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The Race to 5G Era; LTE and Wi-Fi

IOANNIS SELINIS[1], KONSTANTINOS KATSAROS[2], MARION ALLAYIOTI[3], SEIAMAK VAHID[1], AND RAHIM TAFAZOLLI[1], (Senior Member, IEEE)
[1]Institute for Communication Systems 5GIC, University of Surrey, Surrey GU2 7XH, U.K.
[2]Digital Catapult, London NW1 2RA, U.K.
[3]Inmarsat, London EC1Y 1AX, U.K.

Corresponding author: Ioannis Selinis (ioannis.selinis@surrey.ac.uk)

ABSTRACT We are on the brink of a new era for the wireless telecommunications, an era that will change the way that business is done. The fifth generation (5G) systems will be the first realization in this new digital era where the various networks will be interconnected forming a unified system. With support for higher capacity as well as low-delay and machine-type communication services, the 5G networks will significantly improve performance over the current fourth generation (4G) systems and will also offer seamless connectivity to numerous devices by integrating different technologies, intelligence, and flexibility. In addition to ongoing 5G standardization activities and technologies under consideration in the Third Generation Partnership Project (3GPP), the Institute of Electrical and Electronic Engineers (IEEE)-based technologies operating on unlicensed bands, will also be an integral part of a 5G eco-system. Along with the 3GPP-based cellular technology, the IEEE standards and technologies are also evolving to keep pace with the user demands and new 5G services. In this paper, we provide an overview of the evolution of the cellular and Wi-Fi standards over the last decade with a particular focus on the Medium Access Control and Physical layers, and highlight the ongoing activities in both camps driven by the 5G requirements and use-cases.

INDEX TERMS 5G mobile communication, IEEE 802.11ad, IEEE 802.11af, IEEE 802.11ah, IEEE 802.11ax, IEEE 802.11ay, LTE evolution, LTE Release 14, LTE Release 15, machine-type-communication (MTC), millimeter wave (mmWave), radio access network (RAN).

I. INTRODUCTION

The forecasts for the number of devices connected to internet and the expected traffic load by 2021 do vary but it is generally agreed that many billions of devices and 49 exabytes of traffic per month, will need to be supported, with most of the traffic expected to be delivered over wireless networks [1]. To support such massive connectivity and traffic demands, both the cellular systems and Wireless Local Area Networks (WLANs) are evolving [2], [3].

Emerging services, such as remote health care or learning, connected vehicles exchanging safety-critical information and ultra-high resolution video streaming will require higher data rates and lower latency than is available today. To support the stringent requirements of the next generation services will be enormously challenging in terms of capacity and coverage for the next generation networks, a.k.a. Fifth-Generation (5G). The vision for 5G is to provide a perception of an unlimited bandwidth to every user, everywhere, anytime.

The time for 5G networks has arrived, considering that approximately every decade, a new generation is deployed; 1G in 1980s', 2G in 1990s', 3G in early 2000's, and 4G in 2010s'. Different technologies have been deployed for each generation, to accommodate specific/primary use cases. For example, analog Frequency Division Multiple Access (FDMA) was deployed in 1G systems when voice was the targeting use case, Time Division Multiple Access (TDMA)/FDMA for voice and text in 2G networks, Code Division Multiple Access (CDMA) in 3G systems when mobile internet access was supported, and Orthogonal Frequency-Division Multiple Access (OFDMA) is currently applied in 4G when high data rates and video over internet were the targeting use cases. However, 5G systems may comprise various waveforms; new or mature access scheme technologies, to meet requirements in different scenarios.

Some of the 5G requirements described in International Telecommunication Union (ITU) report [4], back in early 2017, include 20 Gigabits per Second (Gbps) and 10 Gbps peak rates for downlink (DL) and uplink (UL), respectively, while DL spectral efficiency of 30 bit/s/Hz and 15 bit/s/Hz for UL are targeted. Moreover, lower latency requirements, very high density of devices e.g. 1 million devices per km^2, and support of various classes of mobility at speeds of up to 500 km/h are also defined in that draft. According to ITU and 5G - Infrastructure Public Private Partnership (5G-PPP) [5], 5G network services are classified into three principal dimensions (also referred to as ''use case families''); enhanced Mobile Broadband (eMBB), massive Machine Type Communications (mMTC), and Ultra-high Reliable and Low Latency Communications (URLLC). To meet these requirements and address the challenges of diverse use cases and vertical industries, heterogeneous ultra-dense networks operating in various frequency bands will be deployed as part of 5G network [6]. Thus, 5G can indeed be regarded as ''a network of networks''.

High frequency spectrum above the 6 GHz band, is likely to be allocated for 5G cellular to deliver very high data rate services [7]–[11]. Many vendors have already released the next wave of chipsets with well known names e.g. Intel, Samsung, Qualcomm amongst them, supporting enormous bandwidths at millimeter wave (mmWave) frequencies [12]. Significant studies and measurement campaigns have also been conducted to provide better understanding of propagation characteristics and validate the channel models at mmWave frequencies [13]–[15]. This in turn, will result in identifying the challenges and technologies that can be used to overcome them.

On the other hand, Sub-1 GHz frequency bands have already been exploited by both the cellular and more recent WLAN amendments, for applications that require lower data rates and wider coverage range [16], [17]. However, additional spectrum is incorporated as it becomes available, e.g. the spectrum at 700 MHz, allocated for long-range communication of low-power devices [18]. The unused broadband frequencies, known as White Spectrum, also enable long range communications suitable for applications such as smart grid or smart cities. The small bandwidths also enable low power consumption, which is crucial for sensors deployed in areas that are not easily accessible e.g. forests.

Energy efficiency is also one of the requirements defined for future networks [19]–[21]. Green communication networks is not a new concept, however, it is even more critical now, with the massive number of devices connected to wireless networks [22], [23]. Energy harvesting is also an approach that researchers are looking to for Internet of Things (IoT) applications [24], [25].

The introduction of new frequency spectrum for wireless communications, does not mean that the conventional 2.4/5 GHz licensed/unlicensed bands are not considered for 5G networks. Advancements have also been proposed in both the cellular systems and the WLANs by the Third Generation Partnership Project (3GPP) and the Institute of Electrical and Electronic Engineers (IEEE) standards respectively, to keep pace with the explosive growth in mobile data traffic, use cases, and user requirements. The unlicensed technologies will play a significant role on forming the future wireless networks (i.e. 5G) and meeting the requirements, since several technologies were initially used in IEEE 802.11 networks before adopted by 3GPP (e.g. Multiple-Input-Multiple-Output (MIMO), channel bonding etc.) [26].

This article focuses on Long Term Evolution (LTE) and IEEE 802.11 Radio Access Network (RAN). We first describe and highlight salient features of the aforementioned technologies in the pre-5G releases of relevant standards by elaborating their functionalities and providing an extensive description of the way these technologies function at the Physical (PHY) and Medium Access Control (MAC) levels. Figure 1a depicts the current key and planned features in LTE and IEEE 802.11 technologies. Although, most of the functionalities and operations in IEEE 802.11 devices are handled locally by the MAC layer, nevertheless, enterprise-level access controllers that are used to manage networks consisting of multiple APs, can add intelligence to the system. We then present an in-depth overview of the 5G-related technological advancements being introduced in both 3GPP and IEEE 802.11. We review the latest amendments (released or under active development) and identify several challenges that need to be addressed. The structure of this paper is as follows. We have classified the work that has been conducted into three main categories, namely, mmWave mobile communications, operating at above 6 GHz bands (Section II), conventional systems operating in below the 6 GHz frequency bands (Section III), and advancements in both LTE and IEEE 802.11 for the support of MTC (Section IV). Each one of these categories is further organized into LTE and WLAN systems, therefore, allowing the reader to draw comparisons between the 5G-enabling technologies and solution approaches that have been proposed for both LTE and IEEE 802.11. A first taste of the similarities and differences of these technologies at a high level, is illustrated in Figure 1b. Section V concludes this article, whereas a list of acronyms and their corresponding definitions is provided in Table 1.

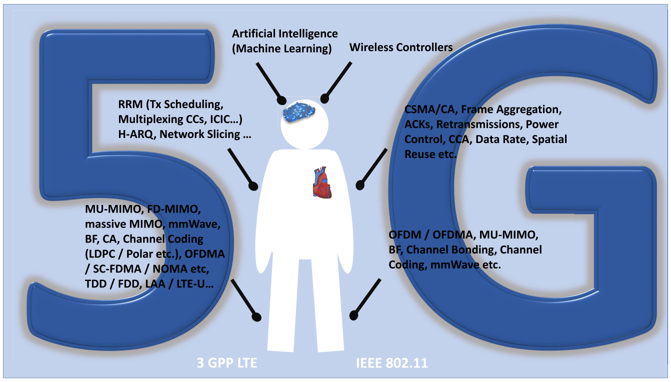
II. TECHNOLOGIES DESIGNED TO OPERATE AT ABOVE 6 GHz BANDS

This section is classified into three parts. The first one presents the potentials, challenges and the enabling technologies at PHY and MAC layers, for systems operating in mmWave bands. The 5G New Radio (NR) technology is explained in the second subsection as part of the 3GPP cellular systems, while the last subsection describes the IEEE 802.11 amendments that have already hit the market or are under active development.

A. OPPORTUNITIES, CHALLENGES, AND CANDIDATE TECHNOLOGIES

Exploiting the mmWave bands[1] can potentially offer many advantages but at the same time impose several challenges. Wider bandwidths can offer not only higher data rates but also lower relative power consumption, provided that the

[1]The 30-300 GHz band is referred to as mmWave (wavelength 1cm to 1mm approx.). Since radio waves above the 6 GHz band share similar propagation characteristics with those at 30-300 GHz band, industry currently considers mmWave as the 6-300 GHz frequency band.



(a)

	3GPP LTE	IEEE 802.11
Technology	Synchronous – Controlled by BS	Asynchronous – (DCF is mainly used)
First Released	LTE – Release 8 (4G), 2008	Late 1990s' (IEEE 802.11-1997, IEEE 802.11a/b-1999)
Channel Access	UEs are allocated with resources after a successful preamble contention. Different channels are used, depending on the traffic and link type (i.e. DL/UL, data/control etc).	STAs grant access to the medium, following CSMA/CA procedure. Once the channel is sensed free, they can initiate a transmission, occupying the whole channel. All transmissions occur over the same channel. Frame collisions are inevitable.
Operating Frequency	Allocated bands in 700 MHz – 6 GHz	TVWS / Sub-1 GHz / 2.4 / 5 GHz / 60 GHz
Support of BS/AP Coordination	Yes	No
Simultaneous connections to multiple BSs/APs	Yes (Dual Connectivity)	No
Deployment	Controlled/Managed (Outdoor)	Uncontrolled/Unmanaged/ Easy (Indoor mainly)
Coverage Range	Multiple km	A few hundred meters
Channel Access Scheme	OFDMA / SC-FDMA	OFDM
Max. Transmit Power	48 dBm for macro cell BS / 24 dBm for UEs	20 dBm
Inter-Cell Interference	Controlled	Uncontrolled
MIMO	8x8 DL and 4x4 UL	8x8 DL/UL (IEEE 802.11ac)
MU-MIMO	DL/UL	DL
Channel Bandwidth	Varies from 1.4 MHz – 20 MHz	20 MHz
Carrier Aggregation	Yes (up to 32 CCs)	Yes (known as channel bonding – up to 160 MHz)
Peak Data Rate	3 Gbps (DL) & 1.5 Gbps (UL) for LTE 4G	6.77 Gbps (DL/UL)

(b)

FIGURE 1. LTE versus IEEE 802.11: a) key technologies and b) high-level comparison.

TABLE 1. List of acronyms and corresponding definitions.

Acronym	Definition	Acronym	Definition	Acronym	Definition	Acronym	Definition
AA	Automotive Association (5GAA)	EAB	Extended Access Barring	MCS	Modulation and Coding Scheme	RLSS	Registered Location Secure Server
A-BFT	Association Beamforming Training	eDMG	Enhanced DMG	MEC	Mobile Edge Computing	RNTP	Relative Narrowband Transmit Power
A-MPDU	Aggregate Medium Access Control Protocol Data Unit	EDT	Early Data Transmission	MEMS	Micro-electro-mechanical Systems	ROM	Receive-only mode
A-MSDU	Aggregate Medium Access Control Service Data Unit	EIFS	Extended Interframe Spacing	MHz	Megahertz	RRC	Radio Resource Control
A/D	Analog-to-Digital	eIMTA	Enhanced Interference Mitigation and Traffic Adaptation	MIMO	Multiple-Input-Multiple-Output	RRM	Radio Resource Management
ABS	Almost Blank Subframe	eMBB	Enhanced Mobile Broadband	ML	Machine Learning	RSSI	Received Signal Strength Indicator
AC_BE	Access Class Best Effort	eMTC	Enhanced Machine Type Communications	MME	Mobility Management Entity	RTS/CTS	Request-to-Send / Clear-to-Send
AC_BK	Access Class Background	eNodeB	Base Station, explicitly for LTE system (4G)	MMSE	Minimum Mean Squared Error	RU	Resource Unit
AC_VI	Access Class Video	EPS	Evolved Packet System	mmWave	Millimeter Wave	S-GW	Serving Gateway
AC_VO	Access Class Voice	ER	Extended Range	MR-FSK	Multi-Rate Frequency Shift Keying	S-RLNC	Systematic RLNC
ACB	Access Class Barring	ESPAR	Electronically Steerable Passive Array Radiator	MR-O-QPSK	Multi-Rate Offset Quadrature Phase Shift Keying	SA	System Architecture Working Group
ACK	Acknowledgment	ETSI	European Telecommunications Standards Institute	MR-OFDM	Multi-Rate OFDM	SC-FDMA	Single-Carrier FDMA
AGC	Automatic Gain Control	FCC	Federal Communications Commission	MTC	Machine Type Communications	SC-OFDM	Single-Carrier OFDM
AID	Association Identifier	FD-MIMO	Full-Dimension MIMO	MTC-IWF	MTC - Inter Working Function	SC-PTM	Single-Carrier Point-to-Multipoint
AIFS	Arbitration Interframe Spacing	FDD	Frequency Division Duplex	MTCH	Multicast Traffic Channel	SCell	Secondary Cell
AP	Access Point	FEC	Forward Error Correction	MU	Multi-User	SCS	Service Capability Servers
API	Application Programming Interface	FFR	Fractional Frequency Reuse	NACK	Negative Acknowledgement	SDM	Spatial-Division Multiplexing
APSD	Automatic Power Save Delivery	FFT	Fast Fourier Transform	NAICS	Network Assisted Interference Cancellation & Suppression	SDN	Software Defined Network
AR	Augmented Reality	FRMCS	Future Railway Mobile Communication System	NAV	Network Allocation Vector	SIFS	Short Interframe Spacing
ARQ	Automatic Repeat Request	FSS	Frequency Selective Scheduling	NB	Narrowband	SINR	Signal-to-Interference-plus-Noise ratio
ATI	Announcement Transmission Interval	FST	Fast Session Transfer	NDP	Null Data Packet	SISO	Single-Input-Single-Output
ATIS	The Alliance for Telecommunications Industry Solutions	Gbps	Gigabits per Second	NDP MAC frame	Null Data Packet MAC frame	SLS	Sector-Level-Sweep
BATS	BATched Sparse Code	GDB	Geolocation Database	NDP short feedback	NDP short feedback for IEEE 802.11ax	SLSSs	Sidelink Synchronization Signals
BB	Base-Band	GHz	Gigahertz	NFV	Network Function Virtualization	SNR	Signal-to-Noise ratio
BCC	Binary Convolutional Code	GNSS	Global Navigation Satellite System	NLOS	Non-Line-of-Sight	SON	Self-Organizing Network
BCCH	Broadcast Control Channel	GP	Guard Period	NOMA	Non-Orthogonal Multiple-Access	SP	Scheduled Service Period
BCH	Broadcast Channel	GPRS	General Packet Radio Service	NR	5G New Radio	SPS	Semi-Persistent Scheduling
BCU	Basic Channel Unit	GPS	Global Positioning System	OBSS	Overlapping Basic Service Set	SR	Spatial Reuse
BEB	Binary Exponential Back-off	GSM	Global System for Mobile Communications	OFDM	Orthogonal Frequency Division Multiplexing	SST	Subchannel Selective Transmission for IEEE 802.11ah
BF	Beamforming	HARQ	Hybrid-ARQ	OFDMA	Orthogonal Frequency Division Multiple Access	SST	Slice/Service Type (Network Slicing LTE Rel-15)
BHI	Beacon Header Interval	HCCA	HCF Controlled Channel Access	OI	Overload Indicator	SSW	Sector Sweep
BI	Beacon Interval	HCF	Hybrid Coordination Function	OMA	Open Mobile Alliance	STA	Station
BS	Base Station	HDMI	High-Definition Multimedia Interface	P-GW	Packet-Data-Network Gateway	STBC	Space-Time Block Coding
BSR	Buffer Status Report	HE	High-Efficiency	PAID	Partial Association Identifier	STF	Short Training Field
BSS	Basic Service Set	HII	High-Interference Indicator	PARP	Peak-to-Average-Power ratio	TCP	Transmission Control Protocol
C-Plane	Signaling Control for LTE	HPLMN	Home Public Land Mobile Network	PBCH	Physical Broadcast Channel	TDD	Time Division Duplex
CA	Carrier Aggregation	HSPA	High-Speed Packet Access	PC-FICH	Physical Control Format Indicator Channel	TDMA	Time Division Multiple Access
CAQ	Channel Availability Query	HSS	Home Subscriber Server	PCCH	Paging Control Channel	TETRA	Terrestrial Trunked Radio
CBAP	Contention-Based Access Period	HT	High-Throughput	PCDCH	Physical Control Downlink Channel	TG	Task Group
CC	Component Carrier	HTC	Human Type Communications	PCell	Primary Cell	TID	Traffic ID
CCA	Clear Channel Assessment	ICD	Inter-Cell Distance	PCF	Point Coordination Function	TID	Traffic Indication Map, for IEEE 802.11ah
CCA/CS	Clear Channel Assessment / Carrier Sensing	ICI	Inter-Carrier Interference	PCH	Paging Channel	TM	Transmission Mode
CCA/ED	Clear Channel Assessment / Energy Detection	ICIC	Inter-Cell Interference Coordination	PCP	Personal-Basic-Service-Set Control Point	TPC	Transmit Power Control
CCCH	Common Control Channel	IE	Information Element	PDCP	Packet Data Convergence Protocol	TRN	Training
CCSA	China Communications Standards Association	IEEE	Institute of Electrical and Electronic Engineers	PDSCH	Physical Data Shared Channel	TTI	Transmission Time Interval
CEF	Channel Estimation Field	IETF	Internet Engineering Task Force	PER	Packet Error Rate	TVWS	Television White Spectrum
CFO	Carrier Frequency Offset	IoT	Internet of Things	PHICH	Physical Hybrid-ARQ Indicator Channel	TWT	Target Wake Time
CMOS	Complementary Metal-Oxide-Semiconductor	IP	Internet Protocol	PHY	Physical	TxOP	Transmission Opportunity
CoMP	Coordinated Multipoint	ISI	Inter-Symbol Interference	PLCP	Physical Layer Convergence Procedure	U-Plane	User Data for LTE
CP	Circular Polarization, Section I	ITU	International Telecommunication Union	PMCH	Physical Multicast Channel	UE	User Equipment
CP	Cyclic Prefix	JQS	Joint Queue Scheduler	PRA	Prioritized Random Access	UHD	Ultra-High-Definition
CRC	Cyclic Redundancy Check	L-SIG	Legacy Signal Field	PRACH	Physical Random Access Channel	UL	Uplink
CRS	Common Reference Signals	L-SIG TxOP	Legacy Signal Transmission Opportunity	ProSec	Proximity Services	UL-SCH	Uplink Shared Channel
CSAT	Carrier Sensing Adaptive Transmission	LAA	Licensed Assisted Access	PS-Poll	Power Save Poll Frame	UMTS	Universal Mobile Telecommunications System
CSI	Channel State Information	LBT	Listen-Before-Talk	PSBCH	Physical Sidelink Broadcast Channel	UpPTS	Uplink Pilot Time Slot
CSM	Channel Scheduling Management	LDPC	Low-Density-Parity-Check	PSDCH	Physical Sidelink Discovery Channel	URLLC	Ultra-high Reliable and Low Latency Communications
CSMA/CA	Carrier-Sense-Multiple-Access with Collision-Avoidance	LHCP	Left-Hand Circular Polarization	PSDU	PLCP Service Data Unit	USB	Universal Serial Bus
CVS	Contact Verification Signal	LMDS	Local Multipoint Distribution Service	PSM	Power-Saving Mode	V2I	Vehicle-to-Infrastructure
CW	Contention Window	LNC	Linear Network Code	PSMP	Power Save Multi-Poll	V2P	Vehicle-to-Pedestrian
D/A	Digital-to-Analog	LoRa	Long-Range	PSSCH	Physical Sidelink Shared Channel	V2V	Vehicle-to-Vehicle
D2D	Device-to-Device	LoRaWAN	Long-Range Wide Area Network	PUCCH	Physical Uplink Control Channel	V2X	Vehicle-to-Everything
DCCH	Dedicated Control Channel	LOS	Line-of-Sight	PUSCH	Physical Uplink Shared Channel	VANET	Vehicular Ad-hoc Network
DCF	Distributed Coordination Function	LP	Linear Polarization	QAM	Quadrature Amplitude Modulation	VGA	Variable Gain Amplifier
DFS	Dynamic Frequency Selection	LP-WAN	Low-Power Wide Area Network	QoE	Quality-of-Experience	VHT	Very-High-Throughput
DFT	Discrete Fourier Transform	LPSC-OFDM	Low-Power-Single-Carrier OFDM	QoS	Quality-of-Service	VNF	Virtual Network Function
DIFS	DCF Interframe Spacing	LT	Luby Transform	RACH	Random Access Channel	VoLTE	Voice over LTE
DL	Downlink	LTE	Long Term Evolution	RAN	Radio Access Network	VR	Virtual Reality
DL-SCH	Downlink Shared Channel	LTF	Long Training Field	RAT	Radio Access Technology	WCDMA	Wideband Code Division Multiple Access
DMG	Directional Multi-Gigabit	LWA	LTE-WLAN Aggregation	RAW	Restricted Access Window	WEP	Wired Equivalent Privacy
DMRSs	Demodulation Reference Signals	M2M	Machine to Machine	RDG	Reverse Direction Grant	Wi-SUN	Wi- Smart Utility Networks
DQS	Disjoint Queue Scheduler	MAC	Medium Access Control	RDP	Reverse Direction Protocol	WiGig	Wireless Gigabit
DRX	Discontinuous Reception	MAX-C/I	Max-Carrier-to-Interference	Rel	Release, for LTE	WLAN	Wireless Local Area Network
DSC	Dynamic Sensitivity Control	MBB	Mobile Broadband	RF	Radio-Frequency	WRAN	Wireless Regional Area Network
DTCH	Dedicated Traffic Channel	MBMS	Multimedia-Broadcast-Multicast-Services	RHCP	Right-Hand Circular Polarization	WSD	White Space Device
DTI	Data Transfer Interval	Mbps	Megabits per Second	RID	Response Indication Deferral	WSM	White Space Map
DTIM	Delivery Traffic Indication Map, for IEEE 802.11ah	MBSFN	Multicast/Broadcast Single-Frequency Network	RLC	Radio-Link Control	2G/3G/4G/5G	Second/Third/Fourth/Fifth Generation
DTX	Discontinuous Transmissions	MCCH	Multicast Control Channel	RLNC	Random Linear Network Code	3GPP	Third Generation Partnership Project
DwPTS	Downlink Pilot Time Slot	MCH	Multicast Channel	RLQP	Registered Location Query Protocol	5G-PPP	Fifth Generation - Infrastructure Public Private Partnership

channel is not severely attenuated [27]. Although, mmWave-based communication systems already exist, e.g. Local Multipoint Distribution Service (LMDS) [28], operating at 23-32 GHz bands with range over 1 km, they are not used for mobile communications. The main obstacles for using those technologies in portable devices, include the size, cost, high losses, and power consumption of the electronic components (e.g. power amplifiers, mixers, antennas) [29].

