An interference-based channel access algorithm for IEEE 802.11ax spatial reuse improvement

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Wi-Fi is the dominant way of connecting indoor mobile devices to the Internet. The main reason behind the huge adoption of this technology is the simplicity of IEEE 802.11 protocols which in turn offer low-cost ownership and maintenance combined with the ability to offer high data rates to end users. The increasing demand in traffic volumes leads to the continuous deployment of access points (APs) resulting in densification of the IEEE 802.11 networks. This fact, instead of enhancing the efficiency of wireless local area networks (WLANs) degrades their overall performance due to co-channel interference between overlapped basic services sets (OBSSs). One of the main goals of the under-development IEEE 802.11ax amendment is to address the WLAN densification problem by improving spatial reuse (SR). In this article we present and evaluate a channel access algorithm, which considers the expected interference that nodes will suffer by a concurrent transmission so to decide if transmission or defer will take place. It is shown that the proposed interference based dynamic channel algorithm (IB-DCA) offers significant SR performance gains comparing to the existing channel access algorithms, in terms of the station mean data rate, for all the stations in a IEEE 802.11ax dense deployment.

The IEEE 802.11ax amendment

According to Cisco [1], the overall mobile traffic load is expected to grow to 49 EB per month by 2021, that is, a seven-fold increase compared to 2016. Furthermore, the offload traffic percentage from cellular to Wi-Fi networks is expected to be 63% of the total mobile traffic load. In order to address the above forecasts, a continuous increasing deployment of APs is expected in the forthcoming years. This densification of [illegible] overall efficiency and offered services due to limited spectrum resources and co-channel interference among them.

The IEEE 802.11 standardization committee anticipating the mentioned challenges decided to develop a new standard named high efficiency WLAN (HEW) IEEE 802.11ax. The functional requirements [2] of the new amendment are set by the Project Authorization Request [3] and the Criteria for Standard Development [4]. The requirements include: a four (at least) times improvement for the average throughput per station in a dense deployment while maintaining or improving the power efficiency per station; efficient use of spectrum in a dense deployment; operation in frequency bands between 1 GHz and 6 GHz; backward compatibility with legacy IEEE 802.11 devices.

A key factor to fulfil the above requirements is the optimum usage of limited spectrum resources. The IEEE 802.11 protocol is contention based. A node that wishes to access the medium has to follow channel access rules defined by the availability of the medium resources in time and frequency, that is, it has first to find the medium free of any other transmission before attempting to transmit. On the other hand, spatial reuse (SR) allows concurrent use of the same medium resources by more than one transmitting nodes in a wireless network under specific constraints that most usually arise by the different positions of the nodes (hence the term “spatial”). A channel access algorithm which maximizes concurrent transmissions and aggregate throughput while at the same time preserves both fairness and the quality of the received signal is crucial for improving SR and overall network efficiency. In order to investigate and implement mechanisms that enhance SR usage, a special Task Group (TG) was established by the IEEE 802.11 standardization committee.

The current channel access mechanism for 802.11 networks

The fundamental channel access mechanism of IEEE 802.11 standard is the distributed coordination function (DCF) that employs carrier sense multiple access with collision avoidance (CSMA/CA) with a binary exponential back off [illegible]k a node that wishes to transmit a packet has to sense the medium for a period of arbitration inter frame space (AIFS) plus a back off duration. The medium is considered to be idle (busy) if the received signal is lower (higher) than two different power thresholds: the first one is the Carrier Sense Threshold (CST) which is applied to successfully decoded IEEE 802.11 signals while the other one is the Energy Detection (ED) threshold that is applied to any non-IEEE 802.11 signal. If the medium is idle for the above mentioned period, the node can access the medium and initiate a transmission while when the medium is considered to be busy, the node defers its transmission. The back off duration is a pseudorandom time interval which is applied in order to avoid collisions between nodes wishing to access the medium.

The CST level is fixed and its value is conservative leading to reduced SR. The proper adjustment of the CST level in relation to the conditions of the network is an important challenge since a reduction of this level reduces SR while an increase results in more collisions.

