Coexistence of Wireless Technologies in the 5 GHz Bands: A Survey of Existing Solutions and a Roadmap for Future Research

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***Abstract*—As the 2.4 GHz spectrum band has become significantly congested, there is growing interest from the Wi-Fi proponents, cellular operators, and other stakeholders to use the spectrum in the 5 GHz bands. The 5 GHz bands have emerged as the most coveted bands for launching new wireless applications and services, because of their relatively favorable propagation characteristics and the relative abundance of spectrum therein. To meet the exploding demand for more unlicensed spectrum, regulators across the world such as the United States (US) Federal Communications Commission (FCC) and the European Electronic Communications Committee (ECC) have recently started considerations for opening up additional spectrum in the 5 GHz bands for use by unlicensed devices. Moreover, to boost cellular network capacity, wireless service providers are considering the deployment of unlicensed Long Term Evaluation (LTE) in the 5 GHz bands. This and other emerging wireless technologies and applications have resulted in likely deployment scenarios where multiple licensed and unlicensed networks operate in overlapping spectrum. This paper provides a comprehensive overview of the various coexistence scenarios in the 5 GHz bands. In this paper, we discuss coexistence issues between a number of important wireless technologies—viz., LTE and Wi-Fi, radar and Wi-Fi, Dedicated Short Range Communication (DSRC) and Wi-Fi, and coexistence among various 802.11 protocols operating in the 5 GHz bands. Additionally, we identify and provide brief discussions on an impending coexistence issue – one between Cellular V2X and DSRC/Wi-Fi. We summarize relevant standardization initiatives, explain existing coexistence solutions, and discuss open research problems.**

I. Introduction

The proliferation of mobile devices has led to an exponential increase in mobile data traffic that shows no sign of being abated. Global mobile data traffic reached 3.7 exabytes per month at the end of 2015, growing 76% over 2.1 exabytes per month at the end of 2014 [1]. It is expected that monthly global mobile data traffic will be 30.6 exabytes by the year 2020. The explosive growth in mobile data traffic has led to a surging demand for more radio frequency spectrum, but the supply has not kept up with the demand. This spectrum scarcity has motivated the development of technologies and techniques for increasing the efficiency of spectrum already in use.

The exorbitant cost of licensed spectrum has led to the development of wireless technologies operating in the unlicensed bands. The two most widely used unlicensed bands are in the 2.4 GHz and 5 GHz range. As the 2.4 GHz band has become increasingly congested, there is a great deal of growing interest in utilizing the 5 GHz bands. There is up to 500 MHz of spectrum in the 5 GHz bands that is available on a global basis for unlicensed applications. The 5 GHz bands have emerged as the most coveted bands for launching new wireless applications and services because of their relatively favorable propagation characteristics and the relative abundance of spectrum therein [2].

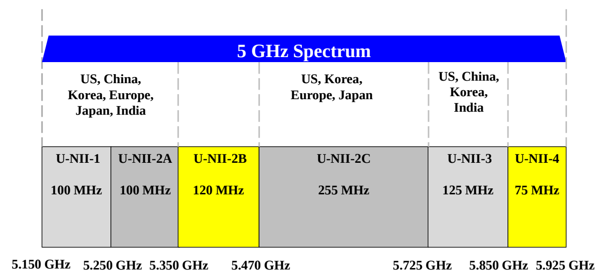


Fig. 1: Unlicensed spectrum and regulations in the 5 GHz band. Regions marked yellow are U-NII bands proposed to open up for use by unlicensed devices in US. NPRM 13-22.

Different countries have their own requirements for unlicensed operations in 5 GHz [3]. The $5.15-5.35$ GHz band is available in the US, China, Korea, Europe, Japan and India. $5.47-5.725$ GHz is open for unlicensed access in the US, Korea, Europe and Japan. In addition, the $5.725-5.85$ GHz is available in the US, China, Korea and India[1]. Fig. 1 summarizes the spectrum regulations in these regions. The spectrum bands marked in yellow are those that are additionally being considered for unlicensed operations in US.

The IEEE 802.11 standard, commonly referred to as Wi-Fi, has rapidly expanded in the 5 GHz spectrum. Presently, the 802.11a, 802.11n and 802.11ac devices operate in parts of the 5 GHz bands. Additionally, the 802.11ax standard is being developed for operations in these bands. The success of Wi-Fi has lead to considerations from regulatory bodies across the world for opening up additional bands for unlicensed access. For example, the US FCC issued a Notice of Proposed Rulemaking (NPRM) 13-22 [4] in 2013 that proposed to open up 195 MHz of additional spectrum for use by unlicensed devices in the 5 GHz bands. Specifically, the NPRM proposed opening up additional spectrum in the $5.35-5.47$ GHz and $5.85-5.925$ GHz bands (see Fig. 1).

[1]Paper [3] claims that the $5.725-5.85$ GHz band is being considered for new spectrum additions to extend unlicensed use in Europe. But as of today, the $5.725-5.85$ GHz is not allowed for unlicensed use in Europe.

However, the $5.35 - 5.47$ GHz band overlaps with several radar systems, while the $5.85 - 5.925$ GHz band overlaps with the spectrum allocated for Intelligent Transportation Systems (ITS). Following this lead, the ECC is also conducting studies to assess the feasibility of opening up $5.35 - 5.47$ GHz and $5.75 - 5.925$ GHz bands for unlicensed operations in Europe. Such unlicensed Wi-Fi devices are expected to coexist harmoniously with the original occupants of these bands.

In this paper, we provide a comprehensive survey on coexistence issues arising in the 5 GHz bands, with a particular focus on four coexistence scenarios. Each coexistence scenario merits individual discussions due to the heterogeneity of the coexisting wireless technologies. Next, we provide brief descriptions of the wireless technologies operating in the 5 GHz bands, including Wi-Fi, LTE, radar, and DSRC in Sec. II. In Sec. III through VI, we provide in-depth discussions on the four coexistence scenarios, including current coexistence techniques, future research challenges, and regulatory policy issues. In Sec. VII, we identify an impending coexistence problem — between Cellular V2X and DSRC/Wi-Fi, and provide brief discussions on the same. Finally, we conclude the paper in Sec. VIII. We summarize the acronyms that appear in this paper in Table I.

II. Wireless Technologies in the 5 GHz Bands

In this section, we briefly describe the wireless communication technologies that currently operate or are being developed for operations in the 5 GHz bands.

A. IEEE 802.11 (Wi-Fi) Family of Standards

Wi-Fi devices use IEEE 802.11 Distributed Coordination Function (DCF) protocol as the basic channel access mechanism, as shown in Fig. 2. Pending transmission, each node performs a Clear Channel Assessment (CCA) to sense the channel for a duration of Inter-frame Spacing (IFS)[2]. If idle, the device enters a backoff procedure [5] in order to avoid simultaneous transmissions with other nodes, thus avoiding packet collisions. If the channel becomes busy during this backoff procedure, the devices freeze their backoff mechanism, and resume when the channel becomes idle once again.

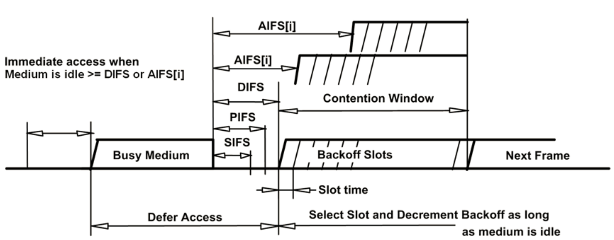


Fig. 2: IEEE 802.11 DCF basic access [5]

In the context of wireless local area networks (WLANs), we use the term "legacy networks" to describe networks based on

[2]The value of IFS depends on the frame type at the transmitter queue. The deferral of channel access for IFS serves prioritization of different traffic types (traffic classes with smaller IFS values have higher priority in accessing the channel).

TABLE I: Summary of important acronyms

Acronym	**Full Name**
3GPP	3rd Generation Partnership
BSM	Basic Safety Messages
BSS	Basic Service Set
ACK	Acknowledgement
AIFS	Arbitration Inter-frame Spacing
AP	Access Point
BE	Best Effort (Traffic class)
BK	Background (Traffic class)
CCA	Clear Channel Assessment
CCH	Control Channel
CSAT	Carrier Sense Adaptive Transmission
CSMA/CA	Carrier Sensing Multiple Access Collision Avoidance
CTS	Clear to Send
DCA	Dynamic Channel Access
DCF	Distributed Coordinated Function
DFS	Dynamic Frequency Selection
DIFS	DCF Inter-frame Space
DSC	Dynamic Sensitivity Control
DSRC	Dedicated Short Range Communication
ECC	Electronic Communications Committee
EDCA	Enhanced Distribution Channel Access
EPC	Evolved Packet Core
ETSI	European Telecommunications Standards Institute
eNB	Evolved NodeB
FBE	Frame-Based Equipment
FCC	Federal Communications Commission
FDD	Frequency Division Duplexed
IFS	Inter-frame Spacing
LAA	License Assisted Access
LBE	Load-Based Equipment
LBT	Listen-before-talk
LTE	Long Term Evolution
LTE-U	LTE-Unlicensed
LWA	LTE Wi-Fi Aggregation
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MU	Multi User
NAV	Network Allocation Vector
NPRM	Notice of Proposed Rulemaking
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PCF	Point Coordination Function
PDCP	Packet Data Convergence Protocol
PHY	Physical Layer
PIFS	PCF Inter-frame Space
PPDU	Physical Protocol Data Unit
QoS	Quality of Service
RAN	Radio Access Network
RTS	Request to Send
RU	Resource Unit
SCA	Static Channel Access
SC-FDMA	Single-Carrier FDMA
SCH	Service Channel
SDL	Supplemental Downlink
SIFS	Short Inter-frame Space
SNR	Signal to Noise Ratio
STA	Station
TDD	Time Division Duplexed
TF	Trigger Frame
TXOP	Transmit Opportunity
U-NII	Unlicensed National Informational Infrastructure
UE	User Equipment
VO	Voice (Traffic class)
VI	Video (Traffic class)
WAVE	Wireless Access in Vehicular Environments
WLAN	Wireless Local Area Network

standards that predate 802.11n. These legacy standards include 802.11a, 802.11b, and 802.11g. Compared to legacy networks, 802.11n has the following distinguishing features.

Multiple input multiple output (MIMO). MIMO is a key enabler to high data rates in 802.11n. Using multiple antennas at the transmitter and receiver, MIMO can be used to achieve higher reliability (via spatial diversity) or higher data rates (via spatial multiplexing). In 802.11n, using 2×2 MIMO, transmitters can theoretically achieve up to twice the maximum data rate of legacy devices.

Higher Modulation and Coding Scheme (MCS). The IEEE 802.11n standard supports modulation schemes up to 64-QAM with coding rate of 5/6.

Channel bonding. The granularity of channel bandwidth in Wi-Fi is 20 MHz. In 802.11n, two adjacent channels can be "bonded" to form a 40 MHz channel. One of the 20 MHz channels, referred to as the primary channel, is used to transmit Wi-Fi control information, while the other 20 MHz channel is referred to as the secondary channel and is used solely for data transmissions.

Different channel sensing mechanisms are followed for the primary and secondary channels. The primary channel is sensed for (DIFS[3] + backoff) duration. The secondary channel, on the other hand, is sensed for a duration of PIFS[4] preceding the end of the primary channel backoff, as shown in Fig. 3. If the secondary channel is idle for a duration of PIFS, data transmission begins immediately on the bonded (primary + secondary) channels. An important reason for this structure of Wi-Fi signals is to provide backward compatability to legacy devices that can decode only 20 MHz-wide signals.

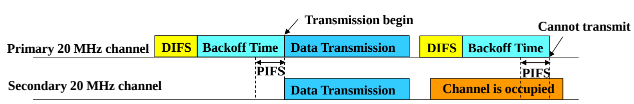


Fig. 3: IEEE 802.11n carrier sensing for primary and secondary channels.

Frame aggregation. Every frame transmitted by an 802.11 device has a significant amount of overhead, including radio level headers, Medium Access Control (MAC) frame fields, inter-frame spacing, and acknowledgment of transmitted frames. In high data rate transmissions, these overheads become comparable to the time taken to transmit the payload frame itself. To amortize this overhead, 802.11n provisions aggregating multiple frames to form a larger frame.