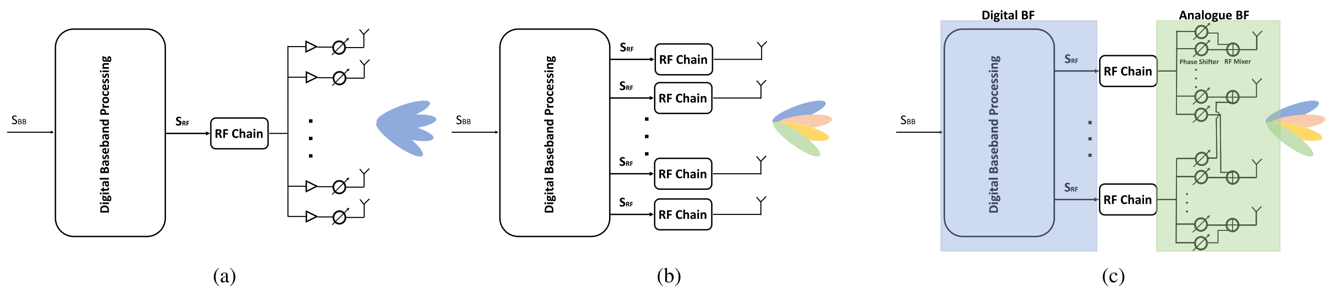


FIGURE 2. **Beamforming techniques: a) Analogue/RF, b) Digital/Precoding, and c) Hybrid.**

The signal in mmWave frequencies can be severely attenuated by absorption due to atmospheric gases, foliage, and rainfall. However, recent measurements in New York City [30]–[32], show that cell sizes of 200m radius can provide the required coverage for mmWave systems; the results of investigations indicate that the signal does not significantly attenuate at this distance, even in Non-Line-of-Sight (NLOS) environments. Path loss however, can be further reduced by enabling highly directional antennas, resulting in similar or even reduced path loss than the current cellular systems experience.

However, highly directional antennas (e.g. horn, patch, and antenna arrays that employ directive radiating elements) suffer from limited coverage, due to their very narrow beams. The coverage can be improved however, by employing beamforming (BF) or using beam steerable, sectorized or switched beam array antennas at the Base Stations (BSs) and/or portable devices [33], [34]. This allows the beam to be directed in the desired direction. BF can also be used to avoid unwanted interference, since the envisaged beams are typically very narrow and are directed only towards specific users.

That is, by combining multiple signals from an antenna array, a directional beam is formed towards a user. Directivity is a function of the number of elements and their spacing [35]. It improves with the number of elements or spacing. However, the number and level of side lobes increase with the number of elements, thus reducing antenna's gain and directivity [36]. Moreover, when the element spacing increases, the amplitude of grating lobes increases. This can in turn lead to high interference to or from close-by-users. Apart from the number of elements and their spacing, unequal power and/or phase distribution (to the elements) can be applied to alter direction, side lobe level, and directivity.

Switched beam antenna arrays and beam steerable antennas require multiple Radio-Frequency (RF) chains, leading to excessive cost and power consumption. At large BS sites, where size is not a constraint, beam switchable antennas can be deployed. However, since for portable devices size is an important constraint, switchable antennas are not a viable option. A beamformer in a directional antenna can give the perception (to a user) of ''full'' coverage, by tracking the user and steering the beam toward it.

B. 3GPP LTE TECHNOLOGY - DIRECTIONS FOR mmWave BANDS

To efficiently support larger bandwidths, deal with the challenges at mmWave bands and the new use cases, 3GPP has been working on a new Radio Access Technology (RAT) and addressing physical and higher layer protocol requirements. Although, the new 5G RAT is being designed for operation at frequencies from Sub-1 GHz to 100 GHz, we, first, describe some of its features relating to the mmWave band operations. This new RAT is not required to be backward compatible with LTE, but forward compatible in the sense that future evolution is ensured [37].

5G NR is the name of the wireless standard for air interface of the next generation of mobile networks [181], [182]. Beamforming (BF), Massive MIMO, Orthogonal Frequency Division Multiplexing (OFDM) scalability, slot flexibility, energy efficiency, and advanced channel coding are the main case studies that have been considered for the 5G NR. The mmMAGIC project [183] that is developed by the European 5G-PPP during Phase 1, has proposed solutions to coding schemes for providing robustness and higher throughput, lower complexity for MIMO, and flexible Frequency Division Duplex / Time Division Duplex (FDD/TDD) frame structure. Multiple contributions have also been submitted to 3GPP and ITU in regards to channel measurements and modelling at frequency bands over 6 GHz. In this section, we describe the BF and Massive MIMO that are strongly related with the mmWave bands.

1) PHY LAYER ENHANCEMENTS

a: BEAMFORMING TECHNIQUES

BF is a technique that can be applied to reconfigure antenna's beam in terms of main beam direction and amplitude. Depending on BF architecture, BF schemes can be classified into three main categories; Analogue or RF, Digital, and Hybrid, as depicted in Figure 2.

The Analogue BF comprises one RF chain even when substantial number of antenna arrays is used. It enables low complexity, low power consumption, and operation at reduced costs if small number of phase shifters is used. The entire phased antenna array is driven by a single base-band (BB) processing module. It uses Variable Gain Amplifiers (VGAs), which enable the amplitude of the applied signals to be varied, along with phase shifters that enable adjustment of the phase of the applied signals. It is therefore, possible to control both amplitude and phase of the signals applied to antenna's elements. Analogue BF is simpler than Digital BF, since it only requires one RF chain per antenna array, which also reduces power consumption (transmit and processing power) and overcomes the RF hardware limitations [38], [39]. Analogue BF provides an effective method of generating high BF gains from substantial number of antennas. It is cheaper to implement and operate than Digital BF. However, Analogue beamformers do not provide multiplexing gains, since transmissions on multiple parallel streams is not supported, resulting in poorer performance than Digital BF.

Digital BF, on the other hand, is achieved using digital precoding, which involves multiplying a particular coefficient to the modulated BB signal per RF chain. This means that multiple beams can be supported simultaneously, theoretically as many as the number of antenna elements, which allows more users to be served at the same time [40]. It offers the ability of sending data in parallel streams, exploiting spatial diversity and multiplexing. It also provides continuous steering and can be used to enhance performance of MIMO systems at the cost of high complexity, especially when using massive MIMO; since one RF chain per antenna would then be required. In conventional (operating below 6 GHz) systems, precoding is usually done in BB, in order to have better control over the entries of the precoding matrix [41]. However, the excessive cost, power consumption of mixed signal components, and complexity (due to Analog-to-Digital converters) make full digital BB precoding prohibitive for millimeter wave frequencies, with the currently available semiconductor technologies. The design of the precoding matrices in Digital BF usually relies on having complete Channel State Information (CSI); an overhead that increases with the number of antennas [41] and is difficult to obtain for substantial number of antennas (e.g. mmWave Systems) [42]. Furthermore, another reason that CSI is difficult to acquire, is the small Signal-to-Noise ratio (SNR) associated with the signals before BF is applied [41]. Digital BF provides higher degree of freedom in comparison to Analogue BF that can be used by MIMO systems to improve system's performance.

There are however, a number of open issues with this technology, including calibration, complexity, and cost [43]. The implementation of a dedicated RF chain per antenna element, makes it unsuitable for cost-limited or small portable power-limited devices [44]. To combine the advantages of both Analogue and Digital techniques, Hybrid BF has therefore been proposed, reducing both the complexity/power consumption and feedback overheads [41], [45], [46].

Hybrid BF offers a trade-off between performance/ flexibility and simplicity/cost [40]. In Hybrid BF, a directive beam is formed through Analogue BF with the aid of phase shifters and VGAs [46], whereas Digital BF is used to provide the flexibility required for advanced multi-antenna techniques, such as multi-beam MIMO [47]. Hybrid BF can overcome the hardware constraints of Analogue-only BF, whilst providing the performance advantages associated with Digital BF, e.g. transmission of multiple parallel streams. On the other hand, it suffers from certain disadvantages. For example, it requires multiple RF chains along with a complicated architecture [43] and the requirement to obtain CSI for large number of antennas is still another obstacle for Hybrid BF.

b: BEAM-STEERING TECHNIQUES

Beam-steering can be considered to be a variant of Analogue BF technique, which is applied to reconfigure the directionality of the main antenna's beam. It mostly offers only discrete steering and not continuous [48]. It is relatively simple and low-cost technique, and is considered to be suitable for small power-limited devices, depending on the structure of the antenna.

Continuous beam-steering is essential for maintaining the communication link between two devices, since it can easily be disrupted in high frequencies. For example, narrow beams are highly affected by wind, which could lead to beam misalignment. However, robustness can be preserved by the antenna array's geometric shape; circular antenna arrays are more robust against small vibrations or angle variations due to axial symmetry [49]. Continuous beam-steering can be achieved either with phased arrays or with Electronically Steerable Passive Array Radiator (ESPAR) antennas.

The phase of each element in phased arrays, is controlled through phase shifters [50], e.g. CMOS, MEMS etc. However, the use of phase shifters imposes some challenges, such as relatively high-cost, complexity, and high insertion losses in high frequencies. Nevertheless, such losses can be mitigated, using phase shifters based on MEMS materials at a price of increased system's cost. Moreover they are inherently narrowband (NB) [51].

On the other hand, ESPARs steer the beam through varactors and have lower power consumption, since only one element of the array is fed by signal power (driven element). However, they suffer from limited steering range and high parasitic losses of the reactive loads in high frequencies. It is also challenging to calibrate all the reactive loads for obtaining the desired steering angle while keeping the antenna acceptably matched [52]. The analysis of these techniques is out of the scope of this article, and the reader can refer to [53]–[57], for more information.

c: MASSIVE MIMO

Massive MIMO is another key technology capable of handling the huge growth in data traffic and coping with the high path loss of mmWave frequencies (enhanced coverage) [58]. Massive MIMO relies on considerable number of antennas to serve multiple users simultaneously. The short free-space wavelength (λ) at high frequencies, enables small sized antennas, thus enabling incorporation of larger number of antenna elements in a given area, compared to centimeter-wave frequencies [59]. However, the shorter coherence time due to higher Doppler spread in mmWave bands, reduces its spatial multiplexing gains. Moreover, the use of substantial number of antennas provides robustness to transmissions (i.e. better bit error rate for the same SNR level, use of lower Modulation and Coding Scheme (MCS) with lower SNR requirements whereas targeted data rate is achieved (spatial multiplexing)), and to failures in one or more antenna units. It also, averages out noise, small-scale fading, and any hardware imperfections [60]. Hence, it can be assumed that all OFDM sub-carriers for example, will experience the same gain. This in turn, will affect the resource allocation algorithms, since users could use (be allocated) the whole bandwidth or any resource block independently of channel conditions. Reduction in transmit power for single-antenna users can also be achieved when combined with a Massive MIMO receiver. Users can scale-down their transmit power proportional to the number of antennas at the BSs with perfect CSI or to square root with imperfect CSI [61]. On the other hand, computational complexity of precoder increases with the number of antennas, thus, low complexity precoding methods are required. Another barrier to fully exploit Massive MIMO, is the pilot contamination issue [62]. The limited number of orthogonal pilots, confines the number of users that can simultaneously be served. Pilot reuse, the usage of non-orthogonal pilots, and blind-techniques for channel estimation are some of the approaches that can be followed to address pilot contamination. Furthermore, data processing is also challenging due to the huge-amounts of data sources that Massive MIMO enables, which will cause high processing complexity at BSs. A potential solution to deal with the high processing complexity at BSs, is to offload data processing to a centralized data center (cloud computing) [63]. However, cloud computing may increase traffic load on the backhaul and latency due to communication link between BSs and cloud servers, which make it more suitable for applications that are not delay-sensitive. For applications that require instantaneous response and where the data volume to be processed is small (e.g. IoT sensors for smart traffic lights), processing can be realized at the edge of a network, close to the source devices (edge computing).

Massive MIMO can work in both Line-of-Sight (LOS) and NLOS environments, but the main challenge is if it can be used in FDD systems [64]. TDD based Massive MIMO can support more users due to a lower overhead, whereas in FDD systems, channel estimation is required in both DL and UL bands as they operate in different frequency. Moreover, the channel coherence (time/bandwidth) that depends on the propagation environment, operating frequency, and user mobility, severely affect the amount of overhead. Therefore, Massive MIMO is more suitable for supporting low-mobility nodes operating in low-frequency spectrum in FDD systems.

d: ADDITIONAL METHODS FOR ENHANCED COVERAGE

In addition to steering and Massive MIMO techniques, two other approaches can be followed to improve coverage in mmWave bands; Distributed Antenna Arrays and Relaying (i.e. Amplify and Forward, Compress and Forward, Detect and Forward, Decode and Forward) [65]. By employing multiple antenna arrays in predefined locations, coverage, cell-edge performance, and energy consumption could be improved (if there is a LOS communication link, a lower transmit power could be used) [66], [67]. However, synchronization of distributed antennas is challenging; Carrier Frequency Offset (CFO) caused by the mismatch of transceiver oscillators due to Doppler effect [68], phase noise due to imperfect hardware; oscillators' instabilities, especially for mmWave frequencies [69], and time synchronization between transceivers' clocks are the main reasons for Inter-Symbol Interference (ISI) and degrade system performance [70], [71]. The use of Separate (independent) or Common Local oscillators also affect phase noise [72]. The former oscillators are mainly applied when the distance between the antennas is large [73], e.g. Distributed Antenna Arrays. There are several algorithms proposed in the literature to address the synchronization of distributed antennas [74]–[76]. On the other hand, Relaying can be used to prevent blockage for low-velocity users.

2) MAC LAYER ENHANCEMENTS

So far, we have discussed the enabling technologies and challenges for mmWave frequency bands in a cellular network. Summarizing the benefits of exploiting mmWave spectrum, we can state the following: mmWave bands i) provide wider bandwidths enabling high throughput communications in the order of Gbps, ii) enable deployment of large number of antennas (packed into a small area), and iii) inherently support Spatial Reuse (SR) enhancements due to the propagation characteristics in high frequencies. SR can be further improved by using directional antennas, lowering down antenna's height (at BSs), and/or down-tilting the beam.

The use of directional antennas in mmWave spectrum, poses some challenges at the MAC layer [77]. Current cellular or Wi-Fi technologies rely on omni-directional communications and contention-based channel access (mainly), thus, alterations are required to some Layer 2 functionalities to support the innovative antenna technologies.

First, the use of directional antennas during the initial access is challenging. With omni-directional antennas acquiring frequency/time synchronization (signals' detection) is relatively easy. However, if narrow-beams are used during the scanning and/or synchronization procedures, additional delays may arise. BSs and users need to transmit and search in various angles/directions until synchronization is achieved.

An overview and comparison of the techniques proposed for the initial access in mmWave systems (e.g. exhaustive, iterative, and Context-Information search algorithms), is presented in [78]. Under the exhaustive search category, both users and BSs use a predefined sectorized antenna, consisting of multiple narrow beams to provide a 360° coverage. The second category, iterative schemes, comprises algorithms that follow a two-step procedure for the initial access. In the first stage, BSs use a sectorized antenna with wide beams. Once, a pair of sectors is established, then BSs initiate the second phase, where they search for a narrower beam within this wide beam sector, to optimize performance. The Context-Information search techniques, follow a three-step procedure. First, the macro BSs broadcast the Global Positioning System (GPS) coordinates of all micro BSs that operate at mmWave frequencies. Secondly, users also get their own GPS coordinates, while in the last step, users select their closest micro BS to connect to. The exhaustive search approach is more suitable for cell-edge users, since it provides better coverage (high gain beams) than the iterative search, which comes at the cost of high discovery delay. On the other hand, iterative search algorithms can be used for users that are close to a BS, exploiting their good channel conditions and the low-delay channel discovery. Context-Information techniques can also be applied in LOS scenarios, providing low-delay channel discovery but increasing energy consumption due to the three-stage procedure.

A two-step synchronization method is proposed in [79], aiming at reducing overhead. In the first stage, users obtain information that is required for switching to the correct mmWave frequency. This is achieved from the synchronization signals that macrocell BSs broadcast in the control channel, using low frequencies and omni-directional antennas. Once, users have switched to the mmWave band for the data frame communication, they extract any additional information from the pilot signals that are periodically sent, using their multiple antennas.

Secondly, during the random-access phase, users either contend for preamble (contention-based) or are assigned a specific one (contention-free, e.g. handover) to reduce overhead and delay. During the contention-based period, a user randomly selects a preamble from a pool and transmits it to the BS. If the user does not receive an acknowledgement, then it assumes that either a collision occurred or the signal was too weak to be detected by the BS. In both cases, the user retransmits the preamble after a random back-off with higher power. However, if transmitter's and receiver's antennas are misaligned, then none of the above mechanisms seem to resolve the failed transmission (deafness problem). A mechanism to distinguish the type of failed transmission; misalignment or preamble collision is presented in [80]. For example, a hard-decision energy detector may be used to identify if there was a preamble collision (high received energy level) or that deafness, blockage etc., was the main reason for the failed transmission. Once the type of failed transmission has been identified, BSs send a MAC frame to inform users about the collision occurred. The absence of the signal or an acknowledgement corresponds to deafness or blockage cases, thus, the user scans other angles instead of performing an unnecessary back-off.

Thirdly, frequent handovers in dense small deployments, is another challenging task for MAC in mmWave. To achieve smooth seamless handover, a user may enable multiple simultaneous connections to different BSs, which requires their cooperation or maintaining a link to a macrocell (operating in low frequencies) for control frames along with data plane links to small cells operating at mmWave frequencies [81].

Lastly, the distribution of Resource Units (RUs) to users is very essential. Due to BF and Massive MIMO, each antenna may simultaneously serve multiple users within a cell. If each group consists of different number of users with diverse Quality-of-Service (QoS) requirements, then fairness issues may arise. Hence, sophisticated scheduling algorithms are required to adjust resources per group, based on the users' needs. Moreover, it might not be possible to employ Inter-Cell Interference Coordination (ICIC) mechanisms to the same extent as in current cellular systems, due to high signal attenuation in mmWave frequencies.

C. IEEE 802.11 TECHNOLOGIES OPERATING IN mmWave BANDS

Most of the challenges and solutions described in Section II-A are also applicable to IEEE 802.11 systems operating in mmWave frequencies. However, the limited capabilities and the size of Access Points (APs) to mainly serve indoor users impose certain constraints. For example, due to application scenarios, AP's limited size and low cost/complexity etc., only a limited number of antennas can be deployed. In this section, we overview the IEEE 802.11 amendments related to IEEE 802.11ad and IEEE 802.11ay standards, that have been introduced or are currently under development, for operation at mmWave bands.

1) IEEE 802.11ad

Although IEEE 802.11ad [82] (a.k.a. WiGig) was introduced in 2012, initial real-world deployments are expected in early 2018 with the first WiGig devices hitting the market. WiGig capable portable devices are also known as Directional Multi-Gigabit Stations (DMG-STAs). Operating at 60 GHz band, it enables a plethora of new applications, such as sync-n-go (file transfer), wireless display, etc., replacing High-Definition Multimedia Interface (HDMI) cables and Universal Serial Bus (USB) flash drivers [83]. Taking advantage of the wide bandwidth (2.16 GHz wide channels), IEEE 802.11ad offers up to 7 Gbps peak rate over short distances (approx. 10m). Moreover, it supports Fast Session Transfer (FST) between the 60 and 2.4/5 GHz frequency bands.

