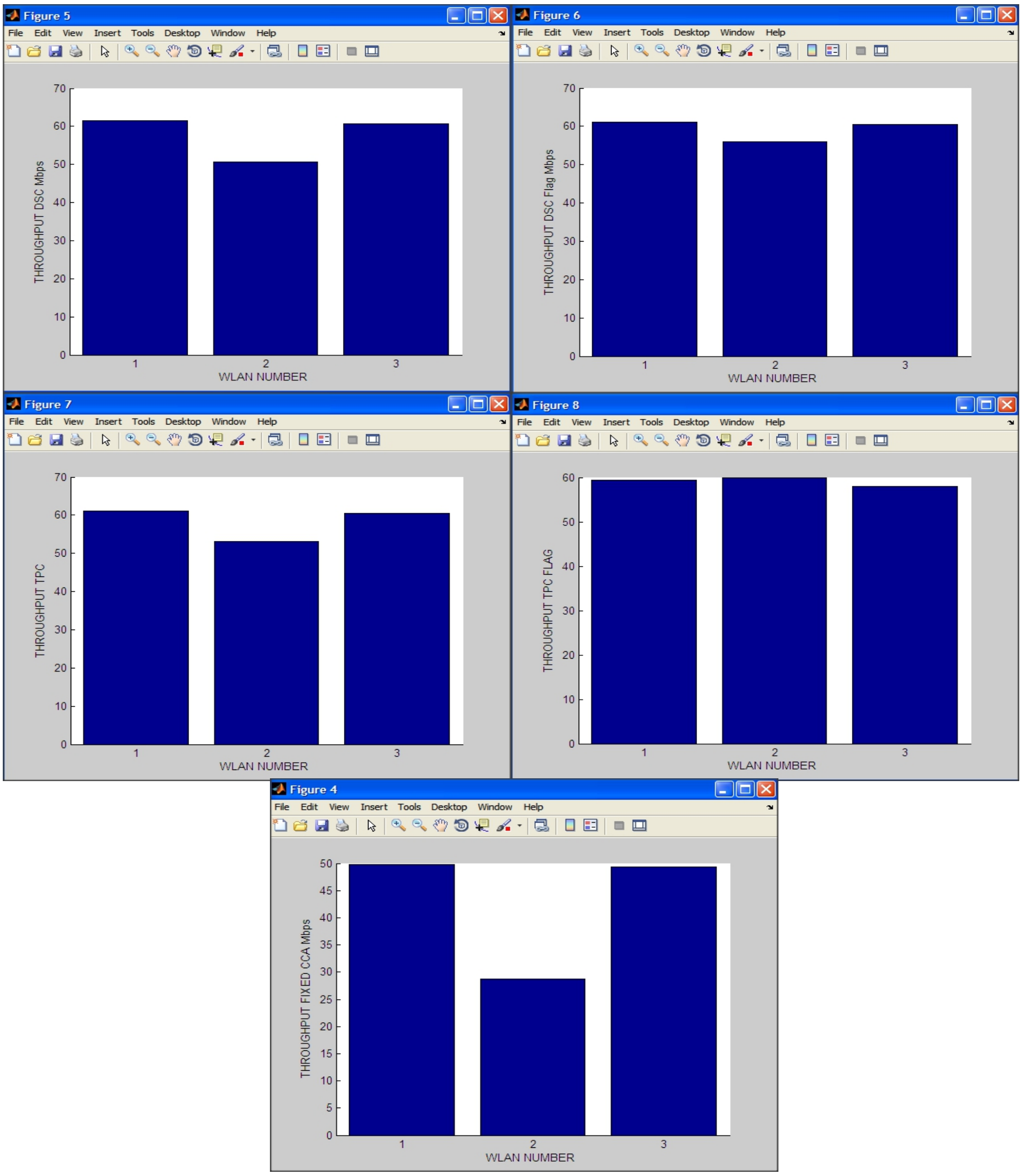


Figure 5.12 Data rate performance per WLAN for each algorithm in 3 WLANs scenario

