ıx High Efficiency WLANs

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A Tutorial on IEEE 802.11ax High Efficiency WLANs

Evgeny Khorov , Anton Kiryanov, Andrey Lyakhov, and Giuseppe Bianchi

—While celebrating the 21st year since the very first .1 "legacy" 2 Mbit/s wireless local area network stan- atest Wi-Fi newborn is today reaching the finish line, : remarkable speed of 10 Gbit/s. IEEE 802.11ax was ı May 2014 with the goal of enhancing throughput-per- h-density scenarios. The first 802.11ax draft versions, .0 and D2.0, were released at the end of 2016 and 2017. ı a more mature version D3.0, in this tutorial paper, we ıder to smoothly enter into the several major 802.11ax ghs, including a brand new orthogonal frequency- ıltiple access-based random access approach as well as al frequency reuse techniques. In addition, this tuto- ghlight selected significant improvements (including yer enhancements, multi-user multiple input multiple nsions, power saving advances, and so on) which make rd a very significant step forward with respect to its r 802.11ac.

***rms*—Wireless LAN, quality of service, OFDM, IEEE high efficiency WLANs, Wi-Fi, dense deployment, JL MU-MIMO.**

cable replacement to a full fledged comp infrastructure and a wireless access alte connectivity [1].

Nevertheless, the impressive deployme Wi-Fi technology is also threatening its fu are more and more demanding; networks' a is ever increasing, and soon the current sta Wi-Fi technology might fail short in effi foreseen customers' base.

The evolution of the standards shows a in nominal data rates: from the "legacy" 2 M 1997, to the 11 Mbit/s of 802.11b, the 54 M the 600 Mbit/s of 802.11n, and the abo the latest 802.11ac. These Wi-Fi rates l plished by means of faster modulation an wider channels, and the adoption of Multi Output (MIMO) technologies [2]. Unfortu sis of the latest 802.11ac networks show increase of Wi-Fi throughput in a legacy s channel access approaches rather than just

I. Introduction

N, in September 1990, the very first meeting of the 11 project was held, hardly anyone could imagine to which that early initiative, devised to - verbatim e original 802.11 Project Authorization Request — *Medium Access Control (MAC) and Physical Layer cification for wireless connectivity for fixed, portable g stations within a local area*", would have changed ctivity habits.

in these last 28 years, Wi-Fi — specified by the the IEEE 802.11 standards — has widely spread tually any user's device, as well as any inhab- vment — homes, offices, cafes, parks, airports, etc. it has been extended with several technical facili- have permitted its evolution from "just" a low-rate

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or increasing the number of spatial stream other documents of the former IEEE 802. Wireless LAN Study Group (HEW WLA albeit being a key asset, a high nomina fully representative for the performance c ment. The network operation is in fact f interference patterns and frequency-select well as medium access inefficiencies and tion scenarios. And sheer capacity might no requirement for several applications and se

A. The 802.11ax Challenge: Dense Netwo

The most notable 802.11ax's design dri tion that, today, WLAN devices are deploy environments, characterized by the presence ber of terminals concentrated in localized Corporate offices, mass events, outdoor malls, airports, exhibition halls, dense resi stadiums, and so on, are all examples *ments* [5], whose coverage requires a mul Points (APs) — in principle even up to hun may therefore require to be operated on (pa channels. In such environments, the aggre not anymore the main performance metric the target should be an increase of the *thro* the *throughput-per-area* which is defined total network throughput to the network ar

TABLE I
List of Acronyms

by forbidding transmissions that may p 11ax focuses at improving spatial reuse by STAs [9].

Apart from that, in real scenarios, networ operate in the saturated mode, i.e., the po able for transmission may be rather smal the size held by an aggregated packet (with limits), there is a fixed toll to pay, in term the channel, to separate frames and to se ment. Thus, for small data payloads the ove percentage of channel time may be huge, si ing the application-layer throughput ultimat the end users [4].

Another challenge comes from the din try in traffic patterns. The widespread de networks characterized by a significant generated multimedia content, as well as continuously interact with centralized clou pose a significant burden not only on t

transmission, as it was the case for tradi
information retrieval applications, but also
For DL the problem was partially solved in
Multi-user (MU) MIMO. For uplink, such a
tight synchronization going well beyond w
standardized in previous 802.11 amendmen

For these reasons, as well as for other r
sons discussed later on, such as an improve
tion for battery-operated devices and suppor
of user Experience (QoE), in May 2013 the
Standards Committee launched a HEW St
was later converted into Task Group AX
Task Group has attracted considerable intere
holders, as for instance witnessed by the r
statistics: during the Atlanta meeting in
much as *half* of the IEEE 802.11 attend
accumulated by this Task Group [10], w
half of the crowd distributed among many
IEEE 802.11 activities [11]. Even though
amendment is planned for finalization by
three years a significant amount of work ha
ried out. The specification framework docu
in 2014 [12] and was finalized in May 2
posal for the draft 1.0 802.11ax amendme
December 1, 2016, while the second one ap

B. Contribution and Organization

It is worth to remark that a final consens
specification has not been reached yet.
802.11ax 1.0 draft standard was balloted
and received just 58% of positive votes o
required threshold, and as many as 7334 c
filed. The second draft standard obtained o
votes. Only the third version passed the ba
of positive votes and 2154 comments.

ly, in such environments, the primary source of
ce degradation is the massive interference. While
efforts aimed at avoiding hidden stations (STAs)

Still, even if the development proces
yet finished and many open issues need
before finalization, some firm landmarks h

we believe this may be the right time to report about
t status of the 802.11ax proposal and discuss the
tions and approaches therein under consideration,
t accessible to the wireless networking community

itorial paper, also leveraging our direct participation
.11ax activities, our goal is threefold:
ding a snapshot of the major solution and

briefly introduce the main characterizing f
technology. In the subsequent sections, we
detail on the specific enhancements sugge
layer (Section III), the major breakthroug
access operation brought about by the ad
and of the MU-MIMO uplink operation and
channel access modifications (Section IV),
that enable spatial reuse (Section V) an

aches included so far in the standardization work;
lementing such an information with selected quan-
e results which suggest the extent to which the
ging standard is able to maintain its promises of
ghput quadruplication stated in the 802.11ax Project
rization Request (PAR) document [7], and
fying the issues or caveats which may require fur-
upport from the research community, e.g., in terms
ther ideas and/or simulation results.

rk is not the first tutorial on 802.11ax. We acknowl-
few earlier overviews have been already written at
ing of the development process, including [13]–[15]
our previous 2015 report [16]. However, such earlier
pers were based on very initial ideas being discussed
es in the 802.11ax task group, and as such are not
ully representative of the evolution of the 802.11ax
n fact, part of the initially proposed features and
pproaches have been further detailed, improved, or
seded by the hectic standardization work carried out
period. In a few cases some proposals have been
d left to future standards. Most notably, the support
plex operation, albeit popular and considered very
by the community, was ultimately considered out
e of the 802.11ax technology.[1]

torial will introduce the reader to the techni-
of the proposed Orthogonal Frequency-Division
ccess (OFDMA) approach (including OFDMA ran-
s). It will clearly describe the already adopted frame
and will give a comprehensive overview of the new
hich enable overlapping Basic Service Set (BSS)
nt and spatial reuse — BSS coloring, usage of Quiet
ods and two Network Allocation Vectors, adjustment
sitivity threshold and the transmit power, and oth-
over, we will give an insight into the novel power
nt techniques which have already become a part of
ax draft standard.