IEEE 802.11ad takes advantage of beamforming in azimuth to cope with the high signal attenuation that 60 GHz frequency bands experience. It uses the concept of antenna sectors (sectorized antennas); each sector focuses antenna gain to a specific-predefined direction.

a: ACCESS SCHEME

In IEEE 802.11ad, prior to data transfer, beamforming training procedure takes place following an iterative search approach, where a pair of nodes agree on the optimal sectors that they are going to use. It is a two-stage procedure, where the nodes initially identify the optimal pair of predefined sectors that optimize performance, known as Sector-Level-Sweep (SLS) phase. This is achieved by transmitting and receiving training symbols as they sweep their sectors. Second stage includes the optimization of their link,

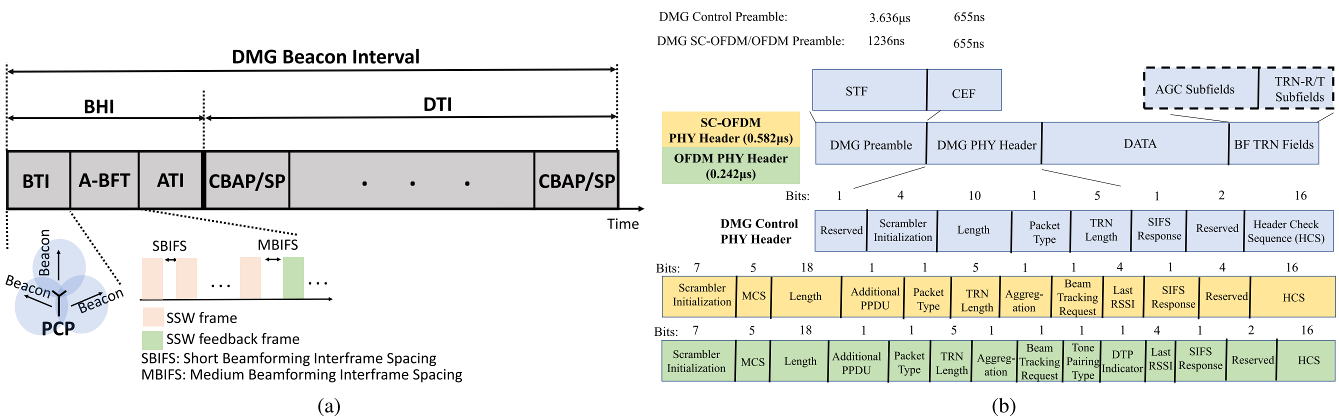


FIGURE 3. IEEE 802.11ad a) Beacon interval and b) PHY frame structure.

by applying antenna weights, known as Association Beamforming Training (A-BFT) [84].

Alterations have been applied to Beacon Interval (BI) to support directional communications, as depicted in Figure 3a. BI duration is advertised in the beacon and can be changed during operation. It comprises two intervals, namely, Beacon Header Interval (BHI) and Data Transfer Interval (DTI). BHI starts with Beacon Transmission Interval (BTI), where the network coordinator, called Personal-Basic-Service-Set Control Point (PCP), transmits multiple beacon frames in various directions. In that way, devices that use directional antennas can detect the presence of PCP. During this period, the first phase of beamforming training (i.e. SLS), occurs. The second period included in BHI, is the optional Beam-Refinement phase (A-BFT), where antenna weights are applied to further optimize a pair of sectors. This is accomplished through Sector Sweep (SSW) frames and SSW feedback frames. The optional Announcement Transmission Interval (ATI) comes last in BHI. During the ATI period, management frames (if required) are exchanged among a PCP and the associated WiGig devices.

The end of BHI period triggers the start of DTI, which comprises Contention-Based Access Periods (CBAPs) and Scheduled Service Periods (SPs). During CBAPs, DMG-STAs contend to grant access to the medium following the IEEE 802.11 Enhanced Distribute Channel Access (EDCA). On the other hand, SPs are assigned to specific pair of nodes for data transfer. Furthermore, beamforming training is also allowed during DTI, either by a DMG-STA that has captured the medium through CSMA/CA and may begin SLS, or by a PCP transmitting training parameters.

b: PHY LAYER

Four different Physical (PHY) layer formats are defined in IEEE 802.11ad [85]; Control PHY, Single-Carrier OFDM (SC-OFDM), Low-Power SC-OFDM (LPSC-OFDM), and OFDM. The first one is used prior to beamforming (BTI and A-BFT periods) for signal detection and pair discovery, hence, the lowest MCS level is used (i.e. MCS0). The second structure is mainly used by power-limited DMG-STAs, while the third one is introduced to further decrease power consumption and complexity. Therefore, Low-Density-Parity-Check (LDPC) has been replaced with Reed-Solomon. OFDM format is used from the devices that require high performance, thus, higher MCSs than MCS0 are used. The PHY structure is depicted in Figure 3b and comprises Physical Layer Convergence Procedure (PLCP) preamble, PLCP header, MAC header, payload, and beamforming training.

Preamble includes the Short Training Field (STF) and Channel Estimation Field (CEF), which are used for packet detection, Automatic Gain Control (AGC), frequency offset estimation, synchronization, modulation indication, and channel estimation. PHY header carries information about the transmitted packet (e.g. MCS, length etc.) while the MAC header contains information required by that layer, such as source/destination addresses, type of the frame (e.g. management) etc. Note that MAC layer is responsible for packets' reordering due to aggregation/fragmentation, generating and transmitting acknowledgements, Request-to-Send and Clear-to-Send (RTS/CTS) frames etc. Following the MAC header, the data payload is appended and thus the PHY layer payload comprises PHY header, MAC header, and Data payload. Cyclic Redundancy Check (CRC) is the last mandatory field that is applied to the whole PHY payload for error-correction, while the optional AGC and Training (TRN) fields might be appended to PHY payload for beamforming reconfiguration after the initial beamforming training. These two fields are used to improve beamforming training in DTI (beamtracking in DTI) through AGC gain calculation and channel estimation. Other DMG PHY characteristics are listed in Table 2.

c: MAC LAYER

The IEEE 802.11ad MAC layer supports CBAPs and TDMA schemes for SPs periods to utilize the whole bandwidth. CBAPs rely either on the Distributed Coordination Function (DCF) that is based on the Carrier-Sense-Multiple-Access with Collision-Avoidance (CSMA/CA) scheme or the Hybrid

TABLE 2. Comparison of PHY characteristics for IEEE 802.11ad/ac/ax/af/ah technologies.

Parameter	IEEE 802.11ad	IEEE 802.11ac	IEEE 802.11ax	IEEE 802.11af	IEEE 802.11ah
Frequency Spectrum [GHz]	Between 57 - 66	5	Between 1 - 7	0.54 - 0.698 in USA and 0.47 - 0.79 in Europe	Sub-1
Channel Bandwidth [MHz]	2160	20 / 40 / 80 / 160 / (80+80)	20 / 40 / 80 / 160 / (80+80)	6 / 7 / 8 / 12 / 14 / 16 / 24 / 28 / 32, where the first three are the BCUs	1 / 2 / 4 / 8 / 16
Spectrum Sharing	SC-OFDM/OFDM	OFDM	OFDM/ DL-UL OFDMA	OFDM	OFDM
Subcarriers per Channel (useful subcarriers)	355, where 336 are data subcarriers, 16 are pilot subcarriers, and 3 are Direct Current subcarriers	56 / 114 / 242 / 484, where 52 / 108 / 234 / 468 are data subcarriers and 4 / 6 / 8 / 16 are pilot subcarriers, for 20 / 40 / 80 / 160 (continuous or not), respectively	$N_{ST} = N_{SRU} * N_{RU}$, N_{SRU} is the number of Subcarriers per RU; 26 / 52 / 106 / 242 / 484 / 996 / 1992 and N_{RU} the number of RUs per channel width, that varies from 1 to 74, depending on channel width and N_{SRU}	114, where 108 are data subcarriers and 6 are pilot subcarriers	26 / 56 / 114 / 242 / 484, where 24 / 52 / 108 / 234 / 468 are the data subcarriers and 2 / 4 / 6 / 8 / 16 the pilot subcarriers, respectively
Modulation	Up to 64-QAM	Up to 256-QAM	Up to 1024-QAM	Up to 256-QAM	Up to 256-QAM
Coding Rates	1/2 (with/without preamble repetition), 5/8, 3/4, 13/16	1/2, 2/3, 3/4, 5/6	1/2, 2/3, 3/4, 5/6	1/2, 2/3, 3/4, 5/6	1/2, 2/3, 3/4, 5/6
FFT Length	512	64 / 128 / 256 / 512	256 / 512 / 1024 / 2048	64 / 128 / 256 / 512 / 1024, with the latter two to be optional	32 / 64 / 128 / 256 / 512
Spatial Multiplexing/Spatial Streams/Beamforming	N/A / 1 / Supported	DL MU-MIMO / Up to 8 / Supported	DL-UL MU-MIMO / Up to 8 / Supported	DL MU-MIMO / Up to 4 / Supported	DL MU-MIMO / Up to 4 / Supported
Symbol Duration (IDFT/DFT period) [μs]	0.194	3.2	3.2 / 6.4 / 12.8	BCUs (6 / 7 MHz): 30, BCU (8 MHz): 22.5	36 / 40 / 48
Guard Interval [μs]	0.0484	0.4 / 0.8 / 1.6	0.8 / 1.6 / 3.2	BCUs (6 / 7 MHz): 6, BCU (8 MHz): 4.5	4 / 8 / 16
Subcarrier Frequency Spacing [kHz]	5156.25	312.5	78.125	BCUs (6 / 7 MHz): 41*(2/3), BCU (8 MHz): 55*(5/9)	31.25
Max PPDU Duration [ms]	2	5.484	5.484	20	27.84
Max PSDU Length [bytes]	262143	4692480	6500631	1065600	797160
Slot time [μs]	5	9	9 / 20 in 2.4 and 5 GHz band, respectively	BCUs (6 / 7 MHz): 24, BCU (8 MHz): 20	52
SIFS/DIFS [μs]	3 / 13	16 / 34	2.4 GHz: 10 / 28, 5 GHz: 16 / 34	BCUs (6 / 7 MHz): 120, BCU (8 MHz): 90	160 / 264
BUSY indication [μs]	within 3	within 4 (primary 20 MHz channel) and 25 (non-primary 20 MHz channel)	within 4 (primary 20 MHz channel) and 25 (non-primary 20 MHz channel)	BCUs (6 / 7 MHz): 94, BCU (8 MHz): 70	within 40 (primary 1 MHz channel with RSSI $\geq$ -98 dBm for type 1 channels or -89 dBm for type 2 channels) and 212 (primary 1 MHz channel with RSSI $\geq$ -89 dBm for type 1 channels or -86 dBm for type 2 channels, and non-primary 1 MHz portion of the primary 2 MHz)
Min Receiver Sensitivity [dBm]	-78 for MCS0, PER less than 5%, for a PSDU size of 256B and -68 for all other MCSs with PER less than 1% for a PSDU size of 4096B	-82 for 20 MHz	-82 for 20 MHz	BCUs (6 / 7 MHz): -88, BCU (8 MHz): -87 with PER less than 10% for a PSDU size of 4096B	-98 / -95 for 1 MHz & repetition on / off with PER less than 10% for a PSDU size of 256B
Max Peak Rate [Mbps]	6756.75	6933.3	9608	570	347

Coordination Function (HCF), which is used for scheduled transmission opportunities. On the other hand, SPs are applicable only to DMG-STAs (not to PCPs) and enable scheduled or dynamic allocation services. With dynamic allocation, a PCP polls a DMG-STA and allocates slots based on its needs. The allocated slots might be within the same or following BI.

Similar to its predecessors, i.e. IEEE 802.11n/ac, in IEEE 802.11ad frame aggregation at the high or low MAC layer is supported. These are known as Aggregate MAC Service Data Unit (A-MSDU) and Aggregate MAC Protocol Data Unit (A-MPDU), respectively. The maximum size of transmitted frame is 262143 bytes, while transmission duration must not exceed 2 ms (PLCP Protocol Data Unit (PPDU) time $\leq$ 2 ms).

2) IEEE 802.11ay

To keep pace with user demands and new applications that require capacities of over 10 Gbps (e.g. cellular offload, HDMI, Augmented Reality (AR), Virtual Reality (VR)), a new IEEE 802.11 Task Group (TG), started its activity in 2015, namely IEEE 802.11ay [86]. The TG is aiming to develop enhancements to the IEEE 802.11ad standard to enable operation in license-exempt bands above 45 GHz. Even though, there is still a lot of work to be done until IEEE 802.11ay reaches a stable release, we overview some of the basic enhancements proposed so far.

IEEE 802.11ay shares a lot of similarities with IEEE 802.11ad, however, a number of new features have been proposed and are currently under consideration in this amendment [87], including: i) Channel Bonding and Carrier Aggregation (CA), ii) MIMO Beamforming, Multi User - MIMO (MU-MIMO) Beamforming, iii) antenna polarization, iv) TDD, and v) Network Coding.

a: PHY LAYER ENHANCEMENTS

IEEE 802.11ay uses 6 different channel bandwidth combinations via channel bonding; the mandatory 2.16 GHz and 4.32 GHz, and the optional support of contiguous 6.48, 8.64 GHz and non-contiguous 2.16 + 2.16, and 4.32 + 4.32 GHz. Note that there is a difference between Channel Bonding and CA, i.e. in the former case a single waveform occupies the whole contiguous bandwidth, whereas in the latter, each channel might use different waveform [88].

Hybrid or even Digital beamforming architecture might be used in Enhanced DMG (eDMG) amendment whilst enhancements in TRN design to increase efficiency are also planned to be introduced. MIMO Beamforming or MU-MIMO Beamforming, comprises two phases, namely Single-Input-Single-Output (SISO) phase and MIMO phase. During the first phase that is further divided into three sub-phases, eDMG STAs identify the potential sectors that will be used during the MIMO phase. The second phase, comprises four sub-phases and enables the training of the sectors selected during SISO phase.

Antenna polarization is another topic that is being studied in IEEE 802.11ay [89]–[91]. The most popular polarization mechanisms used are linear (LP) and circular (CP) polarizations. LP is considered to be the simplest due to the fact that it requires a simple feed network and no external polarizer. There are two forms of LP; horizontal, where the electric field is parallel to Earth's surface, and vertical, where the electric field is perpendicular to Earth's surface. CP is more complicated than LP since a CP antenna usually requires an external polarizer [92]. It is however more resilient to multipath and fading and it does not require perfect alignment between the transmitter and the receiver [93]. These characteristics make CP essential for applications which involve satellite communications (i.e. portable devices with GPS capability) [94]–[96]. LP on the other hand is suitable for applications that have a guaranteed LOS and for applications that require high gain antennas. However, perfect alignment between the transmitter and the receiver is essential which limits their practical use. Practically an antenna is always elliptically polarized since perfect LP or perfect CP are very hard to be achieved. Depending on the level of elliptical polarization applied, an antenna can be distinguished as either LP or CP. Polarization reconfigurable antennas are also very important, as they provide polarization diversity and flexibility [97], [98], meaning that they can be used in various applications. They can be reconfiguring between LP and CP or between Right-Hand CP (RHCP) and Left-Hand (LHCP) modes.

To mitigate interference level and address the blocking effect, where the desired packet is blocked from being detected (a node is locked onto an early packet), the support of TDD is also being studied in IEEE 802.11ay [99]. TDD may simplify the channel sounding and improve time fairness between TX and RX periods. However, challenges as the coordination of the time periods for a network, may arise in TDD systems.

b: MAC LAYER ENHANCEMENTS

The IEEE 802.11ay MAC layer follows the IEEE 802.11ad and IEEE 802.11ac standards, however, modifications will be required to support the new features, e.g. TDD. Relaxation of the Clear Channel Assessment (CCA) thresholds (i.e. aggressive CCA values) could improve the throughput and be more suitable for directional communications. Delayed Block-ACK to a following SP and enhancements in the beacon frames to ensure co-existence with other mmWave-based technologies (e.g. IEEE 802.11ad, IEEE 802.11ay focused on different use cases) are also under consideration in TGay.

c: RELAYING ADVANCEMENTS; A NETWORK CODING APPROACH

To improve multi-hop transmission, relaying will be supported in IEEE 802.11ay amendment (similar to IEEE 802.11ad), based on a network coding technology [111]. The main objective for network coding is to enable combining of information from separate flows within an intermediate node (relay), thus increasing the network capacity [100], [101]. The receiver can, after collecting sufficient information from both links (direct and relaying), successfully decode the message.

The simplest way to perform network coding is by applying *XOR* operation to the input-packet streams [102], [103]. One approach to mixing information makes use of Linear Network Codes (LNC), where coefficients are selected over a finite field, known as Galois Field. For example, operations in a finite field of 2^8 (e.g. numbers ≤ 255) are performed over bytes, while *XOR* is performed over the bits. The computational cost increases with the size of Galois Field. Random LNC (RLNC) [104] is another class of LNC, where coefficients are randomly selected. In that way, the probability that a node will receive coded packets, which are linearly independent, remains high. The main benefit of RLNC is that it can be performed in every hop, protecting the initial message, by adding redundant information. However, this comes at the cost of high overhead due to coefficients that need to be transmitted along with the initial message, otherwise the recipient will not be able to decode the packets.

Two approaches have been widely followed to reduce RLNC overhead, complexity, and to improve performance; a Systematic approach (S-RLNC) and a concatenation of an erasure code with RLNC to combine the advantages of both schemes. In S-RLNC [105], the original packets are transmitted along with the encoded ones. Therefore, if insufficient number of packets is received, RLNC decoder is skipped, while the recipient is still able to retrieve a part or even whole information from the uncoded packets. A two-fold gain in encoding/decoding throughput is reported in [105] as well as lower overheads (especially for good-quality links) and lower computational cost (smaller finite field can be used instead).

There has also been considerable research on concatenation schemes in the literature [106], [107], [109], [110]. Concatenated codes mimic the systematic approach, however, the transmitted systematic packets are encoded, instead. They consist of an outer and an inner code. The outer code is usually a powerful fountain rateless code (e.g. Luby Transform (LT) codes), whereas the inner code is RLNC or S-RLNC, used to allow re-encoding in intermediate nodes. Hence, in case of insufficient number of received symbols, the inner code is skipped and the outer code tries to decode the message. BATched Sparse code (BATS) [106], is an example of a concatenated coding scheme that is under consideration in this task group [111]. The outer code in BATS, operates at the transmitter, whereas the inner code may reside in any intermediate node, which linearly combines only packets belonging in the same batch and flow. However, by applying both outer and inner codes on the same node, a higher performance in terms of decoding success rate can be observed [107].

The main question that needs to be answered here is, what is the best layer to apply coding? The application layer is the most convenient layer to apply a network coding scheme, as there would be no need for the Layer 3/routing and MAC protocols to be modified. However, this comes at the cost of reduced throughput and robustness gains (channel conditions are not known to that layer) [108]. By applying a network coding scheme in Transmission Control Protocol / Internet Protocol (TCP/IP) layer or above it, there is always the risk of overflowing TCP buffer(s) with encoded packets. Moreover, delay may increase, since a node must wait until a sufficient number of encoded packets is received before proceeding to decode. If network coding is performed at the lower layers (i.e. RAN), higher gains could be achieved. However, if network coding is applied at PHY layer then additional delays may arise, since information that is carried in MAC header is now encoded. This means that nodes need to collect a sufficient number of packets before attempting to decode them and accessing this information, e.g. destination address. Moreover, complexity also increases when operating in larger frames due to headers or frame aggregation schemes, especially if the final recipient is not the node that has decoded these packets. Another issue for applying it at PHY layer in an IEEE 802.11 system, is the limited processing time that nodes have, once they grant access to the medium, e.g. dequeuing a packet from MAC queue and applying fragmentation or aggregation.

III. TECHNOLOGIES DESIGNED TO OPERATE AT BELOW 6 GHz BANDS

This section describes the cellular and Wi-Fi technologies operating at frequency bands below 6 GHz.

A. 3GPP LTE TECHNOLOGY EVOLUTION

The core network of LTE is the Evolved Packet Core (EPC), introduced in 3GPP Release-8 (Rel-8), replacing the architecture used in Global System for Mobile Communications (GSM), known as 2G system, and High-Speed Packet Access (HSPA) / Wideband Code Division Multiple Access (WCDMA) [112]. It is part of the Evolved Packet System (EPS) and it was designed to enable flat architecture, cost efficiency, and enhanced performance. EPC comprises the Serving Gateway (S-GW), the Packet-Data-Network Gateway (P-GW), the Mobility Management Entity (MME), and the Home Subscriber Server (HSS). Moreover, it separates the user data (U-Plane) and signaling control (C-Plane), providing more flexibility to vendors and network operators.

1) LTE CHANNEL ARCHITECTURE & INITIAL ACCESS

LTE is the access scheme of EPS, which was designed to provide high spectral efficiency, low delay and overheads, and high peak data rates. LTE Rel-8, was finalized in December 2008 and the first commercial deployments were available in late 2009. It comprises four layers; the Packet Data Convergence Protocol (PDCP), the Radio-Link Control (RLC), MAC, and finally, the PHY. A user may have multiple radio bearers, but only one PDCP and RLC per bearer. On the other hand, one MAC is supported per user, but multiple PHYs; one per Component Carrier (CC) when CA is used (from Rel-10).

Those layers are connected through channels; logical channels that connect RLC and MAC layers, transport channels between MAC and PHY, and physical channels.