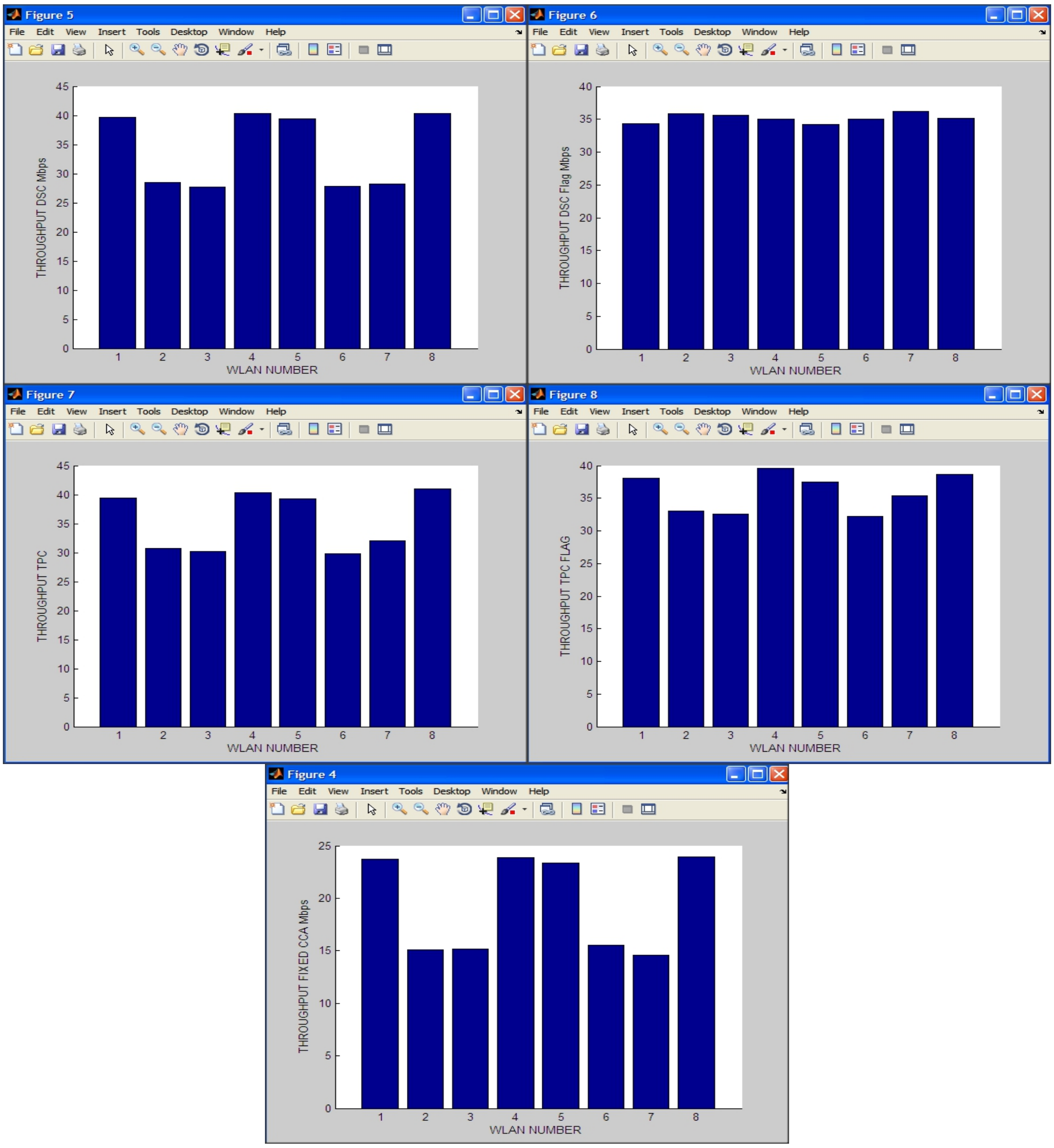


Figure 5.13 Data rate performance per WLAN for each algorithm in 8 WLANs scenario