IEEE 802.11ax SR TG current status of progress

According to the latest Draft 3.0 of IEEE 802.11ax [5], the SR Task Group decided to adopt a combination of three different mechanisms in order to improve SR. The first one is the Adaptive Carrier Sense Threshold (ACST) level, the second one is the Adaptive Transmit Power (ATP) level and the last one is the Basic Service Set (BSS) coloring. Furthermore, according to the Draft, there is the capability of different BSSs to compose a Spatial Reuse Group (SRG).

The BSS coloring mechanism assists any station (STA) to identify the origination of each received packet. If a packet is transmitted from an STA belonging to the same BSS or in the SRG, it is characterized as Intra-BSS packet, or SRG packet, respectively. Otherwise it is characterized as Inter-BSS packet, or non-SRG packet, respectively. Utilizing the coloring information, a station receiving an Inter-BSS or SRG packet, instead of applying the fixed CST in order to access the medium, applies a more aggressive threshold called overlapped basic service set preamble detection (OBSS_PD) threshold. This way more concurrent transmissions can occur in a wireless network with a low collision probability, thus, improving SR.

By applying a more aggressive CST level an STA is benefited compared to others that use more conservative values since it has more transmitting opportunities. On the other hand, a concurrent transmission degrades the quality of received signal in the neighbor BSS. In order to face this fairness problem, the Draft defines that an STA that uses the SR transmission opportunity has to inversely proportional reduce the transmit power level (TX_PWR) in accordance with the rise of the OBSS_PD threshold level – see Figure 1.

In addition to CST determining the medium as idle or busy, the Network Allocation Vector (NAV) is a virtual carrier sense mechanism that is used to ensure medium reservation. The new amendment adopts two different NAVs. The first is the Intra-BSS NAV that is updated by an Intra-BSS packet. The other one is the basic NAV that is updated by an Inter-BSS packet or a packet that cannot be classified neither as Intra-BSS nor Inter-BSS.

The major challenge that the TG is facing, is the proper adjustment of the OBSS_PD threshold and transmit power level. A TG contribution [6] presents an approach to the OBSS_PD threshold adjustment based on an equation that uses the Receiver Signal Strength Indicator (RSSI) from the beacon frames of the AP as a reference. The main idea behind this adjustment is that the OBSS_PD threshold will be at a maximum level and the transmit power will be at a minimum level for close distance links between AP and non- AP STAs and vice versa for far distance links.

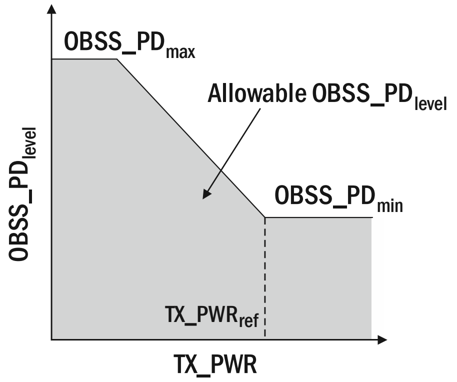


Figure 1 *Inversely proportional relation between transmit power (TX_PWR) and OBSS_PD threshold [5]*

Overall, an algorithm adjusting the OBSS_PD threshold and ATP levels has not been decided yet and this issue is still open or may eventually be left open for implementers to configure. Contribution in [7] analyzes this problem and indicates that SR performance is enhanced when only the ACST in combination with coloring mechanisms are applied. In contrast, the application of the ATP mechanism results in lower Modulation and Coding Schemes (MCS) use, due to reduced Signal to Interference Ratio (SINR), more retransmissions, inferior performance and decreased efficiency. This contribution suggests, in addition, that SR parameters should not left open to implementers and must be standardized by the protocol. Allowing STAs to choose how they implement the SR function without specification of the parameters controlling transmit power and OBSS_PD threshold will impact other STAs performance.