also try to make this tutorial more insightful
ng numerical results obtained by the researchers
industrial companies and the academic community.
e will highlight a number of open issues, some of
e to be solved in the framework of the development
.11ax amendment and some of which will be con-
proprietary algorithms designed by each vendor
y.

of this paper is organized as follows. In Section II,
f review of the state-of-the-art before 802.11ax, we

h to remark that, while we are writing this paper, IEEE 802.11
a Full Duplex Topic Interest Group, which means that the
n process will not likely start before another year or two.

management solutions proposed (Section V

II. 802.11AX AT A GLAN

Before summarizing in the next Section I
ing features currently being proposed by t
Task Group, we start with a brief overvie
of the 802.11 standards (Section II-A). So
able to better appreciate the next steps tak
standardization activity.

A. Before 802.11ax: State of the Art

In the last 20 years, a number of amend
cally 802.11a/b/g/n/ac (we restrict to the or
"traditional" ISM 2.4 and 5 GHz bands), h
to improve the nominal data rate.

The older ones, namely 802.11a/b/g, "
new modulation and coding schemes so a
rate from the original 2 Mbit/s of the "leg
up to 54 Mbit/s in both the 2.4 GHz (802.1
(802.11a) ISM unlicensed bands.

The 802.11n proposal represents a signi
with respect to the above early Wi-Fi sta
significantly increased (up to a theoretical
Mbit/s) via a combination of techniques. T
ability to exploit channels with a width o
is twice larger than those used in previo
ii) the usage of higher 5/6 coding rates oppo
3/4 coding rates, and — arguably the mo
breakthrough — iii) the transition towards
i.e., the usage of multiple antennas to tran
tial streams simultaneously between a pair
significantly increasing data rates.

In addition to the raw data rate increase
several crucial improvements also at the M
is to reduce overhead in terms of interfra
bles, and control frames, which otherwise v
properly take advantage of the performance
the newly designed PHY. Indeed, 802.11n
Reduced InterFrame Space (RIFS) of 2 μs
instead of the 10 or 16 μs Short InterFr
to separate transmissions of the same ST
is expected between these transmissions.
introduces two aggregation methods, nam
(Aggregated MAC Service Data Unit) a
(Aggregated MAC Protocol Data Unit). Th
several aggregated packets with a single
check sum. The second one assigns a MAC
check sum to each aggregated packet. Th
mits the improvement of transmission relia

ng of at least some packets in case of short noise he expense of slightly increased overhead.

ontention-based channel access inevitably leads to from the very beginning IEEE 802.11 tried to add ntention-free channel access mechanisms to the stan- the "historical" Point coordinated function (PCF, ow) and the subsequent Hybrid Controlled Channel CCA) allow an AP to access the channel without . Channel access coordination is accomplished by g an Interframe Space called PIFS (PCF InterFrame ich, being shorter than the DIFS (Distributed coor- unction InterFrame Space) used by the remaining mits the AP to acquire the channel access with- ontention, so as to transmit data or poll the STAs them channel access. In practice, contention-free hniques have seen a very marginal deployment, because of their inefficiency in scenarios when sev- work in the same area. Indeed, if several APs use r transmissions will start simultaneously and col- problem is partially addressed in the HCCA TXOP n mechanism introduced in 802.11aa. The mecha- vs various APs to use different time intervals for on. Unfortunately, HCCA TXOP Negotiation can l collisions between APs which can communicate other. Moreover, it does not reduce the collision es between an AP and the alien STAs, which still ndom access.

E 802.11 Working Group has historically put a sig- fort to improve the Quality of Service (QoS) in works. Specifically, the 802.11e amendment intro- anced Distributed Channel Access (EDCA) and ich distinguish voice, video, best effort and back- ffic and serve them differently. While EDCA just ferent priorities to these types of traffic, the sophis- CA allows an AP to schedule transmissions taking nt specific QoS requirements, like the delay bound, loss ratio, or the required bandwidth. However, g exact requirements is a non trivial task, and nother key reason behind the scarce deployment of tion-free HCCA.

y devices which use Wi-Fi (e.g., laptops and smart- ower consumption is an important issue. In 802.11 power management is based on alternating between awake and doze. In the awake state, a STA can nd receive frames, while in the doze state, its radio d off. An active STA is always awake, while a ng (PS) STA alternates between these states. The s data destined for PS STAs until the STA wakes rieves it. Many amendments introduce new power- tures, but most of them are related to switching off for a rather long time, i.e., for hundreds of mil- or even for seconds. Some of them require a PS ntend for the channel if it wants to retrieve data AP. Such methods are inefficient in dense environ-

The tight dependence of these methods wit ality — specifically with the Traffic Spe information element which parametrizes Q prevents their usage in consumer electroni

Finally, the 802.11ac amendment [17]–[mainly with the purpose of significantly i rate of a 10x factor with respect to 802.11 ing the number of spatial streams up to 8, the problem of how to cope with terminal manufacturing reasons, could not deploy antennas. To this purpose, the 802.11ac f DL MU-MIMO, which allows an AP to spatial streams to different STAs — the sion was postponed to subsequent standard synchronization requirements which woul significant re-design. Additionally, 802.11a mission bands up to 160 MHz (also exploti 80+80Mhz channels) and increases the co 256-QAM, which raises data rates up to the header-induced overhead at such hi amendment increases the maximal length 65 535 (802.11n) to 4 692 480 octets. short packets, such as instant messages, acknowledgments, etc. the channel is still

B. Main Features of 802.11ax

Similarly to the previous amendments nominal bit rates, 802.11ax contains a n with higher modulation and coding schem 802.11ac, 802.11ax does not increase t MIMO spatial streams and does not widen the nominal data rates are increased up to just 37% higher than that of 802.11ac (rath to the 10x growth of 802.11n or 802.11ac! increase of the user throughput is achieve spectrum usage.

The key feature of 802.11ax is the adopt approach, an approach widely used in cel brand new in Wi-Fi. The rationale is that t nels (80 MHz, 80+80 MHz and 160 M 802.11ac suffer from frequency selective i significantly impairs the practically achi OFDMA, adjacent subcarriers (tones) are into a resource unit (RU) and a sender can for each particular receiver, which actuall Signal-to-Interference-plus-Noise Ratio (S and Coding Scheme (MCS) and throughpu the efficiency of high data rates degrades only few data to transmit, advanced aggr aimed to reduce channel access, acknowle preamble-induced overhead become usele row RUs for such STAs is an efficient ren the latest TGax investigations, OFDMA

ause of collisions, huge overhead and large delays.
r methods allow an AP and a PS STA to schedule
' times when the STA retrieves data from the AP.
l of the series depends on the QoS requirements.

higher throughput than legacy DCF [21], s
OFDMA makes Wi-Fi radio access clos
However in contrast to LTE, OFDMA wo
legacy DCF and is coordinated by the AP. It

)MA gain in the overlapped network scenario [21].

example of OFDMA transmission in 802.11ax.

ne channel, the AP can start a usual DL transmission, ransmission (using OFDMA, MIMO or both), or Us for UL MU transmission.