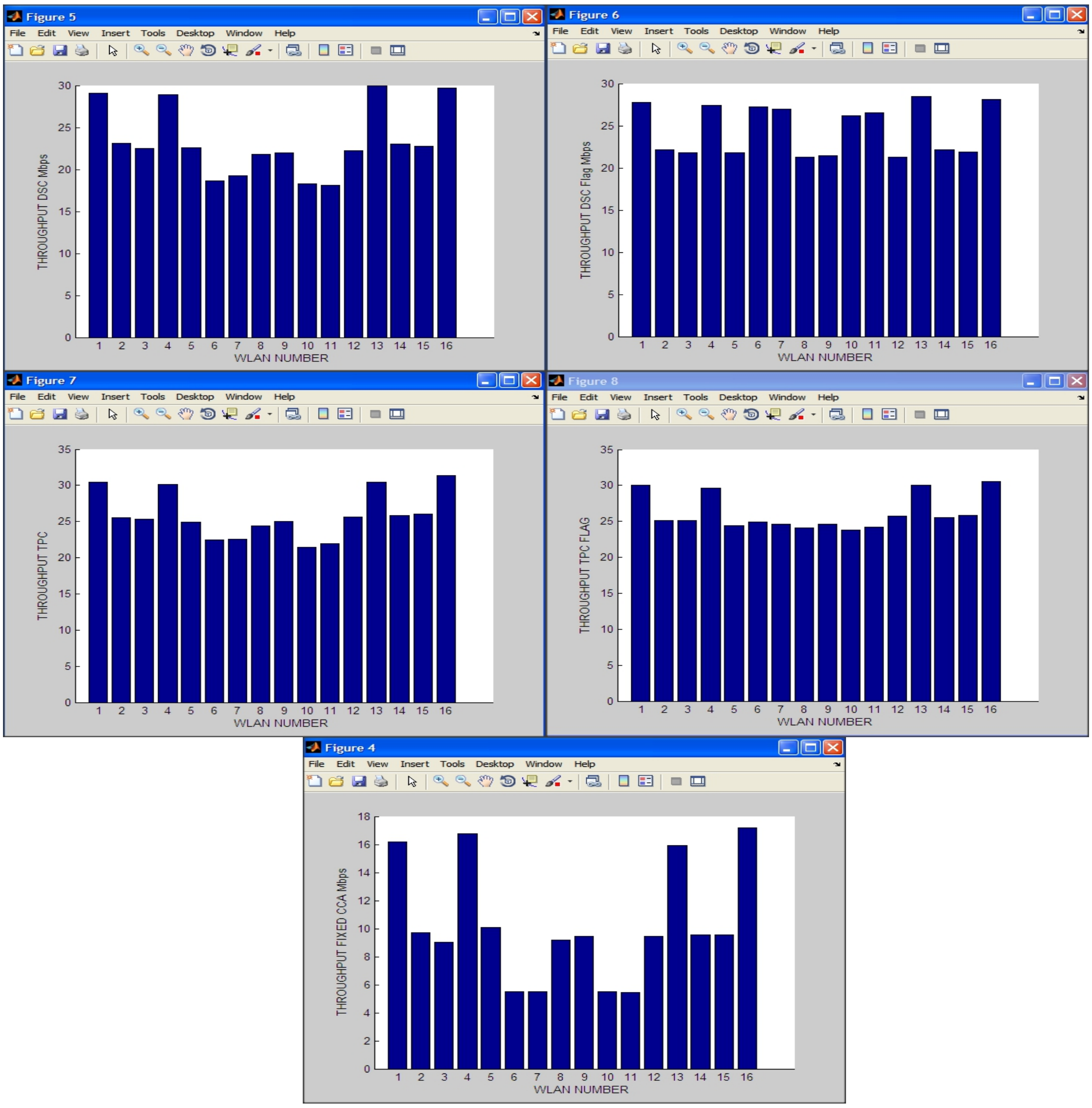


Figure 5.14 Data rate performance per WLAN for each algorithm in 16 WLANs scenario

The last simulation is about the balancing of WLANs performance in a various dense topologies that the algorithms achieve. The metric that is used is the percentage offset between the WLAN which has the lower data rate performance and the one which has the highest. Results shows that DSC and TPC flag algorithms (Fig 5.15) manage to balance the overall performance of network by using the equalizer parameter.