Related work on SR for IEEE 802.11ax networks

A considerable amount of research work has been done since the establishment of the SR TG in order to investigate the performance of the suggested mechanisms and to propose new channel access schemes capable of improving SR in IEEE 802.11ax networks. In this context, we proposed in [8] an Interference Based Dynamic Channel Access (IB-DCA) algorithm for dense WLAN deployments. The algorithm was evaluated on a per WLAN basis and compared with the existing channel access scheme as well as with two mechanisms proposed by the contribution in [6] of the SR TG in various WLAN density scenarios. Simulation results showed that with IB-DCA algorithm the performance of the WLANs involved and the network as a whole outperforms the other channel access mechanisms in terms of throughput and fairness while the poor performance of the TG proposed SR mechanism when using ATP technique was verified, a finding which agrees with TG contribution [7].

An RSSI To OBSS Threshold (RTOT) channel access algorithm was proposed in [9]. This algorithm uses the beacon frame's RSSI to compute the CST and derive dynamically the transmission power to use. The evaluation of RTOT algorithm by simulation in an enterprise scenario (suggested by the SR TG) shows that the overall system throughput can be improved up to 80% compared to IEEE 802.11 legacy networks but at the expense of per-station throughput degradation and, thus, the fairness among stations is severely compromised. The author in [9] suggested that a trade-off must be considered between maximizing the overall throughout and maintaining an acceptable per-station throughput.

A Dynamic Sensitivity Control (DSC) algorithm was presented in [10] that sets different CST values for different links instead of setting just one common CST value. The algorithm first formulates the throughput of each downlink as a function of the related links' CST and then searches for a set of CST values for these links to maximize the system throughput. Simulation results showed that the DSC algorithm can improve the system throughput by up to 30% when compared to a conventional algorithm. An asymptotic analysis of the inversely proportional setting of CST and transmission power in densely deployed WLANs was presented in [11]. The authors obtained the optimal explicit expressions of inversely proportional setting between CST and transmission power in terms of throughput, as a function of SINR and the number of neighbouring potential transmitters. The proposed solution was confirmed through numerical results, where the explicit solution achieved throughput with a loss of less than 8% compared to the numerically evaluated optimal solution.

Authors in [12] investigated the performance of the baseline ACST technique proposed in the IEEE 802.11ax TG under realistic scenarios. Simulation results illustrated that compared with the existing channel access mechanism, the use of ACST may lead to mixed results in terms of throughput and fairness with a variable gain depending on factors like inter-AP distance, node distribution, node density and the ACST margin value. Almost the same conclusions were drawn in [13] where the ACST and ATP algorithms were evaluated in a very dense residential scenario (suggested by the SR TG). Simulation results demonstrated that the algorithms do not significantly improve the overall network performance compared to the legacy baseline, as they increase the throughput of some nodes, while decreasing the throughput of others.

The proposed IB-DCA algorithm

In this paper, extending our work in [8], we focus on the performance of the non-AP STAs, i.e., the end users, of the network, instead of the aggregate performance of the WLANs of the network. Furthermore, we check even denser deployments than the ones analyzed in [8]. We show that the proposed IB-DCA algorithm provides improved performance both for close and distant (from the APs) STAs. This is of major importance and constitutes one of the main goals of the 802.11ax protocol over dense networks.

The IB-DCA algorithm defines the channel access rules and adjusts the transmit power level in a WLAN by considering the SINR level of the received signal at the destination combined with the BSS coloring information. The algorithm divides the links of the wireless network in two categories. The first category refers to SR links and includes those links for which the expected SINR level at the destination is greater than 0 dB in the worst case interference scenario. The second category refers to the non-SR links and includes those links for which the expected SINR level at the destination is less than 0 dB in the worst case interference scenario. The worst case interference scenario for an STA is considered to be the maximum level concurrent transmission from a potential transmitter associated with other BSSs using the same channel.