The logical channels are split into control and traffic channels. The control channels include, Paging Control Channel (PCCH), Broadcast Control Channel (BCCH), Common Control Channel (CCCH) for random access or to set-up a connection, Dedicated Control Channel (DCCH) for handover or power-control, and Multicast Control Channel (MCCH). Dedicated Traffic Channel (DTCH), and Multicast Traffic Channel (MTCH) are also logical channels and defined as traffic channels. The transport channels include the channels for DL and UL transmissions. The former comprises Broadcast Channel (BCH), DL-Shared Channel (DL-SCH), Paging Channel (PCH), and Multicast Channel (MCH). The latter category includes UL-Shared Channel (UL-SCH) and Random-Access Channel (RACH). Finally, transport channels link to the physical ones. The PHY channels for DL include Physical Broadcast Channel (PBCH), Physical Data Shared Channel (PDSCH), Physical Control DL Channel (PCDCH), Physical Control Format Indicator Channel (PCFICH), Physical Hybrid-ARQ Indicator Channel (PHICH), and Physical Multicast Channel (PMCH). PCFICH identifies the number of OFDM symbols used for PDCCH that carries information about DL resource scheduling or UL transmit-power level restrictions. PHICH is used for transmitting a positive or negative acknowledgement for UL data frames. On the other hand, three channels are dedicated for UL transmissions, namely, Physical UL Control Channel (PUCCH), Physical UL Shared Channel (PUSCH), and Physical Random-Access Channel (PRACH).

PRACH has bandwidth of 1.08 MHz and is used to carry random-access preambles during the random-access procedure. It is used by users (a.k.a. User Equipment - UE) to initiate data transfer. A UE randomly chooses a preamble sequence out of a pool containing 64 preamble sequences and transmits it on PRACH. If a UE does not receive a Random-Access Response in PDSCH, it will increase the transmission power and will re-send the preamble. The next step is the transmission of Device Identification Frame in PUSCH by an UE. The last step includes the transmission of the Contention-Resolution Frame in PDCCH by a BS (a.k.a. eNodeB), which resolves preamble collisions due to multiple UEs choosing the same preamble. When a preamble collision has been detected, a UE restarts the procedure after a random back-off.

2) LTE LINK LAYER DESIGN

PDCP is responsible for sequence numbering (delivering in order and removing duplicate data), header compression (only for data frames), ciphering protection against eavesdropping, and integrity protection for C-Plane. It also plays a significant role during handovers.

The role of RLC is to correct any residual errors passed in that layer and missing frames (gap in sequence) with the Automatic Repeat Request (ARQ) and frames' segmentation or concatenation. Frame's size affects the selection of data rate and overhead.Large frames reduce the probability of using low-data rates while small frames result in high overhead due to the headers. ARQ completely discards a packet with an error and requests for retransmission, whilst maintaining low overheads due to its size and its infrequent transmission, but it comes at the cost of low reliability [113].

Three types of ARQ are supported. Stop-and-wait, where the reception of a 1-bit Acknowledgment/ Negative-Acknowledgment (ACK/NACK) indicates if a frame is correctly or not received. The second type is go-back-N, where all packets with sequence number larger or equal to the one indicating as not-being received, are retransmitted. The last type is the selective-repeat, which is similar to the go-back-N technique, but only the missing packets or these that have been dropped due to an error, are being retransmitted. Three different modes are supported by RLC: i) the Transparent Mode that does not add any overhead (RLC header) and does not allow any type of retransmissions, ii) the Unacknowledged Mode that supports all functionalities of RLC, but retransmissions, and iii) the Acknowledged Mode, which supports all features of RLC.

Following RLC, is the MAC layer, which is responsible for random-access, multiplexing logical channels and mapping them to transport channels, and link adaptation where the transmission parameters are set based on channel conditions [114]. Hybrid-ARQ (HARQ) is also part of the MAC layer, a combination of ARQ and Forward Error Correction (FEC), that enables fast retransmissions (frequently transmitted), high reliability, and handles with most of the errors. Three diverse types are defined for HARQ; Type-I, Type-II, and Type-III. The former is similar to RLC ARQ scheme, while Type-II retransmits parity bits that are combined with the buffered received packets. In Type-III, every packet is self-decodable, which means that even if one packet is missing, the decoding procedure does not halt. However, this tremendous advantage of Type-III comes at the cost of high overheads.

In contrast to ARQ that operates per logical channel, HARQ might retransmit data from multiple logical channels. Retransmissions in HARQ can occur either on a specific time after the end of the previous transmission (synchronous) or at any time (asynchronous). HARQ can also be transmitted in a different format and/or frequency resources if the adaptive HARQ is supported. The asynchronous adaptive HARQ is supported in DL, while the synchronous non-adaptive in UL (e.g. retransmissions occur 8 subframes after the initial transmission).

MAC also, takes care of UL and DL scheduling (requests for resources) or multiplexing of multiple CCs when CA is used. A structure of a MAC frame is depicted in Figure 4. Packet scheduling is responsible for allocating resources to UEs in an efficient way to maximize spectral efficiency [115].

Different scheduling approaches can be followed by vendors and neetwork operators, based on the users' needs. However, there is a tradeoff between maximizing fairness and throughput capacity, when scheduling resources to the UEs. There are three main scheduling approaches that can be followed: i) Round-Robin, ii) Max-Carrier-to-Interference

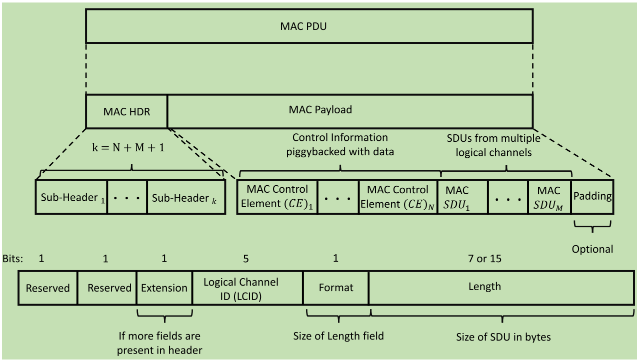


FIGURE 4. LTE MAC frame structure.

(Max-C/I), and iii) Proportional-Fair. Round-Robin distributes the same amount of resources to UEs, without considering the channel conditions. Therefore, this scheduling method preserves fairness in terms of resources, but not in terms of QoS. The second strategy assigns resources to UEs with good channel quality (support of high-data rates (high SNR)). Although this mechanism maximizes throughput capacity, it degrades fairness between UEs with high SNR and those with poor channel conditions (e.g. cell-edge UEs) [116]. To address these fairness issues, Proportional-Fair allocates resources to UEs based on the average SNR over a period (in a long term), improving fairness as long as the average Signal-to-Interference-plus-Noise ratios (SINRs) are uniformly distributed [117].

LTE PHY layer supports both FDD and TDD schemes. TDD has lower cost than FDD, since it does not require a diplexer to separate/combine the different frequency bands used for DL and UL transmissions [118]. It is also, preferred by vendors when the available spectrum is limited and due to the low overheads when it comes to CSI reports. TDD also, efficiently deals with asymmetric traffic, since the resources in UL and DL can dynamically be allocated (DL/UL ratio) based on the user needs [119]. On the other hand, cross slot interference may occur in TDD, hence, larger guard periods (GPs) than in FDD are used, which affect throughput capacity. In FDD, the GP used to separate UL and DL in frequency bands, does not have any impact on capacity (i.e. non-contiguous bands).

Two different frame types are supported; Type-1 for FDD and Type-2 for TDD, illustrated in Figures 5a and 5b. For both types, the frame duration is 10ms and comprises 10 subframes (1 ms each subframe). Each subframe consists of 2 slots with duration of 0.5ms each one. Now, the smallest unit allocated to a user is the Resource Block (RB) that consists of 12 subcarriers in the frequency domain $(12 * (15\ kHz) = 180\ kHz)$ and one 0.5ms slot in the time domain. However, the smallest physical unit in LTE is the Resource Element (RE), comprises one subcarrier during one OFDM symbol. A 0.5ms slot can accommodate either 7 OFDM symbols when the normal Cyclic Prefix (CP) is used or 6 when the extended CP is applied. The useful symbol duration is $66.7\mu s$ $(1/15\ kHz)$, while the normal and extended CP are $4.7\mu s$ and $16.67\mu s$, respectively. When normal CP is used, the CP in the $1st$ OFDM symbol is longer than $4.7\mu s$ to fill the entire $0.5\mu s$ slot. The RBs are defined over one slot and not per subframe due to distributed DL transmission and UL frequency hopping [113]. Further, the number of RBs per carrier, ranges from 6 to 110, corresponding to the channel bandwidth (varies from 1.4 MHz to 20 MHz).

For Type-2; a TDD frame structure, the frame might be divided into two half-frames of 5ms duration each, prior the subframes. There are 7 different frame configurations for different DL/UL ratios; from 1/3 to 8/1. There are some common rules for all configurations, such as the $1st$ subframe is always a DL one carrying information about the structure that is to be followed, while the $3rd$ is an UL subframe. A special subframe is always used when switching from DL to UL subframe that consists of: i) DL Pilot Time Slot (DwPTS) that carries control information and reference signals, ii) GP to control switching from DL to UL, and iii) UL Pilot Time Slot (UpPTS) that is used for channel sounding and random access.

LTE is based on OFDM, due to the inherent advantages that this technology offers; resilience to interference, ISI, selective fading etc. It is based on a parallel data transmission and divides the available bandwidth into smaller channels, namely subcarriers (different frequency per subcarrier), using different modulation scheme for each one. Thus, based on channel conditions, high order of MCS can be used per subcarrier, achieving higher data rate. The long OFDM symbol duration along with the use of CP at the beginning of each symbol, make OFDM resilient to multipath delays and spread. ISI can be reduced by extending the length of CP, such that the maximum delay spread is less than the duration of CP. However, a very long CP reduces the data throughput, while a small one may cause strong ISI. CP is also used for synchronization by identifying the start and end points of a symbol [120].

Further, OFDM improves spectrum efficiency by tightly placing the subcarriers (subcarriers are not separated but ovelapped), that do not interfere to each other due to their orthogonality. If orthogonality is missed (inadequate CP) due to frequency mismatch in the transmitter and receiver oscillators, Inter-Carrier Interference (ICI) may occur. This mismatch may occur due to lost synchronization or the Doppler effect. To mitigate ICI, several techniques have been proposed (e.g. Minimum Mean Squared Error (MMSE)), but they are out of the scope of this paper. OFDM also suffers from high Peak-to-Average-Power ratio (PARP) that occurs because several subcarriers are transmitted with extremely higher power than the average power level used throughout the subcarriers. This requires Analog-to-Digital (A/D) and Digital-to-Analog (D/A) converters capable of handling this range, which may degrade transmitter's power amplifier efficiency. Traditional methods dealing with the high PARP, include clipping and filtering, which suffer from the high BER due to the distortion they cause in the transmitted signals [121].

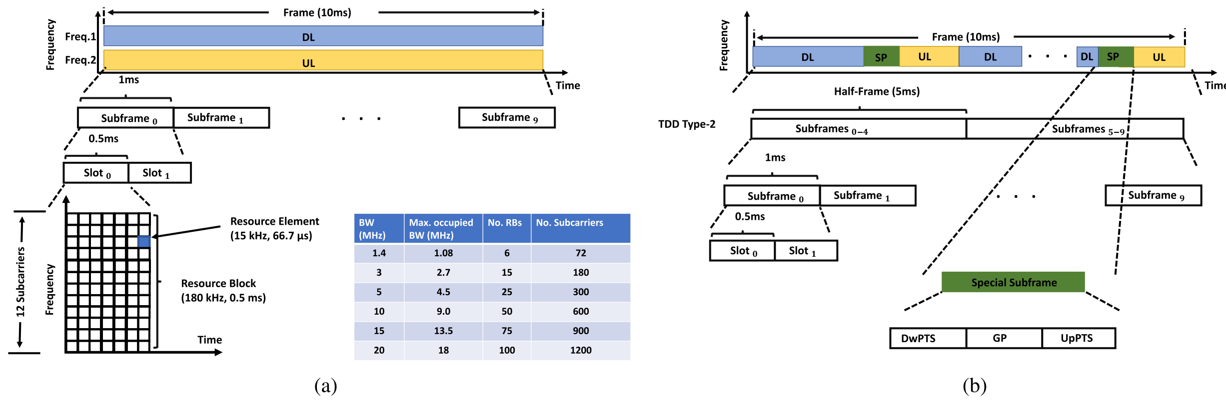


FIGURE 5. LTE a) FDD structure and b) TDD structure.

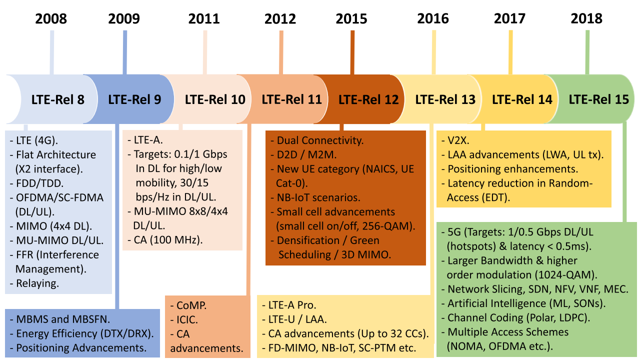


FIGURE 6. An overview of 3GPP LTE evolution.

An alternative access scheme to OFDMA, used in DL, is realized for UL traffic, due to the power-limited mobile devices (power consumption). Therefore, Single-Carrier FDMA (SC-FDMA) is the scheme used in UL, because of the low PARP compared to OFDMA, since the signal is transmitted over a single carrier. On the other hand, SC-FDMA has certain disadvantages against OFDMA that prevent its usage for DL transmissions (e.g. higher computation cost at the receiver, lower spectral efficiency especially for high SNRs, channel estimation using pilots is harder due to the lack of orthogonal data on each frequency bin etc.).

3) LTE EVOLUTION; AN OVERVIEW THROUGH RELEASES

In this section, we overview the main techniques and advanced technologies introduced throughout 3GPP LTE Releases. We start from the first LTE Releases; Rel-8/9 through to the current Rel-14. We describe the potential directions and advanced technologies that 3GPP LTE community is looking at in Rel-15, which is under active development. The evolution of LTE through releases is also depicted in Figure 6.

a: A WALK THROUGH RELEASES 8-12

Even from the first releases (Rel-8/9), a lot of attention has been given paid to ICIC mechanisms, where messages are exchanged among eNodeBs through the X2 interface, aiming to improve not only the average cell capacity but cell edge users' performance. MIMO and MU-MIMO in both UL and DL directions were among the features introduced in the first release, supporting 4x4 MIMO in DL and one-layer transmission in UL to maintain low complexity, initially. Power control in the UL direction and soft/hard Fractional Frequency Reuse (FFR) are also supported to mitigate interference [122]. Soft FFR refers to the case where eNodeBs do not transmit on specific resources, whereas hard FFR to the case where eNodeBs use lower transmit powers on certain resources. Soft FFR improves spectral efficiency, since the UEs close to eNodeBs that experience high SINR can be allocated to those power-limited resources. Two diverse types of relaying schemes, e.g. Amplify-and-Forward in Layer 1, where the signal is amplified along with the noise and Decode-and-Forward in Layer 2, where noise is not forwarded but higher latency to the system might be introduced, are also supported in the very first releases [123]. The support of broadcasting/multicasting of the same content over multiple co-channel cells with Multicast/Broadcast Single-Frequency Network (MBSFN) is also initially proposed in Rel-8/9. MBSFN is an advancement on the Multimedia Broadcast Multicast Services (MBMS), a feature that was initially introduced in 2004 in Universal Mobile Telecommunications System (UMTS) Rel-6, that requires a tight frequency and time synchronization among the cells that participate in those transmissions. With MBSFN, multiple cells transmit at the same time and frequency, using the same waveform. These multiple concurrent transmissions are perceived as a single transmission by the UEs and giving rise to constructive interference when tight synchronization among the cells is achieved (if signals are received within the CP period). Discontinuous Reception (DRX) and Discontinuous Transmission (DTX) functionalities for reducing power consumption in mobile devices and advancements in positioning (i.e. position estimation by monitoring the relative time of arrival of some special signals from multiple cells) are among other features incorporated into Rel-8/9 specifications.

To meet the targets for 4G networks, 3GPP released LTE-Advanced (a.k.a Rel-10) specifications in 2011. The support of higher order MU-MIMO configurations in both directions, CA [124], and heterogeneous networks, can help to boost the peak data rates to 3 and 1.5 Gbps in DL and UL, respectively, in LTE Rel-10 [125]. At the same time a two-fold higher spectral efficiency than Rel-8 was realized. To preserve backward compatibility, the transparent relaying mode was introduced for in-band or out-band relays [126].

CA in Rel-10, allowed up to 5 CCs using the same duplex scheme, forming channel bandwidths up to 100 MHz, while the number of CCs in UL should be less than or equal to that in DL. The Primary Cell (PCell) is used for radio monitoring, re-establishing Radio Resource Control (RRC) connection, maintaining continuous communications due to mobility etc, whereas the rest of the CCs (Secondary Cells (SCells)) are used to provide additional resources. Moreover, each SCell has its own HARQ, implying that most HARQs are transmitted over the same SCell as the original data, while an ARQ (at RLC level) may be sent over different SCell, since CA is invisible above MAC. Three diverse types of CA, namely, intra-band contiguous, intra-band non-contiguous, and inter-band were also specified. The use of different MCS and/or transmit power per CC or non-contiguous CA, especially inter-band CA, and the flexibility of scheduling PDCCH on different CCs (cross-carrier scheduling) can improve system's coverage and reduce inter-cell interference. Two different queuing structures can be used for CA; Joint Queue Scheduler (JQS), where one queue per UE for all CCs is realized or Disjoint Queue Scheduler (DQS), with one queue per CC per UE [129]. It is shown in [130] that JQS outperforms DQS in terms of spectral efficiency as packets can use all RBs in all CCs and not only the one that a queue belongs to. The scheduling of CCs is a new functionality of Radio Resource Management (RRM) in Rel-10 and is based on channel characteristics, QoS requirements, and traffic conditions (e.g. Random, Circular, and Least Selection techniques). On the other hand, implementation complexity and power consumption increase as the number of supported CCs increases [127]. Among the three CA configurations, the non-contiguous has the highest complexity, as the RRM and the RF implementation complexities in the terminal have to take into account the different Doppler shift and path loss that different frequencies experience [128].

The two main foci in Rel-11, were techniques for improving energy efficiency by reducing RAT's capabilities while other RATs providing support [132], and reducing inter-cell interference. Inter-cell interference remains the main obstacle to achieving data rates close to the theoretical bounds. Common Reference Signals (CRS) cancellation [133] and Coordinated Multipoint (CoMP) for constructive interference are among the features introduced in Rel-11, in support of higher capacity.

CoMP allows either a single transmission/reception through multiple eNodeBs with one eNodeB enabled each time, or a joint transmission/reception from multiple eNodeBs. A joint transmission could be of two types; non-coherent where each eNodeB individually and independently from the rest eNodeBs calculates the precoding matrix for a transmission and coherent where multiple eNodeBs act like a single virtual eNodeB. The latter, requires the sharing of data and messages between eNodeBs through the X2 interface. One message defined for DL ICIC, namely Relative Narrowband Transmit Power (RNTP), provides information for specific RBs. RNTP is indeed, a proactive tool that tries to prevent transmissions scheduled in RBs with low SINR. On the other hand, two types of messages are defined for UL transmissions; High-Interference Indicator (HII) and Overload Indicator (OI). The former, works in a similar way to RNTP, while OI indicates the interference levels for different RBs, such that a neighboring eNodeB to re-schedule UEs in order to mitigate interference. Requirements on low-latency, high-capacity backhaul and the tight synchronization in time and frequency domain of eNodeB are the main challenges associated with the CoMP technology [131].

In early 2015, almost two years after the introduction of Rel-11, the Rel-12 was launched. It was the era that made operators and researchers to take into consideration and tackle the emerging issue of energy emissions by the mobile networks due to the support of massive number of portable devices, and seek solutions for improving energy efficiency [135]–[137]. For example, higher MCS might be more efficient than a lower one, considering the energy consumed by the RF components (i.e. power amplifier, circuit, feed losses etc.). The main goals for Rel-12, apart from energy efficiency, were to provide higher Quality of Experience (QoE) and support diverse types of traffic and services [134].

The support of higher order modulation (256-QAM), small cell On/Off based on the traffic demand, and dual connectivity for non-ideal backhaul links were the major features introduced in Rel-12 to enhance per user throughput, reduce signaling load and power consumption, and improve mobility robustness in heterogeneous networks [138]. Although, small cell On/Off technique reduces network's energy consumption and signaling load, there is always the risk of reduced coverage or increased scanning/discovery delay for the UEs, thus, its use was restricted to SCells only. Enhanced Interference Mitigation and Traffic Adaptation (eIMTA) feature was introduced in this release, aiming to dynamically adjust resources for DL and UL (Dynamic TDD), utilizing resources per link. Dual connectivity was introduced for non-ideal backhaul, operating on the same or not frequency band, aiming at improving mobility support whilst reducing signaling overheads during handovers.

CA between TDD and FDD was also supported in Rel-12, whereas enhancements for MBMS when an interface fails and MBMS operation on demand were also proposed for enabling seamless MBSS connectivity. Advanced (higher order) MIMO schemes were also introduced, while the study for 3D MIMO was also started. Furthermore, a new category of UE receivers, capable of Network Assisted Interference Cancellation and Suppression (NAICS), new Device-to-Device (D2D) and M2M scenarios were also part of Rel-12.