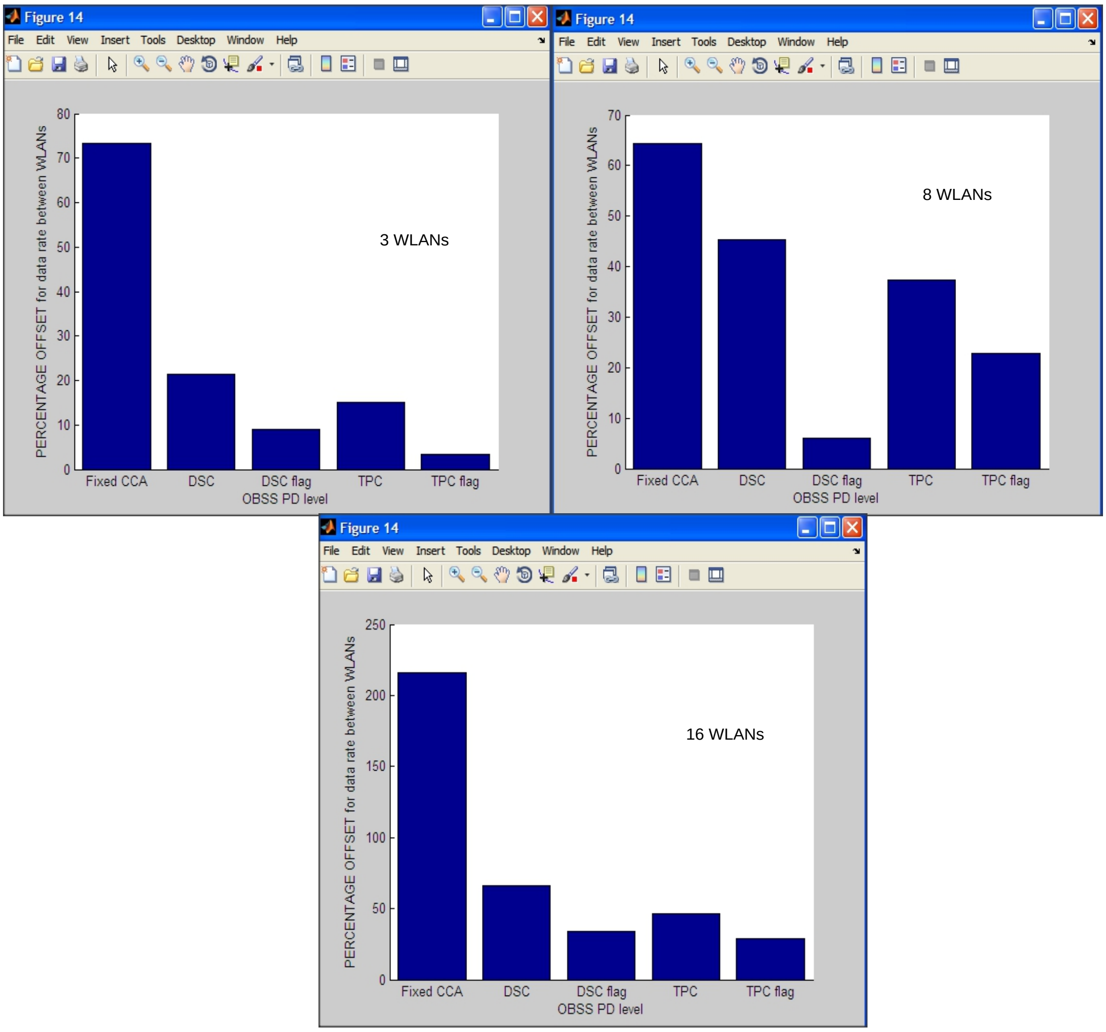


Figure 5.15 Data rate percentage offset between WLANs on simulated scenarios

6

Conclusions and Future Work

6.1 Conclusions

The major goal of IEEE 802.11ax is the efficient operation in dense WLAN deployment environments and in order to achieve this goal the protocol is expected to adopt and implement new technologies. Spatial reuse is a key factor for addressing the mentioned scenarios. Both the literature and IEEE 802.11ax TG suggest several solutions for spatial reuse enhancement. The prevalent technique, according to the latest contributions to the TG that will be implemented is the combination of coloring, DSC and TPC.