OFDMA is time-based, i.e., various tones corre- different user equipment during one Transmission rval (TTI). In 802.11ax, OFDMA is frame-based, U frame contains data to/from different users and nes are assigned to the users for the entire frame ee Fig. 2.

L MU transmission, a PHY preamble specifies the f the frame and the tone mapping between STAs. , for an UL MU transmission, such a schedule is n the preceding frame, which can be either a Trigger ew control frame which allocates the channel for UL nission, or a data frame, the header of which con- luling information. The latter is especially useful for

Apart from OFDMA, many efforts have b throughput and to decrease power consur ping and dense networks. The list of the ne among others:

- BSS coloring: inherited (and extende and 802.11ah, allows to distinguish BSS frames based on their preambles payloads are corrupted by collisions;
- several modifications of the legacy vi known as Network Allocation Vector
- virtualization;
- microsleep operation, which enables a its radio just for the duration of an al
- redesigned Target Wake Time, origin 802.11ah; and
- opportunistic power save.

Apart from that, a considerable volume done to improve spatial reuse in a den changing the sensitivity threshold and the t Actually, to date this topic is still the most TGax ongoing activities, since it might sig fairness in the network and degrade the per devices.

Finally, TGax reuses the concept of peri vations during which only predefined ST Originally introduced in 802.11s (Mesh co Controlled Channel Access, MCCA) [22] in mesh networks, the concept is reused tioned HCCA TXOP Negotiation in 802. Service Periods in millimeter-wave 802.11a Restricted Access Window in 802.11ah [2 Internet of Things. In 802.11ax, periodic c (namely, the Quiet Time periods) can be us link communications. However, the mecha applied for time division between BSSs in

Table II summarizes the main novel fe which are described in greater detail in the

III. PHY: Modulation and Fra

A. Modulation

The 802.11ax PHY inherits several predecessor 802.11ac. Similarly to 802.

ging DL MU transmissions. An UL MU transmis- exactly one SIFS after the DL frame containing a This permits to synchronize the STAs participating MU transmission, whatever techniques the STAs MA, MU-MIMO, or both.

ing OFDMA in Wi-Fi affects the other MAC and ionality. First, TGax changes the OFDM parameters the flexibility and the efficiency of the OFDMA Second, TGax changes the PHY frame format to FDMA-related information in the PHY preamble. TGax continues moving MAC-layer information Y preamble, since sometimes the preamble can be ven if the entire frame is corrupted. Third, OFDMA nerous MAC changes related to the MU operation rness between the devices of different generations.

on Orthogonal Frequency-Division Mult and supports operations in 20 MHz, 40 80+80 MHz[2] and 160 MHz channels.

To increase the number of tones, whic OFDMA, TGax has quadrupled the durat symbols used for the PHY payload [24] u long OFDM symbols are more resilient to inherent in outdoor scenarios, which is ver UL MU transmission which may be simulta by several users. Moreover, longer symbol the overhead due to Guard Intervals (GI). In channel conditions, an 802.11ax device ca symbols by the GI selected among the valu

[2]In contrast to continuous 160 MHz channel, an combined from two non-adjacent 80 MHz channels.

TABLE II
MAIN FEATURES OF 802.11AX

s}, which allows the reduction of overhead down posed to the 12-25% GI overhead in the 802.11ac

.11ax amendment also introduces new modulation in addition to legacy BPSK, 16-QAM, 64-QAM, AM. The first one is an optional 1024-QAM [25], be exploited in indoor scenarios with very good nditions - i.e., a high SINR. Together with forward ction codes (convolutional or low-density parity- which have code rates of 1/2, 2/3, 3/4 and 5/6 —

MU transmission. These four different fran baseline frame structure extended with sele ized for the different frame types (Fig. 3). T the DL MU transmission is that the frame c preamble describing which tones a partic decode to obtain its part of the Data field UL MU transmission, the preamble is com ted by all the STAs. Then, each STA sends Data field using a predefined set of tones (

For all the frame types, the preambl

ulations generate a palette of data rates with a max-
.6 Gbps. Such a high rate is achieved when data is
l at the highest HE-MCS11 with a code rate of 5/6
1Hz or 80+80 MHz channel with 8 spatial streams
of 0.8 μs.

ıally, the 802.11ax amendment describes an optional er Modulation (DCM) [26]. DCM enhances trans- obustness by allocating the same signal on a pair which are separated far apart in the frequency ccording to preliminary investigations carried out by ıbers, such a technique helps to cope with sub-band e and provides more than a 2dB gain in the Packet o (PER) performance [26]. It should be also noted se of duplicating data, the usage of DCM reduces ıte twice, and so DCM is allowed to be used only elatively robust MCS0, MCS1, MCS3 and MCS4.

rame Format

efines 4 types of PHY frames (referred to as PPDU, ocol Data Unit, following the amendment): for the er (SU) transmission, for the extended range SU on,[3] for the DL MU transmission and for the UL

ded range PPDU was designed for robust delivery and can only d in a 20 MHz channel at one of the three lowest MCSs without

every 20 MHz subchannel within the tran
consists of two parts: the legacy part and
Fig. 4 [28]. While the former is included for
ibility, the latter one provides signaling for
functionality and it can be decoded only by

The legacy part contains training fields, the transmitter and the receiver, and the (L-SIG), which describes the parameters frame. Specifically, L-SIG allows the calcu duration. Even though the legacy devices the frame with errors, they consider the cha if the signal strength is too low.

To simplify the 802.11ax frame detecti interference, the HE part of the preamble etition of the L-SIG field [29], which is mandatory HE-SIG-A field, an optional H training fields (HE-STF and HE-LTF) r MIMO.

Let us consider the HE-SIG-A and HE-SI detail. HE-SIG-A provides information a width, a number of spatial streams (NSTS parameters that are needed to correctly dec frame. TGax continues moving some MA PHY preamble, an approach indeed widely from 802.11ah [23]. Since the preamble structure and it is transmitted at the lowes

11ax PHY frame format [27].

gacy preamble and HE-SIG-A are duplicated on each 20 MHz

In case of both UL and DL SU transmis a UL MU transmission, all the necessary i fitted into HE-SIG-A which consists of t symbols. However, in case of a DL MU information for various users may differ ified for each of them separately. In this HE-SIG-B field of variable length is incl preamble [33], [34]. Specifically, the field c one with common and one with per-user etition mode for HE-SIG-A, [30].

onal information is high. However, the inclusion of MAC-related information in the preamble is advan- nce i) the preamble is transmitted with the most S and ii) it can be decoded before the PHY payload ceived and its checksum is calculated. Specifically, also contains information such as network (or Basic t, BSS, in terms of IEEE 802.11) Color — see -A, remaining Transmission Opportunity (TXOP) whether the frame is sent in UL or DL, etc. Apart HE-SIG-A also contains the spatial reuse parameter ch is used to signal the sum of transmission power eptable level of interference to allow for the spatial ation as described in Section V.