Two SR flags are encapsulated in each transmitted packet to define the capability of an Inter-WLAN STA to transmit simultaneously with the current transmission. The first flag is the SR_flag_AP and the second one is the SR_flag_STA. The status of the STA's SR flags defines the capability of an STA to transmit over another packet. For example, when an AP STA detects an Inter-WLAN packet it can initiate a transmission and will not defer if the following conditions are met: (i) the SR_flag_AP of the received packet is set to 1, and (ii) its own ongoing transmit packet SR_flag_STA is set to 1, when the received packet is uplink (UL), or, the SR_flag_AP is set to 1, when the received packet is downlink (DL). The second condition prevents collisions from the initiated new transmission since the RSSI level at the destination is higher than the maximum interference that a concurrent transmission from Inter-WLAN STA can cause. Similarly, when a non-AP STA detects an Inter-WLAN packet, it can initiate a transmission and will not defer if the following conditions are met: (i) the SR_flag_STA of the received packet is set to 1, and (ii) its own ongoing transmit packet SR_flag_STA is set to 1, when the received packet is UL, or, the SR_flag_AP is set to 1, when the received packet is DL.

In order to decide its link category and set its SR flags, every STA records the maximum RSSI levels of Inter-WLAN packets that are successfully decoded using the colouring information of the packet. Two RSSI levels are recorded: one concerning DL packets, that is, the maximum interference $I_{AP,\max}$ caused by AP STAs, and another one concerning UL packets, that is, the maximum interference $I_{STA,\max}$ caused by non-AP STAs. These two levels are advertised to other STAs. Apart from the maximum interference levels every STA has to advertise its transmit power level so that the expected RSSI could be calculated at the destination by:

$$\mathrm{RSSI}_D = \mathrm{RSSI}_S + (P_{TX,S} - P_{TX,D}) \quad (1)$$

where, RSSI_D is the expected RSSI level at the destination, RSSI_S is the RSSI level of the received packet from the destination, $P_{TX,S}$ and $P_{TX,D}$ are the transmit power levels (in dBm) of the sender and the destination STA, respectively. Utilizing the above information, an STA sets its SR_flag_AP to 1 if $\mathsf{RSSI}_D > I_{AP,\max}$. In accor-dance, an STA sets its SR_flag_STA to 1 if $\mathsf{RSSI}_D > I_{STA,\max}$. These conditions guarantee that a concurrent transmission can take place without causing a collision since the received signal level at the destination is greater than the maximum interference level which a concurrent transmission from an Inter-WLAN STA can cause. Moreover, these conditions benefit the non-SR links, since, when a non-SR link packet is transmitted, any concurrent transmission is prohibited thus preserving the SINR level of the received signal. This way the fairness between SR and non-SR links is balanced.

The IB-DCA algorithm also adjusts the transmit power level. Vendors' lookup tables with packet error rates of the available MCS over an additive white Gaussian noise channel (see [14]) show that a 23 dB SINR level is high enough to support the most demanding MCS scheme. Thus, reception above this level does not significantly increase the expected data rate. The idea is to reduce SINR levels that are higher than 23 dB by reducing the transmit power level. This is a win-win approach since a reception of adequate quality is achieved while, at the same time, the interference level to the neighbouring BSSs is reduced. Every STA calculates $I_{\max}$ as

$$I_{\max} = \max(I_{AP,\max}, I_{STA,\max}) \tag{2}$$

and advertises it along with its transmit power level $P_{TX,ref}$. Using this information every STA can adjust its transmission power level P_{TX} by

$$P_{TX} = P_{TX,ref} - (\mathsf{RSSI} - I_{\max} - 23) \tag{3}$$

where, RSSI is the RX level of the packets transmitted by the destination STA. In every case, the transmit power level for an AP STA in (3) has a maximum value of 20 dBm and a minimum of 0 dBm. The transmit power for a non-AP STA has a maximum value of 15 dBm and a minimum of −5 dBm. The transmit power adjustment improves fairness since the non-SR links transmit at maximum power level when SR links may transmit with reduced power.

For a practical implementation of the algorithm, the maximum RSSI and the transmit power levels have to be advertised among the nodes, as mentioned above. These values can be included in the Spatial Reuse element and the Spatial Reuse field of the HE-SIG-A part of the preamble [5] (defined for purposes that do not apply in our algorithm).

Simulation methodology and results

Our simulations are implemented in MATLAB and the methodology follows the physical system modelling, described in [14], closely. This model uses the Received Bit Information Rate (RBIR) physical abstraction in order to accurately predict packet error rate. The underlying principle is the calculation of the effective SINR of a given Orthogonal Frequency Division Multiplexing (OFDM) symbol. The MCS selection method adopted is the *goodput max approach* proposed by the IEEE 802.11ax TG in [15]. In order to make the simulation more realistic we applied a ±5 dB random deviation in the interference estimation level. Table 1 summarizes the employed simulation parameters.