The motivation of enabling D2D Proximity Services (ProSec) communications was to support Public Safety (i.e. police, fire, and ambulance) communications [139]. Up to that time, Public Safety communications were using the Terrestrial Trunked Radio (TETRA) system, developed back in 90s' with limited capabilities. Although, Public Safety applications can use Wi-Fi or Bluetooth technologies in an ad-hoc manner, these technologies are characterized by limited range, inability to provide an adequate level of security and integrity, and independent operation from the cellular systems. Therefore, in Rel-12, 3GPP identified three main scenarios for D2D; the in-coverage, where eNodeBs control the resources, the out-of-coverage, where UEs use predefined resources, and the partial-coverage. The last scenario refers to the case where one UE is in-coverage while the second device is out-of-coverage. The communication link between the devices (PC5 interface) is known as sidelink used in UL subframes by both TDD and FDD modes. Two operational phases have been introduced, namely Discovery and Communication. The former is used for broadcasting short messages and discovering devices in close proximity [140], [141]. For example, a device may transmit a message declaring its presence or requesting what devices are within its range. The latter discovery phase, uses the Physical Sidelink Discovery Channel (PSDCH) and was initially supported only for the in-coverage scenario. Prior the discovery phase, synchronization between the devices is required. Synchronization uses the Physical Sidelink Broadcast Channel (PSBCH) and can be achieved either through eNodeBs or the transmission of Sidelink Synchronization Signals (SLSSs) for the out-of-coverage scenario. Communication mode, on the other hand, uses the Physical Sidelink Shared Channel (PSSCH) and was initially supported only for the out-of-coverage case.

b: 3GPP LTE-ADVANCED PRO - RELEASE-13

3GPP Rel-13, also known as LTE-Advanced Pro, continued the study and work on D2D, M2M, and Narrow-Band IoT scenarios, CA enhancements (up to 32 CCs), and more importantly the new features such as densification (LTE in unlicensed spectrum and dual connectivity enhancements), and advanced MIMO (Full-Dimension MIMO) [142]–[144]. From a system point of view, two are the main objects to highlight here; the study of core network virtualization [145], which is a mature technology that could be incorporated by 3GPP and the study of critical communications [146].

The first step for enabling substantial number of antennas in a 2D antenna array (FD-MIMO), thus, enabling beamforming in both azimuth and elevation, was the study of new 3D channel models and then an evaluation of FD-MIMO's potential benefits [147]. The substantial number of antennas (massive MIMO) could save at least an order of magnitude in transmit power, average out the effects of small-scale fading and thermal noise. On the other hand, complexity, energy consumption, and control overhead (pilot contamination) increase with the number of antennas [42]. To address pilot contamination, usage of MIMO in TDD along with lean communications were proposed [148], [149]. A four-fold gain for both cell-average and 5th percentile user throughputs were observed in [150], when both elevation and azimuth are exploited (FD-MIMO). Moreover, higher order of MU-MIMO can be realized with FD-MIMO, while maintaining the same SINR level per UE if the number of antennas increases at the same rate as the number of co-scheduled UEs [151]. In addition, MIMO is more susceptible to CFO due to multiple simultaneous data streams transmitted, thus, data-aided or blind estimation (e.g. Gardner's non-data-aided) methods are used. However, the first approach is shown to provide better performance at the cost of higher overheads.

To meet the projected traffic demands, 3GPP Rel-13 also studied the case of using unlicensed spectrum in DL along with other technologies (i.e. Wi-Fi). Two different approaches were proposed by the vendors; either a vendor deploys a Wi-Fi infrastructure and a communication link inter-operates between LTE and Wi-Fi or makes use of the unlicensed spectrum through a single network. The second approach reduces operational cost and provides better QoE, since LTE deals with the communications in the unlicensed spectrum.

The main benefits of using unlicensed spectrum are: i) increased capacity, ii) higher number of users served, and iii) enhanced system coverage [152]. On the other hand, the main challenges arising from the coexistence of a synchronous and an asynchronous technology relate to: i) the access control, ii) traffic scheduling, iii) interference mitigation, and iv) fairness issues. Operation of LTE in the unlicensed band is based on CA, with PCells operate always in licensed spectrum, while SCells in both licensed and unlicensed bands. This is because in unlicensed spectrum, QoS is not guaranteed and interference cannot easily be controlled due to the unmanaged/ unplanned deployment of APs. SCells in unlicensed band are usually used to support low-mobility UEs, forming small-cell deployments. Thus, before enabling CA in the unlicensed spectrum, traffic load and channel information must be considered [153]. The two main techniques used in LTE to access the unlicensed spectrum are: Carrier Sensing Adaptive Transmission (CSAT) and Listen-Before-Talk (LBT).

CSAT is used in countries where there are no LBT requirements (LTE-U), e.g. USA, South Korea, and China. It is based on the Dynamic Frequency Selection (DFS), where the devices search for low-loaded channels. They also, continuously sense the medium in order to identify the channel status (BUSY or IDLE). In case that a channel is used by a higher priority technology (e.g. radar), then UEs vacate this channel within a certain period, but are able to use it after a specific time. With CSAT, eNodeBs identify and access channels based on a duty cycle that is adjustable, based on channel's activity.

On the other hand, LBT mechanism (Licensed Assisted Access - LAA) uses CCA to access the medium. Based on CCA, an LAA device monitors the channel for a period of at least 20μs and applies the Energy Detection (CCA/ED) threshold (i.e. −72 dBm) to identify channel's status. If within that period, energy level exceeds CCA/ED, then the channel is considered BUSY and the transmission is postponed. In that case, the Almost Blank Subframe (ABS) technique may be applied, where LTE transmits subframes carrying vital information (e.g. control, synchronization signals but no user-plane traffic). If the channel is sensed IDLE, devices proceed to a transmission. However, the maximum channel occupancy time is up to 10ms. In case that a transmission exceeds the maximum channel occupancy duration, DTX is performed. This, however, comes at a price of affecting frequency/time synchronization, CSI measurements, and AGC.

Since, CSAT is not CCA-based, collision overheads and latency (channel sensing duration of up to 200ms) is higher than in LBT. Moreover, it is usually, more aggressive and less fair than LBT because of the different approach followed, compared to Wi-Fi [154]. However, by utilizing CSAT On/Off periods based on traffic load, Wi-Fi performance and fairness can be preserved.

Enhancements to MBMS (eMBMS) are also introduced in this release. Single-Carrier Point-to-Multipoint (SC-PTM) uses the same system architecture as MBMS, supporting broadcast/multicast services, multiplexed over a single cell through PDSCH, instead of PMCH. It reduces the latency of MBSFN and improves radio efficiency by dynamically assigning resources to a group of UEs, based on real-time traffic load. Indoor positioning was also one of the priorities for 3GPP Rel-13, aiming at improving position accuracy [155], [156]. The requirements for indoor positioning were issued by Federal Communications Commission (FCC) to gradually improve accuracy for public and safety services/calls within a period of 6 years. In particular, until 2021, an accuracy of 50 meters for at least 80% of the calls is required to be achieved [157].

c: 3GPP LTE-ADVANCED-PRO - RELEASE-14

The recent 3GPP release, Rel-14, is generally considered as the last release before entering the era of 5G. This release mainly focused on enhancing LAA to support dual connectivity in UL (eLAA), and enhanced LTE-WLAN Aggregation (eLWA) in UL, FD-MIMO, M2M, and MBMS. At the same time, reduced latency and support of critical Video/Data and Vehicle-to-Everything (V2X) services were also among the items studied in Rel-14 [158].

Extending LAA to UL transmissions is challenging due to the scheduling requests, processing delay, and overhead. UEs transmit the scheduling requests in PUCCH, while eNodeBs respond to PDCCH after performed CCA (in case of LBT). When access is granted, UEs will again perform CCA to ensure that the channel is still available. This delay results in unused subframes between DL and UL transmissions. To cope with the high delay and overhead, CCA time reduction or unscheduled access in UL; similar to Wi-Fi access scheme, could be applied [159].

Limitations of FD-MIMO in 3GPP Rel-13, such as limited number of antenna ports and no support for providing robustness for high-speed UEs, were studied and addressed in 3GPP Rel-14. The number of antenna ports increased from 16 to 32, while enhancements were also proposed on CSI reports to improve efficiency of MU spatial multiplexing [160]. Moreover, features for better CSI accuracy and robustness due to inter-cell interference and high speed, are also included in that release. A possible enhancement for FD-MIMO in the next release, could be the distributed FD-MIMO (D-FD-MIMO) [161]. Further study on MIMO performance requirements for UEs was also performed [162]. As new operating bands are continuously added to 3GPP specification, the implementation of a common radio supporting simultaneous transmission and reception of multiple bands, is a feature under consideration [163]. Benefits of applying this feature at eNodeBs include dynamic power sharing among different bands and reduced installation complexity and insertion losses for multi-band antenna sharing since a single eNodeB will be capable of supporting multiple bands with no combiner required.

Another area studied in 3GPP Rel-14, was the latency reduction [164]. Random-Access and Scheduling Request procedures, the fixed duration of Transmission Time Interval (TTI), the data processing delay, and the high handover latency (approximately 47 ms for 3GPP Rel-8/9) are the main obstacles for improving performance of applications such as gaming, real-time (e.g. VoLTE, video conference), and augmented reality which have stringent low-delay requirements. Viable solutions for reducing latency include: i) increasing the frequency of Semi-Persistent Scheduling (SPS), ii) dynamically skipping of UL Grants by eNodeBs, iii) reducing RACH procedure delay during handover in a synchronized network, and iv) reducing transmission and processing delay. The latter can be achieved by reducing TTI, however, control and reference signal overheads may increase.

Advancements in MBMS were also considered, to support the reception of non-collocated multi-carrier MBMSs to deal with the high demands of diverse types of TV services and mobile video streaming [165]. In particular, advancements in radio interface include high spectrum efficiency for larger Inter-Cell Distance (ICD) by applying a larger CP, the support of new subframe type to reducing overheads, and shared eMBMS broadcast where operators can share content, avoiding broadcasting the same content over different networks. Free-to-air services, receive-only mode (ROM), upgraded codecs for supporting Ultra-High-Definition (UHD) television require a new Application Programming Interface (API) to simplifying eMBMS procedures, and a new transparent delivery mode so that TV formats can be of a wide range are some of the enhancements introduced for eMBMS, in 3GPP System Architecture Working Group (SA). A study was also performed and provided recommendations on the mission critical video/data services that require high availability, low latency, security etc. (e.g. new protocol additions and security functionality). On the other hand, the use of larger CP poses a restriction for supporting UEs with high velocity (i.e. higher than 100 km/h). The lack of feedback in eMBMS, prohibits the use of Closed-Loop MIMO with SC-PTM and MBSFN. Due to the static resource allocation, adaptation to traffic load when QoS characteristic variations are limited, service continuity (e.g. during handover) is achieved through the unicast channel or by overlapping MBSFN areas.

LTE's rival standard for supporting Vehicle-to-Vehicle (V2V) communications i.e. Vehicular Ad-hoc Networks (VANETs), was introduced in 2010, namely IEEE 802.11p [167]. Similar to most of the IEEE standards, IEEE 802.11p is a low-cost solution that is easily deployed. However, it suffers from scalability issues, limited range, low data rates, and most importantly, QoS is not guaranteed [168]. Considering all the latest advancements in LTE and the challenges that V2X communications face, LTE enhancements for vehicular communications were also proposed in Rel-14. Twenty-seven use cases and three distinct types of V2X services; V2V, Vehicle-to-Infrastructure (V2I), and Vehicle-to-Pedestrian (V2P) were considered initially.

LTE cellular V2X is based on D2D communications for supporting vehicle communications when they are in-coverage or out-of-coverage. Moreover, D2D communications (for V2V services based on sidelink PC5) can enable fast transmissions among vehicles when they are in the proximity of each other [169]. To maintain low PARP, SC-FDMA with normal CP is used in PHY layer, while the number of demodulation reference signals (DMRSs) increased from 2 to 4 in a subframe to cope with the high-speed and Doppler effects. To deal with synchronization issues in D2D links, the Global Navigation Satellite System (GNSS) is used, instead of eNodeBs [170].

d: 3GPP LTE IN 5G ERA - RELEASE-15

Rel-15 will be the first release to introduce the 5th Generation of wireless communications. The main requirements on performance targets and capabilities for 5G were approved on March 2016 [171]. Performance targets vary, depending on the environment and application. For example, per user data rates of at least 1 Gbps and 500 Mbps in DL and UL for indoor hotspot environments and 20 Gbps in DL and 10 Gbps in UL for eMBB, whilst latency less than 4ms and 1ms for eMBB and URLLC, respectively, are required. Larger bandwidths and higher-order modulation (e.g. 1024 QAM) can be used to achieve high data rates in small cells. Enhancements to the legacy 4G protocol stack for reducing processing delays have also been proposed, given that the lion's share of latency is contributed by PDCP operations (i.e. de-ciphering, robust header compression etc.) [172].

Moreover, the new network will be characterized by: i) optimizing signaling, ii) reducing energy consumption, iii) network flexibility (optimized service provision based on slicing and flow re-routing concepts in core network), iv) traffic steering through different RATs, and v) enhancing data rate, position accuracy, and further reductions in latency. To meet the requirements of the new use cases, new features and enhancements in both the access and the core network segments will be introduced in Rel-15 and the follow-up releases.

In the first phase, enhancements in LAA and LWA involve service pricing by making the core network able to identify the route of packets (licensed/unlicensed) and the support of 3.5 GHz band. Moreover, there is a focus on V2X services and studies of new scenarios, such as remote driving and vehicle platooning [173]. According to the 5G Automotive Association (5GAA) future V2X services will need to provide support for: i) Safety, ii) Convenience, iii) Advanced Driving Assistance, and iv) Vulnerable Road Users. The safety related use cases aim to reduce the frequency and the severity of accidents by warning drivers of accidents and collision risk through an intersection [174]. Software updates fall into the second use case group, whereas those use cases focusing on improving traffic congestion, high definition maps, road conditions, weather alerts etc., fall within the scope of the third group. The last category comprises those use cases that support communication between vehicles and non-vehicle road users, aiming at detecting and warning drivers about their presence. The support of up to 5 CCs is also under consideration for V2X services in Releases 15/16 [175]. The 5G-PPP Phase 2 Project, 5GCAR [176] works on optimizing V2X connectivity in terms of latency and reliability, whereas improvements in positioning accuracy for both road users and vehicles are also considered. Furthermore, Future Railway Mobile Communication Systems (FRMCS) is currently being studied for future releases [177], [178]; probably after Rel-15 [179], to support seamless connectivity, low latency, and high data rates for the railway users and the safety-related applications (real-time train tracking).

Further advancements to eMBMS for supporting TV services are also expected to be introduced in 5G releases, probably in Rel-16. The 5G-XCAST [166], a 5G-PPP Phase 2 Project, works on addressing the limitations of the current eMBMS systems and developing broadcast and multicast point to multipoint capabilities for 5G networks (e.g. for scenarios such as IoT, Public Warning Systems, etc.). Seamlessly and dynamically switching between different transmission modes (i.e. unicast, multicast, broadcast) or using them in parallel are among the main priorities of 5G-XCAST.

The study of mission critical services continues in Rel-15, where one of the enhancements includes the ability of distributing mission-critical information to a group of users. Further enhancements in D2D and relays for IoT or wearable devices to support diverse types of traffic and services with reduced power consumption and complexity, are also under the microscope [180].

(i) PHY LAYER ENHANCEMENTS

As part of 5G NR, subcarrier scaling is under consideration [184], [185], due to the particularly detrimental impact of white noise on mmWave based communications, resulting in requirement for smaller symbol durations. Different subcarrier spacing values are expected to be supported, based on the scenario, operating frequency, etc. Therefore, alterations in CP length are also expected to be made, with various sizes to be supported. Multiple access schemes are expected to be supported by the 5G NR, subject to application type and requirements. The main challenge is how to ensure the interoperability of the existing mature technology (i.e. OFDMA, SC-FDMA) with Non-Orthogonal Multiple Access (NOMA) schemes [186] that are deemed more suitable for M2M communications. Therefore, one of the first tasks for Rel-15 is the study of dual connectivity of the current LTE-A Pro as PCell and 5G NR as SCell, with up to 4 CCs in DL for LTE-A Pro (4-DL/1-UL and 1 NR) and two MAC entities per UE [187]. Frequency localization to reduce in-band and out-of-band emissions, lower power consumption by utilizing SC-FDMA for UL transmissions, and slot flexibility to support multiple services with different requirements on the same frequency are also part of the 5G NR [188]. The ONE5G [189], a 5G-PPP Phase 2 Project, has already started working on the next release (a.k.a. 5G advanced (pro)) by identifying and addressing the challenges that 5G NR will face for supporting various vertical use-cases in multiple scenarios. The objectives for ONE5G include: i) further studies and enhancements on massive MIMO, access schemes, and provisioning of wireless services to improve user experience.

Channel coding is one of the fundamental areas that is being studied for the 5G NR. There has been a lot of discussions about replacing the mature coding schemes used in the previous generations e.g. Turbo codes, with LDPC or Polar codes [190]–[193]. The recently proposed, Polar codes [194], has been approved by 3GPP as the coding scheme to be used for 5G NR DL/UL control plane for eMBB, and LDPC coding for the data channel. The main reasons for replacing Turbo codes are the higher complexity and inferior performance in scenarios where high throughputs are expected. However, it is shown in [195] that by redesigning Turbo codes at software and hardware level, 5G requirements can be met, whilst maintaining backward compatibility.

(ii) MAC LAYER ENHANCEMENTS

CA, dual connectivity, and CoMP are three technologies that could be used for supporting connection on different/same carrier frequencies from various RATs, also known as inter/intra frequency multi-connectivity schemes [196], [197]. Utilization of CA to reduce delay, UL data compression and signaling reduction (e.g. due to paging and handover), tight interworking to support efficient and high-performance mobility between NR and LTE, and continuing the studies to address the challenges to support aerial UEs (e.g. mobility and DL/UL interference) are amongst the work items for RAN 2 [198]–[201]. A challenging task in supporting multi-RAT operations is the identification of the radio protocol layer where the aggregation of the different technologies should occur. Aggregation at RRC and PDCP layers seems to be the most convenient place, since these layers do not need to be time-synchronized with the lower protocol layers [202]. However, since these layers do not participate in real-time radio resources utilization or medium access, inter-RATs' coordination is limited. On the other hand, RLC and MAC layers are not fully time-synchronized with PHY layer, resulting in packet and call drops when synchronization is lost [5]. Moreover, since information splits in MAC layer for CA, tight synchronization among CCs is required. However, if tight synchronization is achieved between MAC and PHY layers, then inter-RATs' coordination and resource allocation utilization becomes possible. Aggregation of multi-RAT technologies at the PHY layer might achieve higher gains in terms of aggregated throughput and reduced latency, but the requirements and delays associated with different air interface technologies may prove very challenging to implement. Moreover, coordination among multiple Layer 2 entities (i.e. multiple RLC entities) is essential, i.e. for retransmissions due to different HARQ configurations based on the service requirements.

A three-layer RAT switching envisioned in [203], for supporting various RAT technologies (i.e. mmWave RAT with a microwave one). The lower layer (MAC-Low) will be responsible for transmission mode switching, while the 2nd one (RRM/MAC) will be handling control information for several air interfaces. The higher one (Network), will be enabling the slice or interface switching in the Internet Protocol (IP) layer. A three-layer protocol stack to support multi-RAT 5G scenarios is also presented in [204], developed by the European 5G-PPP during Phase 1, SPEED-5G project [205]. MAC-Low is responsible for real-time operation (i.e. multiplexing/demultiplexing), whereas High-MAC deals only with the control plane and those functions that real-time execution is not required. Multi-Path TCP is also used in the 3rd layer to realize the support of multi-RAT, where traffic is redirected through multiple RATs. Clustering of multiple eNodeBs or APs, is another enabling technology that can be applied along with Machine Learning (ML) techniques, to improve networks' efficiency, such as energy efficiency [206], transmission time reduction [207], load balancing [208], and increased reliability [209], which is one of the main targets for high-velocity scenarios.

(iii) CORE NETWORK CONCEPTS

Other complementary technologies that will be incorporated in future releases, capable of providing networks with flexibility, control, and reconfigurability are described in the following paragraphs. Although, they might not directly be related to the RAN segment (for the time being) nevertheless, modifications (or even adoption of similar concepts e.g. slicing in RAN [211]) in the lower layers will be required for supporting them.

Network Slicing will also provide networks with flexibility and scalability [210], by sharing resources; spectrum sharing [212] and processing power or storage [213]. The slices, also known as Slice/Service Type (SST), are classified based on the features and services supported into three (standardized) categories; eMBB, URLLC, and mMTC [214]. The first one aims at supporting high data rates and high capacity for fast large file transfers, high quality video streaming etc. from multiple users. The second one, URLLC, is mostly for industrial automation and remote-control systems, while the last one for supporting massive number of IoT devices. Users will be able to simultaneously connect to multiple SSTs. However, it will also be challenging to support handovers for high-speed users or manage the various levels of QoS, security, and integrity between the services [215]. Multiple MAC/RLC/PDCP entities might be needed to handle and support the diverse SSTs where inter-coordination among them might be inevitable. The control and management of vertical slices in real-world deployments is the main focus for the SLICENET Project [216] from 5G-PPP Phase 2.

Five other technologies/concepts ([217]–[221]) that will be incorporated in future releases, include: i) Software Defined Networks (SDNs), ii) Network Function Virtualization (NFV), iii) Virtual Network Function (VNF), iv) Mobile Edge Computing (MEC), and v) enhancing CoMP using the Self-Organizing Networks (SONs) technology. The former refers to the case where network objects (e.g. routers) are deployed in an automated manner, while the second technology enables SDN functions to be hardware platform-independent (e.g. load balancing in a cloud), enabling reduced energy consumption and complexity at the eNodeBs. VNF is deployed on top of NFV, while MEC is built on the concept of enabling cloud computing at the edge of cellular network (e.g. eNodeBs), which is considered an important technology especially for V2X services where the huge volume of data needs to be processed and delivered to the vehicles in real-time [174]. The 5G-PPP Phase 2 Project, 5G ESSENCE [222] continues the work of the 5G-PPP Phase 1 Projects focusing on SDN/SON (i.e. SELFNET [223], CHARISMA [224]) and envisions a multi-RAT infrastructure where MEC is enabled at a cluster of small cells that are being managed by a centralized controller.