)2.11ax networks are designed for both indoor and ployment, transmissions are prone to the Doppler ly caused by reflections from fast moving objects, rs and trains [31]. To improve the resistance to lity, the amendment proposes to periodically insert Y packet payload midambles, i.e., copies of the eld. Thanks to midambles, the channel can be not only during the packet preamble, but also con- hroughout the packet which is very fruitful for the ity communications, i.e., when the channel quickly

of a $\geq$ 40 MHz channel, the HE-SIG-A field is on each 20 MHz subchannel. In an extended range he SU frames, the content of HE-SIG-A is repeated ditional bit interleaving procedure [30].

common block describes the OFDMA r while the per-user block consists of seve ing for each resource unit its MCS, the streams, etc.

As mentioned above, the HE-STF and used for MIMO. Specifically, the main purp field is to improve the automatic gain cont MIMO transmission, while the HE-LTF fi for the receiver to estimate the MIMO ch set of constellation mapper outputs and th

Similarly to the legacy PPDU, the Dat SIGNAL subfield needed to initialize th scrambler and the encoded MAC frame. transmitted with 4 times longer OFDM sy

Quadrupling the symbol duration means culations at the receiver side, while the the receiver to do such calculations befor acknowledgment or response is limited by bring problems for low-cost Wi-Fi device be able to generate an acknowledgment i forward solution — increasing SIFS — because of backward compatibility as wel have decreased the channel usage efficie provides the possibility to extend the ta an extension. To minimize the overhea extension, its duration is flexible and de intended frame receiver and the payload when declaring its capabilities, each ST maximal extension (0, 8 μs or 16 μs) cess a frame with a given MCS and a streams. Note that this value can be redu payload is not divisible by the OFDM thus, the last OFDM symbol contains pa receiver needs less time to decode the such a thin OFDM symbol. In particul splits the last OFDM symbol into 4 s size. Thus, the extension can be reduced

value by the number of empty segments multiplied 5], [36].

PHY Issues

ourse of the past two decades, the 802.11 standard- ocess has focused on the introduction of new (or functionalities, but it has mostly avoided to deter- to use them. However, the performance of a network ly depends on how these functionalities are used, ax is not an exception. Having extended the set of

TABLE III
THE MAXIMUM NUMBER OF RUs FOR EAC

ıta rates, the amendment also adds new degrees of – such as DCM and shorter GIs — which affect ıission rate and the reliability. A high number of mplicates the selection of the best rate defined by ransmission parameters. Specifically, sophisticated l algorithms (e.g., Minstrel [37]) try various MCS, g obtained statistics, select the best ones for trans- ı wide palette of 802.11ax options increases the ed to obtain statistics. Moreover, in 802.11ax dense every 20MHz sub-band may have its own level of e. Thus, the best rate may be different for various Finally, in 802.11ax networks, the AP not only appropriate rate for its own transmission, but also MU transmission. For that, it collects reports on ıgth from associated devices prior to allocating UL ne to them. Although rate control is out of scope ıdard, this problem is of high importance for the nd 802.11ax developers need to revisit again this tigated area, owing to the new degrees of freedom aints.

issue is that the 802.11ax PHY preamble is longer egacy one. Thus it should be used only for long ons which benefit from the new 802.11ax features. since the 802.11ax frames cannot be decoded by vices, virtual carrier sense does not work prop- ı can degrade performance in scenarios with hidden ; issue needs to be addressed both by the standard (see Section V) and by the community of Wi-Fi ;, which can design smart algorithms to protect ons.

MU TRANSMISSIONS & CHANNEL ACCESS

ıx OFDMA Fundamentals

ıe design of OFDMA for 802.11 networks is a task, it has been investigated in many papers. For 38] proposes a novel OFDMA-based MAC proto- OMAX. Unfortunately, the authors consider only cess. In contrast, TGax has designed a much more d powerful framework, which can be used for both tic and random access. Let us describe it in detail.

1ax, the channel resources are allocated over time ncy, but in order to simplify resource management operation, and to retain compatibility with legacy e OFDMA transmission is organized on a per-frame means that a frame can carry information from or STAs. In such a frame, various tones are assigned to different STAs but the duration of all th a frame is the same.

An RU can contain 26, 52, 106, 242, ı tones (including service ones). The enti 40 MHz band, 80 MHz band and 80+80 corresponds to a 242-tone RU, 484-tone R and two 996-tone RUs, respectively. Each w into two approximately twice-narrower RU them can be split again, separately from only exception is that a 242-tone RU c two 106-tone RUs and one 26-tone RU. F problems with binary convolutional codes in [39], multiple RU allocations for a STA a though MU-MIMO and OFDMA can be u UL and DL MU-MIMO shall be perform tone RUs. The maximum number of RUs f is indicated in Table III.

Thanks to MU-MIMO, up to eight users an RU. It is also possible to allocate up to f per user, if the total number of spatial strea eight.

Let us consider how the DL and UL OFD are organized. In the case of the DL OFD the HE-SIG-B field of the common preamb allocation map which is followed by per- indicating the RUs assigned to an STA an parameters to be used by the STA (NSTS, Note that an RU can represent either an SU allocation. In the latter case spatial configu signaled to the STA.

Organizing the UL MU transmission is task. MU transmissions in Wi-Fi shall be s time domain. Since it is difficult to maint chronization because of clock drifting, an UL MU transmission as follows. The AP tr of a control frame — Trigger frame — in the common parameters of the upcoming sion (duration, GI which shall be the sam participating in the UL MU transmission [for the STAs, and defines transmission p particular STA (MCS, coding, etc.). To ac tion, the MU transmission is performed i SIFS after the Trigger frame [41], see Fi take more than SIFS to prepare a UL tra can pad the Trigger frame [42].

For UL MU OFDMA transmissions, th signals from different STAs at almost the example of UL OFDMA transmission.