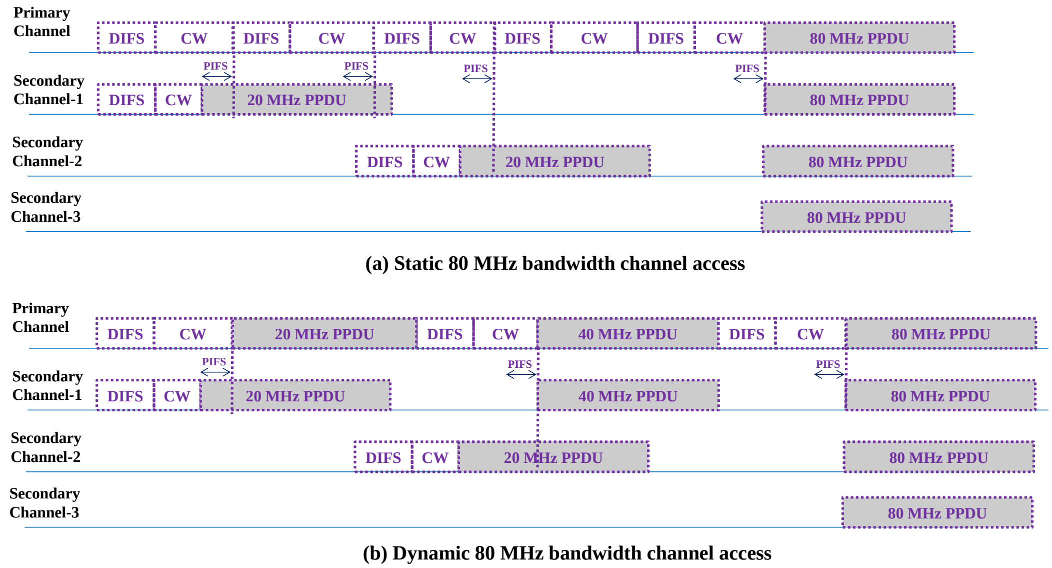
The IEEE 802.11ac standard was approved in 2014. As opposed to 802.11n, which operates both in the 2.4 GHz and 5 GHz bands, 802.11ac operates only in the 5 GHz band. 802.11ac inherits many features from 802.11n while enabling higher data rates using up to 8 spatial streams, higher order MCS schemes (256 QAM, with coding rate $5/6$) and more channel bonding options. 802.11ac supports 20, 40, 80 and 160 MHz channels. Two adjacent 20 MHz channels can be bonded to form a 40 MHz channel, two adjacent 40 MHz channels can form a 80 MHz channel and two adjacent or non-adjacent 80 MHz channels can form a 160 MHz channel [6]. For bonded channels, one 20 MHz channel is selected as the primary channel, while the remaining channels constitute the secondary channels. The channel sensing mechanism is similar to that used in 802.11n. The secondary channels are sensed only for a duration of PIFS immediately preceding the end of the primary channel backoff. The response of 802.11ac transmitter at this stage can be classified as static channel access (SCA) or dynamic channel access (DCA). In SCA, if any of the secondary channel(s) is occupied, the transmitter ceases its transmission on all channels, and restarts the backoff process. In DCA, the 802.11ac transmitter transmits on the primary channel (as long as the primary channel is idle) and available secondary channel(s). SCA and DCA mechanisms are illustrated in Fig. 4.

The next generation of WLAN standard, namely IEEE 802.11ax, is expected to be standardized by 2019 [7], [8]. Unlike previous amendments where the focus was primarily on improving the aggregate throughput, this amendment focuses on improving metrics that reflect the quality of user experience. Improvements will be made to support environments such as wireless corporate offices, outdoor hotspots, dense residential apartments, and stadiums. Current 802.11 standards use Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) to avoid collisions. However, CSMA/CA suffers from poor performance in dense deployment scenarios [9]. The 802.11ax standard aims to overcome this bottleneck of CSMA/CA by introducing protocols to schedule Wi-Fi transmissions, much like cellular standards. IEEE 802.11ax is likely to introduce the following distinguishing features,

- Orthogonal Frequency-Division Multiple Access (OFDMA). The 802.11ax standard uses OFDMA to multiplex more users in the same channel bandwidth. It divides the existing 802.11 channels (20, 40, 80 and 160 MHz wide) into smaller sub-channels with a predefined number of subcarriers. The smallest sub-channel is referred to as a Resource Unit (RU), with a minimum size of 26 subcarriers.
- Multi-User (MU) OFDMA. 802.11ax will not only inherit MU downlink transmission features from 802.11ac, but also support MU uplink transmissions. To coordinate uplink MU-MIMO or MU-OFDMA transmissions, the AP sends a trigger frame (TF) that contains the number of spatial streams and the OFDMA allocations (frequency and RU sizes) of each user, to its associated stations (STAs). TF also contains power control information, so that individual users can adjust their transmit powers.
- MU-MIMO. Borrowing from the 802.11ac standard, 802.11ax devices will use beamforming techniques to direct packets simultaneously to spatially divided users. The AP may initiate simultaneous uplink transmissions

[3]DIFS – DCF Inter-frame Spacing

[4]PIFS – Point Coordination Function Inter-frame Spacing



(a) Static 80 MHz bandwidth channel access

(b) Dynamic 80 MHz bandwidth channel access

Fig. 4: Channel access mechanism for primary and secondary channels in 802.11ac

from multiple STAs by means of a TF. The AP may also initiate uplink MU transmissions to receive beamforming feedback information from all participating STAs.

B. Radars

Radar systems operate in various portions of 5 GHz worldwide. For example, in US, radars operate in $5.25-5.725$ GHz bands [10]. In UK and Europe, radars operate across the band from $5.25-5.85$ GHz [11], [12].

While the nature and applications of these radars vary from band-to-band and from one country to another, these radars are generally used for applications including defense such as tactical and weapon radars and ground-based and airborne weather radars. Radars are used for civilian (such as meteorological radars), military/defense applications as well as radio navigation applications (such as those used by the National Aeronautical and Space Agency in US). A comprehensive summary of radars operating in the 5 GHz band in US is presented in [10].

Unlicensed devices already operate on a secondary basis in the $5.25-5.35$ GHz and $5.47-5.725$ GHz bands in most parts of the world based on ITU regulations [13]. Radars operating in these bands mostly include civilian radars. As far as these bands are concerned, weather radars operating in the $5.6-5.65$ GHz band have been the primary victims of interference from unlicensed Wi-Fi users as described in Sec. IV.

Many of the radar systems operating in the 5 GHz bands are used for mission and safety critical applications. Sharing spectrum with unlicensed or other licensed devices may be highly undesirable from the point of view of such radar operating agencies. Taking these factors into consideration, we provide details of coexistence issues between radar systems and Wi-Fi in Sec. IV.

C. Dedicated Short Range Communications (DSRC)

DSRC is a communications technology specifically designed to support ITS applications [14], [15]. Specifically, DSRC modules can be installed on vehicles to enable vehicle-to-vehicle (V2V) communications, thereby enabling various vehicular safety applications [16]. Across the world, the spectrum reserved for DSRC is in the 5.9 GHz band. Typically, this spectrum is composed of seven 10 MHz wide channels. In US, these seven channels include six service channels (SCHs) and one control channel (CCH). Channel 178 is the CCH, and Channels 172, 174, 176, 180, 182, and 184 are SCHs, as shown in Fig. 5. Channels 172 and 184 are designated for public safety applications involving safety of life and property. Together, these SCHs and CCH are used to communicate safety critical messages[5] that are used in safety applications such as collision avoidance and road hazard notification. In such safety applications, it is critical to ensure that appropriate DSRC messages are delivered reliably with minimal latency.

DSRC systems in Europe, Japan and US are not compatible and include some significant variations. Applications intended for each channel are also different across countries. For example, the European Telecommunications Standards Institute (ETSI) standard EN 302 571 [17] defines ITS spectrum regulations in Europe [18]. Channels between 5.855 GHz and 5.875 GHz are used for non-safety related applications (in contrast to US where Ch. 172 in Fig. 5 is intended solely for safety applications), channels between 5.875 GHz and 5.905 GHz are used for safety applications and control, while channels between 5.905 GHz and 5.925 GHz are reserved for future ITS applications.

[5]The Service Channels are also used to provide non-safety services like congestion control, mobile Internet access, etc.

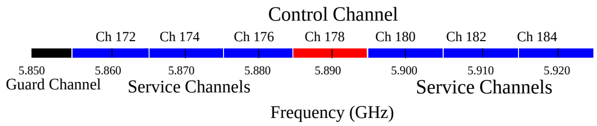


Fig. 5: DSRC spectrum map in the US

The Physical (PHY) and MAC layer protocols for DSRC have been defined in the 802.11p amendment of the IEEE 802.11 standards. This amendment is referred to as Wireless Access in Vehicular Environments (WAVE) [19]. Most of the changes made in the amendment are at the MAC layer, while changes at the PHY layer are minimal [20].

DSRC-enabled vehicles periodically exchange two types of safety critical messages: event-driven messages and Basic Safety Messages (BSMs). Event-driven messages are broadcasted by a DSRC node when the vehicle encounters a potentially unsafe situation, such as an emergency brake or an imminent collision due to vehicle pile-up. On the other hand, BSMs convey the senders' position, speed, acceleration, direction, etc. [21]. BSMs provide information that can be processed at the higher layers in order to enable applications such as blind spot detection, intersection assist etc. that require vehicles to be aware of their surroundings.

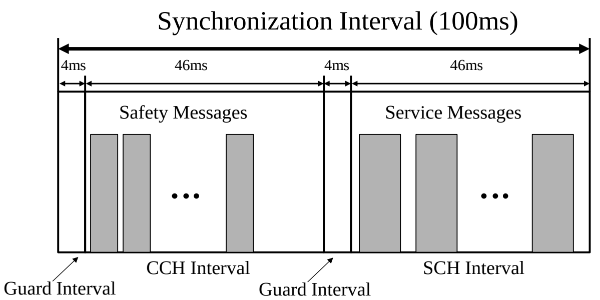


Fig. 6: The multichannel MAC scheme used by DSRC

Vehicles with a single radio can employ time division switching between the CCH and SCHs. Details related to multi-channel operations are defined in the upper layer IEEE 1609.x protocols. Fig. 6 illustrates the basic time division concept defined in the IEEE 1609.4 protocol [22]. Time is segmented into synchronized periods, the default duration of which is 100 milliseconds ($m$sec) each. Each synchronized period consists of one CCH interval followed by a SCH interval. The default division for each interval is 50 $m$sec. Each CCH and SCH interval begins with a 4 $m$sec guard interval, which is used by the radio to transfer control from one channel to another [23].

While the basic channel access mechanism used in 802.11p is similar to that used in other 802.11 standards, 802.11p has a number of distinguishing features. In order to minimize the setup latency, 802.11p eliminates the association mechanism used in conventional Wi-Fi systems and instead defines "communication outside the context of a Basic Service Set (BSS)" MAC. According to this MAC protocol, a transmitter broadcasts each packet to all other nodes in the network. Furthermore, in order to prevent the network from being flooded with ACKs, 802.11p receivers do not send an acknowledgment (ACK) to the transmitter. Thus, there is no feedback mechanism at the transmitter.

If a particular node fails to gain access to the channel within the inter-broadcast interval, the packet is discarded at the transmitter. This is mainly due to the delay-sensitive nature of vehicular networks; the information contained in such a packet is out of date, and a new packet containing updated information should be generated in the next inter-broadcast interval. This is referred to as *packet expiration* at the transmitter. Another notable difference in 802.11p networks is that unlike traditional 802.11 networks, 802.11p nodes do not use the request-to-send (RTS)/ clear-to-send (CTS) handshake mechanism to reduce the number of collisions due to the hidden node problem (explained in Fig. 7), as the exchange of RTS/CTS packets can lead to large overhead in transmissions.

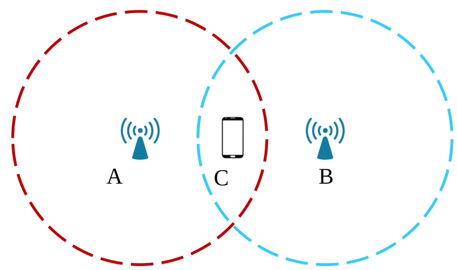


Fig. 7: A diagram illustrating the hidden node problem. Stations A and B are trying to communicate with Station C. However, Stations A and B cannot "hear" each other as they are out of each other's sensing range. In such cases, it is possible that Station C receives signals from A and B simultaneously resulting in packet collisions.