SONs are also studied as the technology that will allow a self-based CoMP management and operation on the fly, based on user and network traffic conditions [225], [226]. The concept of SONs is not new and is based on self-awareness, self-configuration and optimization [227], characteristics that require systems with advanced intelligence for proactive decisions regarding the efficient management of spectrum [228] or the utilization of the new technologies (e.g. Massive MIMO) [229]. SON concept is also to be applied for enhancing Network Slicing operation and management by (re-)configuring, optimizing, and healing a Network Slicing Instance. The ability of identifying the failures and applying corrective actions on the fly is essential for maintaining a stable desired state for the network.

A new group was recently formed by ITU, focusing on ML for future networks, including 5G [230]. ML techniques can be used for predictions and dealing with many issues that wireless systems face. ML is, thus, a proactive tool that enables smart radio devices by adding artificial intelligence mainly in the core network [231]–[233]. For example, ML can be applied to Massive MIMO for channel estimation, finding the optimal handover solution or clustering, which is very challenging in 5G networks due to the diverse cell sizes, technologies, etc. They are categorized into three classes; supervised (labeled samples), unsupervised (unlabeled), and deep learning.

B. IEEE 802.11 TECHNOLOGY

Similar to the 3GPP cellular technology, new amendments are being developed by the IEEE 802.11 standards working groups to address the demands for high data rate and wide coverage in the unlicensed 2.4/5 GHz spectrum (and mmWave and Sub-1 GHz bands). The introduction of IEEE 802.11n [234], in late 00's, was revolutionary. It was a huge milestone for IEEE 802.11 family of standards and it incorporated advanced mechanisms at the PHY and MAC layers. The IEEE 802.11n supports data rates of hundreds Mbps, MIMO, channel bonding, frame aggregation, wider coverage, and dual band support. Following the success of IEEE 802.11n, a new amendment was launched in late 2013, namely IEEE 802.11ac. In contrast to IEEE 802.11n, this new amendment operates only at 5 GHz frequency band, exploiting the benefits of wider bandwidth channels (channel bonding support to channel bandwidths of up to 160 MHz) in the 5 GHz band. By further enhancing channel bonding, MIMO, and the support of 256-QAM along with MU-MIMO in DL, IEEE 802.11ac can boost the peak link-rates to over 6 Gbps.

Although, IEEE 802.11ac can offer high data rates, it has one major drawback; it is designed, as its all predecessors, for small indoor network deployments. Therefore, Task Group IEEE 802.11ax (TGax) was formed in 2014 and is expected to complete standardization activities by the second half of 2019. In contrast to preceding IEEE 802.11 standards aiming at enhancing link throughput, the IEEE 802.11ax amendment focuses on improving spectrum efficiency and area throughput in dense WLAN scenarios, while further reducing power consumption of mobile devices. Moreover, IEEE 802.11ax compliant APs/STAs will operate in 2.4 and 5 GHz frequency bands initially, but they could also operate in the bands between 1 and 7 GHz as they become available. Furthermore, backward compatibility is one of the main requirements in IEEE 802.11ax, since heterogeneous devices are expected to be operating in the same frequencies. Before we overview this amendment, which is under development, we provide a description of IEEE 802.11 access schemes and the most important enhancements that various amendments applied to the MAC and PHY layers, over the last 12 years. This section concludes with the overview of the IEEE 802.11af [235], an amendment that operates in Television/TV White Spaces (TVWS) bands and was introduced to provide seamless wireless connectivity in rural environments. The evolution of the IEEE 802.11 amendments at the MAC and PHY layers, is illustrated in Figure 7.

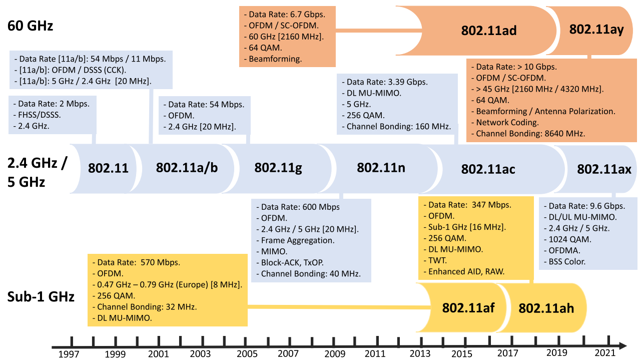


FIGURE 7. An overview of IEEE 802.11 evolution (PHY/MAC amendments).

1) BASIC ACCESS SCHEME

In contrast to the 3GPP LTE standard, the IEEE 802.11 is an asynchronous technology/standard, in the sense that it relies on random-access methods for granting access and transmissions over the shared medium. It also differentiates from LTE in the way that there are no dedicated channels for data, control, and DL/UL frames; all transmissions can be over the same channel. Moreover, preambles precede the transmission of data/control or management frames.

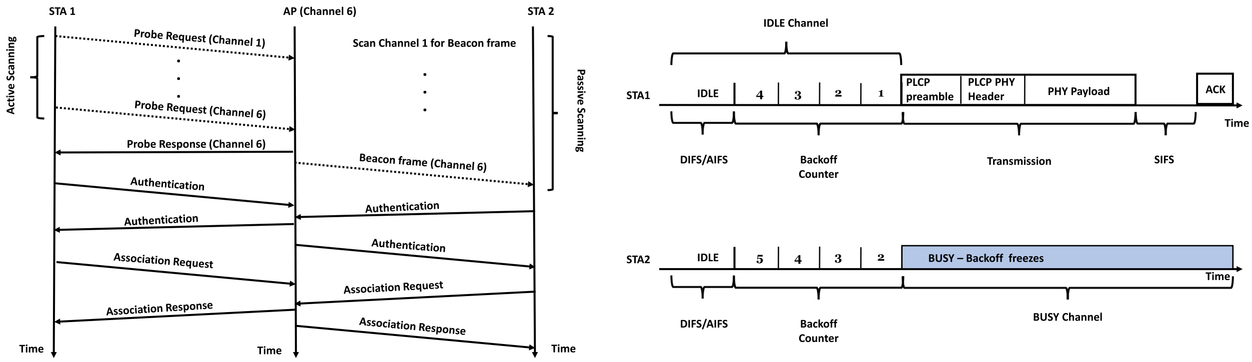
Prior to data transmissions, STAs have to establish a connection with an AP. This procedure comprises three stages: i) detection, ii) authentication, and iii) association, as illustrated in Figure 8a. STAs can passively or actively scan the available channels to detect any APs. When passive scanning is used, STAs monitor a channel for a certain period of time, waiting for beacon frames, before they try another channel. Beacon frames are regularly sent by APs, and carry information about their capabilities e.g. supported MCSs, traffic load, and settings for MAC layer. If active scanning is enabled, STAs transmit a probe request frame to trigger an AP, which responds with the probe response frame. During the authentication stage, STAs establish their identity with an AP. The latter decides if STAs can or cannot access the network. Four different types of authentication exist: i) Open System Authentication, ii) Shared Key Authentication (i.e. Wired Equivalent Privacy (WEP)), iii) Fast Basic Service Set (BSS) Transition of Fast Roaming Authentication, and iv) Simultaneous Authentication of Equals. The last stage is the association of a STA with an AP (typically based on Received Signal Strength Indicator (RSSI))), where their capabilities are exchanged along with the Association ID (AID). AID is assigned to every STA and represents the 16-bit ID of a STA. Re-association is invoked during a handover or when association attributes need to change.

When association between a STA and an AP is established, data frames can be exchanged. In IEEE 802.11, access to the medium relies on DCF or Point Coordination Function (PCF). DCF refers to the case where unscheduled transmissions occur, while PCF is used for scheduled transmissions between beacon frames. For example, PCF comprises two periods: the Contention-Free-Period and the Contention-Period. In DCF mode, every node senses the channel if it is BUSY or IDLE, before initiating a transmission. In the remainder of this section we mainly focus on the DCF, since is the mechanism most commonly used in Wi-Fi networks.

The channel state is determined by two factors; the energy level detected in the channel and the Network Allocation Vector (NAV). In the former case, the CCA threshold is used, which determines a channel as BUSY when the energy level is above a threshold, IDLE otherwise. CCA comprises both Carrier Sensing (CCA/CS) and CCA/ED mechanisms. CCA/CS indicates a channel as BUSY with probability greater than 90% within $4\mu s$ for any Wi-Fi signal detected equal or larger than the minimum MCS receiver sensitivity (i.e. MCS-0), which is -82 dBm for 20 MHz channel bandwidth, according to the standard. However, most products exceed this specification by 5-10 dBs [236], [237]. When the preamble is missed (i.e. nodes not being able to successfully decode all fields), the CCA/ED kicks in and the channel is considered BUSY if energy level detected in the channel is at least 20 dB above the minimum MCS receiver sensitivity (i.e. -62 dBm for 20 MHz channel bandwidth). In some cases, where spectrum-sharing takes place, CCA/ED is applied. CCA/ED sets channel's status based on the energy level of any signal (i.e. at -72 dBm is specified for 20 MHz channel bandwidth). Note that there is always the possibility of a false alarm, even if those conservative standardized values are used. For example, false alarm rate increases with the reduction of CCA/ED (more sensitive CCA/ED). On the other hand, NAV is updated based on the value in the Duration field of any frame received. In that way, a channel is considered IDLE when the NAV timer is expired.

Once the channel is determined to be IDLE for a certain period of time, denoted as DCF Interframe Spacing (DIFS, DIFS = SIFS + 2 * Slot) or Arbitration Interframe Spacing (AIFS) for QoS nodes [238], the Binary Exponential Back-off (BEB) counter is enabled to prevent collisions, as depicted in Figure 8b. It decrements by one for every IDLE slot, freezes when a BUSY slot has been detected, and then resumes from that value after the channel being declared IDLE for DIFS/AIFS period. Transmissions occur when this counter expires. After a successful transmission, the back-off counter is reset and a node randomly chooses a new back-off counter within a Contention Window (CW) (i.e. CWmin) for the next transmission. If an ACK for a transmission is not received, then the node assumes that a collision has occurred, it doubles the CW size and retransmits the frame. Note that the maximum size that CW can have is $2^m * CWmin$ (i.e 1024), where m is the retransmission state.

At the other end of the link, the nodes that have detected a frame with RSSI above CCA/CS lock onto it and reception procedure starts. The first part of a frame, legacy preamble, includes the STF that is used for AGC, frequency correction, and time acquisition, the Long Training Field (LTF) for fine timing/frequency correction and channel estimation, and lastly, the Legacy Signal Field (L-SIG) carrying the length and rate information. The legacy preamble ensures interoperability between different IEEE 802.11 technologies.



(a) (b)

FIGURE 8. IEEE 802.11 a) connection establishment among STAs and an AP and b) data transmission after association setup.

However, this comes at a price of lower throughput, especially when an IEEE 802.11b preamble format is used as we explain in the following paragraph. The non-legacy part, called High-Throughput (HT), Very-High-Throughput (VHT) or High-Efficiency (HE) in IEEE 802.11n/ac/ax amendments, respectively, follows a legacy preamble and carries any additional information needed for the correct reception of a packet (i.e. channel width). Note that the fields that follow STF/LTF, and precede MAC header, form the PLCP header. When the reception of an MPDU finishes, then the recipient of this frame will transmit an ACK after SIFS. Two different SIFS timings are used for IEEE 802.11 technologies, based on the operational frequency; 10μs and 16μs in 2.4 and 5 GHz, respectively. In the case that reception was not successful, then a node defers its transmission not by DIFS, but by the Extended Interframe Spacing (EIFS). EIFS is longer than DIFS and is used to protect any ACK transmission (EIFS = SIFS + DIFS + ACK).

2) IEEE 802.11 MECHANISMS FOR LEGACY INTER-OPERABILITY

There are four protection mechanisms to address coexistence of various IEEE 802.11 technologies, operating at the same frequency bands. The first one, is the preamble format, as already described. The IEEE 802.11b standard comprises two different formats; Long preamble with duration of 192μs and Short preamble of 96μs. A ten-fold and five-fold increase in preamble duration can be observed when the IEEE 802.11b preamble is applied, compared to the IEEE 802.11a/g preamble (duration of 20μs). The IEEE 802.11n employs three different preamble formats; Non-HT format, HT-Mixed format, and HT-Greenfield format (rarely used). The former is used to allow coexistence with IEEE 802.11b devices, the second format is used in the absence of IEEE 802.11b devices, while the latter is used only when IEEE 802.11n devices exist in the network. On the other hand, IEEE 802.11ac employs only one format, namely VHT format, which ensures coexistence with IEEE 802.11a/n devices. A second mechanism for preserving inter-operability with IEEE 802.11b devices, is the RTS/CTS scheme. The RTS/CTS control frame is transmitted at the lowest data rate i.e. 1 Mbps, used by IEEE 802.11b devices. Lastly, CTS-to-Self can also be employed by a non- IEEE 802.11b device, operating at 2.4 GHz i.e. IEEE 802.11g/n, for protecting its transmissions. This CTS frame contains identical addresses in the source and destination fields, while setting the value in Duration field, equal to the duration of data and ACK frames exchange. A fourth mechanism that is used by the IEEE 802.11n devices, is the Legacy-Signal Transmission Opportunity (L-SIG TxOP) protection. It allows for the protection of frames transmitted during a TxOP period by setting the length of the Duration field equal to the duration of the total transmission. In particular, once an IEEE 802.11n has granted a TxOP by using one of the first three mechanisms, it uses the HT-Mixed format to transmit the frames under TxOP. However, all the aforementioned mechanisms increase the overheads and severely affect network's performance. Note that coexistence in the 5 GHz band does not require the use of RTS/CTS or CTS-to-Self to ensure inter-operability, due to the absence of IEEE 802.11b devices. However, RTS/CTS may be applied to address other common issues in the wireless medium, as described in the following section.

3) IEEE 802.11 HIDDEN/EXPOSED NODE PROBLEM

The main shortcoming of IEEE 802.11 technology is that frame collisions may occur due to hidden nodes, while transmission opportunities are reduced due to exposed nodes. Hidden nodes are the nodes that are out-of-CS range of other nodes and their transmissions may interfere with another ongoing transmission. In other words, hidden nodes may sense the channel as IDLE, whilst there is another transmission taking place. Although, the strongest signal may survive a collision, resulting in a phenomenon known as capture effect [239], [240], [268], transmissions by hidden nodes can severely affect network performance under moderate or heavy traffic conditions [241]. On the other hand, exposed nodes lead to poor spectrum efficiency [242], by refraining from transmissions (channel erroneously declared as BUSY), even though, their recipients may well be located sufficiently far away so no interference would have been caused, had the transmission taken place. The exposed node problem is more pronounced in scenarios where multiple co-channel Overlapping Basic Service Sets (OBSSs) coexist in an area. The CCA/CS and Transmit Power Control (TPC) are two mechanisms that are used to address the hidden/exposed node problems. However, it is almost impossible to eliminate both hidden and exposed nodes at the same time within a network, but there is a trade-off that can be reached between them that maximizes throughput performance [243].

Another IEEE standardized (though optional) feature that was proposed to ameliorate hidden/exposed node problem is the four-way RTS/CTS handshake. It was initially introduced to tackle this issue, but can also be applied to ensure interoperability among the different IEEE 802.11 technologies, as described earlier. However, RTS/CTS not only does not solve the hidden/exposed node problem [244], since a node updates NAV on the reception of at least one of those frames (RTS or CTS), but also adds significant overhead [245], especially when small-sized packets are transmitted. Both factors, severely degrade network throughput in high density deployments [246].

4) IEEE 802.11e - THE QoS AMENDMENT

Enhancements in support of QoS and specification of the original coordination functions were introduced in IEEE 802.11e-2005 amendment [238]. A new coordination function (HCF) was proposed, aiming at prioritizing traffic at the MAC layer. HCF comprises the HCF Controlled Channel Access (HCCA) and is used for scheduled transmissions, similar to PCF, and EDCA for supporting QoS when operating in DCF mechanism. Although, HCCA may provide better performance, EDCA is the mechanism that has gained wider acceptance. Both methods define 8 different classes for the traffic with different priority each one. These traffic ids (TIDs) are categorized into 4 Access Classes (ACs), namely Background (AC_BK), Best Effort (AC_BE), Video (AC_VI), and Voice (AC_VO).

Each AC is characterized by different AIFS (AIFS replaces DIFS for QoS nodes) and CW values, which define the priority of each AC. For example, AC_VO and AC_BK has the highest and lowest priority, respectively. Based on their type, packets are tagged with the AC they belong, and placed in the correct MAC queue. If two or more packets with different TID are simultaneously dequeued, then only the packet with the highest priority is transmitted. This procedure is known as internal collision and applies only for QoS nodes. TxOP is another feature introduced in IEEE 802.11e, allowing data transmission in burst mode. TxOP defines the maximum duration that frames belonging in the same AC can be exchanged in burst mode. AC_VO and AC_VI use a TxOP value of 1.504ms and 3.008ms, respectively, while the other ACs use a value of 0. When TxOP is 0, then only one MSDU can be transmitted at a time. To further reduce control overhead, Block-Ack was also introduced in this amendment, as an optional feature. Instead of acknowledging every single MPDU, a Block-ACK frame can acknowledge up to 64 MPDUs.

5) IEEE 802.11n - HIGH THROUGHPUT AMENDMENT

Enhancements in Block-ACK scheme and new technologies, such as frame aggregation, are introduced in IEEE 802.11n. This amendment supports operation in both 2.4 and 5 GHz frequency bands. On top of the IEEE 802.11e Block-ACK, known as normal Block-ACK, IEEE 802.11n proposed the use of Compressed Block-ACK when fragmented MSDUs are not transmitted, and the Multi-TID Block-ACK for acknowledging MPDUs belonging on different TIDs. Moreover, two polices were defined for Block-ACKs; immediate Block-ACK, and delayed Block-ACK. Transmissions under the Block-ACK scheme comprise three phases: the set-up, data frame exchange, and tear-down phases. During the first phase, capability information, such as buffer size, policy etc., are being exchanged between a pair of nodes. Once Block-ACK agreement is established, then data frames are transmitted along with Block-ACKs. The last phase is initiated with the transmission of a DELBA frame by the originator, used to terminate the Block-ACK agreement between the nodes.

Frame aggregation was also first introduced in this amendment, where multiple frames belonging in the same TID can be aggregated into a single one [247]. Two types of frame aggregation have been defined in the standard; A-MSDU and A-MPDU. A-MSDU aggregation takes place on the upper MAC layer and allows MSDUs frames that contain the same source and destination addresses to form a single MPDU, thus, one MAC header per A-MSDU is used. The maximum A-MSDU length is defined to 7935 bytes when the A-MPDU aggregation is disabled, 3839 bytes otherwise. A-MPDU aggregation takes place in the lower MAC and supports the combining of up to 64 MPDU frames, each one with its own MAC header. The maximum A-MPDU size is limited by the number of frames (64) or length ($\sim$ 65 KB). The A-MPDU aggregation outperforms A-MSDU aggregation due to the larger allowable size, especially for high data rates, while it is resilient in lossy channels due to the MAC header per MPDU [248]. Note however that a missed A-MSDU results in the retransmission of all aggregated frames, whereas in A-MPDU only the frame that has been lost, is retransmitted. The maximum PPDU time is limited to 5.484ms and 10ms for the HT-Mixed and HT-Greenfield formats, respectively. This means that with low data rates, A-MPDU is more likely to be restricted due to the maximum PPDU duration rather the maximum number of frames (64) or size ($\sim$ 65 KB). A Two-Level aggregation mechanism is also supported in the amendment, where A-MSDU and A-MPDU schemes are both applied. Two-Level aggregation is more beneficial for small MSDUs sizes [249].

The optional Reverse Direction Protocol (RDP), an advancement to TxOP, is also defined in the IEEE 802.11n. RDP allows two nodes to exchange data frames within the same TxOP. In particular, a node that grants TxOP access by setting the Reverse Direction Grant (RDG)/ More PPDU subfield of the HT Control field in MAC header to 1, thus granting permission to the recipient for responding to the transmission with data frames. However, the first PPDU of the recipient must contain a Block-ACK and the transmission duration must not exceed the remaining TxOP. In that way, overheads are reduced as devices do not have to contend to grant access to the medium.

Furthermore, two different Guard Intervals are defined; 400ns and 800ns. Channel bonding, where up to 2 channels can be concatenated, forming a channel bandwidth of up to 40 MHz, is also supported by the IEEE 802.11n devices. Even though, channel bonding was initially proposed for the 5 GHz frequency band, it is now also supported in the 2.4 GHz too. With channel bonding, the legacy fields along with the HT Signal fields (HT-SIG1/2) in the PLCP preamble and header, are duplicated over the channels; primary channel and secondary. The rest of the fields and MPDU frame are sent across the entire bandwidth channel. Although, channel bonding can potentially double the throughput, it comes at a price of reducing coverage range. This is because larger power amplifier is needed to maintain the same output power, which is costly and power consuming [236]. A good rule of thumb is that CCA/CS threshold should increase by 3 dB when the bandwidth doubles. Two FEC codes are also supported; the mandatory Binary Convolutional Code (BCC) and the LDPC as an optional feature.

One of the most impactful techniques to improve throughput and coverage, is the MIMO technology. IEEE 802.11n supports two MIMO modes, namely Space-Time Block Coding (STBC) and Spatial-Division Multiplexing (SDM). STBC enables the transmission of multiple copies of single data stream across multiple antennas, hence, enhancing range and link robustness. The most common STBC scheme, the Alamouti scheme, is the one used in this standard. For example, two data streams are combined and sent from two antennas over two-time slots. On the other hand, with SDM, independent data streams are transmitted over different antennas. The maximum data rate increases with the number of independent data streams, which is based on the number of Tx and Rx antennas. In other words, data rate increases by $min(Tx\_ant, Rx\_ant, data\_streams)$. Up to 4 antennas are supported in IEEE 802.11n, boosting the peak data rate to 600 Mbps, assuming that channel bonding and short Guard Interval are enabled.