02.11ax defines a power pre-correction mechanism, to which the AP indicates in the Trigger frame its nsmit power and the target signal strength that the ected to receive from a STA in the following UL on. Thus, having known the AP's transmit power nal strength of the received Trigger frame, the STA te the path loss to the AP and it can calculate an transmit power for the following UL transmission. since the AP (not an STA!) selects the MCS for the issions, each STA also includes information about ver headroom, i.e., the difference between its max-smit power and its current transmit power for the ICS.

to be efficient, the AP shall allocate RUs only to h have data to transmit. For that, STAs report to the ount of buffered data they have. Such reports may ed by the AP or sent by STAs on their own [43]. hallenge arises because the AP does not know e channel is idle from the STA's point of view. TA, the AP specifies in the Trigger frame whether hall perform carrier sensing before an OFDMA on or not. If carrier sensing is required, the STA rm both *virtual* carrier sensing and *physical* car-g in at least the 20 MHz channel(s) that contain(s) allocated for the STA. If *physical* carrier sensing busy medium, i.e., the STA detects high energy, it UL transmission. The UL transmission is forbid-f some but not all the subcarriers are idle. However, ases the STA can neglect *virtual* carrier sensing, if it has been set by a frame originating from an neighbor or the STA is going to transmit ACK or which duration does not exceed some agreed value. he STA always cancels the UL transmission if its xceeds the UL MU transmission duration indicated ger frame.

ance Improvements

also allows performing a UL MU transmission DL MU transmission, which can be useful, e.g., acknowledgment frames simultaneously. For that, possibility to solicit a UL MU transmis namely by including information in the header. Similarly, the AP can acknowledg mission by sending acknowledgments via Following the described ideas, 802.11ax al cading MU transmissions which means th DL MU and UL MU transmissions can a within cascading MU transmissions the frames in an MU manner with different se

MU transmissions in Wi-Fi shall be a domain. Thus, if a STA has a short fra either uses padding or tries to aggregat frame. In case when the remaining space aggregating the whole frame, padding is t avoid wasting channel resources, 802.11ax fragment frames in order to fill the rema user payload[4] [44]. To improve the effic the 802.11ax STA can also aggregate fra Access Categories (ACs) [45]. A similar a the 802.11ac DL MU MIMO [19, Sec. 9.1

Since the aggregation of several fragme TGax has found a compromise, having defi levels of HE fragmentation. The first level p one fragment without any aggregation. The a STA to aggregate not more than one fra in an A-MPDU. Finally, the third level allo of two or more fragments per MSDU in a

C. *Special Trigger Frames*

OFDMA permits to cope with fr interference by assigning the best subcarrie from that, it reduces the overhead caused frame spaces, preambles and PHY hea common information for all the STAs in c mission. The overhead is higher for short which OFDMA is especially favorable. T the basic Trigger frame for data and ma 802.11ax has special Trigger frames whi Request To Send / Clear To Send (RTS request block acknowledgments from a g collect beamforming reports or buffer sta Let us consider how these frames are used

To protect a DL MU transmission from h introduces the MU-RTS/CTS handshake [UL MU transmissions in 802.11ax, the C sent simultaneously. The main peculiarity o frames is that a CTS frame is transmitte 20 MHz, 40 MHz, 80 MHz or the en 80+80 MHz channel being duplicated on channel using the legacy CTS frame fo which shall be used by a particular STA to is determined in MU-RTS and shall conta ers which will be used for the following STA. It is done to set NAV at all legacy S

J transmission shall also contain the Trigger frame the UL RU allocations. Moreover, there is another

Note that in legacy Wi-Fi, STAs use fragmen frame size exceeds the fragmentation threshold. Mo of aggregation and fragmentation is explicitly forbidd

example of an MU-RTS/CTS exchange.

and thus to protect the transmission from colli- protocol allows several receivers to transmit CTS ultaneously, however these CTS frames are abso- l from a PHY perspective, thus they do not collide, Nevertheless, such an approach has an important Having received several equal CTSs in the same e AP cannot obtain information which receiver(s) TS. Such a limitation may force the AP either not to el transmissions which occupy subcarriers from the Hz channel, or to ignore the fact that some recip- not answer with CTS. Since both the workarounds de performance, currently TGax is looking for a tion [48].

.11ax amendment proposes an additional way for ging UL MU transmissions by sending new Multi- k ACK (BA) frames. Similarly to the existing BA frame which is used to acknowledge a set of m various ACs, a Multi-STA BA frame is used to Ks or BAs to several STAs [49], [50]. To shorten n, a Multi-STA BA frame can be sent in a legacy th only a legacy 802.11a preamble. A Multi-STA t as a BA or as an ACK.

new frame defined in 802.11ax is the MU Block est (BAR) frame which is a variant of the Trigger s used to solicit acknowledgements from multiple UL MU transmission instead of sending individual es [51]. Similarly, 11ax defines GCR MU BAR to wledgments for groupcast transmission with retries, upcast method introduced in 11aa. In addition to the gment, a recipient of an MU-BAR frame can trans- r data or management frame if it does not exceed

performing random UL OFDMA transmis feature is especially important when the which associated STAs have data to tran unassociated STA wants to transmit an a DCF/EDCA is not efficient for short tran of the large overhead caused by PHY head spaces.

The designed random access is similar t slotted Aloha. Specifically, a Trigger frame RUs for random access. Specifically if the some RU is 0 or 2045, the corresponding re frame defines a group of contiguous RUs which can be used by associated and unas respondingly. The RUs of a group are of have the same transmission parameters. Al ber of contiguous RUs, the AP can indicat for random access is planed in the series transmissions till the end of TXOP.

To decide whether to transmit and in wh the so-called OFDMA Back-off (OBO) pr STA chooses a random value from [0, *OCW* the OFDMA contention window. If the cur less than the number of RUs allocated for a Trigger frame, the STA randomly selects allocated for random access and transmits Otherwise, the STA decreases OBO by th allocated for random access and waits fo frame containing RUs for random access.

If the transmission attempt fails, the STA until it reaches OCW_{MAX} and selects an the new interval. If the transmission attemp STA resets its *OCW* to the minimum valu OCW_{MAX} and OCW_{MIN} are specified by and in the probe response frames.

Since random access is less efficient than it is worth to use it only for short packet tra BSR. In the latter case, a STA having data f generate a BSR and send it with random ac for channel resources. It is clear that such to be more efficient than pure UL OFDMA as confirmed in [55]. Nevertheless, some re preliminary, so the performance evaluation is a topic for future research.

E. EDCA Improvements

ed UL MU duration [52].
re variant of the Trigger frame is used to collect each BSR, each STA informs the AP about the buffered traffic in a queue of the requested AC AC_BK, AC_VI, or AC_VO) or of a subset of ACs. 11ax defines special Trigger frames used to poll ng information or to request information about the

DMA Random Access

the scheduled UL MU access described above, designed an optional mechanism which allows

In 802.11ax networks, OFDMA works o CSMA/CA (Carrier Sense Multiple Acce Avoidance) mechanism called EDCA or DC transmit a Trigger frame, the AP shall cont with other STAs. Consider a network with STAs having UL traffic. Since the number much higher than one, the AP rarely win the AP uses the same channel access par when the AP succeeds, it sends a Trigger resources for the associated STAs. As show

[5]Since both methods are well-known and widely a (see [56], [57]), we do not describe them.

centage of OFDMA UL MU transmissions and legacy STAs vs. the AP CW parameters [58].

s much more efficient than EDCA. So, to achieve oughput, the STAs should rarely access the channel A but they should almost always use OFDMA. In ls, the AP shall almost always win the contention. ely, the AP can change the EDCA parameters for ociated STAs by broadcasting them in beacons. So, high values for CW_{min} and CW_{max}, the AP can oid EDCA transmissions in the network.
em arises, if there are some legacy STAs in the hich cannot use OFDMA transmissions. Since the ameters cannot be set individually, setting the same s of CW_{min} and CW_{max} for both 802.11ax and As will block the legacy STAs. This may lead to a when the performance of the legacy clients signifi-

the data transmission is preceded by an RT TGax has proposed an alternative RTS/CTS has two major distinctions. First, the use o determined by the *duration* of the transmis the *length* of the frame, explaining the na nism — duration-based RTS/CTS threshold to focus on the duration of the transmission packet length, because with a high MCS frame can be transmitted fast enough, wh relatively high overhead caused by the R performed with a slow MCS. Second, the va based RTS/CTS threshold is under the contr can have a better view of the network situa nal the threshold value to associated STAs. AP can lower the threshold if interference is suspected in a dense environment or in to reduce the transmission overhead and of network resources.