D. LTE

Traditional LTE networks comprise of a centralized coordinator — the eNodeB (eNB) communicating with several User Equipments (UEs) such as cellular phones. LTE uses a cellular architecture which enables frequency reuse thereby improving the system capacity. As opposed to Wi-Fi and DSRC systems, all decisions pertaining to when and what resources to use for transmissions are controlled by the eNB's scheduling algorithm. LTE uses different modulation techniques in the uplink and downlink. Downlink transmissions use OFDMA for multiplexing multiple users over a single channel. However, due to the high peak to average power ratio in OFDM based systems, LTE UEs use single-carrier frequency division multiple access (SC-FDMA) for uplink transmissions. The use of a centralized architecture enables reliable communication between LTE UEs and eNB with low latency and no collisions.

LTE is standardized by the Third Generation Partnership Program (3GPP) through its releases, and is a mature technology with widespread commercial deployment across countries. Since the focus of this paper is coexistence between the unlicensed versions of LTE and Wi-Fi, we omit the details of the traditional LTE technology. For more details on LTE, we refer the reader to the vast available literature [24]–[27].

Different unlicensed versions of LTE have emerged based on regulatory requirements, ease of deployment and other performance considerations. Therefore, we introduce these technologies along with a detailed description of the various coexistence considerations in Sec. III.

III. Coexistence of LTE and Wi-Fi

An extensive survey of coexistence mechanisms between LTE-LAA (introduced later in this section) and Wi-Fi has been provided by Chen et al. in [3]. In this section, we extend the overview provided in [3] by considering different unlicensed LTE versions (including LTE-LAA and others) under development and their impact on the performance of Wi-Fi systems.

A. An Overview of Coexistence Mechanisms

One of the primary focus in enabling coexistence between the unlicensed flavors of LTE and Wi-Fi is that of fairness towards existing Wi-Fi devices. This issue stems from the fundamental difference in the channel access mechanisms used by LTE and Wi-Fi. On one hand, LTE uses a centralized scheduling mechanism wherein the eNB decides the time (and frequency) at which each UE in the network transmits or receives. On the other hand, Wi-Fi uses a distributed channel access protocol whereby each Wi-Fi STA senses the channel before its transmission. As a result, it is expected that when unlicensed LTE[6] and Wi-Fi operate within the same spectrum band, transmissions from LTE devices will supersede those of Wi-Fi devices. This is corroborated by findings of Cavalcante et al. [28] and Zhang et al. [29], where the authors use simulations to show that an LTE system operating in the presence of a Wi-Fi network can degrade the Wi-Fi system throughput by up to 68%.

Findings from [28], [29] highlight the need for developing suitable coexistence mechanisms between LTE and Wi-Fi in the unlicensed spectrum. While no metric for such coexistence is widely agreed upon, Paolini et al. [2] suggest that one fairness criteria must be that— the introduction of an LTE system in the vicinity of an existing Wi-Fi system must not cause any additional degradation of Wi-Fi performance as compared to the introduction of another Wi-Fi system.

LTE technologies that operate in the unlicensed spectrum can be classified in one of two categories, (i) *license-anchored* systems, and (ii) *non license-anchored* systems. In license-anchored unlicensed LTE systems (e.g. LTE-U, LAA), the primary carrier, referred to as the anchor, uses licensed portions of the spectrum. Owing to its guaranteed availability, the anchor is used for transmissions of control information and QoS sensitive data where reliability is of primary concern. The secondary carriers can operate in the 5 GHz unlicensed spectrum and are used to carry best-effort traffic. To maximize the contribution of combined carriers, the primary carrier is preferred for voice and uplink traffic, while the secondary carrier transports downlink traffic. The integration of licensed and unlicensed LTE in case of license-anchored systems is summarized in Table II. In unlicensed LTE systems that do not use licensed-anchor (e.g. MulteFire), the control as well as data traffic are communicated over the unlicensed spectrum.

TABLE II: Integration of licensed and unlicensed LTE in license-anchored systems

Licensed LTE	**Unlicensed LTE**
Primary carrier, anchor	Secondary carrier
FDD or TDD[7]	TDD
Preferred for voice, uplink	Preferred for downlink traffic
QoS guarantee	Best effort
Mobility support	Opportunistic use

At present, there are four LTE technologies that are designed with the view of operations in the 5 GHz unlicensed bands. We introduce these four technologies next.

1) **LTE in Unlicensed spectrum (LTE-U)**. LTE-U is the version of unlicensed LTE that was proposed in 2013 by Qualcomm and Ericsson. LTE-U relies on 3GPP Release 10-12 functionality, with specifications defined by the LTE-U Forum. Since LTE-U leverages the functionalities of existing 3GPP releases, changes that are required to the licensed LTE devices are minimal. LTE-U has been designed for operations in countries such as the US, China, and Korea, that do not mandate Listen-before-talk (LBT)[8].

2) **License Assisted Access (LAA)**. LAA is the unlicensed LTE version that was standardized by 3GPP in its Release 13. Unlike LTE-U, LAA is expected to perform LBT, as mandated by regulatory regimes such as Europe and Japan. This LBT requirement requires more changes to be made in licensed LTE as compared to LTE-U systems. LAA is set to become a global standard as it strives to meet regulatory requirements worldwide. However, owing to the incomplete standardization work, commercialization of LAA products is expected to a take longer time as compared to LTE-U products. Both, LTE-U and LAA, are systems that use a licensed-anchor.

3) **LTE-WLAN aggregation (LWA)**. LWA was approved as an LTE-WLAN Radio Level Integration and Interworking Enhancement in 2015, and was standardized in 3GPP Release 13 in March 2016. LWA, like LTE-U and LAA, is a licensed-anchor based system. However, for LTE data transmissions in the unlicensed band, LWA uses Wi-Fi based MAC and PHY.

[6]In this paper, in order to avoid ambiguity, we use the term "unlicensed LTE" as the umbrella term that covers all implementations of LTE in the 5 GHz unlicensed band. We use the term LTE-U to specify the system developed by an industry consortium, the LTE-U Forum.

[7]FDD refers to a system wherein uplink and downlink transmissions occur at the same time over orthogonal frequencies, whereas TDD refers to a system where the transmissions occur over the same frequency, but at different times.

[8]LBT, as the name suggests, requires devices to sense the spectrum before transmitting every packet.

TABLE III: Progress in Unlicensed LTE standardization [2]

Dec 2013	Initial proposal for LTE-U at a 3GPP meeting in Busan, South Korea by Qualcomm and Ericsson
Jan 2014	A 3GPP unofficial meeting held in Paris. Twenty companies presented their views, focusing on such subjects as the motivation for LTE-U, the potential benefits, possible use-cases, the worldwide regulatory landscape, potential requirements, possible bands, performance evaluation, potential features, and the timeline. But the members disagreed on the timing.
Mar 2014	3GPP plenary meeting in Fukuoka, Japan. Crux of the debate centered on the timing. There was broader support from operators for a more accelerated timeline, as Verizon and China Mobile were joined by five others in support of Qualcomm/Ericsson's idea [31].
Jun 2014	A workshop in Sophia Antipolis, France. Outcome included: • A plan to set up a study item in September 2014. • Adoption of LAA designation. • Agreement to focus on 5 GHz. • Commitment to finding a global solution. • Establishment of fair coexistence with Wi-Fi and among LTE operators.
Sep 2014	LAA approved as a study item for Release 13. Release 13 included: • Regulatory requirements, • Deployment scenarios, • Design targets and functionalities, • Coexistence evaluation and methodology. Required functionalities included: • LBT, with maximum transmission duration, • Dynamic frequency selection for radar avoidance, • Carrier selection, • Transmit power control. The primary focus is on downlink, although uplink was also under consideration.
Mar 2016	• Define LBT coexistence mechanisms. • Define the pairing of unlicensed transmission with licensed bands. • Standardize LWA. • Introduce new functionality to improve mobility management and eNB management in LTE and Wi-Fi networks.

As a result, fairness issues arising due to differences in channel access mechanisms of LTE and Wi-Fi can be eliminated.

4) **MulteFire**. MulteFire is a relatively new LTE-based technology that operates completely in the unlicensed spectrum, and thus, does not require an "anchor" in the licensed spectrum [30]. MulteFire Release 1.0 specification was released in January 2017, and is based on 3GPP Releases 13 (for downlink) and 14 (for uplink). MulteFire uses an LBT based protocol for channel access, and as such can be used in any frequency band that requires the use of LBT.

Standardization of different unlicensed LTE mechanisms is an ongoing process with participation from 3GPP and companies such as Qualcomm, Ericsson, etc. Progress in unlicensed LTE standardization is summarized in Table III.

In Sec. III-B and III-C, we provide detailed descriptions on LTE-U and LAA respectively. We compare the advantages and disadvantages of LTE-U and LAA, and summarize their impacts on Wi-Fi performance. While coexistence between LTE-U and Wi-Fi and LAA and Wi-Fi have been studied extensively in the literature, there is limited research on LWA within the academic community. Thus, we introduce LWA from the point of view of developments in the industry in Sec. III-D. Development of MulteFire is still an ongoing research topic. Hence, we introduce basic ideas, alternative architectures and potential advantages of MulteFire in Sec. III-E.

B. LTE in Unlicensed spectrum (LTE-U)

LTE-U is designed such that the unlicensed bands are used to carry downlink traffic. Uplink traffic and control signalling is done over the licensed bands. Thus, LTE-U is said to operate in a supplemental downlink-only (SDL) mode. In US, LTE-U can operate in the U-NII-1 and U-NII-3 bands. This implies that Wi-Fi devices will not have to compete with LTE-U devices for channel access in 355 MHz of spectum in the U-NII-2A and U-NII-2C bands[9] [32].

In order to coexist with existing Wi-Fi devices in the 5 GHz band and other LTE-U eNBs, LTE-U provides a three-step coexistence mechanism [33], [34]. This coexistence mechanism is described using a flow chart in Fig. 8.

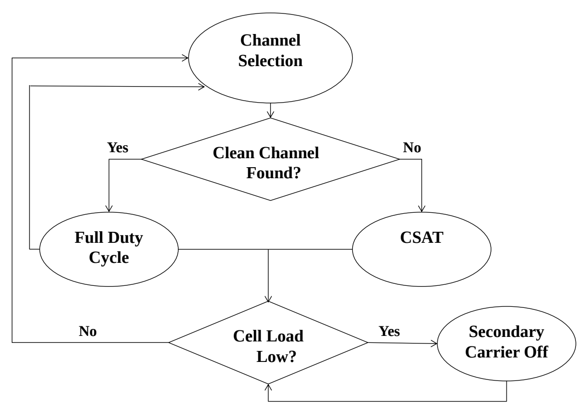


Fig. 8: LTE-U algorithm flow chart

The steps involved in the channel access mechanism of LTE-U are as follows.

1) *Channel selection:* The LTE-U eNB must scan the unlicensed portions of the spectrum in order to determine the availability of a "clean" channel for SDL transmissions. A clean channel refers to a channel that is not used by any Wi-Fi or LTE-U systems in the vicinity of the LTE-U eNB performing the scan. Channel measurements and determination of a clean channel are to be performed at the initial power-up stage, as well as periodically during the SDL operation stage. If a clean channel is determined during the power-up stage, the LTE-U eNBs communicate with the UEs using frequencies in that channel. During subsequent measurements, if interference

[9]However, as introduced in Sec. II-B, these bands are used by radar systems, which will be the primary users of the spectrum.

is experienced on the previously clean channel, and a new clean channel is available, the SDL transmissions shall be switched to the new channel.

The interference level in a channel is currently proposed to be measured using energy detection, which is agnostic to the type of interfering signal and the number of interfering sources. However, advanced technology-specific measurements can be used to improve interference detection sensitivity and additional information collection. For instance, capability to detect and decode Wi-Fi preambles can be added at the LTE-U eNBs to determine the number of neighbouring Wi-Fi users in the given channel.

2) *Duty-cycling:* In high density deployment of Wi-Fi and LTE-U small cells, it is likely that no clean channel is found during the scan process. In such circumstances, LTE-U uses a mechanism named Carrier Sense Adaptive Transmission (CSAT) to coexist with Wi-Fi and/or other LTE-U eNBs in a given channel. The CSAT mechanism is based on duty-cycling — the LTE-U eNB ceases all its transmissions for x $m$sec, followed by a burst of continuous LTE transmissions for y $m$sec. This process repeats periodically with the period ranging from $20-100$ $m$sec as shown in Fig. 9. The durations x and y, i.e. the *on*-time and *off*-time in the CSAT procedure can be adjusted adaptively based on the utilization of the spectrum by Wi-Fi and other unlicensed devices.