6) IEEE 802.11ac - VERY HIGH THROUGHPUT AMENDMENT

The support of higher order modulation (256-QAM), number of spatial streams (up to 8), and wider channel bandwidths (up to 160 MHz) has pushed the peak data rate close to 7 Gbps in IEEE 802.11ac [250]. Five configurations for channel bonding are supported in IEEE 802.11ac, including also non-contiguous frequency channels to form a wider channel bandwidth (e.g. $80 + 80$ MHz). The 80 MHz channel bandwidth is formed by two 40 MHz channels and is a mandatory feature for the IEEE 802.11ac devices. This can provide a two-fold increase in data rate compared to IEEE 802.11n, by keeping a single spatial stream [251].

Although, beamforming is also supported in the IEEE 802.11n amendment, most vendors did not include this capability in their products. The main reason was that many beamforming techniques were included in the standard, which could increase implementation complexity (as both communicating nodes must agree on the same method to use). Thus, to avoid this, the IEEE 802.11ac standard mandates only one method, called Null Data Packet (NDP) sounding, supporting only one feedback format i.e. non-compressed immediate feedback. Moreover, MU-MIMO only supported in the DL was included in this amendment. DL MU-MIMO is based on SDM, where an AP with multiple antennas, simultaneously transmits independent data streams to multiple users. Those transmissions are overlapped in the time-frequency domain. A thorough study of MIMO and MU-MIMO is presented in [253] and [254].

At the MAC layer, the maximum A-MSDU and A-MPDU sizes are further increased to 11406 bytes and 1048575 bytes, respectively, due to the support of higher data rates. Furthermore, Partial AID (PAID), a power-saving feature was also included in this amendment. It is built upon IEEE 802.11n AID feature, but its value is not unique for every STA. Moreover, the relevant Information Element (IE) is carried in the PLCP header, allowing a STA to quickly identify and abandon reception when packets are not intended for it. In that way, a STA may switch to sleep or doze state for the duration of that transmission. Along with the reduction in power consumption, throughput gain can also be observed [269], due to the EIFS impact.

7) IEEE 802.11ax - HIGH EFFICIENCY AMENDMENT

The rapid growth of portable devices and the plethora of new applications and scenarios [254], [255], was the motivation for IEEE 802.11ax [256]. Even though, WLANs were originally developed for small indoor environments, nowadays they can be found everywhere; from apartments, offices to outdoor venues e.g. public transport, stadiums, outdoor hotspots etc. To meet the demand for high data rates in those deployments, IEEE 802.11ax defines 5 scenarios for the assessment of the new technologies; a residential, an enterprise, and indoor small (19 BSSs with 17.32m ICD), a large outdoor (19 BSSs with 130m ICD), and a combination of a residential with an outdoor deployment. Along with the new scenarios, advanced features are also introduced in both MAC and PHY layers, allowing peak data rates close to 10 Gbps.

a: PHY LAYER ENHANCEMENTS

Following the paradigm of LTE i.e. OFDMA and channel sharing among multiple users, the IEEE 802.11ax amendment adopts this same technology for both DL and UL transmissions. It is a mandatory feature for the IEEE 802.11ax devices that requires their tight synchronization in frequency

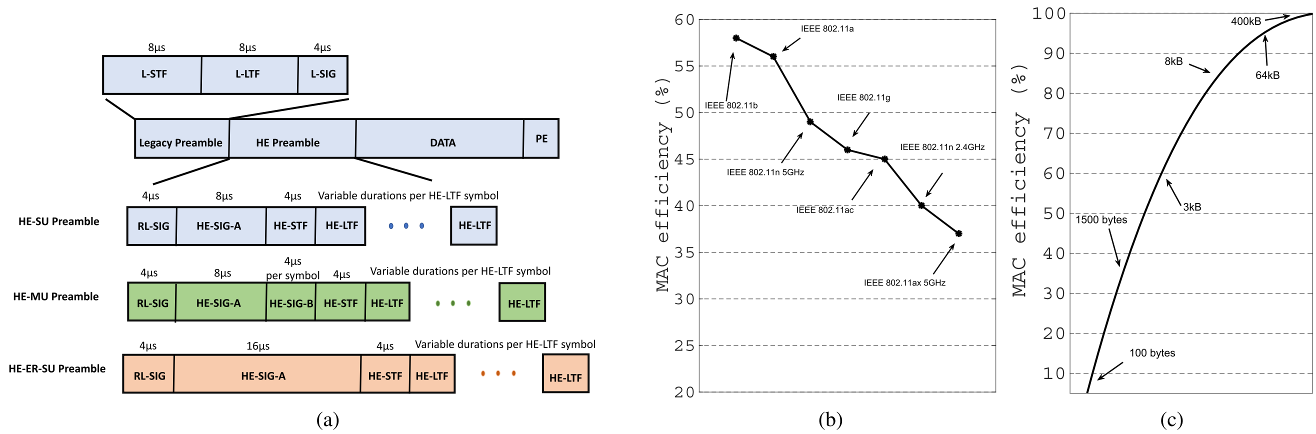


FIGURE 9. IEEE 802.11ax a) HE-Preamble structure, b) MAC efficiency per amendment (highest data rate for 20 MHz bandwidth, 1 spatial stream, and 1500 bytes size) , and c) MAC efficiency with respect to transmitted packet size (20 MHz, 1 spatial stream, and HE-MCS 11).

and time domain, especially in UL direction. Therefore, transmission resources and users participating in UL-OFDMA are announced through the Trigger frame, sent by APs. It is also used for UL MU-MIMO or to reduce power consumption when Target Wake Time (TWT) operation is used. The minimum RU is defined as 26 subcarriers that are distributed among the users, accommodating up to 9 users per 20 MHz channel bandwidth. IEEE 802.11ax also supports a higher order of modulation, i.e. 1024 QAM, as an optional feature, intended for indoor environments.

To improve robustness and performance in fading environments, larger Fast Fourier Transform (FFT) is used. This results in longer symbol duration T_s and a smaller subcarrier frequency spacing. Various T_s are supported for the HE-LTF symbols, whilst only one T_s for the data field. For example, $T_s = FFT/ChannelWidth = 256/(20\ MHz) = 12.8\mu s$, while the subcarrier frequency spacing is $1/(12.8\mu s) = 78.125\ kHz$. Two other techniques for improving robustness in large outdoor deployments, include: i) Extended Range (ER) support and ii) Frequency Selective Scheduling (FSS). With ER, fields in HE preamble are repeated, which along with a 3 dB power boosting of some training fields, may result to 5-6 dB better preamble performance [257]. Some of the frame structures supported by IEEE 802.11ax, are illustrated in Figure 9a. FSS technique has been extensively studied in TGax, aiming at improving OFDMA performance by selecting specific RUs for a user, based on CSI reports [258]–[260]. Furthermore, both BCC and LDPC FEC codes are supported by IEEE 802.11ax devices. However, BCC is used for spatial streams less than or equal to 4, MCS less than 10, and is mandatory for RU sizes less than 484-tone. On the other hand, LDPC is mandatory for MCS-10/11, RU sizes greater than 242-tone, and channel bandwidths larger than 20 MHz.

UL MU-MIMO is also introduced in IEEE 802.11ax, to exploit the advantages of MU-MIMO in UL direction. In that way, nodes with limited number of antennas; 1 or 2, supporting low data rates, do not degrade performance by occupying the channel for long periods. As in OFDMA, a Trigger frame is used to coordinate users.

b: MAC LAYER ENHANCEMENTS

MAC performance decays as higher data rates per STA are used, as seen in Figure 9b, for constant frame sizes. Overheads, such as legacy preamble, IFS etc., make the application-level throughput to significantly vary from the theoretical one. Thus, many enhancements have been proposed to improve MAC efficiency, whilst others are intended to enhance the performance of existing features.

MU-EDCA is used by an AP to adapt to changes in traffic load. Two sets of EDCA parameters are employed; one for all STAs and one for improving efficiency of UL MU capable STAs. These new parameters are carried in selected beacon frames and in all Probe/Association/Re-association responses. However, the APs are not expected to change these values/settings very often. A Multi-STAs Block-Ack control frame is also defined to enable concurrent acknowledgement to multiple STAs after UL MU operation, thus reducing the transmission delay of multiple Block-ACKs. MU-RTS/CTS is also proposed to protect MU-PPDUs, where STAs can simultaneously respond (CTS) to an MU-RTS from their AP.

The maximum PLCP Service Data Unit (PSDU) size is also extended to 6500631 bytes, compared to that in the IEEE 802.11ac, to further improve efficiency when advanced technologies are used (e.g. Channel Bonding, MIMO). The impact of transmitted frame's size is depicted in Figure 9c. Multi-TID A-MPDU is introduced to aggregate frames with different TID values to the same user, utilizing the scheduled RUs. MU-AMPDU is also under consideration, where frames destined to multiple recipients are aggregated into a single frame [261]. This feature further reduces MAC overhead, especially for short-length frames. MU-AMPDU applies to users that experience similar channel conditions (i.e. similar MCS) only if aggregation rules allow it (i.e. length, duration). Moreover, ACKs or Trigger frames can also be concatenated with data frames. However, Trigger frames aggregation with data frames is mandatory.

Two types of frame fragmentation are also introduced; the legacy or static fragmentation and the dynamic one. The latter is proposed to improve efficiency in UL MU operation by filling the empty space with data bytes, instead with padding (static fragmentation). Fragments may have different length, while the first one must be equal or greater than the minimum fragment size threshold. To further improve efficiency for UL MU transmissions, a new frame namely NDP short feedback is introduced - not to be confused with the NDP for channel sounding. It allows APs to collect feedback from a large number of STAs in an efficient way. That feedback frame is sent without data payload. Further to NDP short feedback, STAs transmit the Buffer Status Report (BSR) frames to APs to allocate the right amount of resources in each STA.

Even though, dual beacon was introduced in IEEE 802.11n (STBC beacon) to extend BSS range, it was not implemented by no one. It is shown in [262] that longer CP is needed for robustness, which legacy non-HT PPDUs are not able to provide. Therefore, current efforts focus on replacing dual beacon to ER beacons, since ER exploits OFDMA (i.e. longer CP) [263]. To protect STA-to-STA communications, STAs request from an HE-AP to schedule quite periods to allow STAs communicate directly. Furthermore, a tighter management for association or roaming procedures is also under consideration. It is network's responsibility to inform STAs what is the best AP to associate or when roaming should happen. This is beneficial, especially for cell-edge users, which listen multiple APs at similar RSSI levels.

c: POWER-SAVING ADVANCEMENTS

Power management has been part of IEEE 802.11 standard since its first release. The power-save techniques have been evolving the past years to reduce power consumption in portable devices. Power Save Mode (PSD) was the first technique to be introduced in IEEE 802.11. Nodes sleep for a specific period of time and wake up every X beacons to listen if there are packets buffered in the AP for them. If there are packets, then STAs send a Power Save Poll Frame (PS-Poll) to the AP, requesting for the buffered packets. Automatic Power Save Delivery (APSD) was later introduced to support TxOP and an extension of it, namely Power Save Multi-Poll (PSMP), was proposed in IEEE 802.11n amendment. TWT is proposed for IEEE 802.11ax that was adopted from IEEE 802.11ah [264]. With TWT, STAs wake at specific times to exchange frames with other STAs or an AP. This time or times are agreed in advance between a STA and an AP. TWT also allows STAs not to listen to beacons, which further reduces power consumption.

d: SPATIAL REUSE TECHNIQUES

A completely new mechanism has also been added in the IEEE 802.11ax amendment, namely the introduction of Spatial Reuse (SR) techniques. The main objective is to increase the number of concurrent transmissions within a given area, thus, enhancing both area throughput/capacity and spectrum efficiency. Dynamic Sensitivity Control (DSC) [265], a technique used for tuning CCA thresholds, has been proposed for IEEE 802.11ax devices, where STAs tune CCA thresholds based on beacons' RSSI (received from the associated AP), using a moving average scheme. DSC does not require any additional overhead to be exchanged and it aims at increasing probability of successful transmissions for cell-edge users. The cell-edge users can thus use low CCA thresholds, expanding their carrier range, to reduce the number of hidden nodes. However, an extremely conservative value may lead to spectrum inefficiency due to the exposed node problem and higher probability of a false alarm. The main drawbacks of DSC are that transmission opportunity for cell-edge users further decays due to the extended carrier sensing range and the increased probability of a false alarm. DSC has been extensively studied in residential [266], small indoor [267], [268], and outdoor scenarios [269]. An extension of DSC operating on APs, is presented in [270].

The second spatial reuse technique that is currently included in the IEEE 802.11ax standard, is BSS Color [271]. This feature has been adopted from the IEEE 802.11ah and is based on the PAID feature, aiming at the early identification of the BSS that a frame is transmitted from. The BSS Color scheme uses a 6-bit value carried in HE-SIG field along with the UL_Flag (1-bit value) that identifies the link direction of a frame (i.e. DL/UL). Its value ranges from 1 to 63 and a value of 0 indicates that BSS Color is not used, thus, frame reception follows the legacy procedure. Nodes can abandon reception if a colored frame (Color $\neq 0$) is transmitted by a neighboring BSS, and based on the RSSI, to initiate a transmission to their AP. BSS Color is distributed to STAs during the association stage, while it may change during operation, if color collision is detected. Both BSS Color and UL_Flag features can also be considered power-saving mechanisms, since a color or a link direction mismatch may result to the abandoning of the reception. BSS Color impact on network performance in various scenarios has been evaluated in [269] and [270].

Due to the negative impact of BSS Color on the throughput performance in dense deployments [268] (due to increased interference), a number of enhancements have already been proposed and incorporated in the draft to support this scheme. First, the IEEE 802.11ax nodes are expected to maintain two NAVs; one for intra-BSS (intra-BSS NAV) and one for inter-BSS frames or those frames that cannot be identified (basic NAV). If both NAV timers are zero, the channel is identified as IDLE and BUSY otherwise. Secondly, there is the proposal of a threshold named OBSS Preamble Detection (OBSS/PD), to control the number of concurrent transmissions based on the interference level. It mimics RTS/CTS scheme but without the exchange of control frames. In particular, an inter-BSS frame with RSSI below OBSS/PD, does not update basic NAV, even if the frame duration exceeds current basic NAV. In that way, probability of concurrent transmissions is controlled by the value of this threshold.

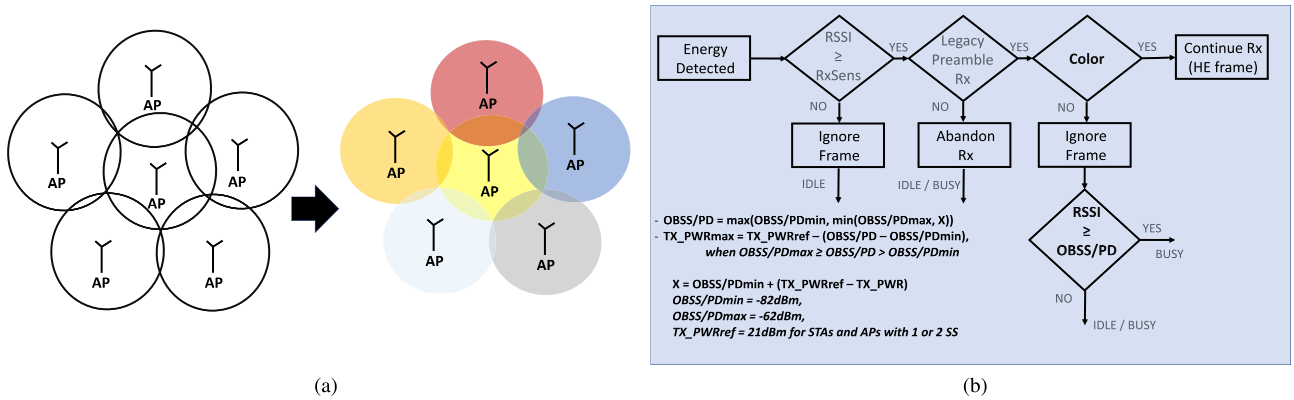


FIGURE 10. IEEE 802.11ax BSS Color a) cell-layout and b) simple flow chart.

It increases with the increase of OBSS/PD threshold, while an extremely low value (i.e. −82 dBm) diminishes the benefits of using BSS Color in terms of transmission opportunity. Lastly, the control of transmit power level through OBSS/PD and vice versa (i.e. control of OBSS/PD threshold through the transmit power level), is introduced in the draft, aiming at controlling the in-band emission interference to neighbouring BSSs. OBSS/PD degrades with the increase of transmit power level. A simple flow chart of BSS Color preamble reception procedure is illustrated in Figure 10.

8) IEEE 802.11af - TVWS AMENDMENT

Although, the IEEE 802.11af amendment is launched before the IEEE 802.11ax (late 2013), it is included after the IEEE 802.11ax due to its: i) different operating frequency (TVWS) and ii) main focus; seamless connectivity in rural environments and low power consumption.

It was introduced as a complementary amendment to IEEE 802.11n that takes advantage of the propagation characteristics of the TVWS spectrum and the additional bandwidth from the unused spectrum of broadcast TV services. One of the main challenges for the IEEE 802.11af amendment (a.k.a. White-Fi) is to guarantee that licensed services are not interfered by its operation [300]. Therefore, new entities were defined in the standard to support the coexistence of IEEE 802.11af (54 MHz 698 MHz in USA, and 470 MHz 790 MHz in Europe) and TV broadcast services.

First, a Geolocation Database (GDB), containing the allowed frequencies and the operating settings for the White Space Devices (WSDs) has been introduced in the IEEE 802.11af amendment. The available frequency bands along with the operating parameters are subjects to country/location specifics. GDB operation can be either open-loop or closed-loop. The former is mainly used in USA, where GDB provides scheduling information every 48 hours, thus, conservative transmit power levels are considered. The latter is used in Europe and provides updates about the channel availability every 2 hours.

Secondly, the purpose of the Registered Location Secure Server (RLSS) is to maintain and provide the GDB information for a smaller area, e.g. small BSS.

Lastly, the Geolocation Database Dependent Entities (GDD) has been defined, which includes the APs and STAs, known as GDD-Enabling STAs and GDD-Dependent STAs, respectively.

The White Space Map (WSM) contains information about the available channels and the maximum transmit power that can be used in each one, based on the location. It is shared between the GDD-Enabling STAs and GDD-Dependent STAs through the Registered Location Query Protocol (RLQP), enabling STAs to effectively select the allowed channels, bandwidth, transmit power etc. GDD-Dependent STAs can also request this information (RLQP) from the RLSS, by sending a Channel Availability Query (CAQ) frame. On the other hand, the GDD-Enabling STAs request for the Channel Scheduling Management (CSM) either from RLSS or other GDD-Enabling STAs to obtain information about the available channels. Contact Verification Signal (CVS) is transmitted by the GDD-Enabling STAs to identify any GDD-Dependent STAs in their proximity. Moreover, the CVS allows the GDD-Dependent STAs to ensure that the signal was transmitted by a valid GDD-Enabling STA.

The GDD-Enablement is called the procedure where GDD-Enabling STAs transmit beacons in the available channels to establish a communication link with GDD-Dependent STAs. Three states are defined for the GDD-Dependent STAs; Unenabled, Attempting GDD-Enablement, and GDD-Enabled. In the Unenabled state, WSDs passively scan the available channels to detect a beacon. A WSD enters the Attempting GDD-Enablement state during authentication/association procedure, while it becomes GDD-Enabled when the association with the corresponding GDD-Enabling STA has been established. The last mechanism defined in the standard is the Network Channel Control, which allows WSDs to exchange information about nearby transmitters and their emissions footprints.

IEEE 802.11af adopts most of the IEEE 802.11ac features in PHY and MAC layer [301], [302]. It is interesting to mention that three Basic Channel Units (BCUs) have been defined in IEEE 802.11af, depending on the country and spectrum availability.

IV. TECHNOLOGICAL SOLUTIONS FOR M2M COMMUNICATIONS

The ability of objects to communicate through internet without requiring human interaction, is referred as Internet of Things (IoT). The direct communication among these devices is known as Machine-Type-Communications (MTC) or M2M communications. The needs of market and industry to automate most of their process (i.e. real-time monitoring) has led to the exponential growth of the number of devices connected to internet. Emerging services, such as remote health care or learning, smart grid, and smart cities where information is efficiently collected through sensors (e.g. traffic conditions, waste collection etc.) are some of the new scenarios considered for 5G networks.

MTC will enable a plethora of applications and increase the number of devices connected to internet to millions or even more, with most of them require adequate coverage and low bandwidths to transmit small sized packets. Various standardization bodies e.g. IEEE, IETF, and 3GPP, have defined technologies to support IoT networks, with Long-Range (LoRa) [272], SigFox [273], IEEE 802.15.4g/e, IEEE 802.22 (Wi-Far), NB-IoT, IEEE 802.11ah etc. among the most well-known standards. In the following paragraphs, we provide a brief description of the technologies developed outside 3GPP and IEEE 802.11, for supporting MTC. A detailed overview of the efforts in 3GPP and IEEE 802.11x driven by MTC is presented in the next two subsections.

LoRa Wide Area Network (LoRaWAN) is a Low-Power Wide Area Network (LPWAN) technology specified to wireless battery-operated devices [274]. It operates in the Sub-1 GHz band and supports rates of up to 50 kbps and supports up to 10k devices with a single BS [275], providing up to 10 km coverage. On the other hand, SigFox, supports up to 1 million devices and provides coverage up to 50 km in suburban areas. It also, enables low energy consumption in the Sub-1 GHz spectrum. However, it provides even lower data rates than LoRaWAN (below 1 kbps).