F. Open MU & Channel Access Issues

Having introduced OFDMA, Wi-Fi deve similar to LTE. Obviously, this means tha evant to channel resource allocation in LT to Wi-Fi. However, resource allocation in W difficult than in LTE for the following reas

First, traditional LTE networks operate This means that an operator can control neighboring cells and adjust inter-cell inte better performance. In contrast, Wi-Fi in license-exempt bands where nobody interference level in future. This complica estimation and makes Wi-Fi developers d algorithms to reduce interference, see Sect rades. Another problem is related to a misbehaving allocates less RUs for a client of a concurrent ven- oid such problems, TGax introduces the second set parameters which is used *only* by those 802.11ax ch were granted RUs during some preceding time

presents numerical results for a scenario with a ith ten legacy STAs and ten 802.11ax STAs. *AIFSN* e for all devices. Legacy STAs use the default *CW* W_{min} = 16, CW_{max} = 1024. For 802.11ax STAs, 128, CW_{max} = 1024, while the *CW* limits of the Fig. 8 shows that by tuning the EDCA parameters, ake sharing channel resource both fair and efficient, 1ax STAs almost always use OFDMA transmis- le legacy STAs obtain as much channel time as in 11ax network. Such suitable values of CW_{min} and t the AP are marked with red ovals in Fig. 8. The different EDCA parameter sets is studied in more 59].

as also improved the RTS/CTS mechanism which mitigate collisions from hidden nodes and reduces uration. Historically, the use of the RTS/CTS mech- determined by the length of the transmitted data the frame length exceeds the RTS threshold then

Second, in LTE networks the channe resource blocks of equal size. For the dov base station can select an arbitrary subset to transmit some data for a user. For the u blocks in the subset need to be contiguo restrictions on possible RUs are more so complicates the development of optimal sc rithms which allocate RUs for each STA in some utility function.

Third, for UL transmissions, Wi-Fi allo the power spectral density if the STA tra RU. Specifically, the STA can transmit wi whatever RU it uses. Note that since the S different places, it does not violate the en straints but brings much benefit. Indeed, th spectral density, the higher MCS can be sight, this means that each Trigger frame sh all the STAs which have data in the uplink after some investigation it becomes clear t much more difficult. The first issue is tha standard the highest MCSs cannot be used Thus by splitting the channel into too na obtain a lower throughput. The second one ity of splitting some channels into a give

throughput with various RU configuration.

le, in case of three STAs with UL traffic, the AP a 40 MHz channel into two RUs (242-tone + 242- to four RUs (242-tone + 2x 106-tone + 26-tone), but ree RUs. This means that a 26-tone RU is wasted. y, such small RUs are favorable to be allocated for

the OFDMA ones, and b) because of the transmitted by the AP, the time needed to with EDCA is much longer than that with

Fifth, a Wi-Fi network consists of device ious manufacturers. In the legacy Wi-Fi, a network should use the same channel access cast by the AP. Thus, all the devices have th to transmit.[6] In an 802.11ax network, the are allocated by the AP. So a misbehavin more channel time to those STAs which a same vendor. The methods of detecting such should be a subject of further investigation

Sixth, an open issue is how to select an a of an MU frame. This may affect the efficie usage as well as the fairness and the QoS shall find a trade-off between long frames f data traffic and short frames efficient for r for BSR.

V. Overlapping BSS Manag and Spatial Reuse

Since the dense deployment scenario is TGax, there are a lot of debates on ho

us reports transmitted with random access. Some
ɔw that there is no straightforward solution for the
:ion and an optimal allocation of RUs depends on
location.
hows the UL throughput in an 802.11ax saturated
perating in a 80MHz channel with ten STAs uni-
ated in a circle of radius 35 m around the AP. The
are allocated in a proportionally fair manner with
l static division of the channel into RUs. The hor-
s represents all the possible combinations of RUs
aphical order. The left combination, i.e., combina-
presents a case when there are zero 996-tone RUs,
one RUs, . . . and 37 26-tone RUs. Combination #2
a case with one 52-tone RU and 35 26-tone RUs.
on #3 has two 52-tone RUs and 33 26-tone RU.
ɛ right combination stands for the case with the only
.U. The results show that the average throughput sig-
lepends on how the channel is divided into resource
ough in all these cases the RUs are assigned accord-
same policy — proportionally fair — the efficiency
resource usage varies more than two times. Thus,
ɛ case of a baseline utility function (e.g., the geo-
rage of the throughputs which gives a proportionally
ce allocation), the selection of the best RU allocation
very sophisticated (see [60]). To a greater extent,
oe the case with other more complex QoS-aware
, like M-LDWF [61] and EXP-PF [62].
a portion of RUs shall be allocated for the RA.
the number of RUs allocated for the RA affects
/ and the network capacity and shall be selected
ome estimation of the traffic patterns. Note that in
' arrival of packets for uplink transmission, the STA
ɛ legacy EDCA to transmit either these packets or
vever, a) such transmissions are less efficient than

performance in case of dense networks.
TGax wants to decrease interference betw
on the other hand, it wants to allow spatial
neous transmissions in overlapping networ
throughput. A considerable activity is rela
ing, dynamic sensitivity thresholds and dy
power control. Since the launch of TGax,
submissions on these topics were propose
were rejected. Here we describe the accept

A. BSS Color

To determine which BSS is the originator
decoding the entire frame, 802.11ax uses
of the BSS, called the BSS color [63], w
in the frame preamble. Initially, the BSS c
length appeared in 802.11ah to reduce po
because the receiver can stop decoding a f
an alien BSS. Since the BSS color is sel
the AP, the colors of two neighboring B
or collide in terms of 802.11ax. To decre
collision probability, TGax has agreed to
of the BSS color field to 6 bits [64]. If the c
STAs associated to an AP can notify it abou
AP can start a procedure of changing its B
it advertises the future BSS color and the
color will be changed by sending special in
in beacons. So all the STAs, even dozin
information about the change of BSS colo

The identification of a BSS by the BSS
for determining channel access rules and

[6] Although having been standardized, the centralize
ods, such as PCF or HCCA, which allow the AP
not used in out-ot-the-shelf devices because of their e
complexity and some flaws in the behavior in dense

ıs. To disable the BSS color for a particular frame,
ɔlor field of this frame is set to zero.