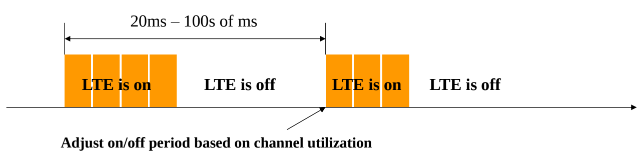


Fig. 9: CSAT process

3) *Opportunistic secondary cell switch-off:* Since the anchor carrier in the licensed band is always available, the SDL carrier in unlicensed band can be used on an opportunistic basis [33]. If traffic demands from the LTE-U UEs can be met using only the primary carrier, the LTE-U system can turn off the secondary carrier to ease the load on the secondary channels.

The primary advantage of LTE-U is that systems based on LTE-U can be deployed sooner than those based on LAA. This is due to the fact that standardization process of the LTE-U protocol has been completed, and the specifications for the implementation of LTE-U devices have been published by the LTE-U Forum.

Despite the attractiveness of using LTE-U in the unlicensed spectrum, there have been some controversies regarding the effectiveness of LTE-U in achieving harmonious coexistence with Wi-Fi devices. For example, in June 2015, Google argued against the usage of LTE-U in its White Paper [35]. There were several arguments made against using LTE-U in the unlicensed spectrum. For instance, as described in the CSAT procedure details, LTE-U devices start their transmissions at the beginning of every cycle without sensing the channel for other unlicensed devices' transmissions. Consequently, the beginning of every LTE-U transmission can potentially interrupt an ongoing Wi-Fi transmission. As a result, Wi-Fi frames during this interval are susceptible to erroneous reception. Moreover, such errors are likely to occur at the beginning of each CSAT cycle, thus resulting in the lowering of the MCS used by the transmitting Wi-Fi devices. This can lead to drastic reduction in Wi-Fi system performance.

Additionally, results of experimental investigations in [35] show that LTE-U is not equipped with an effective coexistence technique to handle scenarios in which LTE-U and Wi-Fi devices sense each other at moderate (below -62 dBm) signal levels. In August 2015, the Wi-Fi Alliance and National Cable & Telecommunications Association (NCTA) also raised opposition to the approval of LTE-U systems in the unlicensed bands without adequate testing, citing concerns that LTE-U operations could degrade performance of existing Wi-Fi systems by 50% to 100% depending on network scenario [36].

In a rebuttal to these claims, Qualcomm [37] stated that results obtained from its field tests show that LTE-U coexists harmoniously with Wi-Fi regardless of whether LTE-U operates above or below Wi-Fi's energy detection level, with Wi-Fi DL data rate remaining the same in the presence as well as absence of LTE-U transmissions. Qualcomm attributed this discrepancy in the results to the pessimistic and impractical technical assumptions made by the other studies [35], [38]. Moreover, tests conducted by Qualcomm used a realistic setup, including actual LTE-U equipment as opposed to signal generators used in Google's study.

Nevertheless, LTE-U is expected to be the first version of unlicensed LTE that will commercially operate in the 5 GHz unlicensed bands with FCC's authorization of first LTE-U devices in February 2017 [39].

C. License Assisted Access (LAA)

In countries across Europe and in Japan, regulations mandate the use of sensing mechanisms before transmissions from unlicensed devices. This requirement is commonly referred to as LBT capability. While LTE-U uses sensing mechanisms to detect a clean channel during the power-up stage, and periodically during its operations, each transmission from an LTE-U node does not precede a channel sensing process. This makes LTE-U unsuitable for markets where the regulations mandate LBT capability.

LAA is a flavor of unlicensed LTE that is designed for operations where LBT capability is desired. ETSI provides two options for LBT schemes: Frame-Based Equipment (FBE) and Load-Based Equipment (LBE) [40], [41].

- *FBE-based LBT.* In the FBE-based LBT, transceivers operate using fixed timing and with a fixed frame period. At the end of each idle frame, FBE performs CCA on an operating channel. If the channel is idle, the transceiver transmits data immediately at the beginning of the next frame. If, however, the channel is busy, CCA is performed in the next frame period.
- *LBE-based LBT.* In the LBE-based LBT, a transmitter performs CCA every time it has data to transmit in its

queue. If the channel is idle during this sensing period, data is transmitted immediately over the channel. If the channel is determined to be busy, a back-off counter is initialized, and the transmitter attempts to transmit the frame when the back-off counter decrements to 0.

Analysis and performance enhancement of LAA systems has received a lot of attention in the literature. An extensive survey of LAA and Wi-Fi coexistence has been carried out in [3]. Interested readers can refer to [3] and the references therein for more details on LAA Wi-Fi coexistence and corresponding deployment scenarios. In what follows, we discuss two primary directions of research followed in most papers on LAA Wi-Fi coexistence.

Control of LAA backoff procedure: In order to achieve fair coexistence between LAA and Wi-Fi devices, one of the most critical issues is to determine how quickly an LAA device starts transmitting after sensing the channel idle. The transmissions could be immediate as in FBE-based LBT, or based on a back-off mechanism as defined in LBE-based LBT. The design of an appropriate channel access mechanism is crucial towards LAA and Wi-Fi performance in this coexistence scenario.

In [42], Chen et al. propose a Markov chain based model to characterize the performance of LAA as well as Wi-Fi devices and determine the downlink throughput for each set of devices. Moreover, the proposed model shows the effectiveness of using the LBT mechanism in terms of the impact of LAA transmissions on Wi-Fi performance. Downlink throughput for both, LTE and Wi-Fi systems, can be theoretically calculated in different coexistence scenarios (LAA and LAA, or LAA and Wi-Fi). Intra-system interference in LAA-LAA and LAA-WiFi as well as LAA-WiFi hidden terminal problems are analyzed by Lien et al. in [43]. Lien et al. [43] also propose dynamic switching between scheduling-based access and random access scheme as an outcome of their model.

Three different Wi-Fi and LTE deployment scenarios, namely indoor, outdoor and indoor/outdoor mixed scenarios are tested by Jeon et al. in [44]. It is observed that if WLAN BSSs are located indoor, the impact of LAA transmissions on WLAN performance is not severe. However, the performance of Wi-Fi devices suffers non-negligible degradation in other cases. Besides the above mentioned works, enhancements to the basic LAA mechanism have been proposed [45]–[52]. An important objective of these works is to ensure fair coexistence in terms of Wi-Fi performance in the presence of LAA.

Control of LAA sensing mechanism: Along with a careful design of the LAA back-off mechanism, appropriate setting of the CCA threshold is also critical to LAA as well as Wi-Fi performance. Chai et al. [53] point out that there exists a subtle, yet critical, problem that arises due to the asymmetric channel access mechanisms employed by Wi-Fi and LTE technologies with the potential to degrade the performance of LAA as well as Wi-Fi users, with more impact on Wi-Fi's performance. Both, Wi-Fi and LTE transmitters, can use energy detection in order to detect signals stronger than -62 dBm. However, Wi-Fi devices can also perform preamble detection, which enables Wi-Fi transmitters to detect signals from other Wi-Fi transmitters that are larger than -82 dBm in signal strength. The performance of LAA as well as Wi-Fi systems is, thus, unclear when the signal strength at both devices is within the $[-82, -62]$ dBm range. Experimental results in [35], [53] show that when the strength of LAA signal at the Wi-Fi transmitter and Wi-Fi signal at the LAA transmitter are in the $[-82, -62]$ dBm range, simultaneous packet transmissions can result in collisions in numerous situations since LTE and Wi-Fi cannot detect each other, resulting in a drop in throughput of LAA and Wi-Fi systems by up to 15% and 37% respectively.

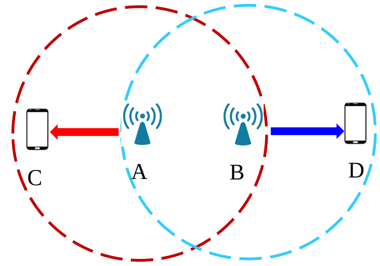


Fig. 10: A diagram illustrating the exposed node problem. Stations C and D are outside each others' sensing and transmission range. Thus, A and B can transmit packets to C and D respectively without any collisions. However, B (or A) senses A's (or B's) transmission to C (or D) and does not transmit, resulting in loss of an opportunity to transmit.

To mitigate the above problem, a naive solution would be to lower the energy detection CCA threshold. However, this would lead to under-utilization of the channel due to the well known exposed-node problem (explained in Fig. 10). The authors in [53] argue that it is critical for LAA systems to homogenize its channel access mechanism with that of the incumbent Wi-Fi system by incorporating the latter's preamble detection and notification capabilities (such as the use of Wi-Fi CTS frame to reserve channel access for LAA transmissions). For more discussions on setting of the CCA threshold in LAA transmitters, readers can refer [44], [54].

D. LTE-WLAN Aggregation (LWA)

The development and deployment of LTE-U or LAA based unlicensed LTE systems would require significant investment in terms of additional hardware (LTE-U/LAA enabled eNBs and UEs) and processing capabilities (detection of signals from Wi-Fi and other unlicensed devices). In contrast, LWA has emerged as an unlicensed LTE alternative to LTE-U and LAA that leverages the existing LTE and Wi-Fi infrastructures.

LWA was standardized by 3GPP Release 13 in March 2016. In August 2016, Singapore's M1 announced its first commercial Heterogeneous Network (HetNet) rollout that would include LWA. Using LWA technology, M1 expects to deliver peak download speeds of more than 1 Gbps [55].

In contrast to LTE-U and LAA, LWA transmits LTE data on unlicensed bands using the Wi-Fi protocol. This is achieved by splitting the LTE payload at the higher layers into two classes

— one transmitted over licensed spectrum bands using the LTE radio, while the other class of traffic transmitted over unlicensed spectrum using the Wi-Fi radio. Thus, a fraction of the total LTE traffic is tunneled over the Wi-Fi interface. The basic idea behind LWA is to use Wi-Fi APs in order to augment the LTE Radio Access Network (RAN) by tunneling LTE data in the 802.11 MAC frame such that despite carrying LTE payload, Wi-Fi devices in the network can "see" this data as Wi-Fi traffic. As a result, problems arising due to differences in the channel access mechanisms of LTE and Wi-Fi can be alleviated.

The architecture of an LWA system is shown in Fig. 11, and consists of an LWA eNB, LWA-aware Wi-Fi AP and LWA UE. The LWA eNB performs splitting of packet data convergence protocol (PDCP)[10] packets at the PDCP layer, and transmits some of these packets over the LTE air interface, while the remaining are transmitted through the Wi-Fi AP after encapsulating them in Wi-Fi frames. These packets can then be reassembled at the PDCP layer of the LWA UE. It must be noted that LWA also leverages the fact that almost all LTE enabled UEs are equipped with Wi-Fi capabilities.

The LWA aware Wi-Fi APs are connected to LWA eNBs, and can report channel information to the LWA eNB, which can use the channel and traffic information to determine whether the Wi-Fi air interface must be used or not. This architecture also enables functioning of the LWA aware Wi-Fi AP to function as a standalone Wi-Fi AP when the LTE network load is low [41].

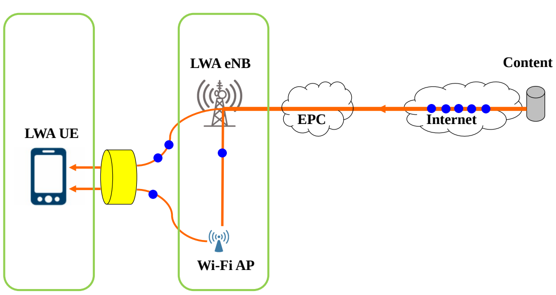


Fig. 11: LWA conceptional architecture [41]

A significant advantage of the LWA system over LTE-U and LAA systems is that it can be enabled using software upgrades at the eNBs, UEs and Wi-Fi APs, thus leveraging existing LTE and Wi-Fi infrastructures. Moreover, Wi-Fi traffic can benefit from the services provided by the mobile operator's evolved packet core (EPC). These services include authentication, billing, deep packet inspection etc.

E. MulteFire

MulteFire has emerged as a standalone version of unlicensed LTE which solely operates in the unlicensed spectrum. As a result, MulteFire systems do not require an "anchor" in licensed spectrum. MulteFire is designed with an objective to bring the best of both, LTE and Wi-Fi, worlds by incorporating features from LTE such as user mobility, seamless handovers, integration with LTE operators and from Wi-Fi like neutral host options – i.e., the ability to serve subscribers from different operators.