The coloring technique that was introduced on IEEE 802.11ah categorizes the received packets according to their transmitter address. Utilizing this information with other conditions a node in a network decides either to transmit in parallel or to defer the intend transmission. The DSC technique implements a new dynamic carrier sense threshold to packets from Inter-BSS according to the distance of STAs from AP, by adjusting properly the level of threshold a node can transmit in parallel without affecting the overall performance of the network. The TPC technique adjusts the level of transmission according to the DSC threshold in order to mitigate interference in the network.

Simulation results show that the current CCA level is very conservative and degrades spatial reuse in a dense network. The proper adjustment of level is also heavily dependent to the distance of STAs from AP and the density of the network. Another major issue is the fairness among the deployed BSS in a dense network, simulation results show an unbalanced performance where the BSS that were deployed in the middle of topology underperform compared to those that were deployed at the edge.

The evaluation of proposed algorithms in the TG show performance enhancement compared to legacy one concerning data rate and percentage of transmission defers. The current thesis proposed algorithms show a further light improvement for data rate and enhanced of fairness compared to TG proposals, according to simulation results, due to additional implemented parameters. In order to summarize, the the implementation of the proposed algorithms can enhance spatial reuse, improve fairness and reduce power consumption for STAs, due to the dynamic adjustment of transmit power. The mentioned level of enhancement, in all cases, increases in relation with the topology density.

6.2 Future works

Future work concerning spatial reuse can be separated into two basic directions. The first one is the enhancement and evolution of suggested technologies and the second one is the prospecting of new one.

The suggested techniques are based on several level parameters like maximum and minimum OBSS_PD threshold, transmitter power reference and margin which can be optimized. The optimization of these levels can be achieved through extensive simulations in different operating environments, in order that the proper levels will be selected in any case. Also new intelligent techniques can be investigated which will allow the AP and STAs to sense the environment where have been deployed, in order to choose the proper parameters for spatial reuse optimization.

Implementation of beam forming technology is able to enhance spatial reuse; this can be achieved by separating the coverage area of BSS in sectors, where specific frequency channels will be used in order to mitigate interference to adjacent BSS. In this way transmission directivity can amplify or mitigate the receive signal level in the desired destination. Furthermore, the network and massive MIMO in conjunction with point coordination function instead of DCF implementation is a possible technology which can enhance spatial reuse. The drawback of this approach is the increased cost and complexity and the reduced versatility.

7

References

[1] Mathew S. Gast , " Wireless Networks: The Definitive Guide, Second Edition" O' Really Media Inc. 2005

[2] Borris Bellalta ,(July, 2015) "IEEE 802.11ax : High Efficiency WLANs", IEEE Wireless Communications Magazine, pp. 38-46.

[3] Osama Aboul-Magd (March 2014) "802.11 HEW SG Proposed PAR" doc.: IEEE 802.11-14/0165r1 SG Submission. https://mentor.ieee.org/802.11/dcn/14/11-14-0165-01-0hew-802-11-hew-sg-proposed-par.docx.

[4] Osama Aboul-Magd (March 2014) "802.11 HEW SG Proposed PAR" doc.: IEEE 802.11-14/0169r1 SG Submission. https://mentor.ieee.org/802.11/dcn/14/11-14-0169-01-0hew-ieee-802-11-hew-sg-proposed-csd.docx.

[5] The zettabyte Era- Trends and Analysis, Web page, Accessed February 2017

http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/vni-hyperconnectivity-wp.html.

[6] Y. Xiao, “Concatenation and Piggyback Mechanisms for the IEEE 802.11 MAC,” Wireless Communications and Networking Conference, 2004 WCNC, Mar. 2004, Vol. 3 pp. 1642-1647.

[7] S.B. Ahsan and N. Vaidya, “O-ACK: An adaptive wireless MAC protocol exploiting opportunistic token-passing and ack piggybacking,” Local Computer Networks (LCN), 2015 IEEE 40th Conference on, Oct 2015, pp.410-413.