ıVs

-Fi channel access follows the listen-before-talk
i.e., a STA performs carrier sensing before trans-
frame. The channel is supposed to be busy in the
cases.
ring carrier sensing a STA detects a frame preamble,
nsiders the channel as busy for the frame duration
is signaled in the preamble.
ring carrier sensing a STA detects an unknown sig-

disseminates information about the reserve
the other STAs to access the channel durin

This mechanism has been proposed r
its description contains many open issues
addressed in the very near future. Specifi
describes the only way — which is defin
without an alternative — to disseminate
QTP: at the beginning of a reserved tim
broadcasts information about its duration
ation which is allowed during the interva
has several drawbacks. First, the informatio
once, so it can be lost. Second, the type of
identify the set of STAs which can access

ıt more than 20 dBm above the minimum sensitivity
e channel is indicated to be virtually busy.

ual carrier sensing in Wi-Fi, called NAV, is orga-ollows. In the MAC header, a STA indicates the e, i.e., for how long the following frame exchange y the channel. Having correctly decoded the frame, STAs set NAV, i.e., they consider the channel to ıring the indicated time. If a STA receives a frame a larger NAV value, it increases its NAV, but the not decrease NAV even if the indicated NAV value The STA cancels its NAV, if it receives a CF-End

gacy Wi-Fi, STAs do not take into account by which NAV value was set. However, this may lead to the misbehavior. Suppose a frame from the same BSS AV value at a STA. After that, the STA receives frame coming from an Overlapping BSS (OBSS). to the existing rules, the STA will reset the NAV not consider the medium to be virtually busy any-e the STA may not hear an ongoing transmission protected by NAV, it can start its own transmis-ı causes a collision. As dense deployment was not scenario earlier, such a situation was not exten-arched. However, this reasoning is no longer true ax networks. Thus, to prevent resetting NAV by CF-an OBSS, 802.11ax STAs will support two NAVs: eir own BSS and the other for all the OBSSs, and nodify the NAVs separately [65].

'ime Period

and direct links[7] operation are promising solutions e the channel busy time. However, such operations imity of an 802.11ax network can increase the over-ence and cause significant performance degradation. this problem, the 802.11ax amendment defines the e Period (QTP) mechanism. QTP allows a STA to e AP for a QTP which is a series of periodic time f equal duration used for ad hoc or direct links oper-QTP is described by the offset of the first reserved e duration and period of the intervals, and the total requested intervals. If the AP satisfies the request, it

ks allow two STAs associated with the same AP to communicate ɔut using the AP as a relay.

the interval. Finally, there is not any explic anism to silence legacy STAs which igno messages.

D. Adjustment of Sensitivity Threshold anc

A possible solution to improve spatial deployment environment is by tuning car anisms [66], e.g., by means of using D Control (DSC). The idea of DSC is base adjustment of the carrier sensing threshold DSC threshold, which determines when the medium to be busy. Obviously, to prevent tr a BSS from being blocked by an OBSS, should be increased. Nevertheless, to allo between all devices within a BSS, the DSC small enough not to miss a transmission w

Smith [9] and Afaqui *et al.* [67] the DSC threshold at the STAs $\max_{i \in BSS} PassLoss(AP, i) - MRG$, where AP's transmit power, *PassLoss*(*AP*,*i*) is the between the AP and STA *i*, and *MRG* (m parameter with a recommended value i 25) dB. Since it may be difficult to obtain and to estimate attenuation, the authors pro practical implementation. Each STA mai received signal strength indicator (RSSI) v beacons received from the AP and set the *AvgRSSI*−*MRG*. However, the attenuation that the signal strength from the AP's beac *AvgRSSI*−*MRG*, and the STA will start t To prevent such an undesirable behavior, decrement *AvgRSSI* by RSSIDEC dBs (so if several beacons are lost in a row and, thu decrease the DSC threshold. The authors the RSSIDEC parameter values to evalu of the proposed scheme in terms of aggr fairness (calculated according to Jain's f number of hidden nodes, and PER (Fig. 10 the increase of these metrics observed wi to the legacy constant carrier sensing th gain in throughput and fairness is achieve higher number of hidden nodes and, conse PER. On the one hand, it is natural to th decrease fairness, because close to the AP crease of Throughput, PER, and the number of hidden nodes, 7].

hold and have more chance to transmit a packet. DSC reduces the number of exposed nodes which achievement of a gain in fairness. Having analyzed , the authors recommend setting *MRG* to 20 and to 6.

reduced the number of exposed STAs, DSC he number of hidden STAs. To address this issue, ethods have been proposed. One of them is using TS mechanism together with DSC. This approach ed in [68] and it has been proved to be effec- 9], the DSC approach is combined with inter-BSS

Fig. 11. Illustration of OBSS_PD and TX_PWR a channel [27].

TDMA (Time Division Multiple Access) v missions of OBSSs orthogonal in the tin severely interfere with each other. Although are opposite approaches and have opposite show that combining DSC and TDMA best performance, simultaneously increasin the worst throughput. Unfortunately, the inter-BSS TDMA is too complicated and re chronization between the OBSSs. So the approved by TGax.

To balance between spatial reuse and c TGax decides to bind changes in the sensi the OBSS frames (named as OBSS Preambl old, OBSS_PD) and the transmit power (T simple rule: the higher the OBSS_PD, the l a rule has a simple explanation. By default signals of power *TX_PWR* and considers the if the signal strength is less than *OBSS_PL* the STA receive a signal from an OBSS S than −82 dBm. This means that the attenu STA and the OBSS STA is *X* dB weaker considering the medium idle. If the STA w transmission in this case, it shall first incr by *X* dBm, and second, it shall decrease also by *X* dB in order not to produce a h the location of the OBSS STA (Fig. 11).