In December 2015, the MulteFire Alliance announced the formation of an international association open to new members for the development of MulteFire. The MulteFire Alliance released its MulteFire specification Release 1.0.1 [56] based on 3GPP Release 13 and Release 14 advancements, including downlink and uplink in the unlicensed spectrum bands.

MulteFire is primarily designed for entities that have limited or no access to licensed spectrum bands, while giving these entities the benefits of LTE technology [30], [57]. Moreover, MulteFire can also be used by mobile service providers that already have access to licensed spectrum in order to augment their network capabilities. Thus, MulteFire is capable of operating either independently as a private network (much like Wi-Fi APs), or work alongside existing mobile networks. There are three types of architectures envisioned for MulteFire operations [58].

- Standalone operations as a private self-contained network.
- A self-contained network working closely with mobile networks.
- A network with a RAN interconnection through an interface with the mobile network.

Moreover, it is possible for a MulteFire network to support one or all of the three architectures simultaneously.

The MulteFire channel access procedure borrows largely from the 3GPP LAA and enhanced LLA (eLLA, an evolution of LAA with boosted downlink performance) procedures. The procedure used by MulteFire devices to share the spectrum with other unlicensed devices (operating over Wi-Fi or LAA air interfaces) is much alike the Wi-Fi CSMA procedure with four access classes and similar contention parameters [30]. The overall procedure is summarized below.

1) Using CCA, MulteFire selects a channel for its operations dynamically, avoiding overlapping transmissions with unlicensed devices such as other MulteFire, LAA and Wi-Fi.
2) If no clear channel can be found, an LBT mechanism is used to contend for the spectrum.
3) MulteFire also supports channel aggregation to improve system capacity.

The MulteFire technology uses the LAA and eLLA in downlink and uplink respectively. This makes MulteFire suitable for operations in any band (including bands other than 5 GHz) and regulatory regimes that require over-the-air contention and coexistence with heterogeneous technologies. For example, MulteFire is a high performance option for General Authorized Access in the 3.5 GHz band in US [58].

MulteFire is a promising technology with characteristics derived from Wi-Fi as well as LTE. However, being a relatively new technology with no devices available, the performance of

[10]PDCP is a set of protocols (layer) that lies between the Internet Protocol (IP) and radio link control (RLC) layers in the data plane, and radio resource control (RRC) and RLC layers in the control plane. PDCP is responsible for functions such as header compression for IP packets, data integrity protection and ciphering.

MulteFire remains unknown. As the channel access procedure in MulteFire is much similar to that of Wi-Fi, MulteFire can be expected to be a friendly neighbor to Wi-Fi systems, while being prone to performance degradation in the presence of LAA or LTE-U systems.

F. Future Evolution of unlicensed LTE

Currently, about 1.3 GHz of spectrum across different frequency bands are used for mobile communications by 3GPP [59]. However, it is estimated that by the year 2020, the amount of spectrum required to support mobile and wireless communications may not be available in the currently supported bands [60]. Many of the currently used frequency bands by 3GPP are in the sub-6 GHz range, majority of which are already in use by different incumbent technologies. In such scenarios, future technologies can use licensing approaches such as the Licensed Shared Access (LSA) [61] in order to share the spectrum with its incumbent users.

Although LSA-based spectrum sharing approaches help in alleviating spectrum scarcity problems, the use of spectrum on a primary basis is a much more lucrative option from the viewpoint of mobile operators. Primary access to the spectrum, despite enormous licensing costs, can significantly ease network planning. Thus, stakeholders are investigating the use of millimeter wave (mmW) frequencies to support 5G mobile systems [62], where spectrum availability is in abundance and existing operations are few. At this stage, there are several challenges in the design and rollout of commercial systems that operate in the mmW frequencies [62], [63]. However, the use of mmW frequencies for 5G cellular systems on a massive scale cannot be ruled out. Under such circumstances, the evolution path of the unlicensed LTE versions developed thus far, along with their 5G extensions remains unclear.

G. Open Research Problems

Based on current standardization and research status, we summarize the following potential research directions in the area of unlicensed LTE and Wi-Fi coexistence.

- Dynamic duty-cycling based on the current channel utilization information in the CSAT procedure can be used to maximize LTE-U performance as well as achieve fair coexistence with Wi-Fi systems. An algorithm to adjust the LTE-U *on*-time and *off*-time based on technology-specific sensing results could help LTE-U systems in achieving larger throughput while sharing the spectrum in a fair manner with Wi-Fi systems.
- Carrier sensing using energy detection can detect signals above -62 dBm, while preamble detection can detect signals above -82 dBm. LTE and Wi-Fi cannot detect each other when signals are between -62 dBm and -82 dBm. Such interference can degrade performance for both LTE and Wi-Fi systems by as much as 40% even if the SINR is above 10 dB [53]. It is, therefore, crucial to design mechanisms to deal with signals in the $[-82, -62]$ dBm range.
- The back-off procedure in LBT based mechanisms has a large impact on balancing spectrum usage between LTE and Wi-Fi devices. Design of optimal LBT schemes for unlicensed LTE devices is an open research problem.
- LWA is efficient in alleviating the interference issues caused between LTE and Wi-Fi due to differing channel access mechanisms. However, determination of data flow routing between LTE and Wi-Fi radio interfaces remains an open problem. Moreover, varying traffic conditions combined with arrival and departure of Wi-Fi devices in the network pose additional challenges in designing efficient flow routing algorithms.
- MulteFire is in its early stages of development. The impact of MulteFire transmissions on Wi-Fi system performance, specially in comparison and contrast to Wi-Fi – Wi-Fi coexistence, is yet to be understood.
- The adoption of channel access parameters similar to those used in Wi-Fi also makes MulteFire devices prone to interference from LTE-U and LAA systems much like Wi-Fi devices. Thus, performance evaluation of MulteFire in the presence of other unlicensed LTE technologies remains an open problem.

IV. Coexistence of Radar and Wi-Fi

The first step toward allowing unlicensed devices (such as Wi-Fi) to operate in the $5.150 - 5.350$ GHz and $5.470 - 5.725$ GHz bands was taken at the World Radiocommunication Conference 2003 (WRC-03) [13]. As per the regulations, unlicensed devices can operate in these frequencies so long as they do not interfere with the incumbent users of the spectrum – radars. Thus, radars are the primary users of the band, and Wi-Fi devices can operate in the shared spectrum if no radar activity is reported.

In this section, we look at the coexistence issues that arise due to the operation of Wi-Fi devices in the 5 GHz bands with radar systems as their primary users. We divide the discussion in two parts — (i) coexistence issues in the $5.25 - 5.35$ GHz and $5.47 - 5.725$ GHz bands, where Wi-Fi devices continue to coexist with radars, and (ii) coexistence issues in the $5.35 - 5.47$ GHz, where WLAN systems are being considered to operate alongside radars in the future.

A. Coexistence issues in the $5.25 - 5.35$ GHz and $5.47 - 5.725$ GHz bands

Wi-Fi devices operating in certain parts of the 5 GHz spectrum must use the Dynamic Frequency Selection (DFS) mechanism[11] to detect the presence of operating radars and avoid co-channel operations. The sensing technique in DFS involves signal detection based on the knowledge of radar parameters, such as pulse width, pulse repetition rate, number of pulses per burst, etc., at the Wi-Fi transmitter.

The DFS mechanism is implemented at the Wi-Fi AP. Associated STAs have to rely on the AP to avoid causing any

[11] The exact frequencies that require the use of DFS is regulation specific. For example, Ofcom in UK mandates the use of DFS from $5.47 - 5.85$ GHz, while FCC in the use requires DFS in the $5.47 - 5.725$ GHz bands [11].

interference to radar systems. Before selecting a channel for operations, a Wi-Fi AP must perform a Channel Availability Check (CAC) whereby the AP must check for the presence of radar signals for a predetermined interval[12]. If a channel has ongoing radar activity (radar energy > -62 dBm), the AP continues to scan for other idle channels in the band. If none of the channels are idle, the AP enters a "sleep mode". If an idle channel is available, the Wi-Fi AP and STAs can continue their transmissions on such a channel. The AP must periodically perform CAC for radar activity in between transmissions. If a radar activity is detected, the AP and its associated STAs must cease channel usage within 10 seconds. During these 10 seconds, the AP can send normal data traffic to the STAs for a maximum duration of 200 $m$sec. The AP can also transmit control information to its associated STAs in order to facilitate moving to an idle channel. The channel must then be declared busy for 30 minutes.

Before WLAN products operating in the 5 GHz bands can be introduced in the market, the product manufacturers are required to test the devices for compliance certifications from the regulatory agencies (such as FCC in US and ETSI in Europe). These compliance tests usually involve checking the ability of the deployed DFS algorithm to detect characteristic radar signals, specified in terms of radar pulse width and pulse repetition factors. In case of the $5.47 - 5.725$ GHz band, where weather radars are prone to interference from Wi-Fi transmissions, it is sometimes possible to provide a predecided set of waveforms for testing. However, with newer radar systems being developed, providing an exhaustive set of waveforms is infeasible, and may be impossible in scenarios where the radars are developed for defense purposes.

The DFS algorithm has continued to evolve ever since the ITU regulations in 2003. Several experimental studies have been conducted to determine the efficacy of DFS in detecting radar activity and the ability of the Wi-Fi devices to move to a different channel when radar activity is detected. Experiments performed by Joe et al. [64] show that Wi-Fi APs are capable of detecting activity of weather radars operating in 5.6 GHz band in a highly mobile environment like inside an aircraft. However, at low enough distances (< 25 km) the WLAN presence can be seen at the weather radars. In [65], the authors show that the detection threshold of -62 dBm is sufficient to detect weather activity at most occasions. However, this detection capability depends to a large extent on the direction of the radar signals. If the AP is unable to detect the radar activity before the radar beam directly aims at the Wi-Fi network, the radar system is blinded by Wi-Fi transmissions. Moreover, radar systems with larger bandwidths are more susceptible to Wi-Fi interference.

Tercero et al. [66] present a mathematical model to analyze the interference caused by aggregate Wi-Fi users to weather radars operating in the 5.6 GHz band. The authors consider the basic DFS mechanism at the Wi-Fi AP and show that in dense urban scenarios where density of Wi-Fi users is greater than 10 WLANs per square kilometer, radar systems experience aggregated interference larger than their interference threshold.

Several approaches have been adopted with the objective of mitigating Wi-Fi interference at radar receivers. For example, the authors in [67] propose a channel allocation scheme that takes into consideration meteorological radar operations and show that by using existing Wi-Fi mechanisms such as the RTS/CTS handshake, Wi-Fi devices can minimize interference at radar systems. Signal processing based interference cancellation strategies have also been proposed in the literature. Take [68] for example. The authors argue that Wi-Fi transmission characteristics can be leveraged at radar systems in order to detect and cancel interfering signals. Moreover, since Wi-Fi standards are universal, the authors claim that techniques based on identifying Wi-Fi characteristics can be used to solve such interference problems universally. The authors test their scheme on time-series waveforms obtained from Brazil, India and Estonia to validate their claims. Similar work has been presented in [69]. In [70], the author proposes the use of computer vision based techniques for removal of interference signals at radar receivers that can potentially filter out transmissions from Wi-Fi like emitters.

Technologies to enhance the DFS mechanisms have also been proposed in the literature. Tercero et al. [71] exploit the temporal nature of radar systems to increase the transmission opportunities for Wi-Fi devices. The authors quantitatively estimate the number of Wi-Fi users that can operate as secondary users in radar occupied bands. Furthermore, they show that using their scheme, a Wi-Fi user operating as close as 4 km from the radar can transmit up to 99.45% of the time without interfering with the radar receiver.

Despite the proposal and adoption of the aforementioned interference-mitigation techniques, incidences of interference caused to radar systems (particularly to the weather radars operating in $5.60 - 5.65$ GHz) by Wi-Fi operations have been reported in US [72], [73], Canada [74], across Europe [75]–[77] and other regions [78]. The primary reasons for such Wi-Fi-induced interference are summarized below.