[8] K.C.J. Lin, N. Kushman and D. Katabi, “Zip-Tx: Harnessing partial packets in 802.11 Networks,” Proceedings of the 14th ACM international conference on Mobile computing and networking Mobi Com, New York, USA, Sep. 2008, Pages 351-362

[9] J. Xie, W. Hu and Z. Zhand, “Revisiting partial packet recovery in 802.11 Wireless LANs,” Proceedings of the 9th international conference on Mobile systems, applications and services, Maryland, USA, June 28 - July 01, 2011, Pages 281-292

[10] M. X. Gong, B. Hart and S. Mao, “Advanced Wireless LAN Technologies: IEEE 802.11AC and beyond,” Get Mobile: Mobile and Communications, Oct. 2014, vol. 18, Iss. 4, pp. 48-52.

[11] D. Bharadia, E. McMilin, and S. Katti. “Full duplex radios”. In Proc. ACM SIGCOMM 2013, Hong Kong, China, Aug. 2013, pages 375–386.

[12] M. Jain et al, “Practical, Real-Time, Full Duplex Wireless,” in Proceedings of the seventeenth annual international conference on Mobile computing and networking, Las Vegas, Usa, Sep. 19-23, 2011, pp.301-312.

[13] Marc Emmelman, “Incorporate Dynamic OFDMA in 802.11”, Web page, Accessed February 2017

http://www.tkn.tuberlin.de/fileadmin/fg112/Papers/DynOFDMAin802dot11.pdf.

[14] S. K. Narware and K. Kumar, “Orthogonal Frequency Division Multiple Access (OFDMA) Based MAC Protocols Survey for the Next Generation WLAN,” International Journal of Science, Engineering and Technology, 2015, Vol. 3, Iss. 6, pp. 23-26.

[15] A. B. Makhlouf and M. Hamdi, “ Dynamic multi-user access scheme for IEEE 802.11 WLAN channels,” in Wireless Communication and Mobile Computing Conference (INCMC), Nicosia, Cyprus, Aug. 4-8, 2014, pp. 18-

23.

[16] B. Li, Q. Qu, Z. Yan and M. Yang, "Survey on OFDMA based MAC protocols for the next generation WLAN," in Wireless Communications and Networking Conference Workshops (WCNCW), New Orleans, LA, Usa, Mar. 9-12, 2015, pp. 131-135.

[17] Q. Qu, B. Li, M. Yang and Z. Yan, "An OFDMA based concurrent multiuser MAC for upcoming IEEE802.11ax," in Wireless Communications and Networking Conference Workshops (WCNCW), New Orleans, LA, Usa, Mar. 9-12, 2015, pp. 136-141.

[18] M. Park, "IEEE 802.11ac: Dynamic Bandwidth Channel Access," in IEEE International Conference on , Kyoto, Japan, Jun. 5-9, 2011, pp. 1-5.

[19] P. Huang, X. Yang and L. Xiao, "Dynamic Channel Bonding: Enabling Flexible Spectrum Aggregation", in IEEE Transactions on Mobile Computing , Dec. 2016, Volume: 15, Issue: 12, pp. 3042-3056.

[20] M. Jiang and L. Hanzo, "Multiuser MIMO-OFDM for Next Generation Wireless Systems," Proceedings of the IEEE, Jul. 2007, Vol. 95, Iss. 7, pp.1430-1469.

[21] H. Lou, M. Gosh, P. Xia and R. Olesen "A Comparison of Implicit and Explicit Channel Feedback Methods for MU-MIMO WLAN Systems," in Personal Indoor and Mobile Radio Communications (PIMRC), 2013 IEEE 24th International Symposium on,, London, England, Sep 8-11, 2013, pp. 419-424.

[22] R. Liao, B. Bellalta, M. Oliver and Z. Niu, " MU-MIMO MAC Protocols for Wireless Local Area Networks: A Survey," Communication Surveys and Tutorials, IEEE, Dec 2014, Vol. 18, Iss. 1, pp. 162-183.

[23] X. Zhang, K. Sundaresan and K. G. Shin, "NEMOx: Scalable Network MIMO for Wireless Networks," in Mobicom 13, Proceedings of the 19th annual international conference on Mobile Computing and Networking, Miami, USA, September 30 - October 04, 2013, Pages 453-464.

[24] K. J. Kim, K. J. Choi, S. K. Lee and K. S. Kim, "Multiuser Massive MIMO for next-generation WLAN systems," Electronic Letters, May 2015, Vol. 51, No. 10, pp. 792-794.