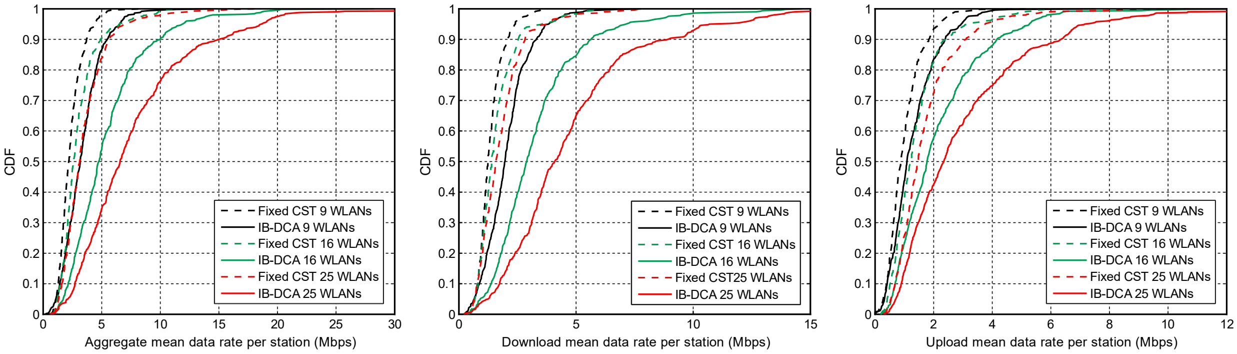
Three different WLAN density scenarios were simulated over a fixed square area of 100×100 m, that is, medium, high and very high density AP deployment cases consisting of 9, 16 and 25 overlapped WLANs, respectively. The area is divided in an identical, to the number of WLANs, number of equal squares that span the whole area, and an AP is put in the centre of each square. One hundred IEEE 802.11ax non-AP STAs are randomly placed in the whole area and are associated with the AP from which they receive the highest power. The area is considered to be managed and an optimal frequency reuse of three different 20 MHz channels is used by the BSSs.

Parameter	**Value**
Physical abstraction	RBIR model
Frequency band	2.4 GHz
Number of Channels	3
Channel bandwidth	20 MHz
MCS selection	Maximizing goodput
Channel Model	TGac F large space indoor
Shadowing	5 dB standard deviation
AP/STA Fixed Tx power	20/15 dBm
AP/STA Dynamic Tx power	0 to 20 dBm / –5 to 15 dBm
Number of Antennas AP/STA	SISO (1 Antenna)
Antenna gain AP/STA	0/–2 dBi
RTS/CTS	Disabled
Interference estimation level	±5 dB
Traffic	Full Buffer

Table 1 *Simulation Parameters*

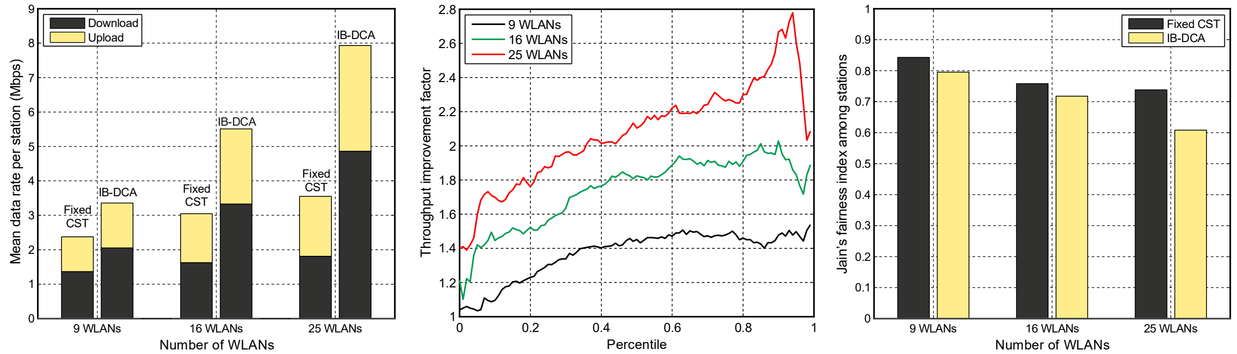
The performance of the proposed algorithm is evaluated via two important (as highlighted in [2]) metrics: the per-station throughput and fairness among users. In this context, Figure 2 illustrates the per-station cumulative distribution function (CDF) of the aggregate, download and upload data rate. Clearly, the proposed IB-DCA algorithm outperforms the fixed CST scheme in all density scenarios in both DL and UL directions. The gain increases with the number of WLANs showing that the proposed scheme is suitable for high WLAN density.