- DFS mechanism can be deliberately turned off by the operator or even by the users. Detection and enforcement of these rogue WLAN devices is difficult even with the presence of azimuth data at the radars. In the past, several cases of interference to the weather radars have been reported in the US and Europe due to deliberate disabling of the DFS mechanism in WLAN devices [73], [75].
- DFS does not address the *hidden node* problem. The DFS mechanism is used only at the AP to detect the presence of radar systems. However, there is a possibility that the radar signal is not detectable at the AP, but associated STAs may cause interference at the radar receivers [67].
- Unlicensed devices operating on an adjacent channel can cause harmful interference to radar systems. In the ideal scenario, once a DFS device detects a radar signal, it must move to a channel that is separated far enough

[12]The exact interval is decided by country-specific regulations. For example, regulations in US require the AP to scan the channel for 60 seconds, while the Canadian regulations specify an interval of 10 minutes – a duration that overlaps with scan cycle time of most weather radars operating in 5.6 GHz.

in frequency to eliminate adjacent channel interference. However, interference investigations lead by the National Telecommunications and Information Administration in US have determined that some devices have not been moving far enough away in frequency, and as a result, their out-of-channel emissions were causing interference to weather radars [10].

B. Coexistence issues in the $5.35 - 5.47$ GHz band

Coexistence between radars and Wi-Fi in the $5.25 - 5.35$ GHz and $5.47 - 5.725$ GHz bands have been a problem worldwide. In this subsection, we discuss issues of coexistence that are expected to arise between the two technologies in the $5.35 - 5.47$ GHz band. It must be noted that Wi-Fi devices do not currently operate in the $5.35 - 5.47$ GHz worldwide, but several regulators are considering the possibility of allowing unlicensed devices to operate in these frequencies [10]–[12]. The primary reason for such considerations is that by allowing unlicensed devices to operate in the $5.35 - 5.47$ GHz band along with $5.85 - 5.92$ GHz band will result in up to 70% increase in the available spectrum, and increase the number of 80 MHz channels by 125% (from 4 to 9) [12].

With considerations from regulators for allowing unlicensed operations in the $5.350 - 5.470$ GHz band, there is a need for developing coexistence mechanisms between unlicensed users and radars in this band. The methods used for detection of radars in the $5.25 - 5.35$ GHz and $5.47 - 5.725$ GHz bands are generally unsuitable for detecting radar signals in the $5.35 - 5.47$ GHz band due to the following reasons.

- Unlike other 5 GHz bands, the $5.35 - 5.47$ GHz band is used for many military and safety-critical applications. Adequate protection for these systems from WLAN-induced interference is extremely important. In the DFS certification test, a set of waveforms is defined, but it does not necessarily include waveforms from all radar systems. There are a large number of radar systems operating in the $5.35 - 5.47$ GHz band, which are not present in the $5.25 - 5.35$ GHz and $5.47 - 5.725$ GHz bands. These waveforms need to be added in the certification list.
- In the $5.25 - 5.35$ GHz and $5.47 - 5.725$ GHz bands, radar parameters such as pulse width, pulse repetition interval, and the number of pulses per burst are well known [10]. On the other hand, a large and diverse set of radar systems operate in the $5.35 - 5.47$ GHz band. The pulse widths, pulse repetition frequency and other characteristics vary significantly from system to system. Even for a single radar, the pulse width can change with time. In addition, some recently fielded radar systems and those under development operate in low power modes or are designed to avoid detection to meet their mission requirements. These radar systems are challenging for the WLAN devices to correctly detect.
- Signal processing techniques are typically employed at radars to minimize the impact of interference caused by other radars. However, these techniques are only effective for low duty cycle emitters. WLAN devices typically use very high duty cycles (for instance, with frame aggregation techniques the duty cycle can go as high as 80% [10]). This makes it difficult for radar systems to mitigate WLAN interference using signal processing techniques that are useful in the case of low duty-cycle (single-pulse) filters at the radars.
- The existing DFS mechanisms were developed specifically to protect radar systems in which the transmitter and receiver are co-located. Airborne systems employ ground and airborne transmitters and receivers located in different locations. Full duplex systems with the uplink and downlink on different frequencies can introduce hidden node problems for WLAN APs that rely on sensing.
- The use of signal detection-based DFS techniques used in other 5 GHz bands may be unsuitable for use in the $5.35 - 5.47$ GHz band. Detection techniques based on the use of geo-location databases used in TV White Space (TVWS) [79]–[82] are more suitable for spectrum sharing in the $5.35 - 5.47$ GHz band [10]. Although database based techniques can be useful in scenarios where the radar transmitter and receiver are collocated, radar systems with non-collocated transmitters and receivers may not be adequately protected from Wi-Fi transmissions.
- Moreover, several database management and authorization related issues while drafting regulations for the TVBDs (e.g., construction of databases, sharing data between databases, how to determine available channels, securing the information etc. [79]) will have to be addressed if geo-location databases are created to protect critical radar systems.
- Furthermore, this necessitates the protection of incumbent information in case of radar systems that are of critical importance for national security. Such studies have been carried out in the context of radar systems operating in other spectrum bands [83], [84].

C. Open Research Problems

We list the following open research problems with respect to the coexistence of heterogeneous wireless systems in the 5 GHz bands.

- Reliable techniques for the detection of radar signals with dynamic pulse characteristics operating in the $5.35 - 5.47$ GHz band need to be designed for Wi-Fi APs.
- Spectrum sensing based mechanisms may not be effective in the detection of radar systems operating in the $5.35 - 5.47$ GHz band. In such scenarios, feasibility of database-based solutions for coexistence of Wi-Fi and radar systems operating in the $5.35 - 5.47$ GHz band needs to be assessed, specifically when the radar transmitter and receiver are non-collocated.
- Because many military and public-safety systems (which are considered incumbent users) operate in the $5.35 - 5.47$ GHz band, regulators and industry stakeholders will need to work together to develop mechanisms, rules, and procedures to protect the operational security (OPSEC) of the incumbent users when they coexist with Wi-Fi

systems. OPSEC is expected to be a critical component in realizing harmonious coexistence between incumbents and secondary entrants in the $5.35 - 5.47$ GHz band.

- Technologies and techniques for detecting, identifying, and adjudicating rogue devices are needed. Here, rogue devices refer to devices that have disabled the DFS functionality or intentionally operate in the presence of incumbent systems. In addition, these enforcement approaches need to be automated and cost effective in order to be considered commercially viable.
- Solutions to combat the hidden node problem in the $5.25-5.35$ GHz and $5.47-5.725$ GHz bands (due to DFS implementation only at the AP), and the $5.35-5.47$ GHz band (due to non-collocated transmitters and receivers) need to developed.
- PHY layer techniques that enable underlay cognitive radio networks, such as transmit beamforming [85], [86] that can null the secondary user waveforms at the radar systems can be an interesting subject of investigation.

V. Coexistence of DSRC and Wi-Fi

The $5.85-5.925$ GHz band, being considered for unlicensed operations overlaps exactly with the band allocated for ITS services. In this section, we address the coexistence issues expected to arise as a result of DSRC and Wi-Fi devices operating in the same frequency band.

Impetus to exploring band sharing techniques between DSRC and Wi-Fi was provided by the introduction of *Wi-Fi Innovation Act* in the U.S. Senate and House [87]. This act directs the FCC to move swiftly in conducting tests to assess the feasibility of opening up the upper 5 GHz band, including the DSRC band, for unlicensed use. In this coexistence scenario, DSRC users shall remain the primary users, while Wi-Fi users will be the secondary users of the shared spectrum. The channelization of the U-NII-4 band in $5.850 - 5.925$ GHz is shown in Fig. 12. It is noteworthy that this DSRC-WiFi coexistence issue has been considered in Europe [12]. However, due to the lack of appropriate interference mitigation techniques that would allow WLANs to coexist in these bands, the coexistence scenario has failed to garner much attention in Europe. Thus, DSRC-WiFi coexistence is, currently, a major concern only in the US [4].

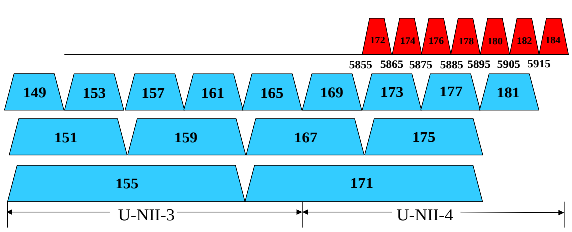


Fig. 12: Channelization of the U-NII-4 band.

A. Status of Existing Research on DSRC-WiFi Coexistence

As described in Sec. II-C, since the 802.11p amendment is derived from 802.11a, the coexistence of 802.11ac and 802.11p may seem similar to coexistence scenarios between legacy devices and 802.11ac. However, there are key differences between the legacy 802.11 - 802.11ac coexistence and 802.11p - 802.11ac coexistence.

Firstly, 802.11p uses 10 MHz wide channels. Present day Wi-Fi transmitters have no support for preamble detection of 10 MHz wide signals, and 802.11p cannot decode 20 MHz preambles. Thus, if 802.11p and 802.11ac transmitters were to operate in the same spectrum, both transmitters would detect each others' presence only using energy detection. The detection thresholds using energy detection being much higher (approx. 20 dB) than preamble detection [5], the sensing range of both transmitters will be much smaller as compared to that in traditional coexistence scenarios, resulting in collisions at both, Wi-Fi and DSRC receivers.

Secondly, 802.11p is the primary user of the spectrum. Thus, if a packet is available for transmission at both, DSRC and Wi-Fi devices, the 802.11p transmitter must be able to gain access to the channel before the Wi-Fi transmitter. The reverse situation, i.e. a Wi-Fi transmitter has a higher priority over DSRC transmitter, is referred to as a priority reversal problem. In order to adhere to the regulations, it is clear that the priority reversal problem must be avoided in a coexisting network.

In August 2013, the IEEE 802.11 Regulatory Standing Committee created a subcommittee called the *DSRC Coexistence Tiger Team* to explore possible band sharing techniques that will enable the coexistence of DSRC and 802.11ac, and also help inform the regulatory process. In March 2015, Tiger Team published their final report [88] that summarizes the issues surrounding the proposed band sharing ideas discussed in the group. Two proposals are summarized in [88]:

- *Sharing using existing DSRC channelization and CCA in* 10 *MHz channels*. Details of this technique are presented in [89]. This proposal is a hybrid solution of the traditional CCA and DFS mechanisms. The proposal assumes that all unlicensed devices must embed hardware that can detect 10 MHz wide 802.11p preambles. If an unlicensed device needs to operate in any of the DSRC channels, the device must sense all seven 10 MHz DSRC channels. If a single 10 MHz 802.11p preamble is detected by the Wi-Fi transmitter, the frequency band from $5825 - 5925$ MHz must be declared busy for at least 10 seconds. During this busy period, the DSRC channels will continue to be monitored, and any new DSRC packet detection will extend the busy state for another ten seconds from the time of detection.
- *Sharing using modified DSRC channelization and CCA in* 20 *MHz channels.* Details of this proposal are presented in [90]. The basic idea of this proposal is that the upper three 10 MHz channels can be reserved for DSRC safety applications, where the unlicensed devices must not be allowed to share the channels with DSRC nodes. The

lower 45 MHz spectrum, on the other hand, can be shared with unlicensed devices. Furthermore, DSRC channelization in the lower 45 MHz spectrum must be changed to 20 MHz instead of the currently used 10 MHz, which would alleviate the constraints of detecting 10 MHz signals at the Wi-Fi transmitters. However, some members of the Tiger Team argue that compressing 7 channels of critical traffic into 2 or 3 may result in excess packet loss and latency, thus degrading vehicular safety application performance [91].

Wang et al. [92] model the coexisting DSRC and Wi-Fi systems as a Poisson point process and characterize DSRC and Wi-Fi performance in different spectrum sharing conditions. The authors also evaluate the performance resulting from the two proposals described above ([89], [90]), and report that while the first proposal ([89]) provides protection to DSRC systems, the second proposal ([90]) exclusively favors Wi-Fi's system performance.

In recent years, several papers analyzing issues of coexistence between DSRC and 802.11ac devices have been published [20], [93]–[96]. These papers explore ideas other than those described in the aforementioned Tiger Team proposals. Lansford et al. [20] qualitatively argue that an increase in the value of Wi-Fi parameter (such as IFS) can ensure higher channel access priority to 802.11p nodes as compared to Wi-Fi nodes. With the help of experiments, Park et al. [94] show that increasing the Arbitration Inter Frame Spacing (AIFS) value of 802.11ac transmitters can indeed help in mitigating the above priority reversal problem. In particular, the authors show that by increasing the AIFS value of Wi-Fi to 17, the impact of Wi-Fi transmissions on the DSRC system performance can become negligible. Liu et al. [95] provide an analytical model to characterize the impact of AIFS and sensitivity control at Wi-Fi transmitters on the DSRC system performance.