[25] C. Thorpe and L. Murphy, "A survey of adaptive carrier sensing mechanisms for IEEE 802.11 wireless networks," Communications Surveys

Tutorials, IEEE, Third 2014, vol. 16, no. 3, pp. 1266–1293.

[26] I. Jamil, L. Cariou, and J.-F. Helard, “Improving the capacity of future IEEE 802.11 high efficiency WLANs,” in Telecommunications (ICT), 2014 21st International Conference on, May 2014, pp. 303–307.

[27] R. Madan, A. Sampath, and N. Khude, “Enhancing 802.11 carrier sense for high throughput and QoS in dense user settings,” in Personal Indoor and Mobile Radio Communications (PIMRC), 2012 IEEE 23rd International Symposium on, Sept 2012, pp. 253–259.

[28] L. B. Jiang and S.-C. Liew, “Improving throughput and fairness by reducing exposed and hidden nodes in 802.11 networks,” Mobile Computing, IEEE Transactions on , Jan 2008, vol. 7, no. 1, pp. 34–49.

[29] A. Kochut, A. Vasan, A. Shankar, and A. Agrawala, “Sniffing out the correct physical layer capture model in 802.11b,” in Network Protocols, 2004. ICNP 2004, Proceedings of the 12th IEEE International Conference on, Oct 2004, pp. 252–261.

[30] S. Merlin and S. Abraham, “Methods for improving medium reuse in IEEE 802.11 networks,” in Consumer Communications and Networking Conference, 2009. CCNC 2009. 6th IEEE, Jan 2009, pp. 1–5.

[31] Z. Zhong et al “Issues and Challenges in Dense Wi-Fi Networks,” in International Wireless Communications and Mobile Computing Conference (IWCMC), August 2015, pp. 947-951.

[32] M. Shahwaiz et al., “Evaluation of Dynamic Sensitivity Control Algorithm for IEEE 802.11ax,” Wireless Communications and Networking Conference (WCNC), IEEE New Orleans Mar. 2015, pp.1060-1065.

[33] O. Acholem and B. Harvey, “Throughput performance in multihop networks using adaptive carrier sensing threshold,” Proceedings of the IEEE SoutheastCon 2010 (SoutheastCon), March 2010, pp. 287-291.

[34] A. Akella, G. Judd, S. Seshan, and P. Steenkiste, “Self management in chaotic wireless deployment,” Wireless Networks, Dec. 2007, vol. 13, no. 6, pp. 737–755.

[35] P. Xia and Z. Teng, “Transmit Power Control and Clear Channel Assessment in LAA Networks”, in European Conference on Network and Communications (EuCNC),2015, pp. 210-213

[36] V. Kawadia and P. Kumar, “Principles and protocols for power control in wireless ad hoc networks,” IEEE Journal on Selected Areas in Communications, Sep. 2006, Vol. 23, Iss. 1, Pages 76-88.

[37] W Li, Y Cui, X Cheng, MA Al-Rodhaan, A Al-Dhelaan, “Achieving proportional fairness via AP power control in multi-rate WLANs,” IEEE Transactions on Wireless Communications, Nov. 2011, Vol. 10, Iss. 11, pp. 3784–3792.

[38] C. Candarilas, C. Martin-Engenos, H.L. Pombo and A.G. Marques, “Dynamic Transmit Power Control for Wi-Fi Access Points Based on Link Occupancy,” Wireless Communications and Network Conference (WCNC) IEEE, Istanbul 2014, pp. 1093-1098.

[39] X. Lei and S.Y. Rhee, “Performance enhancement of overlapping BSS via dynamic transmit power control,” EURASIP Journal on Wireless Communications and Networking, Springer 2015, pp.1-8.

[40] X Liu, S Seshan, P Steenkiste, “Interference-aware transmission power control for dense wireless networks”, in proceedings of the annual conference of ITA, (2007), pp. 1–7

[41] O.Oteri, P. Xia, F. LaSita and R. Olesen, “ Advanced power control techniques for interference mitigation in dense 802.11 networks,” 16th International Symposium on Wireless Personal Multimedia Communications, Atlantic 2013, pp. 1-7.