Figure 3, provides further details on the superiority of the proposed algorithm in comparison with the existing fixed CST channel access mechanism. In particular, Figure 3(a), illustrates the mean data rate, in Mbps, per station for the three density scenarios. The improvement that IB-DCA algorithm provides is significant in all cases and increases with the number of WLANs, as previously noted. However, the mean data rate improvement does not guarantee that all STAs manage to increase their data rates, irrespectively of their physical positions in the network and their distances from the AP.



(a) (b) (c)

Figure 2 *Per-station data rate CDF: (a) Aggregate, (b) Download, and (c) Upload, for three network topologies: 9, 16, 25 WLANs over a square region of 100×100 m.*



(a) (b) (c)

Figure 3 *Performance metrics of existing and IB-DCA channel access algorithms: (a) Mean data rate per station (Mbps), (b) Improvement factor over the percentile range, and (c) Jain's fairness index, for three network topologies: 9, 16, 25 WLANs over a square region of 100×100 m.*

In order to prove the effectiveness of the proposed algorithm in this context, we present in Figure 3(b) the data rate improvement factor of IB-DCA algorithm with respect to the existing channel access mechanisms for the whole percentile range of the mean data rate CDF. With the lower percentiles corresponding to the longer distance links (between STAs and the AP within a WLAN) and the higher percentiles corresponding to the closer distance links, it is evident that all STAs' performance, on average, improves. Cleary the improvement is proportional to the WLAN density scenario and reaches 2.8 for some nodes in the very high density one. Moreover, the improvement factor is higher for the higher percentile values compared to the lower ones. This fact can be explained by the more transmission opportunities that the IB-DCA provides to the close range links. Still, the farthest STAs' performance is improved as well.

In order to investigate the performance of the IB-DCA and the existing channel algorithm with respect to the fairness among stations, we used the Jain's fairness index. The results in Figure 3(c) show that the overall fairness among the stations is slightly reduced with the proposed scheme, in all density scenarios. This is in agreement with the per-station improvement factor of Figure 3(b), which shows that IB-DCA benefits close links more than the long distance ones. This imbalance in the performance gain, introduced by IB-DCA, may be reduced by proper selection of the algorithm parameters; though this is out of the scope of the current paper.

Conclusions

In this paper we presented the current status of undergoing work in the IEEE 802.11ax SR TG. The latest Draft of the new amendment shows that the TG has decided the combination of three different mechanisms in order to improve SR in high density WLAN deployments, i.e., ACST level, ATP level and BSS coloring. In contrast, the TG has not yet decided about the specific way that these mechanisms will be employed. In this context, we proposed and analyzed an interference based (IB-DCA) algorithm. Our proposal suggests that the combination of coloring, estimation of interference level at transmission destination and dynamic transmit power can enhance the performance and spectrum utilization in high density deployments. We evaluated IB-DCA algorithm against the existing channel access algorithm for various density WLAN deployments over a square 100×100 m region. Our simulation results showed that IB-DCA algorithm enhances the per-station performance (in terms of the mean data rate) for all the nodes in a WLAN, offering increasing gain with increasing WLAN density. Overall, in conjunction with our previous work [8], the proposed scheme offers enhanced performance both from the network and the end user points of view. Our future work includes the development of an integrated WLAN system simulator that will consider all the MAC layer procedures as well as the study of hand-over or AP switching.

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