Naik et al. [96] look at DSRC Wi-Fi coexistence from the point of view of Wi-Fi system performance. The authors argue that owing to the Wi-Fi frame aggregation mechanism, an AIFS value much larger than 17 (as proposed in [94]) is required to provide adequate protection to the DSRC users, noting that such a drastic increase in Wi-Fi AIFS may render the shared spectrum useless for Wi-Fi users. Furthermore, the authors also show that because of the differences in the primary and secondary channel access mechanisms in Wi-Fi, DSRC users operating on secondary Wi-Fi channels are prone to higher interference from Wi-Fi transmitters.

B. Open Research Problems

The problem of coexistence between DSRC and Wi-Fi is not a well explored one. We list some open research problems in the coexistence of DSRC and Wi-Fi systems.

- Existing coexistence solutions, such as the one proposed in [89] may starve the Wi-Fi users operating in the shared spectrum. For instance, in dense urban scenarios, a large number of vehicles enabled with DSRC modules may render the shared channel of little use for Wi-Fi devices if they were to vacate the channel for 10 seconds every time a DSRC node is detected. There is a need for more practical spectrum sharing solutions.
- Change of suitable parameters in the current Wi-Fi standards (such as the Wi-Fi IFS, as suggested in [20], [94]–[96]) can be further explored. Such mechanisms can potentially enable harmonious coexistence between DSRC and Wi-Fi, without the necessity of using conservative backoff mechanisms at Wi-Fi transmitters.
- The impact of Wi-Fi devices on DSRC system performance must be thoroughly studied using analytical models, simulations, and extensive testbed experiments.
- As noted in [96], conservative coexistence mechanisms can provide adequate protection to DSRC users, but may limit spectrum access opportunities to the Wi-Fi users. The impact of spectrum sharing (between DSRC and Wi-Fi) on the performance of Wi-Fi systems needs to be studied thoroughly in order to understand the usability of the shared spectrum by Wi-Fi systems.

VI. Coexistence between Heterogeneous Wi-Fi Technologies

WLAN deployments have become heterogeneous due to devices operating with different bandwidth configurations (ranging from 5 MHz to 160 MHz) and employing different PHY and MAC layer techniques. Early Wi-Fi devices (802.11b) were deployed in the 2.4 GHz band. Scarcity of spectrum in the 2.4 GHz band has led to development of Wi-Fi devices operating in the 5 GHz band. Today, the 802.11a, 802.11n and 802.11ac devices operate in the $5.25 - 5.35$ GHz and $5.47 - 5.75$ GHz bands, while 802.11ax is under development. The current channelization in the 5 GHz band is based on 20 MHz channel widths with non-overlapping channels (unlike 2.4 GHz). However, with devices operating on different channel widths, a partial overlap between different devices becomes inevitable, particularly in dense deployment scenarios.

In this section, we discuss coexistence issues arising between different classes of Wi-Fi devices in the 5 GHz band. We identify three key coexistence issues in inter Wi-Fi coexistence, which are described next. We refer to 802.11a devices as legacy devices. While the 802.11n standard has been succeeded by 802.11ac, we consider the two standards together since 802.11n and 802.11ac are similar in many respects. 802.11ac primarily extends techniques that were introduced in 802.11n. For example, the number of parallel streams have been increased from 4 in 802.11n to 8 in 802.11ac, and channel bonding bandwidth has been increased from 40 MHz in 802.11n to 80 and 160 MHz in 802.11ac.

A. Coexistence between DCF and EDCA devices

The 802.11a devices use DCF as the channel access mechanism, while 802.11n and 802.11ac devices use the Enhanced Distribution Channel Access (EDCA) mechanism for channel access. The fundamental difference between DCF and EDCA is that while APs deploying DCF treat traffic to and from all clients with the same priority, EDCA divides traffic into four ACs — Background (BK), Best Effort (BE), Video (VI) and Voice (VO) — and prioritizes traffic from these classes differently. This differentiation is carried out by using different values of contention window and AIFS for each class. The AIFS and contention window of DCF devices and different classes of EDCA are shown in Table IV. It is natural that stations using smaller values of AIFS have a higher priority than those using larger values of AIFS.

TABLE IV: Channel access parameters for DCF and EDCA

Access Category	CWmin	CWmax	AIFSN
DCF	15	1023	2
Background (BK)	15	1023	7
Best Effort (BE)	15	1023	7
Video (VI)	7	15	2
Voice (VO)	3	7	2

Since DCF devices (802.11a) and EDCA devices (802.11n/ac) operate in the same frequency band, fairness issues arise. From Table IV, it is clear that in a heterogeneous network comprising of DCF devices and different EDCA service classes, VI and VO traffic will have the highest priority, while DCF, BK, and BE traffic have similar priorities. Since the CWmin and CWmax values for VI and VO traffic classes are small, the presence of a large number of legacy DCF (or even EDCA) devices can lead to poor QoS due to excessive collisions [97]. Coexistence of DCF and EDCA devices has been extensively studied in the literature. For the sake of completeness, we briefly summarize some of existing work on DCF-EDCA coexistence in Table V.

Coexistence between EDCA and DCF devices has been a well investigated research problem. Although several solutions have been proposed to mitigate the impact of legacy devices on the newer generations of Wi-Fi devices, the inherent nature of the CSMA protocol continues to pose problems for coexistence. With the development of the 802.11ax standard that aims to improve per user Wi-Fi performance in extremely dense deployment scenarios, study of the above coexistence problems can provide insights in the context of 802.11ax - legacy coexistence. We discuss coexistence between legacy devices and 802.11ax in Sec. VI-C.

B. *Coexistence between* 20 *MHz and* $40/80/160$ *MHz devices*

The IEEE 802.11a protocol provided support for only 20 MHz wide channels. The IEEE 802.11n standard [106] introduced the use of 40 MHz wide channels among several other features to increase the maximum PHY layer throughput from 54 Mbps in 802.11a to as high as 600 Mbps (with 40 MHz channel width, short guard interval (SGI) and 4 spatial streams). The IEEE 802.11ac standard further increased the PHY layer data rate to a maximum of 2.34 Gbps (using 160 MHz, SGI and 8 spatial streams)[13]. While the 802.11 family of standards have advanced to make use of sophisticated PHY and MAC layer techniques, the newer standards have continued to support backward compatibility to all existing 802.11 devices (hereinafter referred to as "legacy devices"). Backward compatibility is considered essential for all Wi-Fi standards primarily due to the proliferation of legacy devices in home and enterprise networks.

Wi-Fi devices are capable of using wide-bandwidth channels (40, 80, 160 MHz) to transmit packets. The objective of using wide bandwidth channels is to increase the achievable throughput. However, the presence of heterogeneous Wi-Fi devices in the same geographical area pose network management challenges. Deek et al. [108] have shown that naive channel assignments at 802.11n Wi-Fi APs in the presence of legacy devices can lead to substantial reduction in performance. Intelligent channel assignment (for both 20 and 40 MHz APs) are essential for efficient utilization of the spectrum. Deek et al. show the impact of transmissions from 20 MHz Wi-Fi devices on adjacent channel interference for 40 MHz systems. As the channel bandwidth of the Wi-Fi link increases, the same transmit power is spread across a larger bandwidth, which results in a decrease of 3 dB in power per subcarrier for a bandwidth increase by a factor of 2. This translates to a low Signal to Noise Ratio (SNR) at the intended receiver, resulting in the lowering of the PHY layer data rate. As a result, if a 20 MHz Wi-Fi device is located in the vicinity of a Wi-Fi receiver operating at 40 MHz, and the 20 MHz and 40 MHz channels are adjacent (in frequency), the out of band leakage from the 20 MHz transmitter leads to additional interference at the 40 MHz receiver, and in the worst case can reduce the throughput of 802.11n system down to 50%. Similar phenomenon is expected for 80 MHz Wi-Fi systems.

It is also worthwhile to analyze the impact of a new AP on an existing network that uses wide-bandwidth channels. This problem has been studied in the context of 802.11ac networks. Zeng et al. [109] experimentally evaluate the performance of a Wi-Fi system using 80 MHz channels in the presence of 802.11a and 802.11n devices. The authors conclude that the impact on 802.11ac's performance depends on the sub-channel in which the legacy devices operate. If 802.11ac and legacy systems share the same primary channel, then performance of both systems drops proportionally, as is expected in a CSMA based network. However, if the legacy device's primary channel[14] overlaps with any secondary channel of an 802.11ac system using an 80 MHz channel, then the 802.11ac link throughput drops drastically (even to 0 if the legacy signal is strong enough at the 802.11ac receiver). This drastic drop can be attributed to the different channel access mechanisms for primary and secondary channels in 802.11ac as described in Sec. II-A. In this context, Zeng et al. [109] evaluate the performance of an 802.11ac transmitter operating in the SCA mode. It is clear that if any legacy device operates on one (or more) of the secondary channels of the 80 MHz wide

[13]Although the 802.11n standard allows operation in the 2.4 GHz as well as the 5 GHz band, using 40 MHz channels in the 2.4 GHz band becomes infeasible due to the limited availability of spectrum and the presence of other unlicensed technologies, such as Bluetooth, ZigBee, microwave ovens etc. [107]. Considering this, the 802.11ac standard allows operations only in the 5 GHz band.

[14]The notion of a primary channel exists only for 802.11n and 802.11ac systems using 40 MHz and 80 MHz channels. The only bandwidth configuration available at an 802.11a transmitter is 20 MHz. Thus, the primary channel and 20 MHz operating channel hold the same meaning for 802.11a devices.

TABLE V: A summary of existing research on the coexistence between DCF and EDCA devices

Reference	Contributions	Findings
Xiang et al. [98] and Hwang et al. [99]	Analytical models to study DCF-EDCA coexistence have been proposed.	Performance of DCF stations degrades in the presence of VI and VO EDCA traffic classes. On the other hand, DCF stations gain slight advantage over BK and BE EDCA traffic – an effect that can be partially attributed to the different slot decrement methods used in EDCA and DCF.
Villalon et al. [100]	The authors propose an 802.11e standards compliant extension to EDCA — B-EDCA — which provides QoS guarantees for its clients in the presence of DCF stations.	The 802.11e extension proposed is simple, and involves changing the IFS value used by the QoS enabled transmitter depending on its current state (idle or defer). The proposed method ensures QoS guarantees even in the presence of legacy devices.
Majkowski et al. [101]	Implementation of a Hierarchical Token Bucket (HTB) based traffic differentiation mechanism between the Network and MAC layers of DCF devices is proposed.	HTB based traffic differentiation at the DCF clients not only improve the performance of legacy devices in terms of average throughput and MAC layer delay, but also enable provisioning of QoS guarantees at EDCA devices.
Al-Mefleh et al. [102] and Yu et al. [103]	DCF and EDCA compliant extensions have been proposed that modify the Network Allocation Vector (NAV) field in EDCA frames. By doing so, air-time is reserved for EDCA devices in the network.	When the NAV value is set proportional to the number of DCF devices in the network, the performance of EDCA devices improves substantially, while providing certain degree of fairness to the DCF devices.
Banchs et al. [104] and Watanabe et al. [105]	Schemes based on probabilistic deferal of ACK frames to DCF devices are proposed. The deferral probability is computed based on the proportion of DCF traffic in the network.	Using a controlled deferred ACK mechanisms, EDCA devices can be provided throughput guarantees.

channel, the probability that the entire 80 MHz channel is available diminishes, particularly in dense deployment scenarios. Moreover, every time the secondary channel is sensed busy, the Wi-Fi backoff mechanism is repeated before trying to transmit the packet again. This leads to severe degradation of 802.11ac's performance. This coexistence issue has also been studied in [110], [111], where similar findings are reported.

Another possible reason for the significant degradation in 802.11ac's performance when coexisting with older Wi-Fi systems is the asymmetry between the coexisting Wi-Fi systems in terms of the ability to decode preambles. When legacy systems operate in the secondary channel of 802.11ac, the 802.11ac transmitter can decode the preambles of the legacy systems (preamble detection: sensing sensitivity -72 dBm); however, the legacy systems cannot decode 802.11ac preambles since these preambles are transmitted only over the primary channel (energy detection: sensing sensitivity -62 dBm). This asymmetry puts 802.11ac systems at a disadvantage compared to legacy systems with respect to channel access opportunities. This issue can partially be alleviated by using DCA mechanism for secondary channel access as described by Park in [110], where the author shows that DCA can outperform SCA by up to 85% in terms of network throughput.