[42] D. Sanghi, “CSMA with Collision Avoidance”, Web page, Accessed February 2017

http:// http://www.cse.iitk.ac.in/users/dheeraj/cs425/lec05.html

[43] R. Hedavat et. al, “Adaptive CCA for 11ax “,September 2014,

doc.: IEEE 802.11-14/1233r2

https://mentor.ieee.org/802.11/dcn/14/11-14-1233-02-00ax-adaptive-cca-for-11ax.pptx

[44] E. Tuomaala et. al, “Adapting CCA and Receiver Sensitivity”, November 2014, doc.: IEEE802.11-14/1443r0
https://mentor.ieee.org/802.11/dcn/14/11-14-1443-00-00ax-adapting-cca-and-receiver-sensitivity.pptx

[45] T. Itaghi et. al, “Performance Analysis of BSS Color and DSC”, January 2015, doc.: IEEE802.11-15/0045r0

https://mentor.ieee.org/802.11/dcn/15/11-15-0045-00-00ax-performance-analysis-of-bss-color-and-dsc.pptx

[46] T. Itaghi et. al, “Impact of TPC coupled to DSC for legacy unfairness issue”, March 2015, doc.:IEEE802.11-15/0319r1 https://mentor.ieee.org/802.11/dcn/15/11-15-0319-01-00ax-impact-of-tpc-coupled-to-dsc-for-legacy-unfairness-issue.pptx

[47] Y. Inoue et al ,“Discussion on The Receiver Behavior for DSC/CCAC with BSS Color”, May 2015, doc.: IEEE802.11-15/0595r2 https://mentor.ieee.org/802.11/dcn/15/11-15-0595-02-00ax-discussion-on-the-receiver-behavior-for-ccac-dsc-with-bss-color.pptx

[48] Y. Seok et al, “NAV Operation for Spatial Reuse”, July 2015, doc.: IEEE802.11-15/0797r0

https://mentor.ieee.org/802.11/dcn/15/11-15-0797-00-00ax-nav-operation-for-spatial-reuse.pptx

[49] T. Itagi et al “Dynamic CCA control and TPC Simulation Results with SS1~SS3”, September 2015, doc.: IEEE802.11-15/1545r0

https://mentor.ieee.org/802.11/dcn/15/11-15-1045-01-00ax-dynamic-cca-control-and-tpc-simulation-results-with-ss1-ss3.pptx

[50] J. Iwatani et al, “Simulation results of spatial reuse with various MCSs”, March 2016, doc.: IEEE802.11-16/0360r1

https://mentor.ieee.org/802.11/dcn/16/11-16-0360-01-00ax-simulation-results-of-spatial-reuse-with-various-mcss.pptx

[51] L. Cariou et al, “Clarifications for OBSS_PD-based SR parameters”, July 2016, doc.: IEEE802.11-16/0945r2 https://mentor.ieee.org/802.11/dcn/16/11-16-0945-01-00ax-clarifications-for-obss-pd-based-sr-parameters.pptx

[52] Mathew S. Gast , “ 802.11ac A Survival Guide” O’ Really Media Inc. 2013

[53] March 2016. doc.: IEEE 802.11-16/0024r1. “Wireless LANs. Proposed TGax draft specification.” Date: 2016-03-02 TGax Submission, https://mentor.ieee.org/802.11/dcn/16/11-16-0024-01-00ax-proposed-draft-specification.docx

[54] G.Smith, “Unified SR text DSC, ATPC, inter-BSS”, October 2016

doc.: IEEE 802.11-16-1063-03-00ax, TGax Submission, https://mentor.ieee.org/802.11/dcn/16/11-16-1063-03-00ax-unified-sr-text-dsc-atpc-inter-bss.docx

[55] G.Smith, (October 2016) “A unified approach to spatial reuse ”, doc.: IEEE 802.11-16-1064r3, TGax Submission, https://mentor.ieee.org/802.11/dcn/16/11-16-1064-03-00ax-unified-sr-approach-dsc-atpc-and-inter-bss.pptx

[56] T. S. Rappaport, “Wireless Communications – Principles and Practice,” Prentice Hall PTR, 1996

[57] D. B. Faria, “Modeling Signal Attenuation in IEEE 802.11 Wireless LANs – Vol. 1”, Technical Report TRKP06-0118, Kiwi Project, Stanford University, July 2005.