Wi- Smart Utility Networks (Wi-SUN) consortium, established in 2011, and uses the IEEE 802.15g/e for PHY and MAC, respectively, to enable efficient management of utility services; water, gas, electricity. The Wi-SUN standard PHY layer supports three different formats; Multi-Rate Frequency Shift Keying (MR-FSK), MR- Offset Quadrature Phase Shift Keying (MR-O-QPSK), and MR-OFDM for higher data rates (i.e. from 2.4 up to 800 kbps [276]), capable of accommodating thousands of users. The IEEE 802.15.4m is another/competing standard, enabling data rates of up to 2 Mbps. It operates between the 54 and 862 MHz frequency spectrum and supports three PHY formats; FSK, OFDM, and NB-OFDM. Since most of the channels in those frequencies (TVWS), are 6 to 8 MHz wide, NB-OFDM allows the support of multiple users by dividing channels into sub-channels. Another IEEE (other than IEEE 802.11x) technology, using the TVWS bands is the IEEE 802.22, known as Wi-FAR. It is a standard for Cognitive Radio-based Wireless Regional Area Networks (WRANs) for providing broadband wireless access over large areas. It offers rates of up to 28 Mbps for an 8 MHz channel bandwidth and is suitable for use cases, such as cellular offloading, small office/home office, homeland security etc [277].

The main drawbacks of the aforementioned technologies are: i) only able to offer low data rates and operate in unlicensed bands, which makes them susceptible to interference and ii) unable to meet QoS requirements, such as high reliability and high energy efficiency. On the other hand, cellular systems can overcome those issues due to the controlled access that they offer. Moreover, LTE is a technology widely developed, offering wide coverage, high capacity, and flexibility [278], [279]. However, the enormous number of devices and diverse traffic types pose some challenges for cellular systems, as we explain in the following section.

A. 3GPP LTE ENHANCEMENTS FOR M2M COMMUNICATIONS

Although, a first study for MTC in 3GPP, began in 2007 [280], standardization activities only started in 2010 with Rel-10 (System Architecture Group 2 (SA2) focused on MTC initially). At about the same time, the European Telecommunications Standards Institute (ETSI) and other standardization bodies (e.g. OMA, ATIS, CCSA) started studying MTC with respect to service architecture [281].

Two types of MTC scenarios were initially defined in 3GPP; device to server and device to device through a cellular network. However, only the former was originally covered in 3GPP Rel-10. MTC services are characterized by static/low-mobility nodes, infrequent small size data transmissions, and secure connections.

Right from early stages it was realized that the main challenges for MTC services were the signaling overhead and network congestion due to massive number of devices. Therefore, 3GPP focused on addressing the overhead in C-Plane, since congestion in U-Plane is more unlikely to occur due to the advanced technologies used (i.e. CA, MIMO etc.). Approaches that are followed to tackle signaling overhead, include: i) infrequent Tracking Area Updates (TAU), due to low-mobility, ii) pull-based scheme to trigger MTC devices, iii) grouping MTC devices based on their features, iv) aggregating short messages for delay-tolerant services or when groups of MTC devices are formed, and v) support of grant/forbidden periods.

An overview of scheduling techniques used to cope with the massive number of devices, especially for UL transmissions, is presented in [282]. Although, General Packet Radio Service (GPRS) can be used for M2M communications, when voice users are active in a cell, the number of MTC devices that can be accommodated is limited. To cope with the limited resources in RACH, a new frame structure is presented in [283], supporting 10x more devices/nodes per cell than the standardized LTE/LTE-A frame structure.

One of the first schemes considered and described in 3GPP Rel-10 for addressing the substantial number of devices contending for a preamble, is the Access Class Barring (ACB) [284]. A device generated random is compared against an access probability number that is transmitted by the eNodeB. If the device generated number is higher than the access probability, then a device will access the channel. In that way, eNodeBs can control congestion by tuning the access probability i.e. a high access probability setting leads to low congestion but high delays, whilst a small one may result in consecutive preamble collisions that may in turn cause in extensive delays.

Other mechanisms that have been studied by 3GPP, include: i) Extended Access Barring (EAB), where delay-tolerant MTC devices do not contend for preamble, ii) dedicated slots in RACH for MTC devices, iii) Prioritized Random Access (PRA), where each group of MTC devices applies different back-off, iv) dynamic allocation of Random Access resources, which may result to low data rates, and v) only the leaders from the groups to collect traffic and contend for access in the medium [285]. Furthermore, the importance of prioritizing Human Type Communications (HTC) during the Random Access has also been studied [286].

Two new entities have been defined in 3GPP to support M2M communications; Service Capability Servers (SCS) that connect MTC application servers to a 3GPP network and MTC-Inter-Working Function (MTC-IWF) that resides in the Home Public Land Mobile Network (HPLMN) and forwards or translates signaling protocols to enable specific functionalities in PLMN [287]. An MTC-IWF can be connected to multiple SCSs. The support of D2D communications and NFV, allowing virtual machines to carry the burden of high complexity, can be used to further enhance MTC communications.

New MTC scenarios and a new device category, namely UE category 0, were introduced in 3GPP Rel-12. To further reduce complexity and power consumption, UE Cat-0 was the only UE category to allow the support of single antenna. However, the improved efficiency in power consumption, comes at the cost of worse performance (approx. 5 dB) [287]. A new type of Half-Duplex operation (Type-B) is also considered for UE Cat-0 to further lower the cost and complexity of MTC devices. In particular, devices that belong to that category, are not allowed to skip the last OFDM symbol when switching from DL to UL transmissions as LTE devices do, due to time advance. In that way, MTC devices can reuse oscillators between receptions and transmissions. Power-Saving Mode (PSM) allows devices to remain registered in the network even when they cannot be reached by the network. It is similar to powering off, allowing devices to re-establish connectivity with eNodeBs, only when they have data to transmit.

Further enhancements for MTC are also provided in the releases following 3GPP Rel-12. In particular, Rel-13 introduced enhanced MTC (eMTC), aiming at further reducing the device cost, extending coverage, and improving energy consumption. Only the minimum LTE carrier bandwidth, i.e. 1.4 MHz with 6 RBs of 180 KHz was supported. Moreover, repetition in DL and UL (PUSCH) subframes was used to improve coverage [288]. Data or control channels can be repeated for multiple subframes. Moreover, Power Spectral Density (PSD) boosting in UL and relaxing the requirement on probability of missed detection for PRACH, were introduced to improve coverage [289]. Reduced maximum transmit power and support for simultaneous reception of multiple transmissions were also part of that release. Retransmissions are asynchronous and rely on HARQ, while frequency hopping among narrowband channels and longer transmission time that allows additional energy to be accumulated at the receiver were also included in Rel-13.

Narrowband IoT (NB-IoT) is an LPWAN technology introduced in Rel-13. Operating on a 180 kHz channel bandwidth, NB-IoT is characterized by peak data rates of less than 200 kbps, and limited mobility, an even lower power consumption and component cost. NB-IoT only supports FDD (unlike eMTC) and supports three types of communications; in-coverage, outside-coverage by using GSM carriers, and guard-band, where NB-IoT channel is placed in the Guard Band of LTE-A channels. The narrow bandwidth enables multiplexing more users in the same bandwidth in UL direction.

On the other hand, the minimum resource allocation unit is set to one subcarrier for NB-IoT nodes. Moreover, two subcarrier spacing are supported in UL; short (3.75 kHz) and the one used also in DL (15 kHz), while frequency hopping is also supported in PRACH. To meet the requirements for extended battery life (over 10 years), DRX cycle for NB-IoT devices, is extended from 2.56 seconds to approximately 3 hours [290]. A comparison between the in-coverage and outside-coverage was conducted in [291], showing that the latter scenario outperforms the former one, in terms of battery life extension, latency, and coverage.

Positioning enhancements, support of new UE categories with even lower power consumption, increased voice coverage for LTE MTC, single-cell multicast, and mobility improvements for enhancing service connectivity were the main advancements proposed in 3GPP Rel-14. Due to the power-consumption constraints, achieving less than 50m accuracy is challenging, especially in dense deployments where the low signal strength and high interference level make it even more difficult to obtain a good resolution of the time of arrival [296]. Frequency hopping was also studied for enhancing position accuracy, a scheme that can provide accuracy below 50m for a small number of hop impairments [297]. Multicast transmissions improve networks' efficiency and add more flexibility for use cases where multiple devices require synchronous control, firmware upgrades etc.

Advancements for improving power efficiency by reducing the time that UEs monitor DL channels in idle mode, new use cases including wearables devices, and support for standalone operation are under consideration for 3GPP Rel-15 [292]. Further enhancements for mMTC scenarios that are under development for Rel-15 include: higher spectral efficiency, TDD support, latency support of at least 10 seconds, coverage enhancements, and support of 1 million devices per square km [293]. The support of additional bands for UE categories M2 and NB2 [294], while coverage enhancements in UL include the support of higher transmit power level in cases such as emergency services in rural environments [295] are under consideration in Rel-15. One of the latest techniques proposed in 3GPP, is the Early Data Transmission (EDT) [298]. It aims to reduce latency by allowing data transmissions in UL, even before RRC connection setup is complete (i.e. during Random Access). However, EDT may fail if radio quality changes, due to lack of channel estimation. The FANTASTIC-5G [299] is also a project developed by 5G-PPP Phase 1, focusing on massive MTC access and connectivity solutions. New access-scheme protocols for reducing signaling overhead and waveforms for asynchronous transmissions in UL were proposed in that project and contributed to the 5G standardization framework.

B. IEEE 802.11 ENHANCEMENTS FOR M2M COMMUNICATIONS

To support IoT applications, IEEE 802.11 family introduced the IEEE 802.11ah amendment (Ha-Low) in the Sub-1 GHz band (755 MHz 928 MHz) [264]. IEEE 802.11ah takes advantage of the favorable propagation characteristics that low frequencies offer, to provide long-range communications with low power consumption, in order to satisfy one of the requirements for IoT applications.

The IEEE 802.11ah looks more like a legacy Wi-Fi technology due to the absence of licensed-spectrum services in those frequencies. It supports even smaller bandwidths than IEEE 802.11af; 1 / 2 / 4 / 8 / 16 MHz with 1 and 2 MHz most common in Europe, while an offset of 0.5 MHz in channelization is used in South Korea to prevent interference with other wireless systems [303]. The main aim of this technology is to fill the gap of WPAN and LPWAN systems by providing adequate coverage (up to 1 km) and high data rates (peak data rates of 347 Mbps). Therefore, IEEE 802.11ah facilitates the support of various wireless technologies, by acting as backhaul network.

1) PHY LAYER

The PHY layer specification in IEEE 802.11ah follows the IEEE 802.11ac amendment but with a down-clocked operation. For example, channel bonding is supported for 1 MHz channels to form 2 / 4 / 8 or 16 MHz (in USA) channel bandwidths. The main usage of 1 MHz channel is to extend range, thus, repetition is also considered (MCS10) to further improving coverage [304]. Even though, the channel bandwidth is doubled, the data subcarriers per OFDM symbol is more than double, due to the removal of the redundant guard band when channel bonding in contiguous bands is performed. Other PHY characteristics and a comparison of PHY characteristics between different IEEE 802.11 technologies are listed in Table 2.

2) MAC LAYER

Since inter-operability with legacy IEEE 802.11 is not required, the MAC header size in IEEE 802.11ah is reduced (by up to 20 bytes), by replacing address fields with AID values and moving some fields to PLCP header or completely removing them. One of the fields that has been removed is the Duration field, which enables a new mechanism to replace NAV when short header is used. The Response Indication Deferral (RID) mechanism, works similar to NAV, but instead of providing accurate duration for an ongoing transmission, it estimates duration from the information included in the PLCP header.

Moreover, ACKs may be sent without a MAC header, but include some useful information in their PLCP header. Those ACKs are known as NDP MAC frames [305]. Bidirectional TxOP is a feature based on the IEEE 802.11n RDP, allowing two nodes to exchange data frames within the same TxOP. However, it differs from the RDP, as the nodes may respond with data frames instead of ACKs, further reducing overhead. In particular, all PPDU frames are marked as frames that do not need to be acknowledged, but the last one. The last PPDU may require an immediate response, where in that case, the recipient must respond with an ACK.

3) POWER CONSUMPTION EFFICIENCY

To reduce power consumption for STAs, the IEEE 802.11ah amendment enhances the power-saving mechanisms of legacy IEEE 802.11, by introducing TWT (described for the IEEE 802.11ax amendment). IEEE 802.11ah also extends the maximum idle period of the devices to further improve energy efficiency. In legacy IEEE 802.11, the maximum idle period where a node can be inactive before the AP disassociates it, is a 16-bit field, corresponding to $(2^{16} - 1) * 1000 * TimeUnit = 18.64$ hours, where $TimeUnit$ is $1024\mu s$. In IEEE 802.11ah, the two most significant bits of that field identify the scaling factor, while the remaining 14 bits are used as in the legacy one. The maximum idle period equals to $((2^{14} - 1) * 1000 * TimeUnit) * ScalingFactor = 46600$ hours, where the values of $ScalingFactor$ are 00, 01, 10, and 11 corresponding to 1, 10, 1000, 10000, respectively.

The main challenge is how to accommodate all this information in a beacon frame, make it available to STAs. To address this issue, IEEE 802.11ah enhances the Traffic Indication Map (TID) mechanism by introducing the page segmentation. Now, APs split the whole information (partial virtual bitmap) into consecutive beacons. For example, APs include the buffer status of grouped packets in the first beacon (Delivery TIM DTIM), and afterwards they include the TIM information specific to a group of STAs, in the beacons. However, STAs that do not support TIM (non-TIM STAs) may stay in doze state for longer and wake whenever they have packets to transmit. Color scheme (also described for

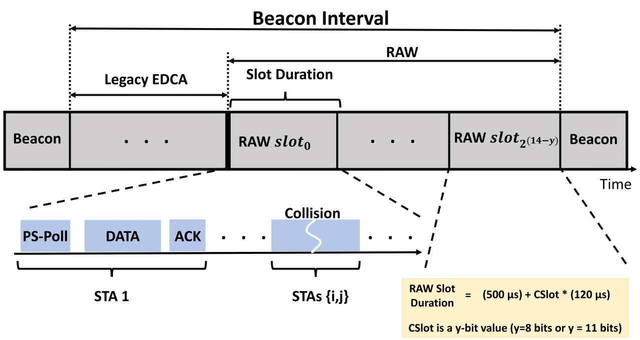


FIGURE 11. IEEE 802.11ah restricted access window (RAW).

IEEE 802.11ax) was initially introduced here, but is restricted to a 3-bit value due to the need of small overhead and sporadic traffic. Moreover, APs may assign Multicast-AIDs to different user groups, to address the issue of energy consumption when all nodes stay awake to listen to broadcast messages.

In case that a BSS operates in a large bandwidth channel, while some STAs support smaller bandwidth channels due to energy consumption, IEEE 802.11ah defines the Subchannel Selective Transmission (SST) mechanism. SST allows nodes to use subchannels instead of the whole bandwidth. It also provides flexibility to STAs, as they can select which subchannel is the best for them, which is achieved by periodic transmissions of sounding frames from APs. Multi-hop transmissions (relays) are also supported in this standard, but the number of hops is currently limited to 2. By using this technique, further reduction in power consumption is achieved. To cope with the increased delay and overhead that a relaying scheme introduces (a frame is sent over two channels), the concept of TxOP sharing was introduced. According to that feature, a relay instead of transmitting an ACK back to a STA after SIFS, it sends the data frame after SIFS, directly to the AP. The source-STA that detects this data frame (omnidirectional transmissions), will identify by the PAID value that its transmission was successful.

4) ADVANCED TECHNOLOGIES FOR SUPPORTING MASSIVE NUMBER OF DEVICES

To support enormous number of users, the AID feature has been enhanced in IEEE 802.11ah. In legacy IEEE 802.11 technology, the maximum number of users that can be accommodated is limited to 2007 due to AID range [1-2007]. By using a hierarchical AID, IEEE 802.11ah can support up to 8191 users. It comprises different fields corresponding to different STA groups. The amendment also describes two access schemes; legacy EDCA and Restricted Access Window (RAW), illustrated in Figure 11. The latter is used to reduce collisions due to large-number of STAs and provide support to densely deployed IoT scenarios [306]. It is based on TDMA, where slots are specifically defined for different users or group of users. In each slot, STAs contend following EDCA procedure, hence, two different sets of EDCA are used; one backoff counter for outside RAW and one for RAW period. To better utilize channel resources, APs may allow transmissions to exceed a RAW slot. Long RAW slot durations lead to higher throughput, but also increase latency, as users need to wait longer time for their slot to come [307]. However, a dynamic RAW slot duration based on the number of STAs in each group and their requirements could improve both throughput and latency [308].

Fast Association and Authentication were also specified in IEEE 802.11ah standard, to cope with the case where thousands of users need to re-establish connectivity with an AP, after a power outage. Two methods are defined; the centralized authentication control and the locally authentication control. In the former case, an AP randomly selects a number from the range [1, 1023], called Authentication Control Threshold, and includes it in a beacon. STAs compare the Authentication Control Threshold to a number that they have randomly chosen from the range [1, 1022]; if the number is lower than the Authentication Control Threshold, they proceed to authentication, otherwise they defer their transmission. In the latter one, STAs randomly draw two number that correspond to a beacon interval and a slot, respectively, where the authentication process will be initiated (following EDCA rules). Apart from RAW scheme to group users, IEEE 802.11ah defines an alternative approach with lower complexity, namely Group Sectorization. During this operation, APs transmit sectorized beacons following the IEEE 802.11ad procedure. Those advancements in IEEE 802.11ah can lead to low energy consumption, high reliability and throughput, low delay, and capability of accommodating hundreds of users, which make it suitable for indoor or outdoor MTC scenarios [309].

V. CONCLUSION

In this article, we overviewed the MAC and PHY layer features being considered by the two main family of standards, namely 3GPP and IEEE for adoption in the fifth generation (5G) systems. As we stand on the verge of a new digital era, where all devices/things will be connected through internet, the cellular and Wi-Fi technologies are evolving and merging into a unified system to provide a seamless connectivity, reliability, and high data rates. Massive connectivity, advanced multi user techniques, power efficiency, network slicing, edge computing, and new frequency bands, e.g. mmWave and Sub-1 GHz bands are among the features that are being studied and evaluated but as highlighted in this article, many challenges remain that are being addressed within the standardization bodies and the wider research community to allow full exploitation of 5G technologies.

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IOANNIS SELINIS received the B.Sc. and M.Sc. degrees from the University of Piraeus, Greece, in 2011 and 2014, respectively. He is currently pursuing the Ph.D. degree in electronic engineering with the Institute for Communication Systems 5GIC, University of Surrey. He is currently a Research Fellow with the Institute for Communication Systems 5GIC, University of Surrey. His main research interests include wireless communications and networking, and performance evaluation and design of MAC protocols.

KONSTANTINOS KATSAROS received the M.Sc. and Ph.D. degrees in electronic engineering from the University of Surrey in 2010 and 2014, respectively, and the university degree (M.Eng. degree equivalent) in electrical and computer engineering from the University of Patras, Greece, in 2009. He was a Post-Doctoral Research Fellow at the Institute for Communication Systems 5GIC, University of Surrey, where he was involved in the mobile edge computing for connected and autonomous vehicles. He joined Digital Catapult as a 5th Generation (5G) Technologist in 2017. He provides oversight and guidance on specific 5G system architecture and subsystem implementations to Digital Catapult Projects, especially around new architectures using virtualization and slicing, and assists with the development and delivery, especially using the experimental network infrastructure run by Digital Catapult. He has published several peer-reviewed papers and holds two patents. His research has been focused on connected and autonomous vehicles and the development of ultra-low-latency, highly reliable, and secured 5G communications and mobile edge computing technologies for the connected and autonomous vehicles and cooperative intelligent transport systems. He has participated in several European and U.K. funded projects.

MARION ALLAYIOTI received the M.Eng. degree in electronic engineering from the University of Surrey in 2013, and the Ph.D. degree in RF engineering from the Institute for Communication Systems 5GIC, University of Surrey, in 2017. In 2017, she joined Inmarsat as an Engineer in operations. Her research interests include beam reconfigurable antennas, polarization reconfigurable antennas, low profile antennas for wireless and mobile communications, and antennas for millimeter wave frequency applications. She received the IEEE Second Year Communications Price in 2011 and The DTI Radio Frequency Engineers Education Initiative Prize in 2012.

SEIAMAK VAHID received the M.Sc. and Ph.D. degrees in electrical and electronic engineering from Kings College, University of London, and University of Surrey, in 1987 and 2000, respectively. From 1988 to 2000, he was a Research Fellow at the Centre for Communications Systems Research, University of Surrey, U.K. From 2001 to 2010, he was with the GSM Networks Division, Motorola UK, as the Team Leader and later as a 3G/LTE System Architect and Product Security Specialist. In 2010, he joined the Institute for Communication Systems 5GIC, University of Surrey, as Senior Research Fellow. His research interests include cognitive radios, communication systems modeling, multiple access, resource management, optimization techniques, and their applications to cellular and ad hoc wireless communication networks. He is currently the Technical Manager of the SPEED-5G project, funded by the European Commission Horizon 2020 Framework Programme.

RAHIM TAFAZOLLI is currently a Professor of the mobile and satellite communications and also the Director of the Institute for Communication Systems 5GIC, University of Surrey, U.K. He is regularly invited to deliver keynote talks and distinguished lectures at international conferences and workshops. He has been active in communications research for over 25 years. He has authored and co-authored over 600 papers in peer-reviewed international journals and conferences, and holds over 30 granted patents all in the field of digital communications. He is a fellow of the Wireless World Research Forum.