STAs may dynamically change thei $TX_P WR$ parameters. During backoff, a *OBSS_PD* to some value. Every time, it a packet it suspends its backoff. Right aft stands that this packet belongs to OBSS, it even before the end of the packet, if the sig than *OBSS_PD* and no other conditions (the channel to be considered as busy. Whe channel access, it can start transmission v higher than that corresponding to the used v Such a power level is used till the end of

The AP may specify the colors of the the described rule is applied. To achieve the from spatial reuse, the rule should be appl the signal from which is much lower than th STAs. Obviously, an algorithm on how to beyond the scope of the standard.

mary and secondary channels in 802.11ac networks.

option allowing spatial reuse operation is related to .mes. Specifically, the AP may allow an alien trans- overlap with the UL transmission in its own BSS, ved signal from such an alien transmission does not ne acceptable level of interference. Such an accept- of interference depends on the current interference nnel near the AP and on the used MCS. To allow an l transmission, in the Trigger frame the AP speci- atial reuse power S as the sum of its transmit power cceptable level of interference minus some margin. ceived the Trigger frame at some power R, an OBSS art a transmission with power $S-R$ after the end of frame if such a transmission does not exceed the scheduled UL transmission. Naturally, to access l, the OBSS STA needs to use backoff, resuming it nd of the Trigger frame and ignoring the upcoming ission.

l Bonding and Preamble Puncturing

1ac, STAs can adaptively select the bandwidth in rticular frame is transmitted. Specifically, the stan- s a hierarchy of channels shown in Fig. 12. Having hannel access in the primary 20 MHz channel fol- EDCA rules, a STA can expend the bandwidth by p concatenation of the secondary channels if they n other words, if the secondary 20 MHz channel STA can transmit in 40 MHz bandwidth. If both ary 20 MHz and the secondary 40 MHz channels 0 MHz bandwidth can be used. In contrast, even ndary 40 MHz channel is idle but the secondary hannel is busy, the STA can only transmit in the

F. Virtualization

One of the widespread features in mode port for multiple "virtual" APs (VAPs). single physical device can create multiple reaching up to 32 VAPs in some equipment ful, when, for example, one wants to sepa network from an internal corporate networ an additional AP. One of the shortcomin VAPs is that a lot of service information be the same, but it is transmitted separatel To decrease the overhead, the 802.11ax am the Multiple BSSID support, which allows t tical information for all the BSSs simultane a common beacon. All the BSSs in the m the same BSS color, and the frames of BS BSSID set are considered as intra-BSS fra

G. Load Balancing

In dense networks, load balancing is an since every STA has several candidate with. Although the problem has attracted c among the researchers, it is out of scope of the decision on association is done by ve rithms. In [72], some algorithms are stud of 802.11ax.

H. Open Issues With Dense Deployment

For several years, the group has been methods which could improve performanc overlapping networks. Some solutions hav the standard by several so-called special int which usually come to an agreement out sessions making it difficult to accept other independent members not involved in SIGs. there was an investigation [73] which reve IEEE rules and ceased the operation of SIG question what to do with all the accepted open.

Since the most severe debates were a solutions that improve performance in scen ping networks, there is a strong need now study on whether the accepted proposals c performance, and in which scenarios. Thi research area.

This task is complicated by the lack c to make an accurate performance evaluat

) MHz channel. This limitation is especially crucial
networks, where the secondary 20 MHz channel of
be the primary 20 MHz channel of another one.
ove the efficiency of channel bonding in dense envi-
302.11ax introduces a new optional feature called
puncturing. For an MU OFDMA transmission in a
eater than or equal to 80 MHz, one or more busy
ubchannels can be punctured. It means that frame
not transmitted and RUs are not allocated in these
ls. In dense deployment, such a feature allows using
sources in a much more flexible way.

networks with mathematical modeling, test
Mathematical modeling typically introduc
tions like so-called protocol interference
unpredictably affects the obtained results.
ing simulation platform is ns-3 [75]. Ho
the necessary 802.11ax functionality, captu
implemented to correctly model collision
are some activities in this direction [76].
although some silicon manufactures have
802.11ax chipsets, the first 802.11ax devic
very soon. Numerous software defined ra

ıes transmitted by an AC during its transmission slot and is given by: (2) where, is the contention-free period
ssion times of the data frame and the block acknowledgement (BA) frame, respectively. ...

tion describes the fact that once the reaches its transmission state, multiple frames from that AC may be
/. The number of those frames is bounded by obtained by (2) . Due to the chain regularities: (5) with: (6)
ıations theory, the solution for the Markov chain is: ...

ɔserve that the VI AC with TXOP sharing outperforms the VO AC (Figure 3(a)). This is also an expected
btained by (2) for is more than twice the value of obtained for (more specifically, and). For FS sharing the
igure 3(b)), i.e., exhibits a higher throughput performance than since in this case. ...

Resource Sharing During Downlink Multi-User Transmissions in CSMA/ECA Full Duplex Wlans

Hristos T Anastassiu

scribed key features of the latest Wi-Fi breakthroughs with particular focus on the draft D3.0 of the 802.11ax leased in May 2018. Orthogonal Frequency Division Multiple Access (OFDMA) is the cornerstone ndard and is aimed to address the throughput bottleneck at the Medium Access Control (MAC) layer. ...

7] have detailed a number of challenges facing 802.11ax implementation (e.g., OFDMA scheduler, dynamic y threshold, and energy savings as an optimization problem between energy consumption and throughput). ...

IEEE 802.11ax

-text available

Jiamiao Zhao · Hazem Refai

Fi users is demanding new optimized standards, as well as refinements in the current ones [1] - [3]. ost used technologies for WLAN environments, namely IEEE 802.11n and IEEE 802.11ac, the concept of been introduced to increase the overall throughput [4]. ...

3R Performance over WLAN

le

Martin Klapez · Maurizio Casoni

ultimedia Streaming in Wi-Fi Networks with Periodic Reservations

le

ıe Length Optimisation in Enterprise SD-WLANs

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Study of various mechanisms of IEEE 802.11ah

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Conference Paper

Performance Evaluation of a Unified IEEE 802.11 DCF Model in NS-3

June 2019

Yachao Yin · Yayu Gao · Xiaojun Hei

The IEEE 802.11 Distributed Coordination Function (DCF) is a basic component in the medium access control (MAC) protocol of Wireless Local Area Networks (WLANS). Recently, a unified analytical framework has been proposed [1] to capture the fundamental features of IEEE 802.11 DCF networks, which provides various accurate performance predication in NS-2 simulations. In the past a few years, NS-3 is ... [Show full abstract]

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Conference Paper

Advanced power control techniques for interference mitigation in dense 802.11 networks

January 2013

Oghenekome Oteri · Pengfei Xia · F. LaSita · Robert L. Olesen

In this paper we propose an enhanced Transmit Power Control (TPC) scheme and a new fractional Carrier Sense Multiple Access with Collision A voidance (F-CSMA/CA) scheme for use in a dense 802.11 network. The new schemes improve the energy normalized Media Access Control Goodput performance in networks with overlapping Basic Service Sets (OBSSs) by mitigating the interference effect using TPC and ... [Show full abstract]

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Article

Fundamental Limitations on Increasing Data Rate in Wireless Systems

January 2009 · IEEE Communications Magazine

Donald C. Cox

There is a continuing quest for increasing the data transmission rate in wireless systems. Cellular mobile radio systems have advanced from second generation digital technology with limited data capability to third generation systems with data transmission rates on the order of a few megabits per second and on to fourth generation systems with goals of even higher data rates. Wireless local area ... [Show full abstract]

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Performance analysis of IEEE 802.11n under different STBC rates using 64-QAM

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The main focus of current research and development for the next-generation wireless local area network (WLAN) communication systems is to enhance the link throughput and channel capacity. In this paper, the performance analysis of the ongoing next-generation WLAN standard, IEEE 802.11n high throughput WLAN PHY layer is presented. The design criteria is based on a 4times4 MIMO-OFDM scheme using ... [Show full abstract]

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