Extensions to the DCA mechanism have also been proposed. Kim et al. [112] propose a virtual primary channel reservation extension to standard DCA that can achieve up to 10% higher throughput than standard DCA. Furthermore, although DCA improves the 802.11ac performance as compared to SCA, some secondary channels could be left unutilized. For example, in Fig. 4, if the 802.11ac transmitter uses DCA, and senses the secondary channel-2 busy, it transmits over 40 MHz bonded channel (primary + secondary channel-1). In the current standard, there is no provision to bond non-contiguous channels. Thus, even if secondary channel-3 is idle, it is left unutilized. This is because the current 802.11ac standard only allows bonding 40, 80 and 160 MHz channels. Thus, if secondary channel-3 is sensed busy, 802.11ac transmitter transmits over 40 MHz bonded channel (primary + secondary channel-1) even though secondary channel-2 is idle and there are three contiguous idle channels. Stelter et al. [113] recommend that in order to maximize 802.11ac performance in the presence of legacy devices, transmitters should be allowed to bond 60 MHz channels (contiguous as well as non-contiguous) in addition to the existing 40 and 80 MHz bonding. The authors propose a receiver design towards this objective, and using simulations, show that the resulting network throughput gain can be as high as 25%. With the next generation WLAN — 802.11ax — designed to use an OFDMA based MAC, such non-contiguous channel bonding can potentially be achieved easily.

The aforementioned studies analyzed 802.11ac performance when legacy devices operate in the secondary channels. However, even when the operating channel of legacy devices overlaps with the primary channel of 802.11ac, the 802.11ac system's performance drops. This phenomenon is due to two factors. First, since legacy devices communicate over narrower bandwidth, the transmission typically occurs at lower PHY layer data rates. As a result, when legacy devices gain access to the channel, they occupy the channel for a longer interval of time [114]. Second, while the legacy devices communicate over the primary channel, none of the secondary channels can be used by the 802.11ac transmitters since all Wi-Fi clients in the BSS expect to receive beacon signals and other control messages which are transmitted by the AP only in the primary channel. Fang et al. [115] propose a solution to address this issue, by adopting an approach wherein if the 802.11ac primary channel is occupied by a legacy device, the clients within the basic service set relay their transmissions to the AP over secondary channels. The authors show that using their proposed scheme, the overall network throughput can increase by up to 38%.

C. Coexistence between 802.11ax and legacy 802.11

IEEE 802.11ax is the latest 802.11 standard under development. While previous 802.11 amendments have increased the PHY throughput using advanced techniques, the MAC layer protocols used have been fairly similar. Inefficiencies at the MAC layer form a major bottleneck in translating the high PHY throughput into high throughput at the application layer in real-world scenarios, particularly when Wi-Fi deployment is dense. The *IEEE Task Group ax* (TGax) was formed in 2014 with an objective to increase the MAC efficiency of densely deployed 802.11ax STAs with overlapping BSS in the presence and absence of legacy 802.11 STAs [116].

802.11ax introduces several modifications to the 802.11 MAC layer protocol, including the use of MU-OFDMA in both the uplink and downlink, TF, Dynamic Sensitivity Control (DSC), etc. [117] in order to improve the MAC layer efficiency. The success of 802.11ax, to a large extent, will depend on the efficacy of such mechanisms in the presence of legacy 802.11 devices, as well as the impact of 802.11ax devices on legacy devices and vice versa.

The DSC mechanism enables 802.11ax APs and STAs to adapt their carrier sensing threshold based on traffic conditions as opposed to fixed thresholds used until 802.11ac. The use of DSC has been shown to improve the performance of 802.11ax devices as well aggregate system performance when the network consists of only 802.11ax devices [118]–[120]. However, in the presence of legacy devices, the impact of DSC on 802.11ax and legacy devices remains unclear. For example, using simulations, Son et al. [121] show that the impact of devices using DSC on the performance of legacy devices is not negligible, and in some cases the legacy throughput may go down by as much as $70-80\%$. This finding is supported by Wang et al. [122], who attribute the drop in the legacy devices' performance to the unfairness caused by Transmit Opportunity (TXOP) rules set by the 802.11 standard[15]. Wang et al. propose an 802.11ah based solution to mitigate this fairness issue. On the contrary, Wikstrom et al. [123] show that in some situations, legacy throughput can improve by up to 10%. Thus, it is clear that the impact of use of DSC in 802.11ax on legacy systems is highly use-case dependent. Moreover, the findings presented in [121]–[123] are exclusively simulations-driven, and thus are not entirely convincing. More comprehensive studies that include analytical evaluation and testbed experiments, are needed to gain a better understanding of how the DSC mechanism impacts legacy devices.

The use of MU-OFDMA in the uplink of 802.11ax is envisioned to enable multi-user transmissions by dividing the entire channel into multiple sub-channels (i.e., a contiguous or non-contiguous group of subcarriers), and assigning these sub-channels to different STAs. The performance analysis of MU-OFDMA in 802.11ax has been carried out in [124]–[126]. However, these papers consider an 802.11ax only network and the performance of a heterogeneous network comprising of legacy and 802.11ax devices remains unclear at the moment. Furthermore, the use of MU-OFDMA in uplink by STAs is likely to complicate the channel state assessment procedure. As described by Hedayat et al. in [127], an STA participating in uplink MU-OFDMA could transmit less or no energy in some of the sub-channels of the channel used by the AP. As a result, a legacy STA present in its vicinity may determine that these sub-channels are idle, and start transmitting data frames, resulting in collisions at the 802.11ax AP. This can potentially degrade the performance of 802.11ax as well as legacy devices. This situation is referred to as the creation of *artificial hidden nodes* in 802.11ax [127].

[15] This was introduced in IEEE 802.11e as a part of EDCA, and enabled transmitters with high-QoS traffic to continue channel access for a time duration up to TXOP.

D. Open Research Problems

Current Wi-Fi standards do not explicitly address the inter Wi-Fi coexistence problems. As a result, reactive mechanisms have been proposed in the literature to achieve coexistence between newer and legacy Wi-Fi systems. We argue that in the upcoming 802.11ax standard, proactive steps can be taken to facilitate harmonious coexistence between current and future Wi-Fi standards. The following prominent research problems have been identified.

- It is well known that providing support to legacy devices results in the degradation of 802.11ax's overall performance. While the initial working documents on IEEE 802.11ax mention the need to provide backward compatibility and support to legacy devices, there are limited discussions on how the coexistence between 802.11ax and legacy Wi-Fi systems may impact 802.11ax's performance. This complex issue needs to be studied qualitatively as well as quantitatively.
- The use of OFDMA for channel access in 802.11ax can potentially solve some of the coexistence problems discussed in the above subsections. For example, in the presence of legacy systems on one of the secondary channels of an 80 MHz-wide 802.11ax link, the corresponding subcarriers can be nulled, and the idle subcarriers can be allocated to the associated clients. The efficacy of such solutions, however, needs to be evaluated.
- The use of trigger frames in scheduling multi-user transmissions is expected to have an impact on the performance of legacy systems, especially because whenever the MU-OFDMA mode is in progress, legacy systems will have to cease their contention process. However, there have been no studies on this important problem. This problem needs to be better understood.
- The impact of using DSC on the legacy performance and other 802.11ax systems needs to be investigated.
- In order to mitigate the artificial hidden nodes problem, Hedayat et al. [127] propose that the AP must assign sub-channels to different STAs in a manner such that each 20 MHz sub-channel has a minimum number of subcarriers so that any legacy device operating in the neighborhood can detect that all sub-channels are busy.

The design of such a subcarrier division mechanism in a heterogeneous Wi-Fi network warrants further studies.

VII. Other coexisting technologies

In the previous sections, we discussed coexistence issues between multiple technologies operating at present in the 5 GHz bands. In future, other technologies can be expected to begin operations in different unlicensed bands within the 5 GHz range. For example, in the 2.4 GHz ISM band, after the initial success of Wi-Fi and Bluetooth, many other small scale technologies were developed for operations in the unlicensed spectrum. In this section, we explore one such coexistence scenarios that is expected to arise in the upcoming future.

A. Cellular V2X

V2V communications have the potential to significantly reduce the number of road accidents [128]. DSRC is the current de facto standard for V2V communications, albeit with no commercial deployments yet. The 5G Automotive Association (5GAA) [129] has been actively developing a cellular infrastructure based solution for V2V as well as vehicle to pedestrians (V2P) and vehicle to networks (V2N) communications. Together, this paradigm is referred to as the vehicle to everything (V2X) [130], [131] communication paradigm. 5GAA's proposed solution is known as Cellular V2X or C-V2X and is expected to operate in the 5.9 GHz ITS band [132].

C-V2X is based on the Ultra Reliable Low Latency Communication (URLLC) mode of 5G which enables one-way latencies of as low as 5 msec while ensuring 99.999% reliability in packet transmissions [133], [134]. With such low latency and high reliability, C-V2X is a perfect contender for enabling delay sensitive and safety critical vehicular applications such as Emergency Electronic Brake Lights, Blind spot detection, intersection assist etc [135]. It is well known that DSRC, owing to its Wi-Fi inheritance, has scalability issues [136], [137]. C-V2X is designed to address this issue by leveraging the cellular infrastructure. Although present day cellular networks have high end-to-end latencies due to an additional hop as compared to DSRC[16], this is set to come down in 5G networks owing to the adoption of mobile edge computing, smaller transmission time intervals etc. [138].

C-V2X is also being developed to operate in the device-to-device mode whereby C-V2X equipped vehicles can communicate with each other (and also with roadside infrastructure and pedestrians) directly when cellular infrastructure is absent such as along remote areas [132]. This mechanism can help in further reducing the communication latency, but the scheduling of users (C-V2X equipped vehicles) is a challenging problem. Where the cellular infrastructure is present, C-V2X can use a semi-persistent scheduling mechanism whereby the eNB can transmit scheduling information at regular intervals which remain valid until the next set of scheduling information is received. Under such a mechanism, C-V2X users do not need to wait for resources to be scheduled before every packet transmission. This is particularly useful in dense roads, where each eNB may have to support up to several hundreds of vehicles. In terms of resource scheduling, an alternative is cross-frequency scheduling whereby eNB can transmit scheduling information over licensed frequencies, while safety critical packets are transmitted over the 5.9 GHz ITS band.

The debate on C-V2X versus DSRC is an ongoing one [132], [139]. Nevertheless, C-V2X is an active contender to operate in the 5.9 GHz band reserved for ITS operations. If such a situation were to arise in the future, C-V2X will have to operate and possibly coexist with incumbent DSRC as well as possibly Wi-Fi users (as seen in Sec. V). Coexistence between C-V2X and DSRC/Wi-Fi will pose interesting research challenges. Much alike unlicensed LTE and Wi-Fi coexistence, C-V2X is based on a centralized schedule based MAC, while DSRC as well as Wi-Fi use a random access MAC. Thus, lessons learnt from unlicensed LTE and Wi-Fi coexistence can be applied to better orchestrate this coexistence problem. However, the primary difference between the unlicensed LTE-WiFi coexistence and C-V2X coexistence with DSRC/Wi-Fi will be that unlike the former, the latter represents a case where one set of users are co-primary while the other set of users may be co-primary (DSRC) or secondary (Wi-Fi). With C-V2X still in its development phase, it is unclear as to how such a coexistence scenario will turn out, but it is clear that – to ensure harmonious coexistence active participation will be required from the automotive and telecommunications industry, regulators as well as the academia.

VIII. Conclusions

In this paper, we provided a comprehensive survey of the various technical challenges that exist or are expected to arise in the near future when multiple heterogeneous wireless systems share spectrum in the 5 GHz bands. We presented relevant background information, and discussed existing research that have studied the various coexistence scenarios between the coexisting wireless technologies operating in the 5 GHz bands. From our investigation, it became evident that while some of the coexistence problems have been addressed, there still remains several challenging problems that remain unresolved. Finding pragmatic solutions to these problems will be critical to the success of next-generation Wi-Fi technologies. In each of the coexistence scenarios, we highlighted some of these open research problems.

[16] All packets in LTE/cellular networks must pass through the eNB, whereas DSRC works in an adhoc fashion whereby communicating vehicles can send packets to each other in one hop.

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